For professionals in shipbuilding, offshore and marine industry
Welcome Message

The Chinese Society for Internal Combustion Engines, as the National Member of CIMAC, has the pleasure of organising the 27th CIMAC World Congress on Combustion Engines, scheduled for May 13th - 16th, 2013 in Shanghai, China.

CIMAC is a vigorous and attractive organisation, which brings together manufacturers, users, suppliers, oil companies, classification societies and scientists in the field of engines. With more than 60 years of diligent, effective and valuable work, CIMAC has become one of the major forums in which engine builders and users can consult with each other and share concerns and ideas.

The Congress will be devoted to the presentation of papers in the fields of marine, power generation and locomotive engine research and development, covering state-of-the-art technologies as well as the application of such engines. Moreover, the event will provide the unique opportunity to meet colleagues and customers from the industry around the world.

Located in the Yangtze River Delta and situated by the East China Sea, Shanghai is the biggest industrial and commercial city in China and also a famous international metropolis. Shanghai showing its own unique makings, ancient and modern, Eastern and Western, and traditional and fashionable, attracts more than 8 million visitors from all around the world every year. Shanghai is very easy to reach with thousands of flights in its two international airports every day, which connect more than 200 cities in the world. In fact, Shanghai hosts hundreds of international exhibitions per year.

The Congress will be held at the Shanghai Exhibition Centre, located in the heart of downtown, a perfect venue for conferences, exhibitions and large-scale events. A well-developed transportation system in the city ensures you a convenient way to explore the fantastic and unusual places at your leisure.

With 194 papers to be published during 48 presentation sessions, 125 papers to be presented in three poster sessions and an exhibition covering an area of 2,500m² to be held simultaneously during the Congress, all the numbers will reach new records high.

The 2013 Organising Committee sincerely invites you to the 27th CIMAC World Congress on Combustion Engine Technology and we are looking forward to meeting you in Shanghai.

Donghan Jin
President of the 27th CIMAC World Congress
The development of the 51/60DF engine started in 2005. The design of the engine considers the market requirements for marine and stationary applications. Driven by those market requirements, the focus of the development was pointed on efficiency, emissions, fuel flexibility and a wide range of application possibilities. The first prototype engine started its test run in 2006. Since then a process of continues development has been started to optimise engine components and engine parameters to fulfill the custommers demands. In addition, new technologies, like a turbocharger with variable turbine area, were introduced and tested. The first type approval for constant speed application was successfully passed in 2007, followed by the order of inline engines for a 174.000m³ carrier delivered in December 2008 to the customer. Up to now more than 50 V-type newbuilt and retrofit engines for stationary power plants and 20 inline engines for marine applications have been placed to the market. As a result of continues development, MAN Diesel & Turbo SE has opened up the application range of the 51/60 DF engine and successfully passed the type approval for variable speed application in 2012. This gives MAN Diesel & Turbo SE the possibility to offer the 51/60DF for mechanical propulsion with controllable pitch propellers (CPP). One further step to fulfill the requirements for stationary application is the development of a pure gas engine – the 51/60G – in addition to the 51/60DF. The first prototype engine was tested at the end of 2012. The paper will give an overview of the achieved results of the prototype and serial engines operating on liquid and gaseous fuels, the improvements and the new applications of the dual-fuel and pure gas version of the MAN 51/60 engine.

Development of Mitsubishi’s large frame gas turbine for power generation – A new 1,600°C, J-class gas turbine
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Keita Takamura, Mitsubishi Heavy Industries, Ltd., Japan
Satoshi Hada, Mitsubishi Heavy Industries, Ltd., Japan
Junichiro Masada, Mitsubishi Heavy Industries, Ltd., Japan

Mitsubishi Heavy Industries, Ltd (MHI) developed a 1,100°C turbine inlet temperature D-type gas turbine in the 1980s and constructed the world’s first successful large-scale combined cycle power plant. Since then, MHI has developed the F- and G-type gas turbines with higher turbine inlet temperatures, and has delivered these units worldwide, accumulating successful commercial operations. Since 2004, MHI has been participating in a Japanese government-funded project called the Japanese National Project. This project is still ongoing and targets combined cycle efficiencies in the 62 to 65% range through the development of innovative technology. The gas turbine for this project is expected to operate at a turbine inlet temperature of 1,700°C. MHI recently developed a 1600°C turbine inlet temperature J-series gas turbine (M501J and M701J for 60 Hz and 50 Hz respectively), utilising some of the advanced technologies developed in the Japanese National Project. This new frame is expected to achieve higher combined cycle efficiencies and will contribute to reduce CO₂ emissions. The target combined cycle efficiency of the J-series gas turbine will be above 61.5% (gross, ISO standard condition, LHV) and the one-on-one combined cycle output will reach 470 MW for 60 Hz engine and 680 MW for 50 Hz engine. This new engine incorporates:
• A high pressure ratio compressor based on the advanced M501H compressor, which was verified during the M501H development in 1999 and 2001,
• A steam-cooled combustor, which has accumulated extensive experience in the MHI G engine (>1,356,000 actual operating hours),
• State-of-art turbine designs developed through the 1,700°C gas turbine component technology development programme in the Japanese National Project for high temperature components.

The M501J started commissioning in February 2011 at the MHI demonstration plant, T-Point, in Takasago, Japan. Upon completion of numerous commissioning tests including measurement of more than 2,300 temporary data points, and a thorough inspection of the hardware, the unit went commercial on July 1st 2011. As of March 2012, M501J at T-point had accumulated more than 5,300 actual operating hours and 62 starts. The first of six M501Js for a Japanese project was already shipped in December 2011, and scheduled to enter commercial operation in 2013. An additional ten M501Js have been sold in South Korea. The M701J is a 50 Hz-version of the J-series gas turbine. It was designed as a full scale of M501J with useful feedback from M501J operation and test result at T-point. The M701J will be ready for delivery in 2014. This paper discusses the technical features and the updated status of the J-series gas turbine, with particular focus on the operating condition of the M501J gas turbine in the MHI demonstration plant, T-Point.

Upgrading emergency diesel generators at nuclear power plants
Arthur G. Killinger, MPR Associates, Inc, USA
Mark J. O’connell, MPR Associate, Inc, USA

Many nuclear power plants around the world have or will receive extensions to their 40-year licenses in order to operate beyond their original design lives. Important plant safety systems are aging and in need of upgrades or replacement to support continued operation for 20 or more years. Emergency diesel generators (EDGs) in nuclear power plants are critical systems necessary to mitigate the consequences of accidents. The EDGs in nuclear power plants spend most of their time in standby conditions, ready to start and power the emergency equipment necessary to safely shut down the plant. These EDGs typically have operated for fewer than 4,000 hours in those 40 years of service and are often considered to be barely ‘broken in.’ In some cases, there is very little margin between the rated capacity of the EDGs and the connected emergency loads, as the plants have increased their emergency safe shut down loads. The original equipment manufacturers (OEMs) of many EDGs are out of business, and as a result, there are limited technical assistance and spare parts support available. All EDGs in nuclear power plants must meet very stringent quality assurance, design and performance requirements defined by industry and regulatory codes and standards. This paper addresses the technical and regulatory issues associated with the replacement of the two existing EDGs at a nuclear power plant in South Korea with a new EDG design that had not previously been qualified for service in nuclear power plants. It describes the approach used throughout the EDG replacement project, including:
• Evaluating the feasibility of replacement of the EDGs,
• Developing the new EDG design requirements,
• Preparing an EDG procurement specification,
• Working with the EDG vendor to qualify the new EDG (if not already qualified),
• Specifying and performing factory testing of the assembled EDGs.
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Achieving of programmable control and management for the emergency diesel generating sets in thermal power plant

Chang Xi-yan, Henan Diesel Engine Industry Co, Ltd, China
Yang Xun, Henan Diesel Engine Industry Co, Ltd, China

This paper introduces an automatic system that takes HMI (human-machine-interface) and PLC (programmable logic controller) as the core for intellectualised control of the reserve emergency diesel gensets in thermal power plant. The system was constituted by network communication electric power system process control-related technologies. Set diesel gensets the operation monitoring control protection measurement remote control for an organic whole, realise the emergency diesel genset control system and the power plant in central control system of comprehensive management of the power system, provided good work independence with high reliability stable performance, strong practicability etc. characteristics, the application of electric power operation can greatly improve the quality and reduce maintenance costs.

Monday May 13th / 13:30 – 15:00 Room B
Component and Maintenance Technology
Bearings, Valves

New bearing concepts to fulfil application-related challenges for future engines

Rainer Aufischer, Miba Bearing Group, Austria
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Jenny Qiang, Miba Precision Components (China) Co, Ltd, China

Engine development is being driven by environmental considerations, tightening emission regulations, fuel economy and availability in combination with economical boundary conditions. It is within this framework that new approaches in bearing material, design and production are needed. New engine families with increased firing pressures are designed to fulfil these requirements. The change in bearing loading and rough running conditions can be met by tailor-made bearings with special performance characteristics. The high firing pressure in combination with a much wider pressure range for gaseous fuels in combination with misfiring will on the one hand change bearing hydrodynamic loading and on the other hand increase cyclic deformation of the bearing structure. Additional features like robustness of bearing types against disturbances as dirt contamination, oil starvation and corrosion are required in combination with extended oil drain intervals and bearing life. In two-stroke applications, dimensional growth leads to exceptional high dry turn loads in assembly and cross production limits of bearing production with standardised and robust production processes. In smaller bearings, a concept to combine different bearing layers is used. The whole multi-layer composite with the bearing back for improvement of the assembly situation, the lining material to gain higher fatigue strength without losing all the tribological properties and overlays for short term emergency conditions and to compensate for the loss of tribological performance in other layers was re-designed. This approach of combining different performance criteria in different layers or areas is also applied in the patch work bearing for two-stroke engines. Not only to fulfill the demand for large bearings with standard material production processes, but also to combine different performance characteristics in different bearing areas, segments can be combined to larger and more robust bearings. For the mentioned bearing concepts the working principles are described and internal validation and base production principles are shown. According to the internal test results and the first engine results, the development targets have been met. Based on engineering and simulation, the bearings can be adapted to the special conditions in specific engine applications. Development and internal test results as well as engine experience will be presented along with possible bearing configuration.

A study on surface protrusion of welding type Sn-Sb-Cu plain bearing for marine engine

Jong-Hyun Hwang, Hyundai Heavy Industries, Co, Ltd, South Korea

The typical plain bearing alloy, Sn-Sb-Cu alloy, is being overlaid on the carbon steel backing metal by either casting or welding. Overlay welding type bearing is a competitive alternative to casting type in terms of higher bond strength and lower cost. Surface protrusion phenomena at the running surface of welding type bearing were occasionally observed after engine operation. Occurrence of protrusion phenomena were simulated as a function of dehydogenising treatment, preheating before welding and postheating after welding. It was found that the protrusion of the weld overlaid bearing surface was closely related to diffusion and build-up of hydrogen from the backing steel.

Improving safety of engines in service by continuously monitoring big-end bearings temperatures

Patrice Flot, CMR Group, France
Alain Meslati, CMR Group, France

In order to stay ahead of their competition, engine builders are permanently reducing manufacturing cost by various means, either by improving manufacturing processes through procurement efforts, or technically by using the latest design and calculation tools made available with the most advanced computer aided systems. Cost is mainly related to weight of the engine, where the sales price is related to mechanical power produced by the engine. The customer is effectively buying power output, when engine builder is paying for weight of materials needed to build the engine. This is why, for many years, engine designers have been increasing power density or the power-to-weight ratio. The typical methods for most of the engine builders to achieve higher power density is to increase power output of an existing engine, step by step, just by slightly modifying the engine. Power is a result of engine rotation speed and torque. But increasing rotational speed faces limitations on mean piston speed, plain bearing peripheral speed, inertia of pistons and connecting rods, and spring systems for valves, so limited progress has been made that way. Increasing torque or BMEP (brake mean effective pressure) has always been, and still is, preferred. There are existing methods to increase the flow of air and fuel, thanks to more efficient turbochargers, and modern fuel pumps delivering higher injection pressures, along with common rail technology. As a result of increased BMEP, the maximum combustion pressure and consequently the peak pressure on the bearings have been dramatically increased. By optimising the bearing design and using better materials for bearing shells, both engine builders and bearing shell manufacturers have been successful at managing bearing pressure increase and reduced oil film thickness. However, during engine service, the slightest maintenance mistake
will result in much higher risk of catastrophic failures. Additionally, end users want to save time on maintenance, and to reduce skill requirements of their maintenance teams; all resulting in higher risk. Thus, to reduce maintenance constraints and mitigate associated risks, engine builders are looking for methods to monitor bearing conditions. Not only high-speed and medium-speed engine builders are concerned, but also low-speed engine builders (although low speed engines do, historically, show high reliability of their bearings). To satisfy this increasing demand, a new sensor, called TB3, has been designed for monitoring the temperatures of moving parts inside the engine, such as the connecting rod big end bearings. Design of the TB3 sensor boasts short response time, easy installation, simple maintenance and low cost in order to be standardised on series engines above 200mm bore. The TB3 sensor is based on the well-known SAW (surface acoustic waves) technology, which has been specifically engineered and patented for serving the purpose of measuring the temperature of moving parts inside engines. Compared with other commercially available protection devices, the TB3 sensor is a technological breakthrough allowing wireless signal transmission up to 1m distance inside the engine. The sensor system is made of several dynamic sensors fitted on the moving parts, and only one large antenna fixed to the crankcase wall inside each cylinder compartment. The large antennas are directly communicating with the ECU by simple connection to the CAN bus line existing on the engine, thus reducing the cost of wiring system outside the crankcase. The paper will review today’s bearing challenges and protection devices. After a quick look at wireless sensors, it will describe TB3 sensor hardware and software technologies, and expected advantages on industrial engines, in regards to installation design, service, and safety.

Future HFO/Gi exhaust valve spindle
Uffe D. Bihlet, MAN Diesel & Turbo SE, Denmark
Harro A. Hoeg, MAN Diesel & Turbo SE, Denmark

State of the art for exhaust valve spindles for large two-stroke heavy fuel diesel engines is currently either a fully forged Nimonic 80A version or a cost-effective version based on an austenitic valve steel weld coated by a specially hardened Inconel 718 seat hardfacing and Inconel 625 disc coating. These three alloys, originally developed more than 50 years ago for the gas turbine and process industry, show comparable corrosion resistance at usual heat load. The general trend in engine design is steadily pushing combustion chamber component temperatures towards higher levels and the hot corrosion resistance of these alloys is currently being tested to the limit. Furthermore, operation on LNG will bring new challenges. Indeed, it would appear that there is much room for improvement as no focused alloy development has been performed aimed at the special conditions found on the thermally and mechanically stressed parts of the exhaust valve spindle. In the present work, new coating alloys, meeting the requirements for the future valve spindle, have been developed by combining literature study, service experience, experimental data and numerical thermodynamic calculations. This paper describes the considerations and results of this alloy development as well as the details of a required new production technique for manufacturing a compound product by the hot isostatic pressing (HIP) technology, which has been developed with advanced finite element method (FEM) modelling.

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Heat
New platform-based common rail injector for MTU series 1163

Clemens Senghaas, L’Orange GmbH, Germany
Marius Ligensa, L’Orange GmbH, Germany
Klaus Reichmann, MTU GmbH, Germany

The successful series 1163, the engine of MTU with the highest power density for marine applications, has to be modified to gain the upcoming emission standards. Up to now, the engine has been equipped with an established pump line nozzle injection system. Since the emissions are essentially influenced by the injection system, some modifications are required. The system needs a more flexible and faster switching with higher injection pressure and also the capability of multiple injections to reduce noise, NOx emissions and soot. The injector, the heart of the new common rail injection system, has been developed by L’Orange in close cooperation with MTU. To reduce development costs and time while achieving highest performance and durability, the injector is based on the third generation of L’Orange’s injection systems for high-speed engines. Since 2011, injectors containing such principles are part of the trend setting fourth generation of the MTU series 4000. The main feature of the injector is the integrated accumulator with the control valve close to the nozzle, known from previous L’Orange injector generations. With an optimised injector design the maximum injection pressure and the capability of multiple injection can be significantly improved. Due to a new control valve design the injector becomes more robust and thereby the injection quantity more stable over the whole lifetime. In a first step, the injector will run with 1,800 bar e.g. for the IMO Tier II requirement. The injected quantity is split in a pilot and a main injection to reduce NOx emissions, fuel consumption and the load of the engine parts. Possibly in a second step, the engine fulfills forthcoming emission legislations. Therefore, the injector is already designed for a maximum injection pressure of 2,500 bar. Additionally, as a new feature, the detection of the beginning and end of the injection will be integrated. This leads to an almost drift-free injector and the possibility to realise minimal injection quantities with highest accuracy. This injector will be another milestone in the long history of L’Orange trend setting innovations. The engine with the new injection system will go in series production in August 2013.

Multi-injection and advanced Miller timing in large-bore C1 engine

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The objective of this paper is to show the results gained from a medium-speed research engine using multiple injection in order to improve the engine performance and especially reduce exhaust emissions. The study is in fact carried out with a single-cylinder large-bore diesel engine (EVE), which is used only for research purposes. Its main feature is that the gas exchange valve timing is completely adjustable with an electro-hydraulic system that uses the engine lubrication oil to open the gas exchange valves. Moreover, the engine does not have a turbocharger, but a separate air compressor supply system that permits to change freely the intake charge air conditions; after the engine, a throttle valve tunes the exhaust back pressure. Many EVE components have been recently upgraded and the engine can withstand high indicated power and peak pressure values. This study includes the comparison between single- and multi-injection timing and the influence on the engine performance. The different injection strategy is also combined with different valve timing: the Miller technique is used in order to reduce NOx, whose regulation is becoming more and more stringent. The research is carried out at high engine load. The in-cylinder compression pressure and the injection quantity per stroke are the parameters that are unchanged in every tested point. The combustion process is analysed and the different setups are compared to understand the influence of the chosen strategy. The results show that it is possible to achieve high NOx reduction but the injection strategy must be chosen carefully with the valve timing.

Fuel injection concept for the future clean diesel engines

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Shusuke Okada, Yanmar Co, Ltd, Japan

Recent progress of fuel injection system like a common rail system makes higher fuel injection pressure possible. With such a state-of-the-art higher injection pressure technology, diesel engines have been improved in all aspects of performance such as higher power density, lower fuel consumption, cleaner exhaust emissions, etc. The injection pressure of latest FIE systems for the heavy duty or passenger car industry reach around 3,000 bar; however, the majority of such high-injection pressure FIE systems is still under development. Their spray characteristics are investigated by using a constant volume vessel, although conditions are different from today’s engines pressure and temperature. Soot and NOx emissions from the engine equipped with such a higher injection pressure FIE are still under investigation. Also, the optimal nozzle dimensions (i.e. number of holes and hole diameter) in accordance with higher injection pressure is still under investigation. In order to estimate the emission performances, CFD coupled with many kinds of submodels about spray combustion is applied as one of the available method. However, a lot of constants in the simulation code have to be calibrated by use of spray measurement data. On the other hand, in this study, soot and NOx emission data from higher injection pressure is estimated by using an engine that is equipped with a practical fuel injection system. And optimised number of holes and hole-diameter for higher injection pressure is estimated. An increase in injection pressure causes an increase in spray penetration and the promotion of atomisation: The higher the injection pressure the less the improvement in atomisation. Thus, in this study, spray penetration is focused on as a main parameter. According to the many empirical models of spray penetration, it is mainly determined by the difference between the pressure of fuel injection and that of ambient gas. Emissions from higher injection pressure under the same excess air ratio is assumed to be obtained by decreasing in-cylinder gas pressure instead of increasing injection pressure for obtaining certain pressure difference that can keep same spray penetration. As for the calculation of spray penetration, this study applied Dents formula (1971). However, under the constant excess air ratio condition, decreasing in-cylinder gas pressure automatically yields to shorter injection duration. In this study, ‘converted injection pressure’ is proposed to estimate how high the injection pressure needs to be without decreasing in-cylinder gas pressure. Converted injection pressure
is calculated by Dent’s formula, whose input is spray penetration experimentally linked with engine out emission. In order to verify the concept of converted injection pressure, two different engines are analysed in this study. At first, a natural aspirated engine with a common rail injection system with a maximum of 1,600 bar is applied for building soot and NOx estimation models. In this engine text, a wide range of emission data is obtained under the various conditions of excess air ratio and pressure difference between injection and in-cylinder gas. The result shows good relationship between converted injection pressure and measured soot. Using this relationship, a soot estimation model can be built and proposed. In terms of NOx, it has a good relationship with injection duration. An NOx estimation model has also been built based on injection duration. Next, a turbo charged engine with maximum 2,000 bar injection common rail system is applied for evaluating this soot and NOx estimation model. It is found that relative changes of measured emissions follow estimated results. But there is a gap in their absolute value because of different combustion chamber shape and direction of nozzle hole axis. Thus, it is found that proposed soot and NOx estimation model is only effective for their relative change against increase in injection pressure. At last, a trend of the optimal nozzle dimensions accompanied with increase in injection pressure is calculated by using soot and NOx estimation models. The result shows that a higher injection pressure requires a larger number of nozzle holes and a smaller nozzle hole diameter.

Development trend and optimised matching of fuel injection system of diesel engine
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The benefit of using Group II base oils in medium-speed engines
Laura Gregory, Infineum, UK

Group II base oils are a category of base oils defined by the American Petroleum Institute as having a sulphur content less than 300 ppm, a saturates content greater than 90% and a viscosity index of between 80 and 120. Group II base oils have been used in automotive lubricants for many years. This was driven by the need to improve performance of the lubricant to meet the demands of new engine technologies. As a consequence, the supply of Group II base oil has been increasing and the capacity of Group I base oil is forecast to decrease. So far, these trends in base oil capacity have left the lubricants for medium-speed marine engines unaffected; such lubricants have historically always used Group I base oils as the diluent for the additive system. With an increasing availability of Group II base oils, there is now a drive to utilise them for medium-speed marine engine applications. The current economic climate is a strong motivator for the shipowner/operator to scrutinise their operation and identify where further cost savings can be made. Hence there is a desire for reduced oil consumption and increased power output. Combine this with increasingly poor heavy fuel oil quality, to which medium-speed engines are sensitive, and it becomes clear that the demands on the lubricant are increasing. This paper discusses whether the use of Group II base oil can go some way to meeting those demands, by providing improved oxidation resistance, viscosity control and lower volatility. An upgrade of these performance features would extend the time before condemning limits for the oil are reached. The capability of these base oils in comparison to Group I is examined in bench and laboratory engine testing. The deployment of a Group II based lubricant in the field, and what benefits have been observed, is discussed.

Cylinder liner and piston ring lubrication issues in relation to increase stroke/bore ratio
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Kazuo Harada, Mitsui Engineering and Shipbuilding Co, Ltd, Japan
Mikio Kotake, Mitsui Engineering and Shipbuilding Co, Ltd, Japan
Christian Lotz Felder, MAN Diesel & Turbo SE, Denmark
Jesper Weis Fogh, MAN Diesel & Turbo SE, Denmark
For the two-stroke marine engines, lubrication of liners and piston rings has always been a field of high interest. Over the years the position and numbers of levels where the cylinder oil is injected, have been subject to many design variants. The issue regarding numbers and positions of the lubrication level is becoming an important subject with the new trend for two-stroke marine engines. The trend towards longer stroke/bore ratio will increase the distance from the injection level leading to longer ‘road of transportion’ of the cylinder oil. A brief summary of lubrication systems used on MAN Diesel engines, and the basic functions of the cylinder oil system is given. The impact of the tribological system from the increased stroke will be discussed. In this paper, service tests with a lubrication level positioned very close to the TDC area is reported in details. The results are compared with a standard execution of the cylinder oil system. Wear measurements and drain oil analysis is used to analyse the effect of different modes of the test unit. In addition to the service test, a simulation of the cylinder liner oil performance is presented. Furthermore, the impact on the oil film thickness in relation to the level where lubrication is injected, and the lubricant transport will be discussed. The later is of great importance in respect to the oil stress around TDC. Finally, the correlation between the service test and the simulations will be discussed.

**Investigation of microstructured cylinder liner surfaces for friction reduction**

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Jan Kaestner, Leibniz University of Hannover, Germany
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Tim Goettsching, Leibniz University of Hannover, Germany

For combustion engines, the specific fuel consumption is significantly affected by friction losses, from which up to 50% can result from the friction of the piston, piston rings and the cylinder. In the consequence of increasing indicated mean effective pressure and maximum cylinder pressure of modern engines, today’s cylinder liner surfaces are exposed to increasing thermal and mechanical loads. To meet these high requirements, the implementation of microstructures is an innovative alternative to adjust the tribological properties. Investigations are presented which innovative microstructures on cylinder liner surfaces have been fabricated and evaluated in a research engine. Two approaches have been followed in a joint research group of the Leibniz University of Hannover. In the first approach, microstructures are machined at the Institute of Production Engineering and Machine Tools. Here axially parallel turn-milling strategies were developed and investigated to machine cylinder liners. By defined feed rates and speed ratios, microstructure-patterns and -geometries can be machined continuously. The average dimensions of the microstructures are 1mm to 2mm in length, 50µm to 100µm in width and 5µm to 30µm in depth. To evaluate the tribological characteristics under fired engine conditions, microstructures are implemented in the low- and high-speed areas of fine-honed cylinder liners. The second approach is based on a microstructured surface, being created by a thermal spray process with defined porosity, which is formed at non-melted or resolidified particles between the spray lamellae, and a subsequent honing procedure. With this process, developed by the Institute of Materials Science, microstructured cylinder liner with defined porosity can be created. The coating material is a mixture of FeCr13 and Molybdenum powder. The layer porosity is controlled by adjustable spray parameters such as spraying distance and current. The experimental analysis of the microstructured cylinder liners is carried out at the Institute of Technical Combustion (ITV) on a heavy duty diesel single cylinder research engine. The determination of friction reduction is done with the ‘Indication Method’ where the friction mean effective pressure (FEMP) is determined from the difference of the indicated mean effective pressure (IMEP) and the break mean effective pressure (BEMP). Due to precise conditioning of the research engine, additional losses of e.g. valve train and main bearing remain constant, so that the influence of surface structure on friction can be evaluated. One figure in the presentation shows the friction effects (presented as FEMP) during a seven-hour run-in programme for a plateau-honed, a fine-honed and two by machining microstructured cylinder liners. The fine-honed liner shows less friction losses in most of the engine operating points (up to -11%), possibly due to the reduced surface roughness. The liner with a fine-honed ground surface and equipped with microstructures in the TDC area shows significantly lower friction losses (-19% in max.). This can be explained by a higher oil capture capability. The liner with microstructures in the hydrodynamic area shows increased friction losses especially in operating points with higher engine speed. This is presumably an effect of a thicker oil film combined with high piston speeds in the hydrodynamic area of the liner, and therefore increasing stress in the oil film. In summary, cylinder liners with microstructured surfaces show a high potential to reduce friction losses in combustion engines. Currently, oil consumption measurements are carried out in cooperation with the Technical University of Hamburg-Harburg, based on a measurement method that uses a mass spectrometer.

**Measurement of piston ring lubricant film thickness in a fired engine using ultrasonic reflectometry**

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Matthias Stark, Wärtsilä Two-Stroke Engines, Switzerland

The lubricating film between piston rings and liners is crucial for correct and continued engine operation. With a worldwide drive to reduce emissions and lubricant consumption in engines, while keeping wear to a minimum, understanding the lubricant film thickness has never been more important. Measurement of lubricant film thickness without disrupting the fluid film has been a significant challenge over the last decades. This paper presents a new technique for measurement of lubricant film thickness based on ultrasonic reflectometry. An ultrasonic sensor is mounted on the back of the component that is to be measured (for example, liner, bearing, piston ring, seal etc). The sensor is excited with a pulse of electrical energy and emits an ultrasonic wave into the components. The ultrasonic wave travels perpendicular to the sensor through the components. When the incident ultrasonic wave interacts with a thin embedded layer (in this case a lubricant film), some of the wave is reflected and some is transmitted. The reflected portion of the wave comes back to the sensor and is converted back to electrical energy. This electrical energy is amplified and acquired by an ultrasonic receiver and digitiser in a PC. The digitised signal is then processed in software to give a measure of the lubricant film thickness. The technique has been applied to a two-stroke diesel engine under fired conditions. Ultrasonic sensors were mounted on the back of the piston ring and connected via cables through a linkage to external electronics. The film thickness over the entire stroke was measured and cyclic variations in the film observed. Results from the experiments are presented and discussed. Ultrasonic reflectometry is demonstrated to be a new technology that has exciting possibilities for many lubricant measurement and monitoring applications.
Operational experiences of DNV-classed gas-fuelled vessels

Thomas Dirix, Det Norske Veritas, Norway

Due to a number of factors, e.g. the increase of the price for fuel oil, air emission regulations and ‘pollution taxes’, the number of vessels using LNG as fuel has increased remarkably in the last few years. Many operators of ‘gas engine vessels’ have chosen to classify their vessels with Det Norske Veritas, thereby confirming the leading role of DNV in the field of rule development for gas-fuelled vessels. The DNV fleet now includes about 30 gas engine driven vessels, having approximately 100 gas engines installed, with contracts for another 40 plus vessels signed. With the oldest engines already in operation for more than ten years, the time seems suitable for an evaluation of experiences with this, after all, relatively young technology and, perhaps, recalibrations of the various applicable regulations. The DNV classified gas engines – both gas only and dual-fuel – are installed on board approximately 30 vessels. These vessels can roughly be divided into three different groups:

- Ferries and patrol vessels equipped with gas only engines,
- Offshore support vessels operating dual fuel engines on LNG bunkers,
- LNG tankers operating dual-fuel engines.

Besides the fact that these three groups all have different operating profiles, they also use two different types of gas engines produced by four different engine manufacturers, and, last but not least, different sources of LNG. However, all vessels have in common that they have electric propulsion motors, i.e. all engines are driving generators. This paper will address, with the support of damage statistics, the experiences gained so far by the various operators of gas engines, experiences with both the engines themselves as well as their ancillary systems. In addition, it will investigate to which degree the vessels’ operating profiles and subsequently the engines’ load profiles are of importance for the successful operation of gas engines as generator drivers. Finally, this paper will, based on the experiences inventoried, identify areas where adjustments, or introduction, of regulatory requirements should be considered.

LNG as ship’s fuel - Bunkering, storage and processing for medium- and slow-speed engines

Juergen Harperscheidt, TGE Marine Gas Engineering GmbH, Germany

Shipping is the most eco-friendly means of transportation. Nevertheless, increasingly strict emission regulation as well as high fuel prices create a demand for innovative solutions in ship propulsion. One way to deal with these challenges is the use of LNG as ship’s fuel, thus significantly decreasing emissions of sulphur oxides, particles, NOx and carbon dioxide. All major engine makers have their designs for gas-fuelled or dual-fuel engines available, but in addition to the engines such ships require sys-
ditional equipments will be taken into account and analysed route as well as implications on the installation due to the ad-
view. Also aspects regarding influence on ship operation and
space demand vs. need of eventual new consumables
limits on some selected ship applications will be discussed. Ad-
ity to switch the engine operation between emission modes.
for reaching the low emission limit and increasing the flexibil-
challenges found in combination of different technologies needed
equal, engines need to be optimised for both sets of require-
technologies that can be activated when entering
in a very early stage of development; only very few places in the
world are prepared to fuel smaller ships. Bunker vessels to cover
for larger vessels are not yet in operation. Us-
ing TGE’s experience from the gas carrier market, we have de-
solved solutions to close this gap in infrastructure in order to
able development of LNG as fuel to take off.

**Tier III technology development and its influence on
ship installation and operation**

Christer Wik, Wärtsilä, Research and Development, Finland

The new emission regulations for marine diesel engines require
that new engines meet substantially lower NOx emissions limits
after January 2016, when operated inside the ‘Emission Control Areas’ (ECAs), whereas outside these regions, the emission limits applicable since the beginning of 2011 remain in force. Moreover, Tier III for the first time is not only limiting the cycle
average value but includes additional constraints for the emis-
sion levels at the individual points of the test cycle. As a conse-
quence, engines need to be optimised for both sets of require-
ments using technologies that can be activated when entering
an ECA in order to allow reducing NOx emissions by about
75% throughout the part of the operating range corresponding
to the test cycle. This paper will elaborate on results from test-
ing different technology options for fulfilling the Tier III NOx
emissions on medium-speed and low-speed engines including
SCR, EGR, wet methods, and natural gas operation. Strengths
and weaknesses of each technology, in respect to fulfilling the
demands as well as regarding implications on engine efficiency,
etc., will be presented. Special focus will be put on the chal-
lenes found in combination of different technologies needed
for reaching the low emission limit and increasing the flexibil-
ity to switch the engine operation between emission modes. Fur-
 furthermore, the best choice of technology for meeting Tier III
limits on some selected ship applications will be discussed. Ad-
itional space demand vs. need of eventual new consumables
will be compared both from a cost and operational point of
view. Also aspects regarding influence on ship operation and
route as well as implications on the installation due to the ad-
ditional equipments will be taken into account and analysed
for finding the most optimum choice of technology.

**EPA Tier IV, IMO Tier III and EU3b emission limits require injec-
tions systems that enable full application flexibility and excellent
mixture preparation. This applies to high-speed as well as medi-
urn-speed engines. NOx emission limits can either be reached by
high EGR rates in the combustion chamber or by SCR aftertreat-
ment of the exhaust gases. EGR applications require excellent mix-
ture preparation and distribution to prevent soot formation dur-
ing the combustion. Applications with SCR aftertreatment have a
penalty due to additional AdBlue costs during engine operation.
They have to compensate the AdBlue costs by significant improve-
ment of fuel economy. This can only be achieved by full flexibility
of injection timing, the capability of multiple injections and ex-
cellent mixture preparation. Both approaches lead to the need of
common rail injection systems with an optimised mixture prepali-
ration. The paper presents system and component designs of the
modular common rail system for high- and medium-speed Diesel
and medium-speed HFO engines up to 2,200 bar fuel pressure.
These injection systems cover the full range from 100 to 350 kW/
Cyl and have full system lay out flexibility for engines from L4 to
V20 engines. The production roll out for the diesel injection sys-
tems starts in 2013 for high-speed engines and will be completed
for medium-speed engines in 2015. It covers marine, C&I, locomo-
tive and gen set applications. Measures to improve the perform-
ance, durability and robustness of the injection system down to
component level are presented, focusing on the key components
high pressure pump and injector. Optimisations of the high pres-
sure injection components for fatigue stress, wear, cavitation and
fuel atomisation as well as the contribution of simulation tools
are shown.

**Advanced HFO common rail injector for maximising
the performance of medium-speed engines**

Marco Coppo, OMT SpA, Italy
Claudio Negri, OMT SpA, Italy
Klaus Heim, OMT SpA, Italy
Alessio Banno, OMT SpA, Italy

A new generation of common rail injector for marine, power and
railway applications was developed by OMT as a result of a decade
of research in high-performance fuel injection systems, and a series
of comprehensive tests with HFO of a previous injector generation
performed by the customer both on test rig and engine. In com-
bination with other key components influencing the combustion
performance of the engine such as, for instance, the turbocharger
and the valve actuation system, an advanced common rail injector
enables the engine designer to optimise the engine for reducing the
fuel consumption and complying with the forthcoming emission
legislation standards. The paper presents the main design princi-
ple s and features of the new injector, as well as the motivations that
led to the choice of such design and the physical phenomena that
play the major role in determining injector behaviour. The injector
CORAL (common rail loading) is shown, representing the life of rettage and serve as basis for the validation of design methods. In pumps, rails, injectors etc. demonstrate the advantages of autofrettage strength under variable amplitude loading. Test results on the compressive stress field. Focus is put on endurance and fatigue life benefits from the compressive mean stress at the notch in the finite life regime the crack initiation life and explicit 3D finite element simulation for crack propagation using LEFM, with crack closure and automatic remeshing fatigue analyses using design method 2 could predict these experimental results with a high accuracy, proving the significance of advanced design methods. For practical application, the second design method can be recommended. The first method can only be applied with a high level of experience usually not yet available in design groups of the industry. A considerable advantage of autofrettage is the very small scatter in life or in fatigue strength, respectively, resulting in remarkably small safety factors for the allowable pressures at small failure probabilities. The methods developed in research for life and endurance prediction have been successfully transferred to the industry, where it has been implemented and adapted to practical needs. MAN Diesel & Turbo SE has accompanied the research work and has used the know-how from the very beginning. The know-how has also been applied in the development of the new common rail injection system CR 2.2 for four-stroke engines operating at 2,200 bar to fulfil future requirements for fuel consumption and emissions. An outlook is given on unsolved design problems concerning high frequency of small cycles, temperatures up to 200°C and load spectra with maximum pressures below endurance.

New low-cost common rail system with zero static leakage

Raphael Fuechslin, Lafei, Switzerland

Fuel economy is more and more important for diesel engines. Emission levels become more and more stringent. To meet these limits, a common rail system is mandatory. Fuel economy yields for a zero static leakage common rail system. Additional to these two requirements, manufacturing costs should be as low as possible. According to the requirements, a common rail system, mainly consisting of a fuel injector and a high pressure pump, was designed, built and tested. Because of costs, the injector uses a solenoid actuator. As usual, the solenoid is about 20mm in diameter. For smaller engines the slim body of the injector does not allow to place the solenoid near the injection nozzle. To avoid static leakage, the injector has a central fuel bore only. This means the injector needle is completely surrounded by pressurised fuel. The needle is very long to reach the solenoid that is placed on the top. This length can cause frictional problems due to misalignment caused by manufacturing imperfections. To enhance the acceptance of manufacturing imperfections, a flexible needle was invented. This invention keeps manufacturing costs low and minimises injector to injector deviations. To keep the costs of a high pressure fuel pump as low as possible, the pump is fuel lubricated. Fuel lubrication additionally minimises the overall costs of the whole engine. The pump has a very simple crank drive with a race ring. This race ring sits on the eccentric part of the crankshaft. The plunger feet are rolling directly on this race ring. Except for the plunger spring, there is no need for an additional part transforming revolutions into strokes. The pump has two plungers. This is the minimum number of plunger to make sure the pump is capable of delivering fuel all the time. The pump is designed for high speed, e.g. 4,000 rpm. If the engine builder uses this potential, the pump can be designed smaller and with less weight, which also improves fuel economy of the whole engine. High speed pumps also cause smaller pressure fluctuations, which is a further advantage. The tests and measurements of the components showed good injection behaviour for the injector and a high efficiency regarding high pressure fuel pump.
CIMAC CONGRESS | SHANGHAI 2013

Monday May 13th / 15:30 – 17:00  Room C

Environment, Fuel and Combustion
Diesel Engines – Fuel Injection 2

30 Mpa mixing controlled combustion
Martti Larmi, Aalto University, Finland
Ilari Kallio, Wärtsilä Finland Oy, Finland
Antti Eloheimo, Aalto University, Finland
Teemu Sarjovaara, Aalto University, Finland
Matteo Imperato, Aalto University, Finland

The level of peak cylinder pressure and indicated mean effective pressure have increased rather constantly in combustion ignition of internal combustion engines over the past decades. Present medium-speed engines are capable of running with about 20 Mpa peak cylinder pressure. In this study, the new values of high-peak cylinder pressure level of 30 Mpa are reviewed for the first time. The goal of the present study has been to build up a medium-speed research engine with the ability of running with 30 Mpa peak cylinder pressure and demonstrate the high-peak cylinder pressure combustion. The ultimate objective of the high-pressure combustion is emission reduction with simultaneous high power density. The research engine has a special crankshaft and connecting rod. Piston and cylinder liner are made for high pressures and high heat load. The cylinder head of the engine is fully machined. Charge air is produced by an external compressor giving 1.0 Mpa charge air pressure at maximum. The engine is equipped with a hydraulic fully adjustable gas exchange valve train. The first engine tests with 30 Mpa peak cylinder pressure have been carried out with high relative air-to-fuel ratio and with various indicated mean effective pressures up to 3.7 Mpa. High efficiency and low fuel consumption values were achieved with no penalty in emissions. The pressure curves and the analysed heat release curves indicate fine mixing controlled combustion. This gives motivation to continue the research work of high peak cylinder pressure combustion with both experimental and numerical methods.

Characterisation of residual fuel compositions and the effect on the ignition and combustion performance
Chiori Takahashi, National Maritime Research Institute, Japan
Shoko Imai, National Institute for Minamata Disease, Japan
Yoshitaka Yamaguchi, National Maritime Research Institute, Japan
Tetsuya Senda, National Maritime Research Institute, Japan

The quality of marine fuels has changed over the last ten years, and it is well known that they have been getting heavier and lower in viscosity resulting in poorer combustion quality. This is caused by recent advancement of oil refining process, economic trend and increasing needs for light distillates, and environmental regulations. Ignition and combustion performances are affected by various factors including the characteristics of the fuel, engine design, operational conditions and settings of the engine, applied load, and ambient conditions. Residual fuels are mixture products consisting of vacuum residue (VR) and some intermediate products of oil refinery process. Thus, to analyse the blending process and characteristic of the residual fuels may lead to better understandings of the combustion process in diesel engines and to take countermeasures against possible engine damages. In this study, the effect of chemical composition of residual fuels on its ignition and combustion quality was investigated. The blend compositions were estimated by thermal and chemical analyses and discussed with the results of combustion characteristics. The sample fuels were blended with different proportions of a straight-run light gas oil (LGO), a vacuum gas oil (VGO), a FCC light cycle oil (LCO), a FCC clarified oil (CLO) and a VR. These blending components and sample fuels were also used for the quality control of the commercial marine fuel oils. The chemical compositions of these fuels were analysed by using thermogravimetry (TG) and gas chromatography / mass spectroscopy (GC/MS). The TG analysis in a nitrogen gas flow and GC/MS gives a distillation curve of fuels and a detailed composition profile of the lower-boiling components, respectively. Their ignition and combustion analysis was also carried out by using fuel combustion analyser. According to the GC/MS, LCO and CLO were characterised by mainly two-ring (especially methyl-, dimethyl- and ethyl- naphthalenes) and four-ring polycyclic aromatic hydrocarbons (methyl- and dimethyl-pyrenes), respectively. The results suggest that the fuel ignition quality is significantly affected by the amounts of both two-ring polycyclic aromatic hydrocarbons and relatively lower molecular weight alkane series (C14-C18), which are interpreted as the amounts of LCO and LGO. Some of the commercial marine fuel oils were found to be ‘gapfuels’, which were estimated to containing only LCO and VR. They exhibited a very low estimated cetane number (ECN), almost the same as that of pure LCO, and can potentially result in serious engine damages.

Measurements of soot particles in single-spray combustion with a rapid compression machine
Hiroshi Okada, Tokyo University of Marine Science and Technology, Japan
Choei Sugawara, Ministry of Transport, Japan

Up until now, there have been studies on the size, the shape and the concentration of soot particles. The focus was put on the size of crystallites in a single soot particle. In order to obtain this value, the size, which was measured through the diffraction of soot particles with an x-ray diffractmeter, had to be compared with the size observed by electron- microphotographs of soot particles. For this research, the combustion device for single spray with a rapid compression machine of one stroke was tried to be manufactured in a way to make the combustion state approaching that in the combustion chamber of diesel engines as closely as possible. A glass window was put into the cylinder head of the combustion apparatus to observe the burning state and take photos. Kerosene and gas oil were used in this experiment. The results of this experiment are summarised as follows:
• The size distribution of single-soot particles is not effected by the compression ratio and the quantity of fuel injection. It is the same as the distribution of single soot particle in the wick flame;
• A single-soot particle is a sphere of 300 angstrom in diameter in the maximum distribution;
• The size of crystallites in a single-soot particle is 13.96 angstrom. It is 1/15~1/25 the size of a single-soot particle in the maximum distribution obtained from the electron-microphotographs;
• The size distribution of single-soot particles in this experiment shows much the same tendency as the one calculated by the Guinier plot method.

Alternative marine fuels and the effect on combustion and emission characteristics
Vilmar AEsoy, Aalesund University College, Norway
Sergey Ushakov, Marintek, Norway
Erik Hennie, Marintek, Norway
Jorgen B. Nielsen, NTNU, Norway

Marine diesel engines are typically operated on high-sulphur residual fuels and can be considered one of the most significant contributors to air pollution. But the current situation is changing in...
a positive direction due to implementing more strict NOx regulations and by setting more strict fuel sulphur limits, which certainly has an effect on emitted levels of SOx and particulates. Although, it should be stated that future dramatic reduction of sulphur content may result in limited availability of low-sulphur marine fuels, so their potential alternatives (substitutes) should be defined and thoroughly investigated in advance. In this study different alternative marine fuels including both biodiesel (fish oil, FO) and synthetic diesel (GTL) have been tested in a medium-speed marine diesel engine and fuel ignition analyser (FIA) to compare their ignition, combustion and emission characteristics in contrast to reference low-sulphur marine gas oil (MGO) and heavy fuel oil (HFO). Experiments were performed at various operating conditions under standard four-mode propeller curve marine cycle with engine performance, exhaust emissions together with particulate matter (PM) size distributions and corresponding total particle number and mass concentrations being measured and compared at each load point. GTL fuel was found to have the highest cetane number, hence the shortest ignition delay among the tested fuels and simultaneously provided 1 to 2% higher shaft efficiency compared with reference HFO. In general, MGO, GTL and FO showed a rather similar combustion performance in terms of both cylinder pressure and rate of heat release, which was distinctively different from that of high-sulphur heavy fuel oil. Both MGO and GTL showed a very similar behaviour in terms of gaseous emissions (comparing with that of HFO) with NOx and CO concentrations being decreased, HC levels being increased and CO emissions showing some variation depending on actual load conditions. FO, in its turn, allows reducing emitted CO2, CO and HC concentrations, but NOx levels were slightly increased. All the effects are likely associated with the alternative fuels chemical composition and physical properties, e.g. lower levels of sulphur, ash and aromatics, higher cetane number and oxygen content (for FO) in fuel. All these factors are believed to be also important in explaining pronounced PM reduction, both in terms of PM mass and number concentrations, that was observed from MGO, GTL and FO. The highest positive effect was found from FO with more than 75% of PM mass reduction (mainly related to reduction in number of big carbonaceous particles) and is likely associated with its high content of fuel-embedded oxygen. The registered particle size distributions were fairly bimodal for MGO, GTL and FO with pronounced carbonaceous accumulation mode and nucleation mode composed of ash compounds and originating from high lube oil emissions with the nucleation for semivolatile compounds is believed to occur via heterogeneous nucleation process. Particle size distributions were unimodal (actually contained two overlapping modes) from HFO fuel and showed somewhat lower concentrations of big carbonaceous particles, which can be explained by high content of metallic ash compounds (in heavy fuel oil) acting as a catalyst and hence enhancing the process of soot oxidation.

**Monday May 13th / 15:30 – 17:00 Room D**  

**Tribology 2**  

**Novel trends in journal slide bearing technology - active use of tribochemical effects**  
Martin Offenbecher, Miba Bearing Group, Austria  
Hellen Li, Miba Bearing Group, Jiangsu Province, China  
Emmanuel Laine, Infineum International Ltd, UK  
Florian Gruen, Montanuniversität Leoben, Austria  
Kartik Pondicherry, Montanuniversität Leoben, Austria  

Future trends in engine design go towards higher firing pressures, which further increase the tribo-mechanical loading of
journal bearing systems to an extent that requires fundamentally new approaches. One of the most important goals in latest research activities is the active use of tribochemical effects of lubricants in journal bearing systems. Positive chemical effects of extreme pressure and antiwear additives, such as ZDDP, have already been well researched in the field of gear and valve train systems over the last decades. For the first time, it was shown that tribofilms can also form in journal bearing systems, which influence the tribological behaviour significantly. In case of Al-based bearing material, which is rather inert to tribochemical reactions, tribofilms formed on the mating steel counterpart increase the load bearing capacity and also the wear resistance. This fact is due to the lubricity the softer tribofilms impose on the harder steel counterpart. The response of Al-based materials towards film formation is effectively improved by adding selected intermetallic hard phases. The research activities further elucidate a synergistic effect between the design of the bearing materials and the employed lubricant formulation. The results obtained so far clearly highlight the need for a combined inter-disciplinary development of all components of journal bearing systems. These are the materials of bearing and shaft as well as the employed lubricants.

System oil for two-stroke marine engines – current and future performance requirements and challenges

John Smythe, Infineum UK Ltd, UK
Georg Bleimschein, Wärtsilä Switzerland Ltd, Switzerland

System oil has had a slow evolution of performance improvement during the past decades. Rapidly increasing fuel injection pressure to reduce fuel consumption and to meet exhaust emission requirements requires increased anti-wear performance to protect gears, camshafts and followers. The introduction of engines with complex hydraulic systems operated by the system oil necessitates a review of the current situation. The oil needs to be very clean to operate effectively in these functions as there are many delicate high-precision control components in the hydraulic oil control circuit. The system oil also operates in an increasingly hot piston cooling and exhaust turbocharger bearing environment necessitating improved thermal stability and anti-oxidation properties. Some new bearing materials require low system oil water content and improved anti-corrosion properties. The quantity of system oil per engine output is also being reduced to save cost and space, thus the oil circulation rate is increasing. This requires that the air release and foam collapse time properties of the oil need to be improved. Not only the new oil performance for all these parameters is important, but the retention of these desirable properties for the life of the oil is essential to ensure good operation. System oils are typically ‘fill for life’, thus these properties need to be maintained for the life of the engine, i.e. 25 to 30 years with only small amounts of top up. One final challenge would be to meet all these requirements as well as allowing the use of the system oil as a cylinder oil for use with low sulphur distillate fuel. These new performance requirements need to be addressed to ensure reliable engine operation now and in the future. To deliver the required performance, the choice of additive chemistries becomes critical. While the range of additive chemistries is extensive, the impact of new system oil requirements makes selecting the right molecules a key step in delivering performance to match engine needs. This is made even more so by the need to consider the impact on the environment and potential future legislation. In addition, as the automotive industry drives basestock manufacture to increased use of Group II, III, and IV product, the impact of these if used to produce system oils, must be taken into account. This paper aims to identify the performance requirements for system oils and show how with careful formulating, these can be achieved.

Impact of marine lubricant additives on SCR catalyst performance

Peter Van Houten, Chevron Oronite, The Netherlands
Maarten Boons, Chevron Oronite, The Netherlands
John Fogarty, ExxonMobil Research and Engineering Company, USA
Maria Brandmair, Johnson Matthey Catalysts GmbH, Germany
Martin Ziesmann, Johnson Matthey Catalysts GmbH, Germany
Joseph McCarney, Johnson Matthey, UK
Paul J. Andersen, Johnson Matthey, USA

Through the IMO’s Tier III legislation, the marine industry is committed to a significant reduction of NOx emissions from shipping in the Emission Control Areas by 2016. Marine engine OEMs & afterservice specialists have been preparing to provide compliant solutions for the industry in reaction to this initiative. Not surprisingly, selective catalytic reduction (SCR), a technique successfully applied on a large scale in other sectors, is often the solution of choice. A known area of caution for SCR installations is the impact of the engine lubricant additives on the long-term performance of SCR catalysts. While SCR is already being applied in a small percentage of marine and land-based power generation installations, data on the impact of marine diesel engine lubricants on marine SCR catalysts in well-controlled engine tests is scarce. John Matthey, Chevron Oronite and ExxonMobil have collectively researched the impact of marine lubricants on various commercial and experimental SCR catalysts for application in large-bore marine and power generation engines operating on heavy fuel oil. An accelerated catalyst aging procedure was developed on Chevron Oronite’s research engine, operating on heavy fuel oil. Using this procedure, the effect of various lubricant additives on catalyst effectiveness was determined through catalyst characterisation and activity testing. The data shows that actual engine testing is a necessary tool to determine the effect of lubricant composition on marine SCR performance and that more data, developed under real-world conditions, is needed to fully understand the effects of lubricants on SCR catalysts as applied in marine installations. The outcome of the research will be further explored using the SCR installation on Chevron Oronite’s full scale Wärtsilä 4L20 marine engine.

Optimisation of the piston ring – cylinder liner system in gas engines for power generation

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Herbert Krampl, Montanuniversität Leoben, Austria
Istvan Godor, Montanuniversität Leoben, Austria
Florian Gruen, Montanuniversität Leoben, Austria
Michael Betz, GE Global Research, Germany
Stephan Laiminger, GE Jenbacher, Austria

The development in almost every industry is currently being steered by environment, climate and energy-related issues. This is especially true for the automotive industry, wherein the advances in the combustion engines, independent of their operational principle and application, are strongly affected by them. While on the one hand it is mandatory to comply with the laws governing emission and environmental concerns, the modifications brought about should also cater for the demands of the customer in terms of higher efficiency and reliability. The current work, carried out in cooperation with GE Jenbacher GmbH & Co OG, deals
and well established. The trend of reduced ship's service speeds 100% of the orders placed and RTA engines are no longer popular, gines had been ordered. As these flex engines now account for more than 1,000 electronically controlled Wärtsilä two-stroke en-
W-X92 will be described in a separate paper. By the end of 2012, gine for VLCC/VLOC (Very large crude/ore carriers) and Panamax RT-flex82T engine has been upgraded for modern requirements to be suitable for a real life engine.

A thorough insight into the behaviour of RTA and RT-
flex48T-D engine passed its shoptest and was commissioned in May 2012. A thorough insight into the behaviour of RTA and RT-flex components will be given, including information on fuel and servo oil pumps, as well as injection control units and a review of pulse jet cylinder lubrication and FAST (fuel actuated sacless technology) fuel valves during shop tests on different bore sizes confirmed the potential of reduced fuel oil consumption over the whole en-

The study also focuses on reduc-
ing the probability of spontaneous failure of this system to result in a greater reliability. This in turn would ensure continuous power generation and safeguard the costs and resources. While modern engine test benches are more than capable of testing the aforementioned system of interest here, they are time consuming and highly cost intensive. Also, post-test damage analysis in such bench tests does not offer much of an insight into the occurrences during the test. Therefore, a model scale, damage-equivalent test methodology, was designed for a comprehensive assessment of the system in a quite economical and time efficient manner. The tests were carried out on a TE 77 test rig from Phoenix Tribology with an analogous ‘ring-on-liner’ configuration. The specimens were cut out from real components. To verify conformity between the two specimens, a light-gap-method was applied. The compo-

pent based test configuration facilitates damage-equivalent investigation of the piston ring - cylinder liner system. Post-test characterisation was also carried out to elucidate and substantiate the findings from the tribological tests. The results obtained for a generic tribo-system consisting of a low alloyed and tempered spheroidal cast iron piston ring with a chrome ceramic layer, and an untreated lamellar cast iron (EN-GJL-250) cylinder liner, were considered as a reference. Numerous base materials with varying surface treatments have been investigated through a series of experiments to find an optimised solution that would offer an increased tribological loading capacity, with improved efficiency and reliability. The corresponding results facilitated in identify-
ing an optimised system w.r.t base material, thermal treatment, topography, and lubricant. Finally, the results will be validated on a test engine in order to verify whether the chosen system would be suitable for a real life engine.

Upgrade of Wärtsilä’s two-stroke engine portfolio to fulfil the changing marine market requirement

Heinrich Brunner, Wärtsilä Switzerland Ltd, Switzerland
Jean-Noel Constantin, Wärtsilä Switzerland Ltd, Switzerland
Beat Schumacher, Wärtsilä Switzerland Ltd, Switzerland
Dominik Schneider, Wärtsilä Switzerland Ltd, Switzerland

Wärtsilä’s current two-stroke portfolio consists of engine-types: RT96C, RT84T-D, RT82C, RT82T, W-X82, RT68-D, RT58T-E, RT60C-B, RT50- D and RT48T-D as well as the newly developed WX35, W-X40, W-X62, W-X72 and W-X92 engines. The RT-flex82T engine a light-gap-method was applied. The compon-
ent based test configuration facilitates damage-equivalent investigation of the piston ring - cylinder liner system. Post-
test characterisation was also carried out to elucidate and substantiate the findings from the tribological tests. The results obtained for a generic tribo-system consisting of a low alloyed and tempered spheroidal cast iron piston ring with a chrome ceramic layer, and an untreated lamellar cast iron (EN-GJL-250) cylinder liner, were considered as a reference. Numerous base materials with varying surface treatments have been investigated through a series of experiments to find an optimised solution that would offer an increased tribological loading capacity, with improved efficiency and reliability. The corresponding results facilitated in identify-
ing an optimised system w.r.t base material, thermal treatment, topography, and lubricant. Finally, the results will be validated on a test engine in order to verify whether the chosen system would be suitable for a real life engine.

State-of-the-art MAN B&W two-stroke super-long-stroke engines

Susanne Kindt, MAN Diesel & Turbo SE, Denmark

Since the economical crisis was recognised worldwide in the au-
tumn of 2008, owners have been looking into cost savings, such as slow steering and optimised low-load operation with turbo-
charger cut-out, exhaust gas bypass, etc. This has led to research into optimised propulsion efficiency, available propeller sizes and possibilities regarding stroke size for crankshafts. The result is now known as the G engine series, including the G40/45/S0ME-B9.3, G60/70/80ME-C9.2, S30ME-B9.3 and S90ME-C9.2. With the G engine series, a new generation of super-long-stroke engines has been introduced to the market and, in many cases, a new design of the aft ship is needed to fully utilise the low revolutions of these engines. However, the interest in the new engines is very high, and
The launch of the Wärtsilä X-engines marks the introduction of a new generation of low-speed engines to the market. The new engines have been developed due to the requirements for lowest total cost of ownership and highest reliability, while manufacturing cost for Wärtsilä’s licensees is reduced from the onset of the design. The new engine types are being developed for the actual IMO Tier II NOx legislations, and the technologies required for the forthcoming Tier III NOx limits are already considered in the engine design for a later effortless integration. As of January 2013, the X-generation engine family comprises six different engine types that either just entered into operation or are currently in different stages of their development, with further engines in planning. These engines are the small bore W-X35 and W-X40, the W-X62 and W-X72 for the medium segment and the new W-X92 or the through-flow oil cooling of the W-X35/40 pistons. All new two-stroke engines of the X type feature the well-known flex system - Wärtsilä’s fully variable, electronically controlled fuel injection and exhaust valve operation, independent of engine load - which has readily proven its advantages on the RT-flex engine series. Extremely slow stable running speeds, optimised brake specific fuel consumption (BSFC) versus NOx trade-off, smokeless operation at all loads and various tuning possibilities are among the most important. The fuel injection valves of W-X35 and W-X40 feature a conventional nozzle, whereas the injectors for the mid and large-bore engines feature the FAST (fuel actuated sackless technology) slide valve nozzle with minimised sack volume for even optimised fuel consumption. The X engines feature extra long strokes, leading to extra low engine speeds. This allows the selection of a larger propeller with higher propulsion efficiency. Furthermore, the bigger stroke-to-bore ratios lead to a better internal efficiency of the engine. The extra long stroke in combination with the fully flexible fuel injection and exhaust valve actuation and the different tuning possibilities give shipowners, shipyards and engine builders the possibility to select the propulsion system with the lowest fuel consumption. By January 2013, a total of 17 W-X35 and WX40 engines had been ordered and two are sailing already in the field. While the design work on the W-X62 is almost finished, the W-X72 and the W-X92 are still under development. Up to date, Chinese shipyards have ordered 14 W6X72 engines for applications in bulk carriers and container vessels.

Contribution of turbocharging solutions towards improved fuel efficiency of two-stroke low-speed engines

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The trend towards higher fuel prices is expected to continue. In addition, the upcoming EEDI scheme requires a reduction in CO₂ emissions. Both are boundary conditions calling for more fuel-efficient propulsion solutions for large merchant vessels. In this respect, ABB has investigated the potential of two-stage turbocharging on two-stroke low-speed engines. Based on experience from preceding tests and extensive simulation exercises, ABB Turbocharging presents two different application cases for two-stage turbocharging of two-stroke engines for marine propulsion. The first system building up on turbo compound by means of a power turbine and moderate increase of power density heads for maximum system efficiency. This system allows for the highest reduction in fuel consumption of all compared cases, but closely followed by a concept without power turbine based on part-load optimised one-stage turbocharging and derating. However, according to rough indications from commercial projects realised in the past, the first costs of the former concept are expected to be high, which relativise the benefits in BSFC of the two-stage turbocharging with a power turbine. The second system focuses on downsizing the engine to extreme power density levels. Extreme downsizing can theoretically be conducted up to a BMEP of 30 bar by scaling engine tuning parameters of today’s typical engines. While offering downsizing potential, it should be considered that with increasing boost, exhaust gas temperature after turbine is reduced and with it the extractable enthalpy for steam production. For both systems available IMO Tier III emission reduction methods can be used.

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firm orders have already now been received for seven-, nine-, ten-, eleven- and twelve-cylinder 90ME-C9.2 engines, six- and seven-cylinder 60ME-C9.2 engines as well as 6G70ME-C9.2, five- and six-cylinder G60ME-C9.2 engines and 6G50ME-B9.3. One of the present goals in the marine industry is to reduce CO₂ emissions from ships and, therefore, to reduce the fuel consumption for ship propulsion to the widest possible extent at any load. This goes hand in hand with the focus on fuel cost savings, including the newly introduced variable exhaust valve timing for ME-B9 engines. This new system will improve the part load fuel consumption cost for Wärtsilä’s licensees and, they will be designated ME-B9.3. Furthermore, the newly introduced Energy Efficiency Design Index (EEDI) will also have an impact on future ship development and engine design. One possible solution to improve the EEDI for a ship is to optimise the aft body and hull lines of the ship, including bulbous bow and operation in ballast condition – making it possible to install propellers with a larger diameter and, thereby, obtaining higher propeller efficiency at a reduced propeller speed. As the two-stroke main engine is directly coupled to the propeller, the introduction of the super-long-stroke G engine series with an even lower-than-usual shaft speed will meet this target. This paper will deal with the overall design platform for these engines, which is mainly based on the service experience as well as production experience with the 80ME-C9 and 35-50ME-B9 engines. Furthermore, dedicated design requirements in order to be able to operate with, for instance, the biggest stroke bore ratio ever of five for the G40/45 and G50-ME-B9.3 engines will also be described. Similar to the situation of the 80ME-C9 and 35/40ME-B9, the new G engine series are only offered as electronically controlled versions so as to obtain the lowest possible fuel oil consumption at all loads as well as optimising NOx emissions. However, if needed, the G engines can be delivered as MCC-engines on request.

The new X-generation low-speed engines from Wärtsilä

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Andreas Kyrkatos, Wärtsilä, Switzerland
Ronald de Jong, Wärtsilä, Switzerland

The new X-generation low-speed engines from Wärtsilä are expected to continue. In addition, the upcoming EEDI scheme requires a reduction in CO₂ emissions. Both are boundary conditions calling for more fuel-efficient propulsion solutions for large merchant vessels. In this respect, ABB has investigated the potential of two-stage turbocharging on two-stroke low-speed engines. Based on experience from preceding tests and extensive simulation exercises, ABB Turbocharging presents two different application cases for two-stage turbocharging of two-stroke engines for marine propulsion. The first system building up on turbo compound by means of a power turbine and moderate increase of power density heads for maximum system efficiency. This system allows for the highest reduction in fuel consumption of all compared cases, but closely followed by a concept without power turbine based on part-load optimised one-stage turbocharging and derating. However, according to rough indications from commercial projects realised in the past, the first costs of the former concept are expected to be high, which relativise the benefits in BSFC of the two-stage turbocharging with a power turbine. The second system focuses on downsizing the engine to extreme power density levels. Extreme downsizing can theoretically be conducted up to a BMEP of 30 bar by scaling engine tuning parameters of today’s typical engines. While offering downsizing potential, it should be considered that with increasing boost, exhaust gas temperature after turbine is reduced and with it the extractable enthalpy for steam production. For both systems available IMO Tier III emission reduction methods can be used.

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The new dual-fuel engine 35/44 DF from MAN Diesel & Turbo SE

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Anthony Gruand, MAN Diesel & Turbo SAS, France
Pierre Berg, MAN Diesel & Turbo SAS, France
Rainer Golloch, MAN Diesel & Turbo SE, Germany

Due to future emission legislation for harbour as well as the upcoming IMO Tier III emission regulation for marine application and the promising development of the price for natural gas, a switch to gaseous fuels in the marine sector is a new line of conduct from customer side. Additionally, shipowners develop more and more environmental awareness. With the latest development of its new medium-speed four stroke 35/44 DF engine, MAN Diesel & Turbo is continuing the expansion of its product program with a dual-fuel engine based on common rail technology. The paper will give an overview of the engineering of the 35/44 DF as well as the new technologies employed to fulfil the future market requirements. In addition, a short overview will be given on the thermodynamical properties and expected performances for a given range of application. This new high-end four-stroke engine with high flexibility was developed within a very short time frame of 18 month. The development objective was a high-efficiency and a high-specific power output in accordance with emission limits IMO Tier II in diesel mode and IMO Tier III in gas operation with high degree of fuel flexibility (HFO, MDO, MGO and natural gas). With an output of 530 kW/cyl, the engine is covering a power output range from 3.2 MW to 10.6 MW. The 35/44 DF has the highest power output in the segment and is complementary to the power output range from current serial engine 51/60 DF from MAN Diesel & Turbo SE. This engine is based on the 32/44 CR-T2 engine, using a high level of component synergies. Therefore MAN Diesel & Turbo can also offer a retrofit solution from 32/44 CR-T2 to 35/44 DF. The prototype engine is currently running and being validated at MAN Diesel & Turbo in Augsburg, Germany, and will end with a classification approval.

Caterpillar M46 dual-fuel engine with new cylinder pressure-based control strategies

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Martin Greve, AVAT Automation GmbH, Germany

Caterpillar has recently announced the development of the new M46 dual-fuel engine. This high efficient engine is equipped with an integrated Caterpillar electronic control system including two ECM’s for the inline engine. They also include the control logic of the FCT flex cam actuator. The safety and protection system is a new Caterpillar development as well and connects to the control system with a redundant bus Interface, providing flexible PLC logic for start stop control, slow turn, purge and all other functions. Besides the known data interfaces to the engine
control room and alarm system, all engine data is now visible on graphical on engine displays. The engine provides an output power of 900 kW/cyl at a BMEP of 21.3 bar in diesel as well as in gas operation. To reach the high efficiency targets while maintaining sufficient safety margins at varying gas qualities, it was decided to equip this engine with cylinder pressure sensors in each cylinder and to integrate these informations into the engine control strategy. While other known cylinder pressure based control strategies focus on Pmax only, the new M46 DF engine uses further combustion characteristics like start-, centre- and duration-of-combustion for monitoring, balancing and NOx control. Time to market was and still is a critical factor for the success of this new project, so it was decided to build up a partnership with an experienced supplier in the technical field of cylinder pressure sensing and processing technology. The company Avat from Teubingen, Germany, has been selected to design and develop the Caterpillar in-cylinder-pressure-module (ICPM). Even more important than achieving maximum control performance was to design a system with highest engine availability. The new system architecture was developed in order to minimise the system’s complexity. Therefore the ICPM was designed as a smart sensing device leading to a clear separation of responsibilities: sensor power supply, sensor signal processing and monitoring as well as online calculation of combustion characteristics and knock levels are encapsulated in the ICPM, whereas mixture control, knock control interaction and balancing strategies are realised completely in the ECM. Consequently, error handling and alarm processing are also located here, giving Caterpillar the maximum flexibility in designing the engine behaviour. The key combustion parameters were defined by the Caterpillar control and performance team. The engine control system receives these values from a high-speed digital bus interface using SAE J1939 CAN protocol. Appropriate extensions to the J1939 standard have been designed and submitted to the SAE committee. This clear interface provides good flexibility of all units and a clear hierarchy of the distributed system enabling Caterpillar to use the ICPM on different engine platforms. During common system function test (FMEA) sessions between Caterpillar and AVAT safety critical functions and performance optimisation could be clearly separated, which, in turn, facilitates the marine classification process. The paper ends with a presentation of test bed results showing the benefits of the new control strategy.

Development of a dual-fuel technology for slow-speed engines
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Marcel Ott, Wärtsilä Switzerland Ltd, Switzerland

Driven by emission regulations and recent fuel price developments, the interest in gas as fuel for shipping is increasing. For medium-speed four-stroke applications, Wärtsilä has developed a range of gas and dual-fuel engines that have penetrated the market and in some applications, like the LNG carrier segment, taken considerable market share. Now Wärtsilä has initiated the development of a dual-fuel technology for two-stroke engines. The main merits of this technology are that low-pressure gas can be utilised, and that no additional NOx reduction technologies are needed to fulfil the IMO Tier III requirements, which will keep both the initial investment cost, as well as operating costs, on a low level. With dual-fuel capability the engine can be operated both on gas and on HFO. This paper describes the initial design, development, and test results of the technology, including selected engine performance characteristics.
Development and application of advanced engineering tools - for description, prediction and optimisation of the two-stroke diesel engine process - is essential for the development of the marine engines of the future. Here, recent developments of optical and laser-based imaging tools will be presented. Such tools can lead to both increased understanding and predictive capabilities of, for example, the scavenging process, fuel spray structure, flame ignition, and thermal loads. For optical studies access to the combustion chamber has been achieved using sapphire windows, mounted in starting air and fuel injector ports on both standard fuel oil and gas cylinder covers, or inserted in the 24 optical ports of a dedicated optical cover. A few examples, highlighting the new capabilities thus offered, will be presented. High-speed imaging offered detailed views of the dynamics of fuel jet ignition. Pulsed laser illumination was used for visualisation of fuel jets, from which information on fuel jet penetration, jet velocity, and spray angles could be gathered. For this purpose, a high-power laser and a custom designed imaging system was mounted directly onto the optical cover. The fuel jet data is qualitatively compared with results from KIVA simulations in order to tune spray parameters in the numerical model. The same laser system was also used for measurements of in-cylinder flow velocities, in order to characterise swirl and scavenging. Particle image velocimetry (PIV) was used for those velocity measurements. Finally, infrared imaging was employed for two purposes, firstly for capturing the evolution of piston temperature distributions during single engine cycles and secondly for visualisation of scavenging of hot product gases.

**CFD simulation of the working process of conical spray combined swirl-chamber diesel engine**

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Thanks to the advantages of lower harmful emissions and noise, the swirl-chamber indirect injection diesel engine has been widely used in small type non-road machinery. With the implementation of harmful emission regulations on non-road machinery diesel engines, the swirl-chamber diesel engine regains attention from the domestic and international internal combustion engine industry. In order to improve the fuel economy, the authors modified a swirl-chamber diesel engine, applying conical spray in swirl-chamber to improve the fuel-air mixture formation and combustion processes. A 3D CFD software package was employed to investigate the match of the conical spray and swirl-chamber and analyse the performance of the modified engine. The simulation results indicate that with the application of the conical spray on the prototype engine, the fuel economy is improved due to finer atomisation of conical spray in the swirl-chamber.

**Development of spray and combustion simulation tools and application to large two-stroke diesel engine combustion systems**

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Sebastian Hensel, Wärtsilä Switzerland Ltd, Switzerland  
Beat von Rotz, Wärtsilä Switzerland Ltd, Switzerland  
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Computational fluid dynamics supporting the optimisation of combustion systems of large marine Diesel engines require sub-models for spray, evaporation and combustion modelling. In this paper, the further development of these submodels and their
application to engine simulations are described. The submodels are validated against reference data from an experimental setup consisting of an optically accessible, disk-shaped constant volume chamber with a diameter of 500mm with peripheral injection into a swirling flow – the spray combustion chamber (SCC) developed in the context of the HERCULES (high-efficiency R&D on combustion with ultra-low emissions for ships) research programme and presented for the first time at CIMAC 2007. This unique experimental test facility for investigating the spray and combustion behaviour under conditions relevant for large marine diesel engines not only resembles the physical dimensions of large two-stroke engines but also the operational characteristics with regard to thermo- and fluid dynamic conditions at start of injection are reproduced with excellent repeatability. In particular, pressure, temperature and swirl are close to the levels experienced in those engines. Additionally, a wide range of fuel qualities can be used. The highly flexible optical accessibility enables the generation of appropriate reference data and the application of non-intrusive spray and combustion diagnostics contribute to an in-depth understanding of the involved in-cylinder processes. Combustion is particularly sensitive to the fuel vapour distribution, therefore the accurate simulation of spray and evaporation processes is seen as a prerequisite for reliable combustion and emissions formation simulation results. The various experimental investigations that have been performed to gain knowledge about the fuel spray characteristics during injection, the evaporation behaviour and the subsequent ignition and combustion resulted in a reference data set that has been applied to the further development and validation of improved CFD sub-models. The in-nozzle flow and primary breakup of fuel nozzles was analysed in detail and intensive investigations will be performed during the course of the research project HERCULES-C, to describe the influence of geometrical design features and flow conditions inside the nozzle. As spray and droplet formation in large two-stroke engines is highly unsymmetrical, a primary breakup model was developed taking into account asymmetric boundary conditions at the orifice outlet. Finally the improved methodology developed is applied to investigate current issues of engine performance optimisation like combustion with high EGR content. The actual CFD supported combustion system product development process is described and exemplified on the basis of the development of the W-X35 engine.

**Flame temperature and soot concentration of single spray flame of bunker fuel oil in OCA (optical combustion analyzer), using two-colour method**

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The regulations for exhaust emissions of NOx, SOx and particulate matters from marine diesel engines have been strengthened. The exhaust emissions depend on fuel properties for combustion as well as the engine operating conditions. Therefore, it is very important to investigate the flame temperature and soot concentration in a diesel spray from the view point of a fundamental study. The OCA (optical combustion analyzer) was used to visualise a transient combustion of diesel spray. The OCA has been developed in our research group and used to judge ignitability, combustibility and afterburning quality of bunker fuel oils by analysing the visualisation images and photosensor signals. Oxygen, nitrogen and ethylene are introduced through mass flow controllers and mixed in a constant-volume vessel. The lean mixture with much oxygen is ignited by a spark. The oxygen concentration in the burned gas was set at 21% in advance. After the maximum pressure, the pressure and the temperature of the gas decrease with a reduction in pressure due to heat loss. When the pressure reaches a certain value, a single spray is injected. A high-speed camera captures the time series of spray flame images and photosensors detects the light emissions from the flame. The repeatability of the history of injection pressure is very good. When exhaust emissions are discussed, the combustion properties of the fuel oil such as flame temperature and soot concentration have to be understood besides the ignition delay, combustibility and afterburning. The two-colour method is widely used to measure the soot temperature and concentration. Based on the empirical correlation, soot concentration can be qualified by the KL factor. In this study, the two-colour method developed with in-house software was applied to analyse the flame temperature and KL value related to the soot concentration. A notch filter was used to divide the images into red and blue ones. The uncertainty of the two-colour method was discussed. At first, the accuracy of the calibration between the colour temperature and the light strength in both red and blue images was investigated because there is non-linear relation strongly. Next, the digitalisation of the camera was also discussed. A diesel fuel oil was tested with OCA and analysed with the two-colour method under the condition of some ambient temperature. The results of some bunker fuel oils were compared. The injection duration was set to 30 ms. As a result, the bunker fuel oil with longer ignition delay showed lower flame temperature and higher soot concentration while the fuel oil with shorter ignition delay showed higher flame temperature and lower soot concentration. These results were also compared with the results of diesel fuel oils.

**Field trial findings on slow-steaming cylinder oil selection**

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Evolving marine fuels sulphur content legislation and the advent of slow steaming have consequences for engine maintenance costs and cylinder oil performance, in turn creating a challenge in maintaining safety margins while optimising operational efficiency. Castrol will present the results of its field evaluations that demonstrate the way slow steaming increases demands on cylinder lubrication. Based on research and development carried out in the laboratory and onboard ships, the company will present data showing that in certain conditions the selection of an 80 BN cylinder oil will prevent cold corrosion if the fuel sulphur level, engine load and feed rate make the lubricant stresses too severe for lower BN lubricants. At a time when the industry is likely to see a higher proportion of fuel bunker deliveries at the highest end of allowable sulphur content range, Castrol will outline why an 80 BN lubricant enables optimised feed rates and provides greater neutralisation capacity, and hence better corrosion protection across the fuel sulphur range while slow steaming. Furthermore, as well as offering fuel cost savings, reducing overall speed can mitigate concerns over ash deposits when operating on low-sulphur fuels in Emissions Control Areas.
Cylinder lubrication – utilising the latest findings on low-speed two-stroke diesel engine oil stress from field and laboratory engine testing in the development of a wide range cylinder lubricant – Shell Alexia S4

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In recent years, legislative changes and financial pressures have driven shipowners and operators to adopt new operational strategies. As a consequence, operational flexibility in terms of main engine loading and fuel choice has become not only a need, but a proven solution used to address environmental and economic performance needs of the marine transportation sector (particularly in the container vessel segment). In this context, a broader operational window for modern low speed two-stroke marine diesel engines has introduced new challenges that need to be considered in cylinder lubrication and have highlighted new performance requirements of the cylinder lubricant in order for it to deal more effectively with these changes. The influence of a highly variable operational profile results in a cylinder lubricant being exposed to stress levels that until now it has not been optimally designed for. This paper provides a summary of new investigations into low speed two-stroke cylinder oil stress under a broad range of operational conditions and presents these findings as the basis for the design of a wide range cylinder lubricant that is able to outperform traditional 70 BN cylinder lubricants across a highly flexible operational profile in terms of fuel choice, ambient conditions and engine loading. As part of the development process of a wide-range cylinder lubricant, the paper will discuss some aspects of how a fundamental understanding of oil stress in the low speed two-stroke diesel engine has significantly increased the importance and relevance of using a laboratory engine. Recent developments of new test protocols and engine control systems of the Bolnes 3(1) DNL 170/600 laboratory engine will be discussed and highlighted, to show how it can be used to generate reliable and repeatable test data for the process of discovering and benchmarking candidate formulations, thus proving their robustness and readiness for testing in the field in a full size engine that is capable of discriminating the performance of a lubricant. In particular this paper will discuss the increasing relevance of using such testing as a means of challenging traditional approaches to base number and performance relationships. Finally, the paper will show summarised results of more than 30,000 accumulated running hours with Alexia S4 on a number of engine types, sizes, ages and operational profiles, referenced against previous conventional 70 TBN cylinder lubricants.

Reliable lubrication of low-speed engines operated with varying fuel sulphur levels

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For the past several decades, the marine industry has been a conservative environment with very little changes in legislations and engine design. By the end of the previous century, however, the demands for more engine power, coupled with increased environmental awareness, have triggered tremendous changes in this industry segment. Recent and upcoming emission legislations require the use of low-sulphur fuel oil in environmentally sensitive areas. This triggers the need to have multiple high-quality cylinder oil grades available to tackle the changing fuel market. Thus, the selection of the correct cylinder oil to optimise engine lubrication is more important than ever. By extensive research on the operation of marine engines, Chevron has developed tools to operate marine diesel engines reliably, even when dealing with high variations in fuel quality. Traditionally, drip oil analysis (also called piston underside analysis) has been used to determine the optimum lubrication parameters to operate a low-speed marine engine. These optimum parameters are achieved by varying the base number (BN) or alkalinity level of the lubricant, or by adjusting the amount of oil injected to match the sulphuric acid present in the combustion chamber. The appetite for alkalinity is an indication of the corrosion sensitivity of the engine, and can vary substantially between different engine types. Every engine has a point at which oil feed rate becomes insufficient, and where iron, an indication of ongoing corrosion and wear, starts to increase. Traditionally, a measured drop in BN was used to determine this point; however, with marine fuels not containing any sulphur becoming more common, BN is no longer a suitable tool to determine optimum lubrication. Chevron has accumulated a vast database, which contains more than 15,000 samples, taken under a wide variety of engines, fuels and operating conditions. This paper will report the findings on research performed on marine engine oil performance under a wide range of residual and distillate fuels.

Multifunctional marine cylinder lubricants

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KBB Turbochargers

Knowledge to Boost The 2-stage charging technology of KBB

KBB Turbochargers

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The IMO classifies the world’s navigable waters into Global Areas and ECAs (emission control areas), with separate exhaust emission regulations governing each. In Global Areas, the sulphur cap is 3.5% and high-sulphur fuels are still used. High BN (base number) cylinder oils (70 BN) are used in Global Areas to prevent corrosive wear that can be caused by the sulphuric acid generated through combustion of sulphur in the fuel. In ECAs, low-sulphur fuel (S < 1%) must be used in order to meet SOx regulations. Engine manufacturers require the use of low BN cylinder oils (40 BN) in ECAs, because high BN cylinder oils are not suitable for two-stroke crosshead engines running on low-sulphur fuel. Because the list of areas designated as ECAs continues to grow, mid BN cylinder oils (55 BN) were developed, which can be used with both low-sulphur and high-sulphur fuels. Meanwhile, shipowners often operate vessels in slow-steaming mode to improve fuel efficiency, due both to sky-rocketing bunker fuel prices and in the interest of cutting CO2 emissions. Slow steaming, however, increases the amount of unburned materials (ex. soot) and decreases heat capacity in the combustion chambers. Therefore, the lubrication conditions in slow steaming are more severe and more corrosive than in normal load operation. Thus, the performance of mid-BN cylinder oils may be insufficient to provide proper lubrication in slow steaming. If high-BN cylinder oils could be modified for use with low-sulphur fuels, these problems would be solved. Therefore, the authors studied the incompatibility between low-sulphur fuels and high-BN cylinder oils and found two contributing factors. One is the previously recognised problem of increased ash deposits from surplus basic additives on the cylinder top lands, and another is a decline in oil spreadability, which is linked to the formation of high-molecular weight substances traceable to the oxidation products of the base oil and surplus basic additives. The decline in oil spreadability can be inhibited by improving the oil’s oxidation stability. We developed an ash softening technology to prevent the build-up of piston ash deposits. This technology can convert what would normally be hard ash deposits into meringue-like soft deposits. The technology was developed by optimising the detergent and dispersant system. The optimisation is based on the selection of the molecular weight and quantity of the dispersant used, and combining the dispersant with a proper detergent. This technology has not only an ash softening effect but also acts to accelerate the acid neutralisation rate. High-BN cylinder oils formulated with this technology are suitable for two-stroke crosshead engines running on either high-sulphur fuel or low-sulphur fuel and operating in slow steaming mode. Thus, these cylinder oils could be called multifunctional marine cylinder lubricants. In addition, 40 BN cylinder oils utilising this technology could be used in two-stroke crosshead engines running on ultralow-sulphur fuel (S < 0.1%, distillate or LNG, etc.).

New cylinder oil for today’s and tomorrow’s heavy fuels – laboratory and field performance experience

Kevin L. Crouthamel, ExxonMobil Research and Engineering Co, USA

Based on existing marine engine oil technologies, marine engine OEMs advise that long-term use of cylinder oils designed for high-sulphur fuels, when burning low-sulphur fuels, can lead to piston ring/cylinder liner micro-seizures and scuffing. The cited mechanisms are insufficient controlled corrosion of the cylinder liner and/or excessive piston crown land deposits. Therefore, they recommend that operators change to a lower BN cylinder oil when engines are required to operate more than two weeks on low-sulphur fuels. This necessitates that some operators carry more than one cylinder oil product on their vessel, which decreases their operational efficiency and increases their cost. In view of this and the recent and planned reductions in the sulphur content of heavy (residual) marine fuels and changes in engine designs, ExxonMobil saw the need to develop a new cylinder oil product that would be suitable for wider sulphur range operation (0.5 - 4.0% of sulphur). A product like this can reduce the total cost of ownership of operators and provide them with a competitive advantage in terms of overall vessel operation. Building upon ExxonMobil’s well-proven and patented cylinder oil technology, a new, 60 BN cylinder oil product, Mobilgard 560 VS, was developed that uses components that are carefully selected and balanced to provide the high performance typical ExxonMobil’s 70 BN cylinder oil with high-sulphur fuels and of ExxonMobil’s 40 BN cylinder oil with low-sulphur fuels, hence with a broader operating range to cover both high and low-sulphur heavy fuels. All this is accomplished at no increase in feed rate relative to that required for a 70 BN cylinder oil. Based on excellent field trial performance in MAN K98 and S-series engines and in Wärtsilä RT-Flex and RTA engines, in some cases using the minimum recommended feed rate (as low as 0.6 g/kWh) irrespective of fuel sulphur content, both MAN Diesel & Turbo and Wärtsilä granted Letters of No-Objection for the use of this new formulation with both high-sulphur and low-sulphur heavy fuels. A field trial with low-sulphur fuel (S < 1.0% S) revealed that the pistons lubricated by the new formulation were significantly cleaner than the pistons lubricated by the reference 40 BN oil. An additional cylinder oil feed rate ‘sweep’ test was run with an MAN S70 series engine operated at high load on high-S HFO that further validated the excellent performance of the new formulation, fully equivalent to the 70 BN reference oil, when used at the same feed rate. Successful field testing was also conducted in an MAN K98 engine that demonstrated the ultra-low feed rate potential for this new oil formulation. Wear rates measured after operation for an excess of 5,000 hours at the extremely low feed rate of 0.45 g/kWh were seen to be low and equivalent to those obtained with Mobilgard 570 under the same test conditions.

The efficient BASicity (EBAS): a method to assess the performance durability of marine cylinder lubricants

Catherine Amblard, Total Marketing-Services, France
Serge Esson, Total Marketing-Services, France

As a result of the drastic lowering of sulphur content in HFO or the introduction of LNG fuel, the basicty of future-generation marine cylinder lubricants should be decreased, provided a high level of neutralisation efficiency can be maintained. The efficiency of the neutralisation reaction will be a key parameter if specific engine operating modes and future engine designs are more likely to produce acids and are therefore more sensitive to corrosive wear. Such protection can be delivered by using innovative ashfree neutralising chemistries to replace the traditional CaCO3, which has been shown to be a poor neutralising agent and prone to generate hard deposits during oil degradation. With the objective to differentiate and quantify this basicty efficient and further to the publication of the Efficient BASicity (EBAS) concept, we have developed an analytical method, derived from ASTM D4739. The chemical background of this method is described as well as experimental details, such as repeatability, reproducibility, selectivity and discriminating ability. EBAS is complementary to BN (ASTM D-2896), therefore the two values should qualify the neutralisation capability of a finished lubricant. We also report about our in-service experience with such methods and our efforts to correlate them with engine reliability. Monitoring two-stroke engines in service is the way to correlate and couple EBAS/BN with Fe content of drain oils, or to other indicators of engine condition such as the position in the viscosity-basicity diagram.
Rudolf Diesel demonstrated his compression ignition engine at the World Fair in Paris in 1900. One year earlier, the first diesel engine outside of Germany was built under license by the Carels Brothers in Ghent, Belgium. In 1912, this license was brought into the founding of the Anglo Belgian Corporation (ABC). Now ABC is 100 years older and celebrates its centennial jubilee. During this time, the engines have undergone tremendous progress, and are produced for applications all over the world. With the increasing focus on emissions and fuel consumption, ABC has taken the next challenge to design and build a completely new engine range with a power output of 650 kW/cylinder at 750 rpm, which is developed to meet the IMO III emission level with engine internal measures. This engine is designed with state-of-the-art components and a unique charging system, which has to make it possible to reach the IMO III limits. Furthermore, the engine is developed to work inside and outside the ECAs, on MDO, HFO and gas. The base design of the engine is foresee to work at different speeds on nominal torque so that the engine has its main applications in both power generation and marine propulsion. This will make it a multifunctional engine that will set the standard in its category. This paper will describe this new developed engine's characteristics and will highlight the new technology that is used to reach the targeted IMO III limit, with measure inside the engine. It will include a discussion on the different issues as there are, mechanical design, thermodynamics, emissions, fuel consumption, etc. We will also describe the current status of the development and show the available test results.

Full line-up of HiMSEN family by newly developed H46V
Chan Yun Seo, Hyundai Heavy Industries Co,Ltd, South Korea
Sung Hyeok Kim, Hyundai Heavy Industries Co, Ltd, South Korea
Jong Suk Kim, Hyundai Heavy Industries Co, Ltd, South Korea
Ju Tae Kim, Hyundai Heavy Industries Co, Ltd, South Korea
Joo Ho Jin, Hyundai Heavy Industries Co, Ltd, South Korea

One of the world’s largest engine makers, Hyundai Heavy Industries (HHI) has grown through customer satisfaction with future-oriented engine development and continuous upgrade of developed engines. To meet the customer requirement such as variation of usable fuel, low emission, large power, etc. HHI develops gas-fuelled engines and various diesel engines with a customer-friendly design. Now HHI’s new medium-speed engine, H46V designed with 460mm bore and 600mm stroke, is developed to satisfy customer requirements. As a result, H46V lead to have enough design potential on low emission, high efficiency and reliability. Thanks to the newly developed H46V, the HiMSEN engine covers an output range of 575 kW/5H17/28 to 26,000 kW/20H46/60V. It can be used in marine propulsion, land-based power plants and military. The new H46V medium-speed engine will have a unique design to meet not only new emissions regulations but also client’s requests for easier maintenance concepts. To realise high reliability and performance, state-of-the-art technology has been adopted together with a huge amount of analysis work and field experience such as high structure strength (minimising thermal load, noise and vibration), highly efficient turbocharging, advanced miller timing, optimised combustion chamber with crown shape, nozzle specification, efficient lubricating and cooling system. Additionally, in order to improve the performance and smoke during low load operation, VVT/VIT technologies will be adopted, which are already developed and applied to the smaller bore HiMSEN engine. This paper describes the full line-up of the HiMSEN engine family and provides an introduction to the H46V engine, which demonstrates HHI’s high capabilities and technologies to that it is able to meet the rapidly change market demands and circumstances.

Update on Wärtsilä’s four-stroke diesel product development
Robert B Ollus, Wärtsilä Finland, Finland
Tero Raikio, Wärtsilä, Finland
Ari Suominen, Wärtsilä, Finland
Jonas Akerman, Wärtsilä, Finland
Paolo Tonon, Wärtsilä, Italy
Diego Delneri, Wärtsilä, Italy
Andrea Bochicchio, Wärtsilä, Italy

Internal combustion development and value proposition within Wärtsilä is increasingly geared towards offering end customers solutions featuring flexibility, agility, and the highest efficiency in both onshore and offshore applications for power plants and marine installations. The ‘must haves’ for both customers and Wärtsilä remain reliability, emissions compliance, and cost-effective solutions. This paper will describe the main technology enablers for delivering these benefits, and will also give an overview of the products available and recently developed that incorporate them. The four-stroke product portfolio overview is divided into two papers: one reviewing diesel and the other reviewing gas technologies/products in more detail. It should be noted, however, that many technologies can naturally be applied for both. Primary measures, such as high-pressure charge air systems, secondary measures such as exhaust gas aftertreatment, as well as multi fuel operation currently appear to be the most robust and promising technologies for compliance with existing and future legislation. They represent the boundary conditions to product development. Unplanned malfunctions are expensive. Therefore, in product development the target is to integrate simulation and self-adapting systems. One of the key technologies for the future is two-stage turbocharging. Wärtsilä presented this idea for the first time at CIMAC 2004 in Kyoto. Through systematic work on this technology, the entire industry as well as customers have been able to harvest the benefits, namely fuel consumption savings, NOx emission reductions, and increased reliability. This paper will describe the products now available and those to come featuring the two-stage turbocharging system. It will also describe the design, the measured customer benefits, and will highlight the issues observed from units that have operated for 10,000 running hours. The paper will also offer a description of the first commercial plants to operate with this technology in both marine and power plant installations. Another key technology is electronic fuel injection. Again here, Wärtsilä was a pioneer in the late 90s when we introduced this as a means for cruise plants to achieve low particulate and smoke emissions. The paper will describe the changes made from the cam-driven pump-accu-injector system to the second-generation system.
will also show the improvements in reliability and customer maintenance. Finally, it will also show the improvements in fuel efficiency and flexibility compared with the first-generation system, and the reasons behind these improvements, as exemplified in Wärtsilä’s portfolio of second-generation CR products. Variable valve mechanisms for optimum performance at all loads and increased flexibility under all conditions have become the standard solution for most engines, the customer benefits being obvious. However, today’s 2013 systems are somewhat different than the systems in the late 90s, when Wärtsilä first introduced variable valve mechanisms for large medium-speed engines. Embeded automation is an enabler for most technologies being used on products in a reliable and repeatable way. Wärtsilä has continued the development of its UNIC system with increased functionalities, while maintaining high safety and offering a better user interface. The paper will describe the benefits of having one system. Aftertreatment systems integrated on engines offer a means of reaching the increasingly challenging emission limits with high efficiency. The paper will include Wärtsilä’s experience and the customer benefits with such systems. The paper will finally include an overview of the new diesel products in the Wärtsilä portfolio where the mentioned technologies are utilised. Examples include a new small bore engine / a locomotive adaption of the Wärtsilä 20 / the industrialised two-stage turbocharged Wärtsilä 32 / field experience with the new Wärtsilä 32 featuring the new generation of common rail / the Wärtsilä 46 and others.

**MAN Diesel & Turbo product portfolio of diesel engines adapted to actual challenges**

Detlef Kurth, MAN Diesel & Turbo, Germany
Sonja Adorf, MAN Diesel & Turbo SE, Germany
Armin Grabmaier, MAN Diesel & Turbo SE, Germany
Ludwig Gruensteudel, MAN Diesel & Turbo SE, Germany
Stefan Kold, MAN Diesel & Turbo SE, Germany
Bernhard Offinger, MAN Diesel & Turbo SE, Germany

The product portfolio of diesel engines by MAN Diesel & Turbo contains several diesel engines adapted to special market segments. There are several challenges driving the actual development of diesel engines. Most important are the rules and regulations regarding emissions, the trend of global economics and the significance of new markets like offshore exploitation. Especially the diesel engines have to include new technologies in order to maintain their role for large medium-speed engines. Embedded automation is an enabler for most technologies being used on products in a reliable and repeatable way. Wärtsilä has continued the development of its UNIC system with increased functionalities, while maintaining high safety and offering a better user interface. The paper will describe the benefits of having one system. Aftertreatment systems integrated on engines offer a means of reaching the increasingly challenging emission limits with high efficiency. The paper will include Wärtsilä’s experience and the customer benefits with such systems. The paper will finally include an overview of the new diesel products in the Wärtsilä portfolio where the mentioned technologies are utilised. Examples include a new small bore engine / a locomotive adaption of the Wärtsilä 20 / the industrialised two-stage turbocharged Wärtsilä 32 / field experience with the new Wärtsilä 32 featuring the new generation of common rail / the Wärtsilä 46 and others.

**The new MTU type L64 of series 4000 gas engines**

Udo Sander, MTU Friedrichshafen GmbH, Germany
Stephan Menzel, MTU Friedrichshafen GmbH, Germany
Markus Raintl, MTU Friedrichshafen GmbH, Germany

The newest version of the MTU series 4000 gas engines, the L64 presents the results of consistent improvements in this highly modern gas engine family. The focus of the development was the increase in power of 130 kW/cylinder and the increase in efficiency of 45% while reducing emissions. With its efficiency and power the L64 will be placed in a crucial market position. The foreseeable power range will be up to 2.6 MW for the 20 cylinder version, while retaining an operating life of 64,000 hours. Furthermore, through the higher cylinder power, a positive downsizing effect is achievable. To achieve the above mentioned customer benefits, there were numerous technical measures necessary and this often in high detail. Here are just a few key points:

- **New combustion process**
- **New cylinder heads for higher peak pressure**
- **Increased engine efficiency**
- **Reduced noise emissions**
- **Easier compliance**

The thermal efficiency improvement is an important item, which not only lowers the operation cost, but also leads to environmental load reduction and energy saving. Enhancement for Miller cycle, high efficiency turbocharger METMB and optimisation for combustion chamber aiming fast burn concept contribute to ful-fil this efficiency improvement, which was thoroughly evaluated through the test engine verification. Three engines applied to this high efficiency specification were already delivered and have been in successful operation. This paper describes the features and technologies, including the latest development for this efficiency improvement, of the KL30GSI gas engine as well as the operation result on actual site.

**MACH II-SI achieved higher thermal efficiency**

Hajime Suzuki, Mitsubishi Heavy Industries, Ltd, Japan
Hiroshi Yoshizumi, Mitsubishi Heavy Industries, Ltd, Japan
Michiyasu Ishida, Mitsubishi Heavy Industries, Ltd, Japan
Shoji Namekawa, Mitsubishi Heavy Industries, Ltd, Japan
Shinnosuke Osafune, Mitsubishi Heavy Industries, Ltd, Japan

Against a background of recent energy issues, demand of more efficient operation for power plants typified by the distribution of power plants involving the smart-grid concept are growing, while the use of shale gas as well as the extension of gas pipelines has been steadily progressing. Therefore, the gas engine market is defi-nitely expected to grow at a steady pace. Gas engine power generation has a lot of characteristics: High environmental performance, high thermal efficiency, high quickstart and load following capability, high exhaust heat recovery. The KL30GSI gas engine has already realised the superior utilisation for exhaust energy and cooling energy, like steam, hot and cold water, and, thus, fulfi-l the higher efficiency as a cogeneration unit. In addition, its excellent performance for rapid starting potential makes it possible to apply to the back up for renewable energy powers. Mitsubishi Heavy Industries, Ltd (MHI) has already received orders of over 30 sets of the KL30GSI, and requests from many clients regarding the consideration of the introduction of the KL30GSI with the favour-able feedback of its reliability based on the abundant track record. To cater for the recent demand of the customer, focusing on the power generation, MHI has completed the work for its efficiency increase, and achieved an excellent efficiency of 48.8% (ISO3046). The thermal efficiency improvement is an important item, which not only lowers the operation cost, but also leads to environmental load reduction and energy saving. Enhancement for Miller cycle, high efficiency turbocharger METMB and optimisation for combustion chamber aiming fast burn concept contribute to ful-fil this efficiency improvement, which was thoroughly evaluated through the test engine verification. Three engines applied to this high efficiency specification were already delivered and have been in successful operation. This paper describes the features and technologies, including the latest development for this efficiency improvement, of the KL30GSI gas engine as well as the operation result on actual site.

**Tuesday May 14th / 10:30 – 12:00 Room B**

**Product Development**

**Gas and Dual-Fuel Engines – New Gas Engine Types 2**

**MACH II-SI achieved higher thermal efficiency**

Hajime Suzuki, Mitsubishi Heavy Industries, Ltd, Japan
Hiroshi Yoshizumi, Mitsubishi Heavy Industries, Ltd, Japan
Michiyasu Ishida, Mitsubishi Heavy Industries, Ltd, Japan
Shoji Namekawa, Mitsubishi Heavy Industries, Ltd, Japan
Shinnosuke Osafune, Mitsubishi Heavy Industries, Ltd, Japan

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New high-pressure turbocharging,
New Miller engine timing,
Advanced ignition system for low NOx combustion,
Dethrottling and optimising all associated flow components.

Extensive testing has been taken to validate these results, in addition several engines have been placed in the field running thousands of hours. The market launch will be in 2013/14 with all cylinder versions eight, twelve, 16 and 20 V, beginning with 50-Hz followed by 60-Hz versions.

**Update on Wärtsilä’s four-stroke gas product development**

Miikael Troberg, Wärtsilä Power Tech, Italy
Kaj Portin, Wärtsilä Power Tech, Finland
Arto Jarvi, Wärtsilä Power Tech, Finland

Gas engines have during the years been a derivate of the diesel engine development. The diesel engine families have given a reliable and cost-effective platform for developing gas engines. By adapting gas technologies to existing platforms, the development time has been significantly reduced, which has lead to reduced lead times and cost-competitive products. The first Wärtsilä gas engines were introduced to the power plant market driven by the fuel price, operational flexibility and emissions. The awareness of utility companies has increased and gas engines are considered reliable, flexible, efficient and cost-competitive energy converters. Yearly, the global electricity demand grows by 10 to 15%. Renewable fuels have gained momentum and will stand for 20% of the total production. The main challenge with renewable energy is related to availability and predictability. Big wind mills producing 500 MW might lose their total power in a few minutes, which needs to be compensated. Traditional coal and turbines can not cope with these rapid power demands, if starting from standstill.

Shipping is facing tough emission restrictions in 2016 when the requirements on fuel quality and NOx emissions will be introduced. Gas engines will be a competitive choice as the availability of gas is improving especially in ECAs. The use of gas engines in the merchant and offshore segments is already a standard as the first installations for cruise and navy are under delivery. In addition to reliability, output and life-cycle cost improvements, this paper will describe a summary of challenges like engine loading, methane slip and how they have been tackled. The paper is devised in two parts, one reviewing the diesel engine and one reviewing the gas engine in more detail. To be noted, however, that many technologies naturally can be applied for both.

**Advanced development of medium-speed gas engine targeting marine and land**

Koich Watanabe, Niigata Power Systems Co, Ltd, Japan
Satoru Goto, Niigata Power Systems Co, Ltd, Japan
Toru Hashimoto, Niigata Power Systems Co, Ltd, Japan

Niigata power systems has been developing the gas engine for about 30 years as one of the best matched products, which satisfies the trend of social requirements, such as an environmental preservation and fuel economy, and an electrical demand in industrial field. About 15 years ago, the gas engine with the Niigata original micro pilot ignition system, which has BMEP 2MPa and more than 43% of thermal efficiency at 3 MW class, was developed. This engine series consists of two types with a power range of 1, 3 and 6 MW. These engines have been acting as a key role as cogeneration system in more than a hundred units in the domestic market in Japan. Moreover, since this engine can employ the minimum maintenance interval in 4,000 hours, it is contributing to the big economic saving in the running cost in particular continuous running power-generating plant. Recently, the gas engine was welcomed both in land-based and maritime power generation because of the environmental advantage, the economical efficiency based on the spread of gas resources, and a viewpoint of long-term fuelling prediction. To adapt to these situations, Niigata power systems has developed two new gas engines designed as spark-ignition method and dual-fuel engine, which are launched as key hardware for power generation and marine propulsion system. The spark ignition gas engine has been mainly developed as power generation for 2 to 6MW, and the dual-fuel engine will mainly be applied for marine propulsion system with a power density of 2 to 3 MW. A newly developed 6 MW class spark ignition gas engine has attained approximate 47% of power generation efficiency with low NOx emission, based on the design technique of the lean burn technology, main combustion chamber, and precombustion chamber and combustion control technology. A marine dual-fuel engine was designed through diesel design experience and micro pilot technology for diesel-mode operation and gas-mode operation, respectively. Niigata developed the propeller direct drive type dual-fuel engine to meet the desired load operation characteristics of a tugboat that works in a harbour without generating abnormal combustion such as a knock, with original combustion technology.

Sudden acceleration torque and slowdown torque are required of a tugboat at the time of navigation of a large-sized ship. Moreover, a dual-fuel engine can shift smoothly the mode of operation arbitrarily by the change of oil or gaseous two-sort fuel. For this reason, in the viewpoint of safety cruise of a ship, the reliable diesel engine is an advantage as redundancy system. Niigata’s dual-fuel engine meets NOx emission level in IMO Tier II and Tier III at diesel operation and gas operation, respectively. This performance can be accepted in ECAs. This paper describes the newly developed spark gas engine and marine dual-fuel engine.

**Recent developments in the understanding of the potential of in-cylinder NOx reduction through extreme Miller valve timing**

Panagiotis Kyrtatos, ETH Zurich, Switzerland
Klaus Hoyer, Paul Scherrer Institut, Switzerland
Peter Obrecht, ETH Zurich, Switzerland
Konstantinos Boulouchos, ETH Zurich, Switzerland

In-cylinder NOx reduction is becoming increasingly important for stationary and marine DI diesel engine applications, where progressively more stringent emission legislation has significantly reduced allowed NOx limits. Extreme Miller valve timing, coupled with two-stage turbocharging, has shown significant NOx reduction potential, with increased engine efficiency and similar power density as conventional engine setups. Under the Miller cycle, the inlet valve is closed before bottom dead centre, allowing the charge to expand before compression. This leads to a reduced charge air temperature at top dead centre and a reduction in reactant temperatures, resulting in a lower adiabatic flame temperature and correspondingly lower NOx formation during combustion. Nonetheless, experimental investigations have shown limitations in the amount of NOx reduction that is possible solely through the reduction of reactant temperature. At extreme Miller degrees,
reductions in the reactant temperature have been observed to result in increases in NOx emissions. Limiting the applicability of the use of Miller valve timing for NOx reduction. The improved understanding of the source of these limitations could lead to improvements in the potential of in-cylinder NOx reduction through Miller valve timing. The current paper aims to provide an understanding of the effects of cyclic variation of in-cylinder soot mass on the overall trend of NOx emissions. At extreme Miller conditions, high cycle-to-cycle variations of in-cylinder pressure and soot concentration, measured using an in-cylinder optical light probe and the method of three-colour pyrometry, were observed. Cycles with reduced soot concentration also showed increased soot temperature, pointing to the assumption that the reduced soot presence results in reduced flame radiation heat transfer, leading to increased flame temperature. Under conventional diesel engine conditions, the flame radiation heat transfer through the presence of soot particles in the flame leads to flame temperatures well below the adiabatic flame temperature. Thus, the reduction of soot presence results in flame temperatures closer to the adiabatic, leading to increases in NOx production rate. This reduced flame radiation heat transfer at these conditions is understood to contribute significantly to the observed NOx trends with extreme Miller valve timing.

Computational analysis of different EGR systems combined with Miller cycle concept for a medium-speed marine diesel engine

Federico Millo, Politecnico di Torino, Italy
Marco Gianoggio Bernardi, Politecnico di Torino, Italy
Emanuele Servetto, Powertech Engineering S.r.l., Italy
Diego Delneri, Wärtsilä, Finland

In this work different EGR systems, combined with extreme Miller cycles, were analysed by means of a one dimensional CFD simulation code for a Wärtsilä six-cylinder, four-stroke, medium-speed marine diesel engine; to evaluate their potential in order to reach the IMO Tier III NOx emissions target. Extreme Miller cycles, with early intake valve closures (up to 100 crank angle degrees before BDC), combined with two-stage turbocharging were firstly evaluated and the best solution in order to reduce NOx emissions without excessive penalties in terms of fuel consumption was found to be the adoption of a 30 CA deg EIVC, coupled with a symmetric overlap of 30 CA deg, which allowed a 35% NOx abatement with BSFC values comparable with the reference solution. Afterwards, four different external EGR architectures were evaluated for the assessment of their NOx emissions abatement potentialities. Although all the tested external EGR systems were capable to reduce NOx emissions down to approximately 20% of the reference engine when using the highest EGR rate (20%), the use of an EGR turbocharger (i.e. of an additional small turbocharger used to pump the EGR flow between the exhaust and the intake manifold), allowed maintaining components thermal loads under control, with still acceptable fuel consumption penalties (about 4%). In conclusion, the achievement of IMO Tier III NOx emissions levels was proved to be feasible, although further experimental investigation will be needed to confirm the numerical simulation results.

Experimental experience gained with a long-stroke medium-speed diesel research engine using two-stage turbocharging and extreme Miller cycle

Mathias Friedler, FMC Friedler-Motoren GmbH, Germany
Hugo Friedler, FMC Friedler Motoren GmbH, Germany
Peter Boy, Flensburg University of Applied Sciences, Germany

The objective of the paper is to present experimental results gained from a long-stroke medium-speed diesel engine. The study is carried out on the three-cylinder long-stroke FMC 4524 research engine located at Flensburg University of Applied Sciences in cooperation with ABB Turbo Systems, Baden. Based on a IMO II layout of the engine featuring

- High stroke/bore ratio of s/d = 450mm/240mm = 1.875,
- Optimised mechanical efficiency based on crankshaft design acc. to classification rules,
- Combustion chamber design optimised for high compression ratio (\(\approx 17.8\)),
- Two-stage high-pressure injection system with variable injection pressure,
- Single-stage turbocharging,
- Standard inlet valve timing.

Two-stage turbocharging and Miller cycle inlet valve timing were applied in several steps. In parallel, modifications to the exhaust gas system were applied to improve part load and startup performance. Also variations of exhaust gas timing and injection characteristics were executed. The project is primarily aimed at reduction of CO\(_2\)- and PM emissions in the envelope of IMO III exhaust gas regulations for non ECAs. In an intermediate development step, inlet valve timing was moved to 42°CA before BDC (Miller 42) and 50°CA before BDC (Miller 50). The first results of Miller 42 showed a reduction of fuel consumption to 16 g/kWh, meaning a CO\(_2\) emission reduction of approximately 6% based on the values of the base engine. PM emissions stayed constant on the low level of the base engine. In opposition to the expected trend NOx emissions could be reduced by 20% down to about 8 g/kWh. Further development steps will include tests with more extreme Miller configurations up 60°CA before BDC. Additionally, pilot applications of other means for emission control like EGR and fuel water emulsion are planned to evaluate further emission reduction potential aiming at emission regulations for ECAs.

Investigation on the control strategies of a heavy-duty diesel engine with high efficiency and low emissions

Mingfa Yao, Tianjin University, China

Exhaust gas recirculation (EGR) is widely used due to its efficiency impacts on the NOx reduction with the increasingly stringent emission regulations. However, the introduction of EGR can lower in-cylinder oxygen concentration and increase combustion losses, which will increase soot and brake specific fuel consumption (BSFC) simultaneously. In this paper, the integrative optimisation for the combustion system and fuel injection parameters, the introducing way of EGR, turbocharger matching, fuel injection strategy for the combustion system and fuel injection parameters, the introducing way of EGR, turbocharger matching, fuel injection strategy was conducted in a heavy-duty diesel engine with common rail fuel system. The results showed that soot, BSFC and the maximum in-cylinder pressure can be lowered by properly reducing compression ratio, optimising the structure parameters of the combustion chamber (shrink diameter and bowl depth, etc.) as well as using a Bosch injector with eight taper holes. Relative to high-pressure EGR (HEP EGR), low-pressure EGR (LPEGR) can significantly enhance the EGR recyclability and air/fuel ratio (AFR) at low-speed conditions, thus improving soot and BSFC performances. Conversely, the HPEGR can reduce pump losses and BSFC at medium- and high-speed conditions. Compared with a constant pressure system, the EGR recyclability and the NOx:BSFC trade off can be improved by pulse boost systems for HPEGR. The trade off between NOx, soot and BSFC will worsen with the increased intake charge temperature at high load cases under the low speed. However, the effects of intake charge temperature on the engine performance and emissions can be weakened by optimising turbocharger systems, EGR system, fuel...
The most important technology drivers in the development of modern four-stroke medium-speed engines are high total engine efficiencies, low operating costs and high power density while complying with ever more stringent emission legislation. In addition, optimisation of initial costs has been considered during the development to allow for short payback time and thus for a competitive advantage in the area of power generation where reciprocating engines compete with gas turbines. Improvement in all areas mentioned above can be achieved with the application of the latest turbocharging technologies. ABB Turbocharging is currently developing the second generation two-stage turbocharging system for medium-speed gas and diesel engines. The work comprises a complete portfolio with four sizes covering the entire power range of large medium-speed engines. All components of this new system will be fully optimised for combined use in the two-stage system. Completely new designs are being developed for the thermodynamic components. The focus is on high efficiencies for fuel savings, system compactness and flexible operation. Axial turbines will be applied for both low and high pressure stage. The turbine stage designs take into account the diverging needs between high- and low-pressure sides. These result from different temperature levels and flow area requirements. And, as contamination build-up is not comparable, this results in different turbine cleaning concepts. Compressor stage designs are specifically optimised for two-stage requirements. Consequently dedicated designs, highly efficient and compact turbochargers are being realised. Low and high pressure turbochargers will be based on the new concept of an extended cartridge which will facilitate service down times even shorter than those on existing single stage applications. The second generation system is the result of a step change development process motivated by field experience gathered from first generation serial systems. Studies presented at the CIMAC conference in 2007 revealed that two-stage turbocharging systems would soon become a commercially attractive alternative to state-of-the-art single-stage turbochargers. Three years later, the first two-stage turbocharger designs for medium- and high-speed gas and diesel engines were presented. The first serial engine applications were introduced to the market with claimed benefits proven. With the development of the second-generation Power2 turbocharging system, ABB Turbocharging provides an optimised technology enabling full exploitation of the advantages of two-stage turbocharging for large medium-speed engines.

TCX – the new high-pressure turbocharger for two-stage turbocharging

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Vladimir Hort, PBS Turbo, Czech Republic
Markus Haidn, MAN Diesel & Turbo SE, Germany

New, stricter emission limits and engine development are continuously increasing the requirement to boost pressure level. Turbocharger manufacturers have been trying to fulfil this requirement by increasing the maximum pressure ratio of single-stage compressors, until material limits were achieved. The situation changed when engines with Miller timing were put into operation and showed their potential for additional emission reductions. As a consequence, a pressure ratio well above six was required. This was the impulse to start thinking about multi-stage compression with intercooling. From the start, the requirements of potential customers were included into the design. Based on application investigations, it was decided to keep the low-pressure unit inside the standard product portfolio and develop a new high-pressure turbocharger according to the special requirements. In reference to...
market potential, a medium-size unit was chosen to be designed and tested as a pilot version. Highest efficiencies at low-pressure ratios and increased mass flow capacities corresponding to high engine power density, together with higher mechanical load, were a considerable challenge in developing a new turbocharger. After the initial study, which defined operating conditions and ranges, the new compressor and turbine were designed using advanced CFD and FE tools. Some well-proven concepts from NR/S and TCR turbochargers were adopted for the project. The best versions were built by rapid prototyping methods and tested separately on compressor and turbine test benches. Simultaneously with production of prototypes, a new two-stage turbocharger test bench has been prepared capable of pressure levels up to 11 bar g, for which more sophisticated controls have been installed. The measuring system was upgraded for two-stage group measurements as well. The test of the main parameters confirmed the reliability of the design and thermodynamic expectations. Based on single-stage and two-stage configuration measurements, a significant increase in the efficiency of the turbocharging system compared with just one stage was recorded. Special component tests were performed as well. In recent years, the TCX 14 has been developed as the basis of a new series of high-pressure turbochargers for two-stage turbocharging, suitable for the upcoming generation of reciprocating engines. The turbocharger performance fully covered the planned range and confirmed the potential of two-stage turbocharging to achieve charging group efficiencies far above maximum single-stage figures. PBS Turbo, a member of the MAN group, is ready to provide the new technology – comprising TCX as high pressure and TCR/TCA as low pressure turbochargers. In the paper the development steps are presented, with main focus on the TCX design features including comprehensive results of the component validation as well as test data in single-stage and two-stage configuration.

Development of high-pressure ratio and high-efficiency type turbocharger
Keisuke Matsumoto, IHI Co, Ltd, Japan

In recent years, various approaches to environmental problems were carried out. As for marine diesel engines, the IMO (International Maritime Organization) has phased in emission regulations mainly against NOx reduction in exhaust gas. To comply with this emission regulation, all marine diesel engine manufacturers are advancing the development of next-generation marine engines. Some typical technologies effective for reducing NOx in exhaust gas are the Miller cycle engine, EGR (exhaust gas recirculation), SCR (selective catalytic reduction), gas fuel engines, and the application of water emulsion fuel, etc. Among these technologies, the Miller cycle engine has already been put to practical use by many marine diesel engine manufacturers, because of the great advantage in development cost due to smaller change necessary in structural design compared with conventional designs. Additionally, the Miller cycle engine is known to be effective in combination with other NOx-reducing technologies and is expected to be applied continuously. Higher supercharging is necessary to realise the Miller cycle engine. Therefore, a higher pressure ratio is coming to be required for marine turbochargers in the next years. In addition, there are constant requirements for marine turbochargers such as higher efficiency, wider operational range and higher performance at low speed. To meet these demands, IHI has developed a radial type high-pressure ratio turbocharger, named high-pressure ratio AT14 (New AT14). The New AT14 has achieved a higher pressure ratio than usual by improving some design methods such as the increase of circumferential speed of compressor wheel and optimisation of compressor blades and recirculation devices aerodynamic geometry by using CFD etc. These technical efforts lead to the improvement of the pressure ratio from 3.8 up to 5.0 at the engine operation point. The New AT14 turbocharger has already been adopted as a standard model by some engine builders, and is expected to show its high performance in the global market. In this paper the development of the AT23 turbocharger will be shown with some of the obtained test results. The AT23 turbocharger is the turbocharger IHI has developed lately for smaller marine diesel engines than engines that apply AT14 turbochargers. Aerodynamic parts such as the compressor and turbine were redesigned and the shafting was also redesigned to reduce mechanical loss. The AT23 turbocharger has achieved a higher pressure ratio and efficiency compared with IHI’s conventional turbochargers. On the other hand, turbochargers are required not only to feature a high-pressure ratio and efficiency but also safety, durability, longer mechanical life and easier maintenances. The AT23 turbocharger has improved some of the structures to respond to these requirements.
According to a Chinese engine builder’s commission, the Shanghai Marine Diesel Engine Research Institute developed a new medium-speed marine diesel engine CS21 together with FEV. The engine’s bore diameter is 210mm, with a stroke of 320mm. Its output covers from 1200 to 2070 kW with 6 -9 cylinder inline, which is available for propulsion and genset units. The engine will offer customers high reliability, technical competitiveness, easy maintenance, low prospective cost, low fuel consumption, and it will meet the IMO Tier II regulation. Based on Chinese domestic manufacture and supply, the proven design concepts were adopted and CAE simulations were extensively performed for estimating components and systems in CS21 engine developing process. The compounding of Miller timing, latest turbocharger with high compression ratio and high pressure common rail injection system help the engine achieve good performance. The prototype engine has accumulated more than 800 hours in operation on the test bench. It is proven that the development targets have been met.

Development of Niigata medium-speed diesel engine 17AHX
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Toshiyuki Saito, Niigata Power Systems Co, Ltd, Japan

Recently, the four-stroke engines have been developed mainly with the environmental preservation in mind as well as taking economy, durability and maintainability, etc. into account. Niigata has developed a new high-power density new four-stroke medium-speed diesel engine: The 17AHX has a 165mm bore and 265mm stroke and engine speeds of 900 rpm, 1000 rpm and 1200 rpm, respectively. The 17AHX has an output range of 500 kW to 1,125 kW for marine auxiliary engines, marine propulsion and electric propulsion engines that run on MDO and heavy fuel oil. Niigata achieved a shortened development period of around one year by using front loading such as performance simulation. like CFD, FEA that were carried out in an early development stage. Niigata improved the durability and reliability by the advanced analysis technology such as performance simulations like FEA and CFD. In order to improve environmental concerns, Niigata considered optimising compression ratio, valve timing, piston bowl shape, turbocharger matching and fuel injection system by using performance simulation. Niigata carried out simulation analysis for the optimum fuel injection system at the beginning of the development stage. The fuel injection system performances such as the stable injection, improved performance during idle and full loads were confirmed by the component tests. The combustion chamber is the most critical component for life time. Niigata has designed carefully the combustion chamber to achieve longer life time. Especially, FEA and CFD were applied to produce a highly rigid construction and effective cooling on the combustion chamber. The moving parts were optimised and reduced weight through FEA. The engine was tested with two exhaust systems such as constant pressure and pulse. The valve timing is inference of engine performance. Niigata tested the engine with cam timing variants and turbocharger matching optimisation. Niigata investigates main components of prototype engine stress distribution and temperature profiles. The prototype engine verifies the durability of the new engine, endurance tests have been performed. This paper describes the design features of the main components of the 17AHX, simulation results and engine test results.

Small bore four-stroke engines from MAN Diesel & Turbo
Finn Fjeldhøj, MAN Diesel & Turbo SE, Denmark
In recent years, the market for small bore four-stroke gensets and small bore four-stroke propulsion engines has moved to the Far East. The organisation and handling of these engines have changed accordingly within MAN Diesel & Turbo. In 2011, the responsibility for the MAN Diesel & Turbo small bore four-stroke engines shifted to Denmark. Our duty and commitment is to be the preferred licensor. We have changed the organisation in Denmark in order to be able to handle this new responsibility with a strong focus on engineering, R&D, promotion, support and troubleshooting service. Thus, we are launching a number of initiatives to further improve the performance of the engines as well as to update the small bore four-stroke engine programme. Over the years, a comprehensive amount of technical modifications has been introduced to the engines. These modifications have been implemented to counteract problems occurring in service as well as to reduce production costs. This paper describes the service experience of the large number of GenSet engines, propulsion engines and engines in power stations with a detailed explanation of what has been done to cure the problems experienced. In the paper we also describe how these findings and countermeasures will make it possible to increase the recommended time between overhauls, depending on engine type. We have released a number of design changes to the small bore engine programme with a view to further increasing the competitiveness of the engines. Furthermore, we are launching a new engine type in the programme. A description of what has been done, engine design details as well as what is in the pipeline for the future, will be included in the paper. The paper also outlines how MAN Diesel & Turbo cooperates with the licensees worldwide. Our licensees contribute with production know-how, design optimisations, standardisations, shipyard feedback, local market overview and overall experience. All these contributions and our own know-how will be reflected in our new engines.

The new Bergen B35:40 lean-burn marine gas engine series and practical experiences of SI lean-burn gas engines for marine mechanical drive

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The pioneering Bergen SI lean-burn marine gas engine portfolio has been established and launched to the market through the previous eight years. The gas engine portfolio builds on the strong pedigree of the Rolls-Royce Bergen lean-burn SI gas engines for land-based power applications. The first steps towards the marine gas engine applications were taken by the initial adaptation of the classic KV-Gas series for gas electric propulsion in a series of Norwegian car passenger ferries in 2006. The first 16 engines have now accumulated more than 500,000 running hours with individual engines at 41,000 hours +. The next major move was the introduction of the B35:40V marine gas series in 2008, and the newly designed C26:33 L-series in 2010. Both of which have been put to use in mechanical drive variable speed applications. In 2012 the range was completed by the introduction of the B35:40-L-series. The development of the marine gas engines aims at mechanical drive propulsion application as well as marine genset applications, both incorporating the ‘Inherently Safe Gas Concept’ with double-walled gas supply systems with ‘block and bleed systems’ installed. Strong aspects of the marine lean-burn gas engines are low specific fuel consumption, good transient load performance combined with very low NOx, SOx, CO₂ and UHC emissions. This paper will concentrate on:

a) The development of the B35:40-series with emphasis on the L-version;

b) Reviewing experience and practical aspects of lean-burn gas engines in general and marine mechanical drive variable speed applications in particular.

a) Engine Design: The B35:40L marine gas series is a relatively compact design comprising a 350mm bore on a 520mm cylinder distance. The stroke remains at 40mm as for the V-version. Also, the engine series is equipped with the latest version of the fuel gas piping system where the engine is fed with a single pressure regulated gas supply which is split on the engine between prechamber and main chamber supply. This design allows a simplified piping arrangements on the engine and between the gas regulating ramp and engine without any sacrifices in performance.

b) Practical aspects of using SI lean-burn marine gas engines: Applications so far employed and to be covered in this paper are: ferries for passenger and cars, cargo ships, RoPax ferries and tug boats with both gas-electric and mechanical drive of controllable pitch propeller; variable speed and variable load, also twin-input single-output gearbox applications, including individual requirements for different applications. Included is also a review of the engine operation limits, as employed in the Bergen lean-burn marine applications, showing how transient loading limits and load increase rates affect the applications of Bergen lean-burn gas engines.
the engine power was increased from 550 kW to 900 kW, further power improvement is expected through the use of Miller cycle technology. Until now, the low concentration gas generator has a nationwide application, and achieved good economic benefit and environmental benefit.

The potential of exhaust gas recirculation in large gas engines

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In the future, emission regulations for large gas engines will be more stringent. According to IED, the EU has set a NOx limit of 200 mg/m³ for large stationary gas engines. In certain countries and regions, limits under 100 mg/m³ are even required. With-out exhaust gas aftertreatment, these emission limits can hardly be met using conventional lean-burn concepts. Possible additional strategies are the further enlancement through substantially improved ignition systems and prechamber concepts or exhaust gas recirculation. This article focuses on the application of exhaust gas recirculation. For a long time, exhaust gas recirculation has been a reliable method for reducing the emissions of diesel engines in passenger cars and heavy-duty vehicles. Consequently, the paper first presents the basic effects of exhaust gas recirculation in gas engines as compared with diesel engines based on simulation results. Next, three different EGR concepts are evaluated: lambda 1 operation, lean-burn engine with moderate EGR use and the HCCI process. The concepts examined offer additional challenges in terms of reliable ignition systems, obtainable ignition delay, combustion stability and component stress. Based on simulation calculations and measurements from a single-cylinder research engine, statements are made about the values obtained for power output, efficiency, and emissions. Finally, the achievable efficiencies are evaluated using a detailed breakdown of individual losses relative to the ideal engine. Significant differences between each concept and advanced lean burn operation are shown.

Progress and development of next generation ignition systems for Guascor gas engines

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For modern, high efficiency stationary, lean-burn natural gas engines there are different drivers for an improvement of the ignition system:
- Higher brake mean effective pressure (bmep),
- Higher turbulences to maintain short combustion durations,
- Higher performance requirements of ignition systems,
- Improvement the combustion stability (COVbmep coefficient of variation of the bmep) or extension of the lean limit.
- Extension of the spark plug lifetime,
- Robust and reliable starting of the engine.

On three different DR Guascor natural gas engines three different ignition systems with open chamber spark plugs (OCSP) J-type and pre-chamber spark plugs (PCSP) have been tested:
- HGM240: 8 line; displacement 24dm³; bore 152mm; stroke 165mm; 1800 rpm; 520 kW; 17,4 bar bmep; lambda about 1,7; Miller cycle;
- PCSP SFGLD560: 16 V; displacement 56,3dm³; bore 160mm; stroke 175mm; 1500 rpm; 985 kW; 14 bar bmep; lambda about 1,6; Otto cycle;
- OCSP HGM560: 16 V; displacement 56,3dm³; bore 160mm; stroke 175mm; 1500 rpm; 1240 kW; 17,6 bar bmep; lambda about 17,6; Miller cycle; PCSP

Three different ignition systems have been used.

Ignition system 1: single pulse capacitive discharge system, max. 125 mJ, no control of the discharge characteristic.

Ignition system 2: pulsed, modulated, capacitive discharge system, max. 500 mJ, control of the energy and spark duration possible in a rectangular shape possible.

Ignition system 3: pulsed, modulated, capacitive discharge system, max. 700 mJ, complete control of the discharge characteristic possible (energy, spark duration and shape of the energy release).

Over the last years, different PCSP designs have been developed together with suppliers and tested on DR Guascor engines. For this publication a non-optimised version and an optimised PCSP are presented with different electrode gaps.

1) HGM240: With the not optimised PCSP one result was that with higher ignition energy the lean limit could be extended clearly – from 270 mg/Nm³ NOx with ignition system 1 to 180 mg/Nm³ or even to 120 mg/Nm³ NOx with increasing ignition energy with ignition system 2. The lean limit could be reached with ignition system 3 – from 120 mg/Nm³ NOx with ignition system 2 to 70 mg/Nm³ NOx with ignition system 3 with optimised discharge characteristics (with max. 4,5 % COVbmep). If the discharge characteristic of ignition system 3 was not optimised, about the same performance as with ignition system 2 with 270 mJ could be observed. With the optimised PCSP no difference between the ignition system 2 and 3 (also with optimised discharge characteristic) was seen but both ignition systems had a clear advantage to ignition system 1. One explanation is the difference in flow velocity in the electrode gap for the two different PCSP geometries. With increasing flow velocity a controlled shape of the discharge characteristic is needed so that the spark does not collapse.

With the optimised PCSP a very low improvement with the optimised discharge characteristic could be observed. With the optimised PCSP, no improvement of the COVbmep could be observed. The COVbmep could only be improved with the ignition system 3 together with the not optimised PCSP – at 150 mg/Nm³ NOx from 3,5 % down to 2,5 %. PCSP with different gaps have been tested and starting was possible with increasing ignition energy together with decreasing electrode gap. No definite influence of the spark duration, spark current or discharge shape could be found.

2) SFGLD560: No difference in the lean limit or COVbmep could be observed. The main reason for this could be that with the J-type SP the flame quenching is much lower than in the used PCSP and so less ignition energy is needed. Another reason is the lower lambda with which the SFGLD560 is operated in comparison to the HGM240 and so the needed ignition energy is lower. An extensive comparison of different ignition systems on different DR Guascor engines has been conducted and the advantages / disadvantages of the different ignition system characteristics based on engine results are displayed. Further on, different designs of PCSP have been tested together with different ignition systems and the influence on the engine performance is reported.
Tuesday May 14th / 13:30 – 15:00 Room C
Environment, Fuel and Combustion
Diesel Engines – Combustion Simulations

Strategies for switching between ECA and non ECA operation for a medium-speed diesel engine with EGR
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Peter Eilts, TU Braunschweig, Germany

The next stage of the IMO emission standards (Tier III) requires the reduction of NOx emissions compared with current engine designs from 2016 by 75% in coastal and designated areas. But IMO Tier II limits continue to apply on the open sea. Against this background, SCR and exhaust gas recirculation got into the focus of marine engine designers. While the switching between the different modes of operation with an SCR catalyst can be regulated by a bypass, the switching is more difficult with an EGR concept. Nevertheless, there is a desire to use the EGR technology in order to avoid a further operating fluid and the large volume of an SCR catalyst. The approach presented in this paper includes two-stage turbocharging with an EGR turbocharger as additional EGR pump. For switching between operating modes, all three charging units need to be coordinated. Simple switching without any additional control leads to extremely high-peak cylinder pressures above the mechanical limit. Therefore additional switching control needs to be provided to ensure safe engine operation and an optimal operating range of the charging units. To ensure a good predictive quality for the analysis a DI-jet-model for the prediction of the net heat release rate which was further developed during the research work is used. Furthermore, a refined approach for the estimation of nitrogen oxides, which uses empirical relations for the influence of different operation parameters to estimate the nitrogen dioxide emissions based on one baseline operation point, is used. In this study possible strategies including higher variability for the charging system, such as the use of a turbine bypass or variable turbine geometry, and variable valve timing are analysed and compared critically. However, current engine designs already have cam phasing technologies to switch to low soot operation at low engine load by delaying the inlet valve closing. These can also be used for different modes of operation with an SCR catalyst.

Potential investigation of PCCI combustion as NOx reduction measure at low-load operation with low CN LCO fuel
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The IMO Tier III regulations require rigorous reduction of SOx as well as PM and NOx. From 2015, LSFO (low sulphur fuel oil) required in ECAs should decrease its sulphur content to 0.1 mass % of fuel, which is equal to one tenth of the present sulphur level required of LSFO. The NOx emission rate [g/kWh] should be reduced by as much as 75% from the present Tier II level from 2016. Although various anti NOx pollution technologies, like EGR or SCR have been ardently investigated, there exist three strong obstacles to inhibit these technologies from practical use. The first is that the sulphur content of the LSFO is still high enough to result in metal corrosion in the EGR system by sulphuric acid and in catalyst occlusion in the SCR system by ammonium hydrogen sulphate after long-term use. The second is a wider load range required for propulsion engines by the emission regulation in the marine sector. It is difficult in general to adjust the exhaust clarifying devices especially at low-load operations, since the enthalpy of the exhaust gas is not sufficient to activate such devices. For example, more EGR rate is necessary in lower-load conditions to avoid severe combustion deterioration due to the lack of oxygen, but this implies more power consumption of an EGR blower in the system and the total thermal efficiency could be disastrous. The third is the additional operational cost of the NOx reduction systems. The EGR system needs a neutralising treatment system of the sulphuric acid scrubbed down from the EGR gas and the SCR system consumes urea or ammonia water according to the NOx concentration in the exhaust pipes. Moreover, the LSFO would be very expensive marine fuel as long as it is supplied with gas oil classification of low sulphur content, so that other low-sulphur, yet inexpensive components are desirable to burn in marine engines. On the whole, a supplementary and economical anti NOx pollution system is definitely wanted to cover the lower-load range without fear of the cost increase in fuel consumption and device operation. From the above point of view, PCCI (premixed charge compression ignition), which has been studied in smaller onroad fields for long time, could be a practical remedy for the first time for the emissions from marine diesels. In this study, a new PCCI combustion system is proposed to achieve drastic NOx reduction for marine diesels. This system utilises a set of sprays from closely aligned holes having injection directions intersecting one another so as to cause mutual interaction and merger of the sprays by overlapping injection periods and applying different injection rates. It can enhance the mixture stratification suitable for the PCCI combustion. As for the cheaper substitute of the low-sulphur gas oil, neat LCO (light cycle oil) was also firstly introduced as a potential LSFO in this study. LCO is composed from distillate components produced in a FCC (fluid catalytic cracking) process in modern oil refinery plants and it has sometimes notoriety for its poor ignitability thanks to its high aromaticity. LCO was casted in a new light here by utilising its good calorousness and its long ignition delay for the PCCI combustion. Lower-load operation also favours the PCCI concept because the abnormal combustion of the PCCI mode usually happens at higher-load conditions. The durability against the pre-ignition of LCO was greatly enhanced by water emulsification. The potential of the strategy was examined through observation of the spray merging and combustion process in a rapid compression expansion machine. All in all, the ignition control of PCCI combustion in large engines was successfully realised for the first time.

Partially premixed combustion (PPC) for low-load conditions in a marine engine using computational and experimental technique
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Ossi Kaario, Aalto University of Technology, Finland
Martti Larmi, Aalto University of Technology, Finland
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The diesel engine has been the most powerful and relevant source of power in the automobile industries from decades due to its excellent performance, efficiency and power. On contrary, there are numerous environmental issues of the diesel engines hampering the environment for which it has been a great challenge for the researchers and scientists. In the recent years, numerous strategies have been introduced to eradicate the emission of the diesel engines. Among them, partially premixed combustion (PPC) is one of the most emerging and reliable strategy. PPC is a compression
ignited combustion process in which ignition delay is controlled to enhance better homogeneity of air-fuel mixture. PPC is intended to endow with better combustion with low soot and NOx emission. The paper presents the validation of the measurement data with the simulated cases followed by the study of the spray impingement and fuel vapor mixing in PPC mode for different injection timing. The study of the correlation of early injection with the fuel vapor distribution and wall impingement has been done in details. The engine is a single-cylinder engine EVE, installed in Aalto University Internal Combustion Engine Laboratory with the bore diameter of 200mm. This implies the use of PPC strategy in large engine environment. The simulation is carried out with the commercial CFD code software STAR CD. Different injection parameters have been considered to lower the wall impingement and to produce better air-fuel mixing with the purpose of good combustion and reduction of emissions. The result of the penetration length of the spray and the fuel vapor distribution for different early injection cases have been illustrated in the study. Comparisons of different thermodynamic properties for different injection timing such as average density, average temperature, droplets evaporation percentage rate and liquid penetration length have been very clearly illustrated to get an insight of the effect of early injection. The parameters like injection timing, injection period, injection pressure, inclusion angle of the spray have been taken as a major parameter that influence the combustion process in PPC mode. Extensive study has been made for each of these parameters to better understand their effects in the combustion process. Different split injection profiles have been implemented for the study of better fuel vapor distribution in the combustion chamber. The final part of the paper includes the study of the combustion and implementation of EGR to control the temperature so as to get more prolonged ignition delay to accompany the PPC strategy.

**Combustion development of new medium-speed marine diesel engine**

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Tao Ping, Shanghai Marine Diesel Engine Research Institute, China
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Franz Maassen, FEV GmbH, Germany

Marine diesel engines face double the pressure from both the energy sources and more strict IMO emission regulation. According to a Chinese engine builder’s commission, SMDERI developed a new medium-speed marine diesel engine together with FEV. The new medium-speed marine diesel engine must satisfy the high endurance, the fuel consumption and IMO emission regulation at the same time. The paper will present the technical solution to meet the requirement of good BSFC and NOx emission. The success development of the new medium-speed marine diesel engine will promote Chinese medium-speed marine diesel engine to new technical level. This article presents the combustion development of the new medium-speed marine diesel engine: through performance and combustion simulation, to define the main characteristics of performance. To define the suitable Miller timing, together with one-stage high compression turbocharger; Through CFD and DOE technique, define the experiment case of combustion system, which contain the piston bowl, the nozzle pattern and so on. The experiment was carried out based on the SCE21/32, which is specially developed for the new technical investigation and new engine combustion development. Different Miller timing, different piston bowl and nozzle pattern were tested, and the performance of the common rail fuel system have been studied in detail. Through the SCE21 combustion and 6CS21/32 performance test, the experiment results presented show that, for the new medium-speed engine of CS21, the NOx emission can meet the IMO Tier II emission regulation, and the fuel consumption can achieve 185 g/kWh at the same time.

**Tuesday May 14th / 13:30 – 15:00 Room D**

**Turbochargers – New Products 2**

**VTG turbocharging – a valuable concept for traction application**

Jacoby Pierre, ABB Turbo Systems Ltd, Switzerland
Xu Henry, ABB Jiangjin Turbo Systems Ltd, China
Wang David, ABB Jiangjin Turbo Systems Ltd, China

Greater demands are being placed on railway engine applications as the impact of rising fuel prices underscores the need for more efficient solutions and, simultaneously stricter emission legislation comes into effect. Focusing on these two challenging aspects existing and upcoming engine power-packs still need to cope with the known specifics of traction applications in terms of high reliability, long durability and operation in an extremely wide range of ambient and load conditions. This paper describes how ABB turbocharging products and related concepts support railway engine builders and operators in ongoing and future engine development as well as in upgrading existing platforms. After a brief review of ABB dedicated rail turbocharger platform, TPR, the focus will be on newly developed VTG technology and its related control unit. Tangible results to improve fuel efficiency and to enhance operating flexibility will be evaluated with alternative solutions. The paper presents a proposal on how to cope with stricter emission legislation with minimum compromise on fuel efficiency and the description of a concept in which the VTG turbocharging module is deployed in combination with a high-speed electrical blower to realise external cooled exhaust gas recirculation. ABB VTG turbocharging module, applied on the TPR platform, enables significant fuel economy on existing and upcoming engine platforms while increasing the operating range of traction applications. It is a base for promising concepts targeting stringent emission legislation with positive effects on traction economics.

**TCS-PTG – MAN Diesel & Turbo’s power turbine portfolio for waste heat recovery**

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The increase in fuel oil prices, tightening regulations regarding emissions no longer limited to NOx, the public discussion on global warming and requirements of the Energy Efficiency Design Index (EEDI) all clearly ask for an emission reduction. According to the EEDI, CO2 emissions will have to be reduced by up to 30% depending on the ship type by 2025. This results in a vast range of applications for waste heat recovery systems in general and the power turbine of MAN Diesel & Turbo in specific. Using standard parts and proven technologies from our turbochargers for tailor-made power turbine solutions, MAN Diesel & Turbo is capable of offering cost-efficient and reliable solutions at present mainly focused on highly efficient two-stroke engines. With the help of our power turbines, shipowners and power producers can lower their fuel oil consumption significantly. The ap-
plication range of the power turbine comprises any mode where excess exhaust gas from the turbocharging system is available. This is especially the case when the two-stroke engine is charged by highly efficient MAN turbochargers of the TCA series. Current projects show that the turbines are suitable for both stationary and marine applications. The modular arrangement of the power turbine allows for the utilisation within full-scale waste heat recovery solutions such as the MARC_HRS system of MAN Diesel & Turbo, as mechanical drive for hydraulic pumps, as drive for power take in to the crankshaft or as standalone units for power generation in the form of turbo compound system with power turbine and generator (TCS-PTG). With the enhanced automation and control system, the stand-alone TCS-PTG on board the vessel is capable of operating in island mode which makes it an alternative to auxiliary gensets. With proven components from MAN TCA and TCR turbochargers, it is possible to provide power turbine solutions ranging from 500 kW up to 4 MW. The system consists of the turbine itself, with axial and radial type turbines capable of covering a wide flow range, gearbox, generator and an advanced safety and automation that can be adapted to the customers’ specifications. Integrated gear solutions result in a compact and robust design. Matching the power turbine with engine requirements results in a superior overall performance of the complete system regarding the reduction of fuel oil consumption. The arrangement of the valves together with the drives as well as the advanced control system with redundant safety features are considered as MAN Diesel & Turbo’s core competencies that guarantee a smooth and reliable operation. The convincing technical and commercial concept led to several customer orders. In the course of order processing, the performance of all components and systems has been scrutinised excessively via burn rig and factory acceptance tests. The results are used to further enhance the performance and reliability of the system. By consequently following the building block principle, we exploit internal and external synergies and make sure that our power turbine creates real value added, reasonable amortisation periods and a sustainable reduction of the emissions of modern diesel engines. In the paper the design, automation and control philosophy is presented in detail as well as the product portfolio and the test results related to the current customer projects.

**Solutions for better engine performance at low load by Mitsubishi turbochargers**

Yoshitaka Ono, Mitsubishi Heavy Industries, Ltd, Japan

Due to recent increases in fuel prices, many shipowners are seeking reductions in operating costs, with particular emphasis on lowering fuel consumption. Furthermore, for the sake of environmental preservation, international societies have been moving to tighten regulations on marine emissions of greenhouse gases and NOx. With Tier II NOx regulations for ships having been implemented in 2011 and Tier III regulations coming into force in 2016. Also, a CO2 emissions index (EEDI) will be applied to vessels built from 2013 onwards, and CO2 emissions regulations based on this index will be become mandatory. Given that turbochargers used for diesel engines have a substantial influence on the combustion of fuel, they can play a major role in addressing the above-mentioned issues. Of particular note in this context is the fact that low load operation has come to be utilised in recent years in order to reduce fuel consumption by ships. The author of the present report, being associated with a turbocharger manufacturer, is of the opinion that the application of several new turbocharger technologies will be contributed to improved performance under low load operating conditions, in the form of turbochargers specifically intended for these requirements. This paper introduces technological efforts aimed at improved turbocharger performance under low load conditions, incorporated into the newest MET-MB series of high efficiency turbochargers by Mitsubishi Heavy Industries (MHI). Also presented, MHI has developed a new type of variable nozzle structure. The proprietary MHI approach, known as the variable turbine inlet (VTI), has been introduced not only for newly manufactured turbochargers, but also as a retrofit option for turbochargers in current service. The MET-VTI turbocharger is aimed at reduced fuel consumption at low load for marine diesel engines. In order to actively increase the amount of air in the low load operation, this MET-VTI was increased turbine output by means of reducing the geometry turbine area, thus enabling higher turbocharger rpm. In addition, in the wake of the world’s first practical application in 2011 of a turbocharger equipped with a high-speed generator (hybrid turbocharger), discussion is presented on the current state of efforts related to new hybrid turbochargers equipped with motor on the rotor shaft, enabling motoring assist aimed at meeting low-load operation requirements.

**Computational investigation of turbocharger performance degradation effect on two-stroke marine diesel engine performance**

Nikolaos Sakellariadis, National Technical University of Athens, Greece

Dimitrios Hountalas, National Technical University of Athens, Greece

Turbocharger condition is critical for the performance of turbocharged diesel engines and especially large scale two-stroke ones. In this case, in addition to increasing power density, the turbocharger must also maintain a positive difference between exhaust and inlet pressure to facilitate cylinder scavenging. In large scale two-stroke diesel engines the mass flow through the engine, and therefore A/F ratio, is greatly influenced by turbocharger performance. In the present paper a theoretical investigation to determine and quantify the effect of turbocharger performance degradation on the performance characteristics of a slow speed two-stroke marine diesel engine is presented. The closed cycle is modelled using a multi-zone phenomenological combustion model. For the gas exchange, the filling and emptying method is applied. The model has been extensively validated for cases of heavy duty four-stroke diesel engines, and has been modified to capture special characteristics of large two-stroke diesel engines operating on HFO. The T/C turbine and compressor are simulated using newly developed physically based quasi-dimensional models. Flow is solved at key stations along the T/C components, while flow losses and angles are derived from semi-empirical correlations. For the turbine a modified version of the Ainley and Mathieson axial turbine performance prediction technique is applied. The compressor is modelled using a meanline model of radial compressor performance. For the turbomachinery models calibration, data from the engine’s NOx technical file are used (where air and exhaust gas flow data are provided). Thus, the problem of limited availability of turbomachinery maps is resolved, which is very common for field applications. The complete engine model is validated through the comparison of predicted performance data with the corresponding values of the shop tests. Using the model, various scenarios of turbocharger performance degradation are investigated. The effect of turbine efficiency reduction, compressor efficiency reduction saw as their simultaneous reduction are investigated with respect to their impact on engine performance. The effect of turbine nozzle ring fouling on engine operation is also investigated since this is a common problem for two-stroke marine diesel engines. From the analysis of generated results it is possible to develop a methodology for turbocharger condition monitoring that will allow safe detection of the actual component fault.
GE Transportation is in the process of updating its EVO and Powerhaul line of diesel engines to meet the requirements of EPA Tier IV and EU Stage IIIb emissions standards. The base engine with the largest production volumes continues to be the locomotive version of the twelve-cylinder EVO rated at 3,375 kW. Additionally, in-line six- and eight-cylinder and V twelve- and 16-cylinder versions of the EVO engine are under development to serve the marine market along with an update to the Powerhaul 16-cylinder engine for the European locomotive market. The EVO engine has been one of GE Transportation’s most successful products. Over 5,000 engines have been built to date. The product line has been expanded from its original offering to serve higher power applications and the marine market. This engine has also undergone a pervious emissions update to meet the requirements of EPA Tier III with the introduction of common rail and Miller cycle. Tier IV emission levels for US locomotives present significant challenges in the reduction of NOx and particulate emissions compared with Tier III. These challenges require the introduction of technologies such as aftertreatment, exhaust gas recirculation (EGR), advanced turbocharging, aggressive Miller cycle, variable valve timing, and higher pressure common rail. This paper will cover the concept selection process by which these various technologies were evaluated and the selection of the best concept to serve GE Transportation’s customers. The selection process included a combination of modelling and single cylinder research engine testing to evaluate the various emission reduction technologies. The first field trials of the EPA Tier IV-compliant EVO engine were scheduled for spring of 2013.

**Series 1163-04**

Martin Kurreck, MTU Friedrichshafen GmbH, Germany

Werner Remmelz, MTU Friedrichshafen GmbH, Germany

In 1985, the engine series 1163 with a maximum power of 7,400 kW was introduced into the market. The engine had been developed for military applications and is unrivaled both with regard to its power-to-weight ratio as well as its space-to-power ratio. The two-stage sequential turbocharging with intercooling allows for maximum power concentration and a highly compact design while at the same time permitting a wide performance map. These characteristics turned it into the preferred engine of the world’s most renowned navies. In addition, the use of Series 1163 engines in megayachts and fast ferries highlights the versatility of this engine. To ensure compliance with the IMO II emission regulations, a new version of the engine series 1163 will be introduced into the market: the build sample 04. The modernised version retains the key characteristics of the engine, i.e. power-to-weight ratio, wide performance map, reliability, engine dimensions and compliance with military requirements. The running gear as well as the turbocharging concept remain unchanged. New features for this engine series are a common rail injection system, state-of-the-art engine electronics as well as the use of the Miller cycle with optimised turbocharging. One of the major changes reducing emissions is the common rail injection system with eight high-pressure pumps on the 20-cylinder engine. It replaces the previous unit pump system. The significant increase in injection pressure from 1,300 to 1,800 bar resulted in a cleaner combustion with a lower emission of particulate matter. By means of pilot injection, the stress on the running gear can
be kept at a low level despite the increased combustion requirements. To control the common rail injection system, new engine electronics were required. For the build sample 04 of the engine series 1163, the ADEC system used on MTU Series 4000 engines was developed further. All military requirements regarding EMC (electro-magnetic compatibility) are being complied with. Given the use of new technologies, the efficiency of the sequential turbocharging system was increased significantly. The Miller cycle results in an increase in charge-air pressure. The new build sample was developed in a SE process using the latest methods of design, calculation and testing. For the twelve-cylinder, 16-cylinder and 20-cylinder engines of the build sample 04, the following characteristics/improvements were achieved compared with build sample 03: Emissions: Compliance with IMO II (NOx) and reduction of PM: Charge-air pressure (abs.): Increase from 4.6 to 5.7 bar; Total ETC efficiency: Increase by 8%; Fuel consumption: Reduction by 10% in performance map. This paper describes the key development steps.

**Tuesday May 14th / 15:30 – 17:00 Room B**

**Product Development**

**Gas and Dual-Fuel Engines – Mixture Formation**

Uff Waldenmaier, MAN Diesel & Turbo SE, Germany
Stefan Djuranec, MAN Diesel & Turbo SE, Augsburg
Gunnar Stiesch, MAN Diesel & Turbo SE, Germany
Fridolin Unfug, KIT, Germany
Uwe Wagner, KIT, Germany

For future gas and dual-fuel engines mixture formation is one of the most important development areas to fulfil upcoming emission legislations and to improve combustion efficiency. Therefore MAN Diesel & Turbo SE is optimising the mixture formation of gas and dual-fuel engines with support of advanced CFD-optimisation techniques and single-cylinder engine measurements. Today’s CFD optimisation of an intake port with gas admission pipe is an iterative process starting with an educated first guess design, which has to be evaluated with simulation results and engine measurements. This evaluation is base of the first optimisation loop. The experience of the CFD engineer is the optimisation tool in that process. In general four to five iterations are necessary to improve the mixture formation and flow behavior in the intake port. With this state-of-the-art method, it takes about two weeks to reach the design target for mixture formation. With advanced CFD simulation and optimisation tools it is possible to get the best possible design under consideration of the available design parameters within days. Nevertheless, the quality of the CFD optimisation is directly linked to the quality of CFD simulation methods. The easiest way to validate mixture formation simulation results is an indirect validation with engine measurements. The validation is a comparison of the simulated mixture formation quality at the start of ignition with engine measurements considering emissions, knocking behavior and gas consumption. For bigger variations, this validation shows a surprisingly good agreement. Still, investigating flow details and a direct validation of the mixture formation is not possible. Up to now, no optical investigations considering mixture formation in the intake port for large engines are known. To close this gap, MAN Diesel & Turbo SE in cooperation with the Institut für Kolbenmaschinen of the Karlsruhe Institute of Technology have done PIV and Mie-scattering measurements on a modified flow bench for gas and dual-fuel engines. The measurements aimed at flow behavior and mixture formation for different gas admission pipes and intake valve seat rings for varying the flow behavior in the combustion chamber. The optical measurements helped to raise the quality of CFD-simulation methods and to improve the mixture formation of gas and dual-fuel engines to fulfil future emission legislation limits.

**Functional improvement of a gas metering valve**

Jorg Hess, Heinzmann GmbH Co KG, Germany

More stringent legislations regarding the emission of pollutants are a big challenge for engine manufacturers, suppliers and operators. As a result of those strict targets for CO2 reduction, the use of alternative fuels is moving forward. An interesting alternative to diesel engines is presented by gas-powered engines, where it is possible to reduce emission of pollutants significantly. Typical gaseous fuels for gas engines include natural gas, biogas, propane and butane, differing mainly in the calorific value, density and stoichiometric ratio. As a consequence of the different gas properties, depending on which gas is used in a particular engine type, the gas flow rates can differ immensely for the same engine power output and, conversely, different dimensions of the gas train have to be designed and installed for the same engine type. In the power range of 0.5 MW up to 4 MW, for high-speed engines (1500 rpm) typically a gas dosing unit is applied, which actuates a throttle valve to control the gas flow. The limited control of small gas flow rate due to the nonlinear behavior of the throttle valve leads to different valve sizes for the different gas types on one engine type and to increasing costs of stock holding and production. Due to these facts, Heinzmann decided to begin the development of a new generation of gas flow control valves. An essential target of this development was a wider variety of the turndown ratios compared with the existing systems in the market. Furthermore, special attention was paid to the production costs. Both requirements could have been met with the use of special geometries and the implementation of existing control devices. In this presentation the stages of development, design and bench testing are presented.

**The power and efficiency upgrade approach for the development of the new Caterpillar 10 MW medium-speed gas engine**

Volker Salzinger, Caterpillar Motoren GmbH & Co KG, Germany
Hendrik Herold, Caterpillar Motoren GmbH & Co KG, Germany
Werner Rebelein, Caterpillar Motoren GmbH & Co KG, Germany
Ioannis Vlaskos, Ricardo Deutschland GmbH, Germany

Increasingly stringent exhaust emission legislation combined with economic pressure to realise the best achievable fuel efficiency, which recently also is expressed as CO2 emission, make natural gas a promising alternative fuel for power generation plants and marine propulsion. This is due to the combined effect of high knock resistance of lean natural gas fuel/air mixtures, which enables high efficiency combustion systems and the lower carbon content in the molecules of natural gas, which reduces CO2 emission relative to liquid fuels. Setting the target for a new or updated product was driven by market requirements and availability of new technologies. The targets had to be validated by high level considerations in order to generate a robust project plan and achieve the best possible matching between objectives, resources and timing. As a result, a preliminary selection of individual solutions is generated, which is expected to enable the realisation of the specification. In order to assess the consequences of each and every decision made right through to the final product, a perfect balance between...
Ported fuel injection for maritime gas engines
Gerhard Ranegger, Hoerbiger Ventilwerke, Austria
Gerhard Kogler, Hoerbiger Ventilwerke, Austria
Peter Steinrueck, Hoerbiger Kompressortechnik Holding, Austria

Future emission limits for maritime engines call for dramatic reduction of particle matter, NOx and SOx in emission regulated areas. With the expected demand for ultra clean propulsion systems, the engine industry has started the development of gas-fuelled engines. Gas-fuelled ferries are operated successfully in Norway, tug boats will follow soon. These ships are propelled by spark ignited engines. For many more years, dual-fuel and tri-fuel engines have been in service, powering LNG ships and offshore oil and gas rigs. Most of these engines are using LNG that is used in bone dry condition. The absence of any oil mist or oil vapour implies special challenges for the equipment in contact with this gas, in particular the solenoid valves that are used for ported fuel injection suffer from excessive wear reducing engine service intervals and causing reliability problems. Compliance with stringent protection systems and safety regulations – like mandatory double-wall sealing of the gas piping system – impose other challenges for the design of such ported fuel valves. The authors present a novel design of ported fuel injection valves for large-bore engines, which incorporates design elements successfully deployed for ported fuel valves for cryogenic hydrogen-fuelled internal combustion engines. By use of special combination of material for the sealing elements to avoid cold welding, which leads to increased leakage, a longer life time can be achieved. The new design is prepared for leak detection systems and incorporates unique solutions with respect to the electrical connections and wiring to comply with existing regulations. Stable operation of the gas-fuelled engine requires high repeatability of valve operation and low valve to valve variances. A low-lift concept derived from Hoerbiger experience in compressor valve design reduces response time for more accurate gas metering. In conjunction with the need to operate the fuel valves in a large operating range, the valves have to work under elevated differential pressure exhibiting only insignificant leakage. In applications with a two-stage turbocharger and increasing gas supply pressure, the leakage of the PFI valves becomes even more important. In this paper a method will be presented how to fulfil this requirement by a nonpressure balanced concept and reduce closing time at the same way in order to avoid post injections or residual gas in the air manifold. The electromechanical design of the presented solution copes with these challenges, thus offering the engine designer new means to realise efficient and reliable maritime engines complying with tomorrow’s emission regulations.

Reduction of NOx emission by 80% using the newly developed system with a polymer membrane in marine diesel engines
Kazuyuki Maeda, National Fisheries University, Japan
Akihiko Aizetsu, Tokai University, Japan
Hirokazu Ohno, Asahi Kasei Chemicals Corporation, Japan

By 2016, under the IMO Tier III rules, NOx emission from ships sailing in ECAs should be reduced by more than 80% relative to the IMO Tier I levels. A selective catalytic reduction (SCR) system, a water treatment (such as emulsification fuel) system and an exhaust gas recirculation (EGR) system are proposed as concrete methods. Recently, the nitrogen-enrichment humidification membrane (NHM) system developed by Asahi Kasei Chemicals Corporation has received much attention. This device reduces NOx emission by decreasing the oxygen density in the suction air using a special membrane while increasing the moisture content in the suction air. Because this device is installed on the suction air side, it will not be affected by trends on marine fuel sulphur content regulations or supply trends of marine fuel in the future. Moreover, because the operation materials are water and air, this system is environmentally friendly. In this study, in order to reduce NOx emission from marine diesel engines, the following experiments were carried out. At first, to explore the spray combustion characteristics of diesel fuel under very low oxygen density ambient condition, a high-temperature and high-pressure combustion vessel with two observation windows was observed. Second, the NHM system was connected to the suction line of a high-speed marine diesel engine and a low-speed two-stroke single cylinder engine, and the effects of the oxygen density and the moisture content in the suction air on NOx emission were investigated. The NHM system with a polymer membrane that has selective permeability with respect to oxygen and water vapour is composed of an oxygen reduction system that can freely establish the oxygen density and a humidifying system that can freely establish the moisture content in the suction air. The following experiments were carried out:
- Visualisation of combustion: high-temperature and high-pressure combustion engine with two observation windows was photographed by a high-speed colour video camera through one of the windows.
- Effect of the oxygen density: Humidity of the suction air was adjusted to 0% using a dryer. The oxygen density of the suction air was then reduced from 21 to 16.2% using the oxygen reduction system.
- Effect of the moisture content: The moisture content in the suction air was increased from 0 to 16% using the humidifying system.
- Combination effect of the oxygen density and the moisture content: The oxygen density was set to 21, 20, 19 and 18% using the oxygen reduction system and the moisture content was then increased for each density. Results clarified that the IMO standards can be satisfied based on the following conditions:
  - The flame temperature becomes lower as the decrease of oxygen density mainly due to the dilution effect and as the increase of CO2 mixing due to the increase of specific heat, and results in the low NOx emission.
  - NOx emission decreased as the oxygen density decreased for each load factor, and thus the restriction on NOx emission set by the IMO standards can be satisfied simply by setting the oxygen density at less than 17%.
  - NOx emission decreased because the oxygen density decreased for increases in the moisture content, and thus the IMO standards can be satisfied simply by adjusting the humidity of the suction air at more than 16 mol.%. Taking into account the operating conditions of the engine, NOx emission can be effectively reduced by decreasing the oxygen density as well as increasing the humidity of the suction simultaneously.
Development of integrated EGR system for two-stroke diesel engines

Johan Kaittoft, MAN Diesel & Turbo SE, Denmark
Mikkel Preem, MAN Diesel & Turbo SE, Denmark

The IMO Tier III NOx regulations will come into force in 2016. This means that NOx emissions from large two-stroke diesel engines must not exceed a cycle value of 3.4 g/kWh, and NOx emissions must not exceed 5.1 g/kWh on the individual load points of the load cycle. To comply with the Tier III requirements, MAN Diesel & Turbo is involved in a targeted and continuous development of exhaust gas recirculation (EGR) for NOx reduction on low-speed two-stroke diesel engines. The latest investigations on MAN Diesel & Turbo’s research engine in Copenhagen regarding the next generation of EGR system, scrubber performance, high speed and high efficiency EGR blower and water treatment system will be covered. The following topics will be described: confirmation test of integrated EGR system design, sulphur and particle reduction ratios in the EGR scrubber, blower performance and water treatment system functionality and requirements. The first MAN B&W Tier III EGR diesel engine has been successfully delivered for a 4,500 TEU container vessel. The following topics regarding the first Tier III EGR two-stroke diesel engine will be covered: engine integrated design with multiple turbochargers, EGR auxiliary equipment, installation aspects and shop test performance results. The development process of the 6S80ME-C9.2 EGR engine has resulted in a finalised EGR engine design, and implementation on other engine sizes is in progress.

Newly developed combined EGR & WEF system to comply with IMO NOx Regulation Tier III for two-stroke diesel engine

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Takuro Nakamura, Kawasaki Heavy Industries, Ltd, Japan
Ikumi Onishi, Kawasaki Heavy Industries, Ltd, Japan
Katsuhiko Yoshizawa, Kawasaki Heavy Industries, Ltd, Japan
Hirotaka Takata, Kawasaki Heavy Industries, Ltd, Japan
Takamichi Hosono, Kawasaki Heavy Industries, Ltd, Japan

The IMO NOx emission regulation Tier III will come into force from 2016 and requires marine two-stroke diesel engines to reduce their emission below a cycle value of 3.4 g/kWh in ECAs. To cope with this regulation, the combined EGR (exhaust gas recirculation) & WEF (water emulsified fuel) system, aiming at effective NOx reduction with the minimum penalty in fuel oil consumption, has been newly developed and provided for the fullscale test engine Kawasaki-MAN B&W 2S50ME-C. The applied EGR is a high-pressured EGR, featuring compactness in components. A Turbocharger cut-out system and a VT (variable turbine nozzle area) turbocharger are incorporated in the EGR system, which enables it to reduce NOx with only a minimal impact on fuel oil consumption, and to switch on/off depending on the sea area. A wet scrubber is also incorporated in the EGR system to remove SOx and PM in the recirculating gas, which prevents corrosion and contamination in the scavenging air system during EGR. Detection and control methods for water carry-over have been newly established and tested. The water treatment system is one of the most important systems for EGR and has been developed to remove PM in the washing water out of the scrubber. A special compact settling tank with unique ditches has been developed based on the sewage treatment technologies and secures the efficient removal of PM. This paper describes 1) the characteristics of the EGR system, such as relations between EGR ratio and NOx emission, EGR ratio and fuel oil consumption, etc. both on newly developed EGR system with turbocharger cut-out system and VT and on conventional EGR system without them; 2) the performance of the scrubber including water carry-over; 3) the capability of the water treatment system; 4) the result of the combined EGR & WEF system measured on the test engine is reported in comparison with using EGR alone. In addition to the test results by the test engine, this paper describes the outline of our original ‘package type EGR system’ for onboard tests. The package EGR system that major components of EGR are equipped on the main engine is introduced to facilitate the installation of on the ship. On the other hand, WEF technique is preceding EGR and now provided for long-term operation in order to accumulate experiences in service field. The latest condition is reported additionally.

Demonstration of emission control technology for IMO NOx Tier III

Yoshiyasu Murayama, Niigata Power Systems Co, Ltd, Japan
Tetsuya Tagoi, Niigata Power Systems Co, Ltd, Japan
Takahisa Mimura, Niigata Power Systems Co, Ltd, Japan
Satoru Goto, Niigata Power Systems Co, Ltd, Japan

In order to meet stringent emission standards for marine engines, we at Niigata have been continuing the development of low emission technology for a long period. Three emission control technologies – exhaust gas aftertreatment, alternative fuels and combustion improvement – were developed to meet upcoming IMO NOx regulations (Tier III), and these countermeasures can be selected due to required output, applications and ship design. The first measure is the exhaust gas aftertreatment by using selective catalytic reduction (SCR). Niigata has started to provide the marine SCR system from the middle of the 1990s, and has gained some good experience about performance design and operation. The key issue for marine SCR system is the installation size and control technology that handles suitable amount of reducing agent for each engine loads. Onboard tests were carried out to verify that performance of our newly developed SCR system fulfills a required specification for Tier III. The required injection amount of reducing agent is determined by using several ordinary sensors on the engine. In addition, the effect of atmospheric conditions on NOx emission is also considered. Therefore, the developed SCR system is useful not only for inland but also oceangoing vessels. The test system was operated to maintain 80% NOx reduction rate from Tier I condition through the onboard test, and it was successfully controlled without ammonia slip. The second measure is the usage of alternative fuels. To date, gas engines were employed for land-based power generation and cogeneration, several types of gas engine – dual-fuel, spark ignition and micro pilot engine – are reliable. Due to lower adiabatic flame temperature with leanburn combustion, the NOx emission is extremely low and the emission level is a tenth of that of diesel engines. Consequently, gas engines have a potential to comply with Tier III without any further additions. The third measure to reduce NOx emissions is the improvement of the combustion for diesel engines. The Miller cycle is an essential combustion technology to decrease NOx emission due to lower incylinder gas temperature and to improve cycle efficiency. This technology was employed on diesel engines to meet Tier II; however, the magnitude of the effect is enhanced to achieve remarkable NOx emission reduction in this study. Since the extremely high boost pressure is required when a stronger Miller cycle is applied, the two-stage turbocharging system was employed. The obtained NOx reduction from Tier I condition was reached up to 50% due to double improvement effect regarding the turbocharger efficiency and the cycle efficiency. The EGR, which is well

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known as low NOx emission technology, is a good match for the two-stage turbocharging, with which a further NOx reduction can be achieved. In other words, the improvement of fuel consumption is possible by a synergy effect of two-stage turbocharging, stronger Miller cycle and EGR. In this paper, the characteristics of each emission control technologies are described. The main part of this paper is SCR and combustion improvement.

Tuesday May 14th / 15:30 – 17:00 Room D
Turbochargers – Turbocharging & Components

IMO Tier II: Gas and dual-fuel engines as a clean and efficient solution
Claudio Christen, ABB Turbo Systems Ltd, Switzerland
Daniel Brand, ABB Turbo Systems Ltd, Switzerland

Gas and dual-fuel engines applying the Otto cycle are commercially available solutions undercutting the NOx limits set out by the IMO Tier III regulation. Furthermore, it has been demonstrated that the concept of the strong Miller process enabled by two-stage turbocharging and variable valve timing is an attractive solution to considerably improve the tradeoff between fuel consumption and NOx emissions for diesel engines. For gas engines, the concept can be utilised to bring the tradeoff between fuel consumption and power density to a new level. The potential has been confirmed on real gas and diesel engines with excellent results. A comprehensive simulation study has been carried out in order to transfer the concept of strong Miller cycle, two-stage turbocharging and variable valve timing to dual-fuel engines. The study identified great potential for improving fuel consumption in both diesel and gas mode when integrating ABB’s two-stage turbocharging Power2 and variable valve train VCM® into a seamless concept. Furthermore, the flexibility of VCM resolves some of the compromises needed when designing an engine capable of running according to the diesel and the Otto cycle. In addition, FPP operation as well as improved manoeuvrability and load pickup for gas and dual-fuel engines may be realised, as the extensive thermodynamic simulation work indicates. The publication presents the assumptions and boundary conditions that were used, the underlying modelling approach and the potential found, while also discussing expected challenges.

A new sequential turbocharging system
Guohua Xie, Shanghai Diesel Engine Co, Ltd, China
Xiaoyu Xie, School of Mechanical Engineering, Shanghai Jiao Tong University, China

The sequential turbocharging technology is the most effective method to improve diesel engine performance at low condition (low speed and low load). The technology can extend engine operation range at low condition, improve engine economy performance and reduce engine exhaust emissions. A new type of sequential turbocharging system – a split intake and exhaust boosting system is proposed here. The new system consists of two turbochargers of a large one and a small one. The adjustment range of intake and exhaust flows of such system is twice that of a normal turbocharger with two identical turbochargers. The adjustment of intake and exhaust flows of the new sequential turbocharging system is stepless, which can avoid some problems such as compressor surge, turbocharger overspeed and high oil consumption in engine transient process. The system enables a turbocharged engine to obtain high LGR rate at all operating points with the energy of a turbocharger system itself, thus meeting much stricter exhaust regulations.

Recommendations for the use of sequential turbocharging systems

Study on the variable geometry exhaust manifold turbocharging system and other turbocharging systems of 8170 marine diesel engine
Lei Shi, Shanghai Jiaotong University, China
Kangyao Deng, Shanghai Jiaotong University, China
Shaoming Wang, Technology Center of the SAIC Motor, China
Chongmin Wu, Shanghai Jiaotong University, China

In order to achieve the optimum performance of a high-load operation and the low load operation of an eight-cylinder marine diesel engine, this paper studied a newly designed variable geometry exhaust manifold (VGEM) turbocharging system by simulation and experiment. The VGEM turbocharging system can switch the charging system between two charging modes by a controllable valve according to the engine load. The one-dimensional simulations of VGEM turbocharging system was developed for a marine eight-cylinder diesel engine using GT-POWER. The effects of the charging mode on engine performance were analysed and the switch point was found according to the BSFC. The result showed that the switching point should be set at 70% load which could make the engine get optimum performance both at high- and low-load operation. The comparison of four-pulse, PC, MPC, and MIXPC turbocharging systems was studied respectively for this diesel engine. The simulation results indicated that the BSFC of the VGEM turbocharging system is always less than that of the four pulse, MPC, MIXPC turbocharging systems at all four loads of 25%, 50%, 75%, 100%.

Transient performance of three-phase sequential turbocharging with unequal size turbochargers
Yi Cui, Shanghai Jiaotong University, China
Kangyao Deng, Shanghai Jiaotong University, China
Zhe Zhang, Shanghai Jiaotong University, China

In order to improve the part load and transient performance of a diesel engine, a three-phase sequential turbocharging system with unequal size turbochargers was investigated by experiments in this paper. The performances of load acceptance processes under different speeds of three matching schemes (one small turbocharger, one big turbocharger and small with big turbochargers) were studied first. It is found that the response performance is better with a small turbocharger, but the discrepancy of response time decreases as engine speed increases. The three-phase switching boundaries of sequential turbocharging system under steady states were obtained according to the principle of optimal fuel efficiency. For speed characteristic, the small, big and small with big turbochargers are sequentially used along with the engine speed increasing from low to medium and high speed. For propeller characteristic, the small, big and two turbochargers are used along with the engine speed increasing from low to medium and high speed. Based on steady states switching strategies, the transient performance and soot emissions during acceleration processes were studied. It is found that the response performance and soot emissions of the sequential turbocharging system are better than those of one turbocharger system. But the switching process of cut in of big turbocharger and cut out of the small turbocharger has adverse effect on response performance, because it takes time for big turbocharger to speed up and for boost pressure to recover. The switching strategies suitable for transient processes were also investigated. The allowable operation boundary of small turbocharger under steady states was used as small turbocharger switching boundary during transient processes, and two-phase switching strategies (shift between small and big turbocharger)
was used instead. The results showed that the transient performance can be improved further by using transient switching strategies. For acceleration process with constant torque, the stagnation time of speed up during cut in and out point is reduced. For acceleration under propeller law, the stagnation phenomenon is more obvious with transient switching strategies, because at least one turbocharger is running when switching with steady state strategies.

**Poster Sessions Tuesday May 14th**

**Session 1**

**Effects of Charge Density & Oxygen Concentration on Thermal Efficiency & Emissions in a Heavy-Duty Diesel Engine under High-Load Operations**

W. Su, Tianjin University, China

**A Semi-Experimental Modelling Approach for a Large Two-Stroke Marine Diesel Engine Simulation**

K. Harroubi, H. Chen, Wuhan University of Technology, China

**High Turbocharged Four-Stroke Diesel Engine Performance in Further Improved – Split Turbocharged Exhausted System**

X. Xie, Shanghai Jiao Tong University, China, G. Xie, Shanghai Diesel Engine Co., Ltd., China

**Session 2**

**Dual-Fuel for Maritime Application**

A. Rendler, Heinzmann, Germany

**The Effect of Miller Cycle on the Spark Ignition Combustion Gas Engine**

S. Tavakoli, N. Ghadimi, M. Gorji, D. Domairi, G. Javadirad, DESA, Iran

**The Investigation of Spark Plug Position on the Spark Ignition Combustion Performance**

N. Ghadimi, S. Tavakoli, M. Gorji, D. Domairi, G. Javadirad, DESA, Iran

**Development of the Gas Engine Based on AVL-Boost**

Y. Li, L. Han, X. Ren, Henan Diesel engine industry, China

**Session 4**

**Simultaneous Reduction of Fuel Consumption & Toxic Emission of Exhaust Gases of Fishing Fleet Engines**

G. Klyus, Maritime Academy of Szczecin, Poland

**Sampling Method Evaluation for Measurement of Solid Particle Number Distributions from Marine Diesel Engines & Fuels**

J. Nielsen, Marintek, Norway, S. Ushakov, Norwegian University of Science and Technology, Norway

**Using the Fuel Combustion Analyzer to Evaluate the Particle Number Distribution from Different Marine Fuel Qualities**

J. Nielsen, Marintek, Norway

**L’Orange Fuel Injection Systems in China & Asia – Past Experience, Today’s Expertise & Examples for Tomorrow’s Excellence**

M. Heller, T. Stelzer, M. Riegert, L’Orange GmbH, Germany, S. Li, Jenin Diesel Engine Co., Ltd., China

**Research on Upgrade of Existing Medium-Speed Diesel Engine for IMO Tier II**

X. Li, R. Zhang, T. Ping, Shanghai Marine Diesel Engine Research Institute, China

**Research on Diesel Engine Combustion Mechanism and Simulation of Engine In-Cylinder Combustion Process**

S. Zhou, C. Li, P. Zhou, Y. Zhu, Harbin Engineering University, China

**Impact of Nozzle & Spray-Hole Design on Mixture Formation at Medium-Speed Diesel Engines**

F. Pinkert, I. Najar, C. Fink, H. Harndorf, University of Rostock, Germany, C. Schmalhorst, M. Frobenius, AVL, Germany

**Experimental Study on the Particulate Emissions & Unregulated Emissions of DI Diesel Engine Fueled with Ethanol- Biodiesel Blended Fuel**

L. Zhu, W. Zhang, Z. Huang, Shanghai Jiao Tong University, China

**Optimisation of 2-Stroke Marine Diesel Engine Fuel Consumption via VIT Setting Using a Model Based Monitoring & Diagnosis Technique: On-Board Test Case**

D. Hountalas, N. Sakellaridis, G. Zovanos, National Technical University of Athens, Greece

**Investigation on Combustion & Emissions Characteristics of Ethanol-Diesel**

L. Ye, P. Sun, Q. Wu, Jiangsu University, China

**Simulation & Analysis on Effect of Injection System Parameters to Double-Ω Combustion Chamber Performance**

S. Wei, H. Chen, Jiangsu University, China

**Fuel Injection System to meet Future Requirements for Large Diesel Engines**

Z. Gao, J. Du, B. Yin, Jiangsu University, China, M. Gutierrez, A. Marti, E. Vogt, DUAP, Switzerland

**The Effects of Different Methanol Ratios on the Integrated Fuel Economy of a Heavy-Duty Diesel Engine**

L. Bingxian, Wuhan University of Technology, China, L. Haiyan, L. Zhiming, Z. Ke, Y. Yong, Y. Songlin, Dongfeng Motor Company, China, Y. Chunlei, Tianjin University, China

**Emission Characteristics of Common Rail Engine Fuelled with Biodiesel Fuel from Waste Cooking Oil**

G. Miao, Z. Wang, Jiangsu University, China

**Session 10**

**Experimental Study on the Operation Rules between Turbocharging System & 4-Stroke Medium-Speed Marine Diesel Engine**

J. Huang, Z. Yin, Y. Qiao, Jimei University, China

**Research on Dynamic Behavior of Ball Bearing-Rotor System with Damper for Turbocharger**

M. Rizai, S. Nawel, China North Engine Research Institute, China

**Wednesday May 15th / 08:30 – 10:00 Room A**

**Fundamental Engineering – Mechanics 1**

**Integrated design, analysis and development processes applied to the design of a high-specific output gas engine cylinder head**

Ian Calvert, GE Jenbacher, Austria

Ben McCully, Ricardo UK Ltd, UK

Alessandro Zucchelli, GE Jenbacher, Austria

Martin Krajicek, Ricardo UK Ltd, UK

The General Electric Gas Engines division has established a product line centered on very high efficiency and specific output due to industry leading two-stage turbocharging, lean-burn combustion strategy and Miller valve timing in combination. This ongoing strategy to continually increase engine efficiency has pushed engine development to higher peak firing pressures and thermal loads on key components. This continuous efficiency increase is demanded with the proviso of maintaining or improving product reliability, robustness, unit price and the associated life-cycle costs. To meet these demands, the engineering team at GE Jenbacher has been continuously developing new technologies and new design and analysis methodologies in conjunction with Ricardo Consulting Engineers. This paper provides an overview of the methodologies applied to the design, analysis and development of a new cylinder head as part of the overall development programme for the recently released two-stage 624 engine into the GE Jenbacher gas engine portfolio. The design methodologies developed and applied over the course of the cylinder head development have at their foundations the core tools and methodologies used throughout all General Electric engineering departments, namely DFSS DFR etc. Experience gathered within the existing GE
Jenbacher customer fleet over hundreds of thousands of engine operating hours combined with the broad variety of customer operating conditions have been at the core of developing accurate reliability models down to the component level. This data has been further analysed through the use of Design for Reliability (DFR) tools and processes to allow clear failure mode identification and determination of key failure mode accelerating factors. This is key in predicting the response of current components placed under new boundary conditions, i.e. higher pressures and temperatures. Single cylinder testing has been used to gather the detailed component operational data to allow this correlation to occur. These factors have then been used as assessment criteria within the design and analysis of the new cylinder head. The new cylinder head assembly is a design that incorporates both a different material, a new head structure and with a new water jacket design that includes cooled exhaust valve seats. The new cylinder head assembly has been subjected to an extensive design and analysis optimisation process involving multiple iterative FEA and CFD loops, full conjugate heat transfer analysis and a number of breakout studies to examine the detail of certain components within the assembly. Confidence in the analysis methodologies has been further increased by extensive single cylinder testing of the current production cylinder head. This allowed a closed loop correlation process to be established in order to increase accuracy of the analytical approach and thereby allow the design of the new cylinder head to progress with high confidence. Specific accelerated tests were developed for the full-sized development engines in order to confirm reliability predictions on both the baseline and newly developed engines in order to confirm progress with high confidence. Specific accelerated tests were developed for the full-sized development engines in order to confirm reliability predictions on both the baseline and newly developed engines in order to confirm progress with high confidence. Specific accelerated tests were developed for the full-sized development engines in order to confirm reliability predictions on both the baseline and newly developed engines in order to confirm progress with high confidence. Specific accelerated tests were developed for the full-sized development engines in order to confirm reliability predictions on both the baseline and newly developed engines in order to confirm progress with high confidence. 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### Low vibration design of large diesel and gas engines by predictive simulation

**Martin Wyzgala, MAN Diesel & Turbo SE, Germany**  
**Peter Boehm, MAN Diesel & Turbo SE, Germany**  
**Dietmar Pinkernell, MAN Diesel & Turbo SE, Germany**

Diesel and gas engines are considerably excited to structural vibrations by enormous forces caused primarily by fuel combustion and moved crank drive masses. Customers and classification societies demand low vibration engines. At MAN Diesel & Turbo (MDT), the engine vibration is limited to an acceptable level by purposive measures regarding the engine design already during concept and detail design phase - long before the first engine test and measurements are possible. Front loading by virtual engineering plays an essential role in the development process of diesel and gas engines. By combining engineering tools for analysis, simulation and optimisation, virtual engineering facilitates a multi-disciplinary and result oriented product development. It supports classical design approaches as well as traditional experimental testing and validation. Virtual engineering assists the development process from the very first design idea to the final validation of the product. MDT demonstrates successful frontloading by means of the exemplary resiliently mounted 20V 35/44G engine, its latest four-stroke medium-speed gas engine for power plant applications. MDT designs a low-vibration engine, even though facing new, challenging boundary conditions such as high mechanical efficiency, higher firing pressures, and light-weight design. In addition to topology optimisation of the crankcase and an investigation of different firing sequences, an essential element in vibration optimisation is a highly advanced vibration analysis and simulation process delivering accurate, reliable and predictive results. The vibrations of entire engines are investigated by means of FE simulations and appropriate shell models. Because of its comparably small size and their parametric properties, an evaluation of a high number of design variants within an admissibly short time is feasible. The simplification of the complex solid geometries to a mid face design of a shell model inevitably implicates deviations. However, an optimum quality of the simulation model is indispensable. Therefore an updating procedure on numerical basis is introduced, which is already performed by standard long before any engine part is available in hardware for an experimental modal analysis. Moreover, the numerical method offers equivalent results, that a late and expensive test of core assemblies is not required. Each derived model of a core part e.g. the crankcase, base frame and turbo charger attachment is updated with respect to its original structural properties. The updating is carried out once firstly by correlating modal results like eigenfrequencies and mode shapes of reference solid FE models and their corresponding shell models and finally by adjusting parameters such as material properties, element thickness or mesh density. More detailed information about the model updating procedure will be given by the paper. Due to certain tolerances of boundary conditions, such as damping, non-linearity and fabrication tolerances, local inaccuracies will always exist. Local systems can react not exactly as predicted. Nevertheless MDT is conscious of these remaining, local inaccuracies and is taking them into account already during the concept and detail design phase. Local design alternatives are determined by help of the vibration simulation and hold available for testing. If necessary, the appropriate solution is chosen and verified by measurement. High costs and long-testing periods for the product validation are avoided. Finally, the comparison of simulation and measurement results received later from the test bed illustrates, that the simulation has an excellent quality and accuracy. Having established the presented simulation process, MDT possesses the proper methods and tools respectively know-how in order to cope with the ambitious engine design demands. This ends up in a low vibration design of new medium-speed engines taking care of customer needs and assuring a safe long-term operation without the necessity of spacious, costly and less reliable external equipment increasing damping respectively decreasing vibration.

### Structural optimisation method and low vibration design of HiMSEN engine's genset

**Kun-Hwa Jung, Hyundai Heavy Industries Co, Ltd, South Korea**  
**Jun-Ho Lee, Hyundai Heavy Industries Co, Ltd, South Korea**  
**Jung-Ho Son, Hyundai Heavy Industries Co, Ltd, South Korea**  
**Young-Seok Ryoo, Hyundai Heavy Industries Co, Ltd, South Korea**

Recently, a diesel engine that has more specific power output and compact feature was developed to cope with customer's needs. From a vibration point of view, high power output results in increasing the excitation force and compact design reduces the structural rigidity. Antivibration design of a diesel engine is necessary to prevent high vibration and durability problem. Since the beginning of HiMSEN engine's production in the year 2000, HHI has made a remarkable effort to reduce the vibration level of engine. HHI has provided suitable solutions for various characteristics of excitation force and genset's configuration using the measurement and FE-based simulation technique. Vibration response prediction is made by two FE-solving schemes that are a frequency-domain and time-domain analysis technique. These days, the flexible multibody dynamic (MBD) simulation based on the timedomain analysis technique is more popularly used because the nonlinear characteristics of mount, journal bearing and interactions between shaft and engine body can be considered. The MBD-based realistic simulation was applied to newly developed HiMSEN engines,
H25/33UV and H17/21UV. The simulation is greatly influenced by the FE model of each component. The engine’s assembly and reliability of FE model was verified by a modal test. The base frame of the engine is a key component to have an effect on the genset’s vibration. The design-of-experiment (DOE) technique is widely used to obtain the target natural frequency of genset’s base frame. DOE could give us a direction to design by sensitivity analysis. However, it is a time-consuming technique. Topology optimisation technique is widespread because the optimum design under the defined restraint is automatically shown. The vibration of additional structures, which are attached to the genset, is controlled by minimising the displacement transmissibility from the engine’s vibration. A topology optimisation technique was applied to reduce the excessive vibration of the engine’s gallery, which is one of typical additional structures.

Global vibration challenges for a V12 medium-speed locomotive engines using a post-turbine mounted aftertreatment system to meet the EPA Tier IV emission standard
Sven Lauer, FEV GmbH, Germany
Gonzalo Garcia Gorostiza, FEV GmbH, Germany
Marc Bleijlevens, FEV GmbH, Germany
Michael Kotwica, FEV GmbH, Germany
Klaus Lierz, FEV Inc, USA
Kevin Bailey, GE Transportation Systems, USA

The vibration level of medium-speed engines is critical to quality measures like durability and noise. In combination with engine mounted aftertreatment systems used to meet the EPA Tier IV emission standard, it becomes more and more important and challenging to control the global and local vibrations. The durability of the power train components is not only dictated by the crank train excitation forces but can also be influenced by the structural component vibration behaviour. The objective of the global engine vibration analysis method presented in this paper is not to consider the dynamic loads as discrete static loads but to calculate the component durability under realistic time-dependent operating conditions including the dynamic structural behaviour. The hybrid analysis procedure uses the synergy of two widespread analysis types: multi-body analysis and the finite element analysis, to simulate the dynamic component loading but also the assembly, thermo-mechanical loads and local contact slipping/gapping effects. The simulation procedure has been verified in the past based on acceleration and strain gauge measurements at numerous engine components. The comparison between measurements and simulation results has shown that a good correlation of both the global deformation as well as the local strains can be achieved.

Wednesday May 15th / 08:30 – 10:00 Room B
Environment, Fuel and Combustion
Gas and Dual-Fuel Engines – Status and Outlook

An updated survey of gas engine performance development
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Kevin Hoag, Southwest Research Institute, USA

In 2003, the first author of this paper presented a survey of gas engine current production and development trends. Since that time, interest in gas engines has continued to grow at an unprecedented rate as worldwide customers have sought the most cost-effective, emission-compliant, and fuel-efficient ways to meet increased electricity and heat and power demands. The improved efficiency while simultaneously meeting lower NOx standards projected in the earlier paper has proven to hold true, with such trends continuing in future developments. The same can be said regarding specific power output, with recent advances in turbocharging boost levels and control systems allowing significant BMEP improvements. This paper surveys the improvements in current natural gas engine performance and emissions and again projects forward with a look at current development efforts.

Current status and future strategies of gas engine development
Shinsuke Murakami, AVL List GmbH, Austria
Torsten Baufeld, AVL List GmbH, Austria

The present paper describes the current development status of high-speed (with nominal speeds of 1,200 to 1,800 rpm) and medium-speed (with nominal speeds up to 1000 rpm) large gas engines as well as their future development strategies for the short to middle term. The population of natural gas engines for stationary applications such as power generation or gas compression has expanded significantly in the last few decades. Growing attention to the reduction of CO2 emission as well as upcoming more and more stringent regulations for NOx emission will make gas engines attractive also to marine and locomotive applications. In order to boost a long-term growth trend of gas engines, further improvement in power density and thermal efficiency is demanded. Gas engines today have already reached competitive BMEP levels and comparable or even higher thermal efficiency levels compared with those of diesel engines. Gas engines owe such improvements greatly to the lean-burn combustion principle, the Miller valve timing and incremental combustion developments such as optimisation of combustion chamber geometries, increase of compression ratio, etc. Performance development of gas engines has been a struggle against knocking combustion all the time. In order to further increase the BMEP and/or thermal efficiency, knock resistance is yet to be improved. Miller cycle in conjunction with the charge air cooling suppresses the onset of knocking by reducing the combustion temperature. However, it raises requirement for the higher intake manifold pressure. As the compressor pressure ratio of a single-stage turbocharger is limited, even more aggressive Miller timing than today requires an application of two-stage turbocharging. Another important aspect is the peak firing pressure capability of the engine platform. Considering that many of the gas engines currently in the market started their history with the BMEP of 10 to 12 bar and reached 20 to 22 bar up to now, they may be already close to their peak firing pressure limit. A further increase of the BMEP would impose a massive design change or even a new engine development. Based on experiences of gas engine developments with AVL proprietary single cylinder engine as well as with AVL proprietary simulation codes, the present report reviews key technologies of gas engines and their current development status and discusses their limitations, potentials and requirements for the future gas engines. The most important key technologies that enable future development of gas engines are the application of even more aggressive Miller timing in conjunction with two stage turbocharging as well as the peak firing pressure capability of up to 250 bar and above.

Advanced spark ignition technology for gas-fuelled engines and its impacts on combustion stability and performance optimisation
Joseph Lepley, Altronic, LLC - Hoerbiger Engine Solutions, USA
Arno Gschirr, Altronic, LLC - Hoerbiger Engine Solutions, Austria

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This paper addresses the critical role of evolving spark ignition technologies in expanding the envelope of effective operation specific to both in-cylinder combustion stability and the overall performance and efficiency of the associated engine. The reviewed advances in spark ignition technology describe a new means whereby previous boundaries of gas engine design and operation might be extended. Optimisation of key engine performance parameters such as consistency and phasing of individual cylinder firing pressures and accelerated flame kernel development are fully explored. Additionally, the practical impacts of these fundamental changes in performance as observed during engine testing results are discussed with respect to the successful management of difficult to ignite mixtures inclusive of those engines operating in a low emissions environment, on sub-optimum fuels, or even in off-design conditions.

Valve control management – the possibility of improving gas engine performance

Christoph Mathey, ABB Turbo Systems Ltd, Switzerland

ABB Turbocharging presented the electro-hydraulic variable valve timing system VCM® during the 2010 CIMAC congress in Bergen. The VCM® has a considerable degree of flexibility, allowing it to be used on diesel and gas engines of different sizes and for different purposes. The system also has the inherent possibility to be customised in such a way that easy integration without major changes to an existing engine design is feasible. After extensive mechanical testing of the full system, including a validation and qualification programme on a small medium-speed diesel engine, the possibility of the VCM® improving the performance of a gas engine has been investigated. On performance we found an improvement in fuel consumption and other engine parameters. The control unit in a conventional high speed premix gas engine consists of a throttle valve and a compressor by pass. Both consume a substantial amount of energy as they provide a pressure reserve for acceleration and control purposes. One concept by which the performance of such an engine could improve is to substitute these control devices with variable inlet valve timing and lift, i.e. the application of VCM®. This paper shows the design of the VCM® unit for a high-speed gas engine where the mechanical boundary conditions are discussed, how these could be fulfilled and how they are influencing the performance of the engine with regard to how the engine reacts to certain variations in the system. With regard to thermodynamic performance, the paper considers possible improvements brought by dethrottling and how the engine operates in normal conditions as well as during load changes. The application of skipping/cylinder cut-off is also discussed. Furthermore, the paper looks at the required setup of the inlet valve under changing ambient conditions as well as changing gas qualities and applications with variable engine speed.

Wednesday May 15th / 08:30 – 10:00 Room C

Environment, Fuel and Combustion

Diesel Engines – Exhaust Gas Recirculation (EGR)

EGR system development on MES test engine 4S50ME-T9

Toshinori Shrai, Mitsui Engineering and Shipbuilding Co, Ltd, Japan
Peter Skjoldager, MAN Diesel & Turbo, Denmark
Sumito Yokobe, Mitsui Engineering and Shipbuilding Co, Ltd, Japan
Shoichi Ibaragi, Mitsui Engineering and Shipbuilding Co, Ltd, Japan

The IMO Tier III regulation will apply to ships constructed on or after January 1st 2016, operating in ECAs. The Tier III regulation requires an 80% NOx emission reduction compared with IMO Tier I. SCR and EGR are expected to be the most feasible NOx reduction technologies. SCR reduces NOx using catalysts and is a well-known technology for land use. Mitsui Engineering and Shipbuilding Co, Ltd, (MES) has already established an SCR technology to comply with NOx Tier III. However, the catalyst reactor seems to be rather large as marine use. De-NOx principle of EGR is to reduce the generated NOx during the combustion process by decreasing the O₂ content and increasing CO₂ content in the scavenging air, resulting in the reduction of the peak combustion temperature. MAN Diesel & Turbo (MDT) investigates EGR systems and makes a service test on the Alexander Maersk, Mitsui Engineering and Shipbuilding Co., Ltd. (MES), under license of MDT, set an EGR system on its test engine 4S50ME-T9. This EGR system is the first build-in type on the engine. The purpose of this work is to design and experience build-in EGR equipments in terms of gas flow system components such as EGR scrubber, EGR cooler, EGR blower, control valve, etc. and scrubber water supply system such as scrubber pump, centrifuge, etc. Moreover, the purpose is to decide optimum EGR and engine operating parameters such as fuel injection timing to obtain the best operating efficiency. Our recent results are:

• On Tier III emission test, we achieved 80% NOx reduction rate at E3 mode test;
• On Tier II emission test, we reduced fuel consumption rate at engine part load by using EGR system to limit NOx generation at better fuel efficiency mode of the engine;
• The EGR can be applied not only on a one turbocharger system but also on a two turbocharger system on an engine;
• Parameter variation by ECS parameters was investigated (Injection timing, Exhaust valve closing and opening, Injection pressure);
• The electrical power consumption of EGR blower was investigated.

NOx reduction by combination of charge air moistureriser and exhaust gas recirculation on medium-speed diesel engines

Hyong-Keun Park, Hyundai Heavy Industries Co, Ltd, South Korea
Myung-jik Bae, Hyundai Heavy Industries Co, Ltd, South Korea
Jong-il Park, Hyundai Heavy Industries Co, Ltd, South Korea
Hyun-Chun Park, Hyundai Heavy Industries Co, Ltd, South Korea

NOx emission from diesel engines is a principal toxic ingredient of environmental pollutants. Thus, NOx from diesel engines has been limited by the global and local regulations, which have become more stringent in connection with the recent environmental problems. The IMO Tier III regulation, which requires to reduce NOx by 75% from the current Tier II regulation (20% reduction from Tier I regulation), will be effective from 2016. Several methods such as combustion optimisation, EGR, water addition, high-pressure turbocharger etc. have been developed to reduce NOx. Each method is not enough to abate NOx to comply with the IMO Tier III regulation, but combination of the NOx reduction methods is able to satisfy it. Hyundai Heavy Industries Co, Ltd (HHI) has developed a charge air moisturiser (ChAM), which humidifies charge air with water vapour and has also tested EGR system for NOx reduction. HHI has enhanced NOx reduction efficiency by a combination of the EGR and the ChAM systems on a medium-speed diesel engine, and has confirmed that NOx emission has been kept under the IMO Tier III regulation. The combination of the EGR and the ChAM system can be a candidate as the main NOx reduction technology to comply with the IMO Tier III regulation.
Combination of post-injection and cooled EGR at a medium-speed diesel engine to comply with IMO Tier III emission limits

Marko Pueschel, FVTR GmbH, Germany
Bert Buchholz, FVTR GmbH, Germany
Christian Fink, Universität Rostock, Germany
Carsten Rickert, Caterpillar Motoren GmbH & Co KG, Germany
Kai Ruschmeyer, Caterpillar Motoren GmbH & Co KG, Germany

With introduction of IMO Tier III in 2016 the marine diesel engine technology faces a radical change. The IMO Tier III requires NOx reductions of 75 % compared with the current level (IMO Tier II). In connection with the stringent NOx reductions massive SOx reductions will be introduced stepwise until 2015. In light of this, the potential of EGR to fulfil the IMO Tier III NOx limits at medium-speed marine diesel engines is systematically analysed. The targets are defined by a NOx emissions level of 2 g/kWh, invisible smoke and minimum fuel consumption penalty. The analyses are carried out at a six-cylinder medium-speed test engine with 1,000 kW output at 1,000 rpm. The research engine is equipped with a cooled EGR system, a common rail injection system and a programmable engine control unit. The CR injectors are solenoid operated and allow multiple injections. Systematic variations of EGR rate, injection pressure and injection timing were carried out and the results regarding combustion process, NOx and soot emissions as well as fuel consumption are presented. The results show that significant EGR rates are necessary to obtain NOx-reduction rates as required for IMO Tier III compliance. These high EGR rates result in unwanted and unacceptable soot emission levels even at increased injection pressures. To reduce these soot emissions, post-injection strategies were analysed at the medium-speed test engine. Post injection proved to be an efficient soot reduction measure in onroad diesel engine. The effect of different post injections on the soot emissions is shown. Based on the results, the soot emission reduction potential of postinjections at marine medium-speed diesel engines is outlined and the requirements for a successful implementation of post-injection strategies are discussed. The application of post-injections requires detailed information on the dynamic behaviour of the common rail system and especially on the CR injectors applied. Due to this, the dynamics of the CR injectors in case of post-injections were established at an injection rate analyser and the findings are discussed. The functionality of the CR injectors at the test engine is monitored by measurements of the current feed signal and the injection pressure at the injector inlet. Finally, the preconditions for a successful application of EGR at medium-speed marine diesel engines are summarised. The use of EGR not only challenges the injection (rail pressure, post injections), charging and the cooling system (EGR, charge air) but also the engine control system.

Ten years after: results from the major programme HERCULES A-B-C on marine engine R&D

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Lars Heisell, Wärtsilä Corporation, Finland
Christian Poensgen, MAN Diesel & Turbo SE, Germany

In the year 2004, the integrated project HERCULES-A (Higher-Efficiency Engine R&D on Combustion with Ultra-Low Emissions for Ships) was initiated by the major engine makers MAN and Wärtsilä, which together hold 90% of the world market. It was the phase I of the HERCULES R&D programme on large engine technologies. The HERCULES-A involved 42 industrial and university partners, with a budget of EUR 33 million, partly funded by the European Union. The project was broad in the coverage of the various R&D topics and considered a range of options and technologies in improving efficiency and reducing emissions. HERCULES-B was phase II of the programme, from 2008 to 2011, with 32 participating organisations and EUR 26 million budget, partly funded by European Union. The general targets for emissions and fuel consumption were retained in HERCULES-B. However, based on the developed know-how and results of HERCULES-A, it was possible to narrow the search area, to focus on potential breakthrough research and to further develop the most promising techniques for lower specific fuel consumption (and CO₂ emissions) and ultra-low gaseous and particulate emissions. The HERCULES-C project (2012-2015), with 22 participant organisations and EUR 17 million budget, is phase III of the HERCULES programme and adopts a combinatory approach, with an extensive integration of the multitude of new technologies identified in phase I and phase II, for engine thermal processes optimisation, system integration, as well as engine reliability and lifetime. This paper provides an overview of the complex structure, as well as the main achievements of the HERCULES R&D programme in the past ten years.

Benefits of propulsion integration on fuel efficiency of marine vessels

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A major effort is undertaken to improve the energy efficiency of shipping. This requires that the (engine) thermal efficiency and the ship propulsive efficiency are addressed simultaneously. New IMO rules are referred to the vessel environmental indices (as overall energy efficiency per carried load and distance transported) than only to the efficiency of individual engine types and systems. The reciprocating engine concept seems to remain the basis for fuel energy conversion to mechanical energy, with emphasis on fuel versatility and the broad introduction of gas. The ship propulsion systems (fixed or controllable pitch propellers, steerable thrusters and advanced designs of high-efficiency potential) undergo new developments with emphasis on high vessel propulsive efficiency and engine compatibility. The vessel design itself is also to be adapted to the new propelling and machine room equipment. Obviously this integration can better be done in early ship and system design phases. The current paper describes the impact of the propulsion system and the propeller selection on the overall vessel efficiency optimisation. A number of vessel cases are examined in detail:
- Large container ship applications at slow steaming/propeller selection;
- Drilling vessel application/thruster optimisation;
- Gas engine application/propeller control;
- Special vessel diesel mechanic application with two-stage gear boxes;
- Propeller power loading on vessel performance.

Propulsion System Integration

Wednesday May 15th / 08:30 – 10:00 Room D
Integrated Systems and Electronic Control
Piston Engines, Gas and Steam Turbines and Applications – Propulsion System Integration

Analysis and evaluation of innovative hybrid powertrain architectures combining gas engines and electric propulsion for tugboats

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The introduction of more stringent emission legislation (IMO Tier III, ECA, etc.) and the continuous requirement of fuel efficiency improvements set up new challenges in the marine sector. The gas operation was identified as one of the most promising solution for high- and medium-speed engine powered vessels to meet the required NOx emission level. But this approach is less attractive in comparison with traditional propulsion systems using diesel engines due to highly dynamic duty cycles, i.e. tug boats. In this case the transient engine control of a gas-operated engine could become very difficult, setting unacceptable constraints to the vessel’s dynamic. The excellent propulsion control and its dynamic behaviour are on the other hand one of the most important characteristics of electrified propulsion systems. Nevertheless, it is well known from other applications that the biggest challenge of electric propulsion system is linked to the poor power and energy density of the currently available energy storage systems; moreover, these are connected to their prohibitive costs, weight and dimensions. On the contrary, a hybrid solution seems to be really promising; the combination of both approaches, gas engine operation to reduce fuel consumption and improve the emission levels with electric propulsion, seems to represent a feasible and flexible solution. A general receipt to dimension such hybrid systems does not exist: the best architecture need to be defined for each application, depending on many parameters, as vessel characteristics, duty cycles, power, costs, etc. In this paper the authors have performed an analysis on different hybrid architectures and configurations applied to a typical tugboat, assuming the following constraints and boundary conditions:

- Operational only near port or in ECAs,
- Need for an extremely compact design,
- Power range: 0.5 MW to 4 MW,
- Fulfilment of new IMO legislations requirements (e.g. EEDI and NOx standard in Tier III).

The modelling of a tug boat powertrain has been performed using Ricardo’s software tools: performance simulation models will be built using Ricardo Wave for the gas engine as well as for the original diesel engine. The hybrid component’s behaviour (e.g. energy storage system, electric drives, etc.) will be simulated and assessed with Ricardo V-Sim, defining different architectures and developing optimised control strategies. The defined technical solutions will be assessed and compared with current diesel powertrains. The presence of auxiliary systems as well as the combination and integration with other powertrain components (gearbox, propeller, shafts, bearings, etc.) will be also taken into account. A cost and economical analysis for the different architectures will complete the assessment and close the paper.

**Development of turbo hydraulic system on large marine diesel engine**

Nobuyuki Sakairi, Mitsui Engineering and Shipbuilding Co, Ltd, Japan
Ichiro Tanaka, Mitsui Engineering and Shipbuilding Co, Ltd, Japan
Morio Kondo, Mitsui Engineering and Shipbuilding Co, Ltd, Japan
Atsushi Otsuka, Mitsui Engineering and Shipbuilding Co, Ltd, Japan
Kazuoru Ohta, Mitsui Engineering and Shipbuilding Co, Ltd, Japan

Under the situation that preventive effort to global warming is becoming more active in various fields, the reduction of CO2 from marine diesel engines is also required. The effective solutions for this challenge are reduction of fuel consumption by improvement of thermal efficiency, utilisation of waste heat energy, and a change to low-carbon fuel such as liquefied natural gas. Mitsui Engineering and Shipbuilding Co. Ltd. (MES) has developed the Turbo Hydraulic System (THS), which is one of technologies of the utilisation of waste heat energy (WHR). The THS makes it possible to recover the exhaust gas energy in the form of hydraulic power. In THS, excess energy of the exhaust gas is recovered with hydraulic pumps in the form of hydraulic power, and the recovered power is supplied to a hydraulic motor connected to the crankshaft for assisting to drive the engine. Accordingly, the actual fuel consumption is reduced. The performance test of the THS on MES’ test engine showed that the fuel oil consumption was reduced by maximum 4% without increasing NOx emission compared with the original condition. The THS is available in two versions: One type has four pumps, which are installed on the turbocharger. The pumps are connected to the turbocharger rotor shaft through a reduction gear. This type of THS is suitable for single turbocharger. The other type has pumps that are connected to a power turbine, which is driven by energy of bypassed exhaust gas, instead of the above mentioned direct-driven pumps on the turbocharger. This type is more suitable for multiple turbochargers. Generally, hydraulic equipments are more compact than electric ones. In addition, the main components of the THS are integrated on an engine. Finally, the THS is more compact and cheaper than conventional WHR system, utilising electric equipments such as frequency converters and electric motors. Furthermore, we are planning to retrofit a THS system on a ship that is already in service. The purposes are to confirm the reduction of fuel oil consumption as the propulsion system and the reliability and durability of THS system.

**Development of the hybrid tugboat system**

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Kazuyuki Kobayashi, Niigata Power Systems Co, Ltd, Japan
Masanori Kodera, Niigata Power Systems Co, Ltd, Japan
Syunichi Minami, Niigata Power Systems Co, Ltd, Japan

It is necessary to design a vessel with consideration for greenhouse gas and fuel consumption reduction. In general, the propulsion system of a tugboat is designed with rated horsepower for the required bollard pull. However, in basically every harbour, tugboats are operated under the low load except the moment of ship berthing to fulfil the operation pattern. To meet customer’s need, it is necessary to design a ship to operate in good conditions of the system performance. Therefore, we have developed a hybrid system for a tugboat, applying electric motor and battery similar to a hybrid vehicle. The propulsion system power source of this system consists of a diesel engine and electric motor powered by electric current from a high-density battery. The installation area becomes smaller in comparison with a lead battery. Adopting the high-density battery is effective for the ships whose installation space is relatively limited, such as tugboats. This hybrid system could reduce fuel consumption and greenhouse gases by 20% in comparison with the conventional system. The first hybrid tugboat in Japan entered into service in early 2013. If the new development, called the hybrid propulsion system ship, can be established, this system will be in contribution to the shipping industry. This paper explains the introduction, development summary and effects of the hybrid system.

**Wednesday May 15th / 10:30 – 12:00 Room A**

**Fundamental Engineering – Mechanics 2**

**Investigations on injection-rate oscillations in common rail injectors for high-pressure injection**

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Florian Schwarzmueller, Technische Universität München, Germany
Georg Wachtmeister, Technische Universität München, Germany
An approach for dimensioning case hardened components through utilisation of sophisticated fatigue analysis with the finite element method

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Roger Rabb, Wärtsilä Finland Oy, Finland
Anton Leppänen, Wärtsilä Finland Oy, Finland
Aulis Silvonen, Wärtsilä Finland Oy, Finland
Sylvia Leever, Wärtsilä Netherlands BV, The Netherlands
Wolfgang Luft, Wärtsilä Switzerland Ltd, Switzerland

Component design procedures have developed significantly during the last decades. As a part of the process, the prediction of accurate stresses using the finite element method (FEM) as well as the calculation of fatigue strength with specific codes, have become common practice. Due to ever increasing computational power, different surface treatments, which contribute to the formation of the local microstructure and stress situation, such as heat treatment or shot peening, can also be integrated in the FE model. The determination of the fatigue life of a component can be automated to some extent for the sake of decreased design time by using numerical methods. When the outcome of a surface treatment is taken into account in such an analysis, it naturally gives the analyst an opportunity to optimise not only the geometry but also the desired surface treatment influence on the component. In turn leads to the fact that the parameters of the surface treatment procedure in manufacturing can be defined more precisely already in the designing phase leading to obvious cost savings. Case hardening is a surface treatment process in which the surface of a metal is hardened by infusing elements into the material. More specifically, the component is introduced to a carbon-rich environment at an elevated temperature and afterwards quenched so that the carbon stays in the structure, is a commonly used method for improving the wear and fatigue resistance of several engineering components. The advantage from the fatigue point of view of this procedure is naturally the increase in hardness as well as the compressive residual stresses in the surface of the component. The disadvantage, on the other hand, can be found underneath the surface in a form of balancing tensile residual stresses, which in turn may be a source location for a possible failure initiation. This paper introduces an approach for dimensioning a component, which has been hardened by carburisation. The focus of the exercise is on defining the correct case hardening profile in order to meet the required probability of survival. As an example, a gear from a thruster manufactured by Wärtsilä Netherlands BV is investigated, where the teeth of the gear wheels are treated. The examination is conducted through the component surface until a certain depth in order to also take into account the influence of the tensile part of the residual stresses. Those are then combined with the working stresses during operation, and based on the result, the fatigue analysis is performed. That is done by adapting existing Wärtsilä tools including the multiaxial damage models of Findley and Dang Van together with the concept of local fatigue strength, which defines local fatigue limits through depth based on the hardness variation. The material parameters used are obtained by testing and finally the calculated results are compared to available real world data.

The valve seat ring shrink fit simulation methods in the finite element modelling of the cylinder head

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In this paper, the uniform pressure method, the contact model method and the temperature method are used to simulate the shrink fit of the valve seat ring. Based on theories and calculation results, it is concluded that the contact model method can reflect the real contact condition. In order to investigate the influence of the valve seat ring on the fire deck stresses, the contact model is used. The mechanical stress, thermal stress and thermomechanical stress are calculated. With the valve seat ring, the mechanical stresses increase while the thermal stresses and thermomechanical stresses decrease in the valve bridge areas. Therefore, the influence of the valve seat ring can not be ignored when calculating the stresses of the cylinder head.

Visualisation of the combustion in Wärtsilä’s 34SG pre-chamber ignited lean-burn gas engine

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Jari Hyvonen, Wärtsilä, Finland
Rikard Wellander, Lund University, Sweden
Olivind Andersson, Lund University, Sweden
Matthias Richter, Lund University, Sweden

An experimental study is carried out to investigate the combustion process in a Wärtsilä 34SG spark ignited lean-burn four-stroke large-bore engine (cylinder bore of 340mm and stroke of 400mm) by means of passive optical diagnostics when operated with natural gas. The main focus of this work is to gain qualitative and quantitative knowledge about the in-cylinder combustion phenomena when igniting a lean air/fuel mixture, i.e. lambda about 2, with pre-chamber induced igniting jets. The work consists of two-dimensional imaging of the combustion process in single cylinder research engine with optical access to the combustion chamber under relevant operating condition. To gain further knowledge of the ignition and combustion process in the SG optical engine,
high-speed imaging (20 kHz) of the flame chemiluminescence was performed. The high-speed image sequences captured the full duration of the ignition and flame propagation processes in a single cycle. The topology of the flame is studied during the whole combustion duration in order to understand how the velocities of the jet are affecting the flame propagation. The analysis is based on pre-combustion chamber and main chamber apparent heat release rates from the pressure measurements and from the recorded flame images. The results showed that the pressure difference between the pre-combustion chamber and main combustion chamber is due to the pre-combustion chamber apparent heat release rate. The combustion of the main chamber takes place after about 95% heat is realised from the pre-combustion chamber. Based on the cycle-to-cycle variations, the flame propagation from the precombustion chamber to the main combustion chamber is faster due to a lower pre-combustion chamber apparent heat release rate.

**Wednesday May 15th / 10:30 – 12:00 Room B**

**Environment, Fuel and Combustion**

**Gas and Dual Fuel Engines – Performance and Diagnostics**

**Large gas engines – 75 mg/Nm3 at 15%O2 NOx ‘engine-internal measures or exhaust aftertreatment?’**

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Large gas engines are gaining more and more importance within the global energy mix. The long-term availability of natural gas is comparatively secure and gas engine power plants are reaching high efficiency levels while meeting stringent emission limits worldwide as well as customer needs for matching electricity generation with demand. This makes large gas engines a clean technology for supplying electricity and heat around the globe as part of a decentralised energy concept. Emission legislation always drives technology, and there is a clear trend towards decreasing the emission limits for large combustion plants. For example, the European Union has issued the Industrial Emission Directive (IED) with a NOx limit for new gas engine plants of 75 mg/Nm³ at 15% O₂ and 100 mg/Nm³ for CO. These limits have been in force since 2010 and are mandatory for power plants with an energy input above 50 MW that consist of engines above 15 MW. Due to the IED and other emission legislation, it is necessary to decrease plant emissions. As a result, customers are requesting engines with lower NOx, CO and THC emissions. Up to date, engines with 500 mg/Nm³ NOx at 5% O₂ dominate the market share, but it is likely that there will be a shift to low NOx engines. From the perspective of both technology and life cycle cost, there is always the question of what technology fits best. Consequently, this paper discusses the trade-off between emissions and engine performance and also highlights various technological approaches that are used to achieve the highest engine efficiency with the lowest possible engine-out emissions. The focus is on the design of the prechamber and the main combustion chamber, operational strategy and the turbocharging system including gas exchange. Finally, the engine-internal measures are compared with competing exhaust aftertreatment solutions.

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**Newly updated combustion system for HiMSEN gas engine, H35/40G**

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Hyun-Chun Park, Hyundai Heavy Industries Co, Ltd, South Korea
Jong-il Park, Hyundai Heavy Industries Co, Ltd, South Korea
Ki-Doo Kim, Hyundai Heavy Industries Co, Ltd, South Korea
Jong-Ha Son, Hyundai Heavy Industries Co, Ltd, South Korea
Chang-Min Jung, Hyundai Heavy Industries Co, Ltd, South Korea

Natural gas has received much attention as the new energy source due to its cleanliness and low price. There is a lot of interests and researches about gas engines and Hyundai Heavy Industries Co, Ltd, (HHI) also developed H35/40G gas engine successfully in 2010. Further researches including experiments and simulations proceeded to improve efficiency. For the minimisation of the methane slip, the optimisation of the gas supply timing and pressure was conducted and effects of the reduction in crevice volumes was evaluated. Ignition timing and AFR were varied to investigate the gas engine operating characteristics. The operating condition for the highest efficiency could be estimated and the maximum efficiency and limiting factors to the higher efficiency were found with the initial engine specifications. The numerical simulations were carried out to optimise the main components of the gas engine combustion system – prechamber, valve timing, intake port and piston bowl. The volume of prechamber was the dominant factor to control combustion speed. Advanced Miller timing with the turbocharger matching was investigated and the higher flow coefficient and proper swirl ratio were mainly regarded in the intake port design. Proper piston bowl shape was searched to have better combustion phase. New designs of the main components of the gas engine combustion system were suggested through the simulation and their effects were confirmed by the experiments. Finally, EGR test was conducted to evaluate the efficiency improvements by reducing NOx and suppressing the knocking.

**Method to quantify and visualise abnormal combustion of an SI engine**

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With increased power density on gas engines, an increase in cylinder temperature deviation was observed. The combustion shows temperature variations from cylinder to cylinder. The differences can be caused by variations in the air/fuel ratio, in the homogeneity of the mixture, in the charge movement, in the wall temperatures, in the manufacturing tolerances, and the oil entry on valves and pistons, etc. All parameters lead to deviations from the optimal centre of combustion and in burning efficiency of the fuel. In particular, oil entry leads to abnormal combustion in single or multiple cylinders caused by self-ignitions. Strong self-ignitions can express themselves by generating spontaneous cyclically unsteady combustion chamber temperatures. Further investigations with pressure sensors identified abnormal combustion with higher peak pressures sometimes combined with knocking. Nevertheless, these strong self-ignitions do not always appear but they are probably affected by the amount of oil entry into the cylinder. Self-ignition was found during normal combustion following a spark ignition, and also when a cylinder was not ignited by a spark at all. Self-ignition occurs with intensity levels related to the engine power. In extreme cases, they lead to a derating or shutdown of the engine by the monitoring system. A new procedure was developed to quantify the self-ignition. The electronic spark ignition was shut off in each cylinder, one by one and the cylinder pressure was measured by a quartz pressure sensor. Based on the cylinder pressure curves, the heat release per cycle was calculated by thermo-
dynamic analysis. If the unfired cylinder starts with a combustion (depending on the amount of engine power) after a self-ignition, an accordingly statistically distributed number of visible combustions arises during the recorded working cycles. These combustion processes are different due to the amount of burnt fuel. The comparison of approximately five working cycles of multiple cylinders on the basis of the single burn functions is not revealing. The comparison of 100 working cycles is impossible. The newly introduced evaluation method presented here allows the quick detection of the number and the intensity of the abnormal combustions.

High-speed flame chemiluminescence investigations of prechamber-jets in a lean mixture large-bore natural gas engine

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Ulf Waldenmaier, MAN Diesel & Turbo SE, Germany

Large-bore natural gas engines are a promising technology to meet future demands for environmentally friendly cogeneration and industrial applications. The challenge to develop ultra-lean mixture combustion processes with the highest thermal efficiency and power output, under terms of lowest level of raw emissions is strongly affected by the capability of a stable and reliable ignition process. The ignition in the main combustion chamber is usually initiated by flame-jets of a gas-scavenged prechamber spark-ignition system. To examine the potential of an increased equivalence ratio level in the main combustion chamber, a detailed knowledge and understanding of the prechamber-jet propagation process is essential. An exclusive thermodynamic investigation is not able to show spatial and temporal details of lean mixture combustion processes. For a comprehensive study, the thermodynamic investigations have to be combined with optical measurement techniques. The results, presented in this technical paper, were carried out using a MAN 32/40 multi-cylinder research gas engine, equipped with a prechamber spark-ignition system. The integration of the endoscopic optics was realised so that the design changes were kept at the lowest possible level. This ensured that the engine could be operated during these optical investigations nearly like a corresponding series production variant. The optical access was prepared as a kink angle arrangement which offered a field of view to observe the prechamber-jets beginning with the penetration and continuing until the lean mixture in the main combustion chamber is ignited. An improvement of the lean mixture combustion process requires the detailed observation of the prechamber-jet characteristics. This was realised with an endoscopic high-speed camera system in combination with a UV-intensifier, visualising the chemiluminescence intensity of the flame front propagation. The camera framing rate was set to 9 kHz. The measurement setup was finally used to analyse the characteristics of three different prechamber designs. A precise observation of the diameter’s influences was arranged in a way so that an individual prechamber-jet was ‘optically isolated’ in the field of view. This arrangement offers a selective detection of an individual prechamber-jet. Three different orifice pattern designs with various diameters have been tested. The penetration length of the orifices has been kept constant for all prechamber designs. The tests, performed at various operating points, reveal the prechamber characteristics in the context of prechamber-jet propagation area, spatial and temporal formation, penetration length and chemiluminescence signal intensity. In addition, the measurement setup was used to identify and evaluate combustion phenomena, occurring before and even during the prechamber-jet propagation. The results, presented in this technical paper, show exemplarily the potential of high-speed camera investigations to enlarge the knowledge on prechamber-jet ignition characteristics and to be an effective method in the challenge to improve future lean mixture large-bore natural gas engines.

High-performance solutions for IMO Tier III – System integration of engine and aftertreatment technologies as element of success

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In 2015/2016 stricter limits for marine engines concerning sulphur and nitrogen oxide emissions will come into force with IMO Tier III. A NOx reduction of approximately 75% compared with today is demanded as well as a desulphurisation of over 85% in designated ECAs. MAN Diesel & Turbo SE is developing robust, reliable and high-performance solutions to meet the future emission limits. Besides the intensive development and test of selective catalytic reduction (SCR) technology to minimise NOx emissions, other emission reduction methods as desulphurisation are analysed and optimised in Augsburg. Besides the optimisation of the single technologies, the focus of development activities is to find the best possible combination of the solutions. A core competence is the proven MDT safety and control system SaCoSone, enlarged by aftertreatment modules of SaCoS. Up to now, a wide experience is available on the various aftertreatment technology demonstrators. The most effort is placed in the field of SCR technology, which is the basic solution for reaching IMO Tier III emission limits. With the valuable measuring results theoretical models have been adopted and validated, so that the prediction of relevant characteristic parameters is possible with a good accordance to the test results for the MDT engine family. With these models an optimisation of the chosen technologies has been executed. Compared with the initial configuration, significant improvements have been achieved in the fields of catalyst type and size, reductive injection and mixing unit. A uniform distribution of the exhaust gas, mainly in velocity and composition as well as an improved thermolysis of the reductive to ammonia led to series modules with less installation space. Further potential is seen in the development of innovative concepts for ammonia generation. To be able to operate the aftertreatment technologies with minimised consumption of energy and reductive, the system control is executed with SaCoS, including the safety strategy of the complete system. An intelligent control unit, which controls all relevant parameters as a function of the engine, is also important when switching between ECA and non-ECA mode. Besides the efforts to develop a high-performance SCR system, some predefinitions from engine side have to be fulfilled. The composition of the raw emissions has a great influence on type of catalyst to be used, and boundary conditions concerning optimal temperatures have to be met. For a further reduction of particulate matter (PM) emissions and to eliminate the sulphur oxides, dry and wet scrubber techniques are tested in-house as well as in field tests. The first step towards IMO Tier III-compliant systems is the development of the single techniques. More benefits
The objective of the article is to present critical design aspects of SCR systems suited for high-sulphur fuels in combination with exhaust gas boilers, silencers and scrubber. The combination is presented by going through the challenges of the general system design. Regarding the challenges the main focus of the paper is in the SCR unit, a much better quality of the exhaust gas is entering the SCR unit, a much better quality of the exhaust gas is entering the SCR reactor, boiler and Wärtsilä CSS (compact silencer system) elements are discussed. This combination can be designed to meet various sound attenuation requirements. Space restrictions are a well recognised concern for many shipowners, ship operators and shipyards. The needed performance of the exhaust gas line after turbocharger plays a significant role in the design of the ship. The paper presents the typical sizes of different equipments and the feasible ways to minimise the needed space for the whole exhaust gas line.

Advanced emission abatement – 144 MW diesel based power production with NOx, SOx, and PM abatement – design – commissioning – early production experience

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Knud Hvidtfeldt Rasmussen, Burmeister and Wain Scandinavian Contractor AS, Denmark
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Burmeister & Wain Scandinavian Contractor AS has designed, constructed, and commissioned a 144 MW diesel engine based power plant for Enemalta Corporation in Malta in 2012 with an exceptionally low level of emissions. The low-emission level is based on a combination of well-proven and new advanced abatement techniques capable of complying with the most stringent emission norms. The power producing units of the plant are eight diesel generation sets, Wärtsilä 18V46 medium-speed diesel engines with ABB AMG1600 alternators, each rated 17.1 MWe, and as bottom cycle one common Dresser Rand steam turbine generator with a Convatec alternator, rated 13.2 MWe. The fuel of the plant is HFO with a maximum of 1% sulphur. The flue gas abatement includes NOx abatement by SCR, SOx and particulate abatement by dry flue gas desulphurisation (FGD) with Sodium Bi-Carbonate injection followed by filtration in a Bag-House filter. The plant is cooled by sea water. The obtained net plant electrical efficiency with the extensive utilisation of the exhaust gas energy in boilers and the steam turbine generator is 46.9% with due consideration of auxiliary power consumption for emission abatement purposes. In addition, the plant includes two desalination units, each rated 700 m3/day, driven by engine cooling water, thus achieving a total thermal efficiency exceeding 50%. The major unabated flue gas emission with the installed equipment would have been approxi-

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Marko Lehikoinen, Wärtsilä, Finland
Dustin Osborne, Southwest Research Institute, USA
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Bombardier ALP-45DP locomotive

The Bombardier ALP-45DP is a dual-power (electric and diesel-electric) locomotive manufactured for the North American market. It is rated at 5.0 MW in catenary-electric mode, and 3.0 MW in diesel-electric mode. In diesel-electric mode, power is provided by two 1.5MW Caterpillar 3512C-HD diesel engines. This paper describes the challenges and solutions in obtaining US EPA Tier III locomotive certification for this locomotive. There are several unique aspects of the Bombardier ALP-45DP locomotive that required dialogue with EPA for the exhaust emissions certification process. These included an infinitely variable throttle in contrast to the North American convention of ‘throttle notches’, where engine speed and load are predefined by the locomotive manufacturer, and hence selection of the exhaust emissions test modes is straightforward. Bombardier performed extensive analysis of the launch customer route (New Jersey Transit) to develop expected locomotive power requirements, and subsequently used this information to help define specific emissions test modes and associated duty-cycle weighting factors. The two Caterpillar 3512C-HD engines in the ALP-45DP locomotive are each equipped with a diesel oxidation catalyst (DOC). This was relatively new for the North American locomotive market, and considerable effort was required to detail the DOC degreening requirements, and to provide sufficient technical basis for the deterioration factor (DF) required by EPA as part of the certification process. Exhaust emissions test results from US EPA certification testing are included in the paper, including regulated emissions of HC, CO, NOx, and PM, as well results for new EPA requirements for reporting greenhouse gas emissions of CO2 and methane (CH4). Methane measurement and reporting is a new requirement by EPA for new locomotives starting in 2012, and these procedures are detailed in the paper.

The objective of the article is to present critical design aspects of SCR systems suited for high-sulphur fuels in combination with exhaust gas boilers, silencers and scrubber. The combination is presented by going through the challenges of the general system design. Regarding the challenges the main focus of the paper is in SCR operation when using high sulphur heavy fuel oil. The message is that by designing the exhaust gas treatment combination effectively, it is possible to meet IMO ECA requirements for NOx and SOx emissions in the future while utilising the whole exhaust gas system design also e.g. for noise attenuation. The intention is to explain the most important phenomena influencing on the design and by what terms the different exhaust gas equipment affect each other and the engine itself. The main focus of the article is on SCR operational requirements. Therefore the paper will review the exhaust gas temperature window requirements for SCR and will explain facts behind the recommended temperature limits. The paper will present how the SCR design is effectively implemented to high sulphur heavy fuel oil operation by optimised catalyst design and improved catalyst cleaning system and by following the temperature requirements. In some engines there is a certain need to control the temperature after the turbocharger during the operation with high sulphur HFO and SCR. The need for control also applies to applications that have significantly low engine intake air temperature. The most suitable way to carry out the temperature control strongly depends on the operation profile of the engine and SCR and if the SCR is operated only on certain sailing areas or continuously. Aspects of the combined engine and SCR design are reviewed in general level. The paper also reviews the whole exhaust gas line. Temperature changes, back pressures, and noise attenuation features of the different equipments are discussed. Back pressure of the whole exhaust gas line can be optimised by sufficient dimensioning and combination of the equipments. Sound attenuation features of the combination of integrated mixing duct silencer, SCR reactor, boiler and Wärtsilä CSS (compact silencer system) elements are discussed. This combination can be designed to meet various sound attenuation requirements. Space restrictions are a well recognised concern for many shipowners, ship operators and shipyards. The needed performance of the exhaust gas line after turbocharger plays a significant role in the design of the ship. The paper presents the typical sizes of different equipments and the feasible ways to minimise the needed space for the whole exhaust gas line.

US EPA exhaust emissions certification of the Bombardier ALP-45DP locomotive

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The objective of the article is to present critical design aspects of SCR systems suited for high-sulphur fuels in combination with exhaust gas boilers, silencers and scrubber. The combination is presented by going through the challenges of the general system design. Regarding the challenges the main focus of the paper is in SCR operation when using high sulphur heavy fuel oil. The message is that by designing the exhaust gas treatment combination effectively, it is possible to meet IMO ECA requirements for NOx and SOx emissions in the future while utilising the whole exhaust gas system design also e.g. for noise attenuation. The intention is to explain the most important phenomena influencing on the de-
A self-tuning engine concept
Fredrik Oestman, Wärtsilä, Finland

A novel self-tuning engine control concept has been developed by Wärtsilä to ensure optimal control of the engine throughout its lifetime, without the need for manual adjustment of the control parameters. For large low- and medium-speed internal combustion engines, the process dynamics is subject to significant variations due to nonlinearities and a wide range of operating conditions. To ensure the control quality at all times, the behaviour of the closed-loop controllers need consequently to be continuously matched with respect to the state of the process, subject to control. Failure to do so typically results in increased fuel consumption and emissions, and excitation of oscillations in dynamically linked processes, which otherwise would be stable. For example, if the wastegate valve is slowly oscillating due to poor control parameters, it will directly affect the efficiency of the fuel combustions and the fuel-injection process. With the increased price of fuel oil and stricter emission legislations, a large number of various advanced technologies has been developed, such as electronically controlled fuel injection, high pressure fuel systems, two-stage turbocharging, exhaust gas treatment systems, variable valve timings, etc. Modern marine and power plant engines comprise an increasing number of complex subsystems that are dynamically interlinked. The question of how well these subsystems are controlled will consequently become more important in order to ensure the fuel combustion efficiency, emission levels and overall stability. To provide the best control performance for an arbitrary process, it is essential that the control parameters are closely matched with the dynamics of the process. For large low- and medium-speed engines, the dynamics are affected by several factors, such as the operating point of the engine, external conditions and mechanical wear of components. It follows that to guarantee a good control performance throughout the lifetime of the engine, it is necessary to adjust the behaviour of the regulators in accordance with the dynamic changes. Typically, gain scheduling control schemes are used to cope with the dynamic influence from the operating points. This approach, however, needs periodic manual retuning in order to meet the long-term expectations. To deal with these variances, Wärtsilä has developed a self-tuning control concept, which automatically adjusts the behaviour of closed-loop controllers of the engine so that optimal control performance is achieved at all times. Diagnostic features have been, in addition, included in order to detect faults within the closed-loop circuit in order to detect malfunctions despite the adaptivity of the control loop. In this paper, the self-tuning engine control concept is presented with examples from fullscale engine tests, proving the robustness and performance of the control strategy and the performance of the self-tuning engine.

Modular automation platform for efficient integration of new technologies and flexible adaption of customer requirements
Jürgen Ammer, MAN Diesel & Turbo SE, Germany
Thomas Brendle, MAN Diesel & Turbo SE, Germany
Roland Hirt, MAN Diesel & Turbo SE, Germany

Nowadays, and even more in the future, electronics and software belong to the main fields of product innovation. Therefore it is necessary to continuously concentrate on how to ensure an efficient and flexible integration of new technologies, as well as to focus on the integration of market demands into the engine control system. Based on a modularised portfolio of components, SaCoSone provides automation solutions for four-stroke engines that can be adapted to individual technical requirements. One of the key factors to restrain complex control-, monitoring- and governing functions is a decentralised and function-oriented system architecture in combination with distributed intelligence and local signal acquisition. Managing future challenges, such as emission reduction or the development of adaptive engine control methods in particular can be seen as examples for the necessity of flexible integration of technological innovation in automation systems. But even in times of rapid technological and systemic changes, SaCoSone still guarantees an identical interface for control signals and data communication in order to reduce efforts during system integration on the customer’s side. Efficiency and flexibility are major requirements for the whole product life-cycle and are reflected by the SaCoSone spare part philosophy. This philosophy provides long-term availability and world-wide storage to ensure very short response times. In combination with our online service support via a remote network access, customers all over the world that are equipped with a SaCoSone automation system can easily be assisted to analyse operational conditions and system messages of their engines.

Marex by Rexroth: Efficient ship controls ready to meet the challenges of the future
Andreas Ruether, Bosch Rexroth, Germany

A ship control system today covers more functions than the standard electronic remote controls. Marex OS was applied basically for controlling the engine speed and gear setting of a ship’s propulsion system. Today, additional requirements must be met, many more functions need to be controlled and monitored for the efficiency and safety on board. With its subsystems, the Marex ship control system is able to cover most of the required functions, which may be very different depending on the size and purpose of a ship. The Marex OS II control can be adapted perfectly to any propulsion system, from standard diesel engines with reversing gear over con-
trollable pitch propellers to the latest hybrid systems with diesel-electric drives. Different automation modes are available such as diesel, sailing and diesel-electric. The subsystem Marex AMC is a state-of-the-art alarm and monitoring system. Besides engine safety and ship alarm functions, subsystems like an exhaust gas deviation monitoring, navigation light control or integration of video can be realised. Marex ship control systems use a safe CAN-bus protocol for the communication between its main components, analogue or digital signals are standard, CAN SAE J1939, Modbus RTU, Modbus TCP or others can be implemented on request. Marex equipped ships are available for any type of vessel, low cost, standard or complex, from small pilot boats, workboats, yachts, mega yachts or oceangoing vessels. Their high-quality components are well-proven and tested and meet the classification requirements. A service network is supporting the partners worldwide. Rexroth puts special attention on manufacturing environmental compatible products. The Green Passport (in accordance with the IMO Guidelines on Ship Recycling) is already available on request for Marex systems. In cooperation with Bosch, Rexroth can now supply the full scope of products from diesel injection system up to the control lever. The newly developed marine platform from Bosch based on the electronic diesel control system (EDC) integrates seamlessly with Rexroth’s class-compliant engine safety and alarm system Marex AMC and the remote control system Marex OS II. This technical paper will describe the ship control system Marex with its subsystems Marex OS II and Marex AMC. A short technical introduction will be followed by functional information on two to three existing ship control systems.

**Machine test on fuzzy PID control strategy of diesel engine basing on Microautobox**

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Enzhe Song, Harbin Engineering University, China
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In order to develop and research the intelligent fuzzy self-tuning PID controller, the simulation can not fully show the ever-changing characteristics of diesels practical work in nonlinear time-varing. To further validate the design of the fuzzy self-tuning PID controller speed performance used in the electronic governor, the controller must use a real diesel engine. Therefore, with the D6114 diesel engine as the control target, the auto-adjusting load system of Shanghai Chuangxiang Power Supply Equipment Co Ltd was taken to adjust the load. Been equipped with machine test on the D6114 diesel engine. Therefore, firstly in the paper design and debug the hardware board; then match the new-designed controller with the real diesel basing on microautobox in order to verify and improve the speed governing systems control strategy and performance. By no-load start, load mutation assay and steady speed test, being proved the new design of intelligent fuzzy self-tuning PID controller is superior to conventional PID controller to the purpose of well meeting the diesel engine speed control requirement.

**Combustion and radiation modelling of laminar premixed flames using OpenFOAM: A numerical investigation of radiative heat transfer in the RADIAD project**

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The RADIAD project is initiated at TES-DTU in collaboration with MAN Diesel & Turbo AS. The aim of the RADIAD project is to enhance capabilities of computational models to understand the complex coupling between the radiant heat transfer, rate of combustion progress and formation of harmful products in combustion processes. The interest in radiation comes from the large dimensions of marine diesel engines, where radiation as a consequence is expected to be more influential on heat transfer than heat convection. The model results will be validated by conducting detailed experimental measurements. In parallel with the various experimental works in the RADIAD project, multi-dimensional computational fluid dynamics (CFD) modelling is meanwhile carried out to study the radiative heat transfer under diesel-like combustion. In this reported work, the open source CFD software OpenFOAM is employed to simulate the combustion and radiation processes in laminar premixed flames. This flame type offers the highest level of flame control. The stability and uniformity of the flame achieved in this setup facilitate the
optical line of sight diagnostics and hence the in-situ measurements of temperature and soot concentrations. Effects of diffusion and turbulence are minimised here and efforts are therefore paid on the modelling of combustion chemistry, radiation, and soot formation. For improved computational runtime, a two-step chemical reaction scheme proposed by Westbrook and Dryer is used together with a steady-state solver. The steady-state solver is developed by modifying an existing solver, Local Time Stepping (LTS) ReactingParcelFoam. Akin to reactingFoam, which has been widely used in combustion simulations, LTSReactingParcelFoam is also applicable for laminar and turbulent reacting flow but it is a local time stepping solver for steady-state simulations. The modified version is henceforth addressed as radiationReactingLTSFoam (rareLTSFoam). In order to simulate the radiative heat loss, P1 radiation model is used. The model validation uses two test cases of laminar premixed flames with different equivalence ratios. In the first case, a stoichiometric flame is produced in which soot radiation process can be omitted; while in the second case, a rich flame with equivalence ratio of 2.15 is used. The results generated by the integrated CFD chemistry model are validated against temperature measurements at different heights along the axial direction. For the radiative heat transfer, a parametric study is conducted using P1 model. The absorption coefficients are modeled using RADCAL and WSGGM models. Implementation of the steady-state solver has been proved to simulate the stabilised, laminar premixed flame accurately with an expedited calculation. This serves as a useful platform when comprehensive radiation model such as Discrete Volume Discrete Ordinate Method (fVDOM) radiation model is implemented. Understanding and further improvements on the robustness of numerical models achieved at this phase are critical prior to computationally investigating the radiative heat transfer process in turbulent diffusion flame and diesel engine combustion that have higher levels of complexity.

Flow and pressure simulation of cooling water, lubricating oil and fuel supply systems
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Juha Ervasti, Wärtsilä, Finland
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Antonino Di Miceli, Wärtsilä, Finland

When designing fluid systems for four-stroke medium-speed diesel engines, it is beneficial to use modern simulation tools to achieve an optimised design in an early phase. Today’s engines have become very compact and typically have a high degree of integration of fluid channels into castings. Therefore, changes to address flow problems after design is complete will require big re-design efforts and should be avoided. The heat balance of the engine determines the needed cooling water flow to achieve sufficient cooling without excessive temperature increase in the water. As the pumps used are of centrifugal type the flow in the system is determined by the needed cooling water flow to achieve sufficient cooling with-
on knock tendency is not well documented. Combustion rate and stability affect knock behaviour as well for a given engine geometry. The faster heat release rates that are desirable from a thermal efficiency standpoint can either increase or decrease detonation margin as they tend to drive up peak temperatures while at the same time reducing the time available for end gas chemistry and pushing the engine operating point to leaner conditions in order to maintain constant NOx emissions levels. Poor combustion stability, which often results from very lean operating conditions, can also impact knock margin as some very fast burning cycles give way to ignition delays far away from the knock limit, points typically studied with simulation tools. A combination of test results, simulation data and statistical tools can be utilised to understand these combustion stability effects. This paper seeks to provide insight into the relationship between these secondary effects (heat transfer and combustion behavior) and combustion system development as regards knock avoidance. Simulation results and engine test data are provided that highlight the role of heat transfer and heat release on knock tendency. Detailed single cylinder engine measurements, including surface temperatures, heat release rates, and inferred heat transfer rates, are provided to clarify the performance trends. Multiple zone cycle simulation results are used to provide further clarification of the knock impact of heat transfer and heat release for a given engine geometry. Combustion system development that includes an understanding of these processes inevitably yields production engines with superior market potential. The availability of a fundamental framework for these physical processes, supported by research grade test and simulation results, will be a key enabling technology for the next generation of high performance natural gas engines.

**Ranking the knock resistance of gaseous fuels by their physical and chemical properties**

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In this paper, we present a method for characterising the knock resistance of gaseous fuels based on the physical and chemical properties of the fuel, and their effects on in-cylinder processes. As a result of the globalisation of the energy market and the drive towards sustainability, natural gas with significantly different composition are being traded and distributed. Natural gases that contain substantially larger fractions of higher hydrocarbons than the traditional pipeline gas are being introduced into grids; and the introduction of hydrogen-containing gases is being discussed in many countries. In addition, fuels derived from local sources, such as industrial or well-head gases are becoming more popular as engine fuel. The compositions of these gases, possibly containing H₂, CO, unsaturated hydrocarbons and inerts, can vary greatly as compared to pipeline natural gas. Given the impact of non-methane components on engine knock, the correct characterisation of the effects of fuel composition on engine knock has reemerged as a critical issue. In addition, a correct and accepted method for characterising knock resistance is an essential enabling tool for the success of the emerging market for LNG as a transport fuel. Rather than rely on the empirical methods using gas mixtures and standard engines traditionally employed for this purpose, we derived a method based on the combustion properties of the fuel mixtures, and have tested its predictions in our engine. Engine knock is characterised by spontaneous ignition (auto-ignition) of the unburned fuel mixture, the so-called end-gas, ahead of the propagating flame in the engine cylinder. Obviously, engine knock should be avoided since it can physically damage the engine and increase pollutant emissions. As a result, engine knock imposes limits to the (variation in) fuel gas composition. The core of the method described in the paper is the computation of the auto-ignition process during the burn period. The detailed chemical mechanism used in the simulations has been tested against experimentally determined autoignition delay times of the alkanes up to pentane (including the isomers of butane and pentane), H₂, CO and CO₂, measured in our rapid compression machine (RCM). In addition to the effects on auto-ignition itself, fuel composition has other effects on in-cylinder processes that exercise a direct influence on auto-ignition, which have also been observed in experiments in our engine. Since auto-ignition of the end gas is critically sensitive to the pressure and temperature during the burn period, changes in the heat capacity of the fuel-air mixture, variations in initial pressure arising from changes in heating value and changes in the ‘phasing’ of the combustion process with varying fuel composition can all affect the occurrence of autoignition during the cycle. We consider and identify the magnitudes of these effects, and their impact on autoignition and engine knock; these aspects are all incorporated in our method for characterising knock. The predicted ‘ranking’ of different gas compositions determined using the method are seen to agree very well with the measured ranking using knock-limited spark timing in our engine. The results thus show that the effect of higher hydrocarbons in engine knock is predominantly caused by the (chemical) autoignition behaviour of the hydrocarbons themselves, while the impact of hydrogen is to arise from substantial changes in the ‘phasing’ of the combustion process. These and other observations based on the method will be discussed in the paper. In addition to being valuable as a physically correct and unambiguous basis for agreeing on fuel specifications, the possibility of coupling the combustion cycle of a given engine to the determination of autoignition and the occurrence of knock will provide an excellent tool for engine manufacturers to define knock-free gas engine performance ratings for today’s and tomorrow’s fuel gases. We are currently extending the method to other types of gas engines and a broader fuel specification.

**Predicting autoignition caused by lubricating oil in gas engines**

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The BMEP of gas engines has been increasing for the last two decades thanks to the advancement in technology allowing for the efficiency of the latest gas engines to surpass that of diesel engines in several categories. But at the same time, the stochastic occurrence of high firing pressure resulting from abnormal combustion can be seen more in many types of premixed gas engines having higher BMEP. This situation is worse in the Japanese market where the methane number of gaseous fuel is much lower than typical natural gas and has negatively affected the stable operation of the engines in service. Research conducted by the authors confirmed that this type of abnormal combustion is caused by the auto-ignition of lubricating oil in the cylinder. Lubricating oil existing in the cylinder undergoes auto-ignition before the intentional ignition from electrical spark or injection of pilot fuel takes place. This phenomenon increases not only the firing pressure due to the advanced combustion timing but also the cyclic variation of firing pressure from the multiple ignition points created by the presence of lubricating oil mist. The trend of developing higher BMEP gas engines will continue along with the increase in variation of the methane number due to the expansion of utilisation of...
LNG all over the world. Under these circumstances, the abnormal combustion caused by lubricating oil could become one of the crucial hurdles for the development of future premixed gas engines. Therefore, autoignition of lubricating oil must be carefully considered in the optimisation of engine parameters required for the development of higher BMEP engines from now on. Recent developments in numerical techniques and computational processing power are now permitting time-dependent, multi-dimensional computational fluid dynamic (CFD) calculations with reduced chemical kinetic mechanisms. Tools, such as the CONVERGE CFD code, enable to predict diffusion combustion as well as premixed combustion phenomena. Further advancements in combustion CFD modelling were achieved at Prometheus as a result of abundant research with combustion visualisation, accurate surface temperature boundary conditions and appropriate turbulent models coupled to an in-depth knowledge of experimental combustion physics of gas engines. Prometheus’ combustion CFD modelling technology, using the CONVERGE CFD code, is capable of high fidelity simulations of ultra lean, high BMEP gas engine combustion with either spark ignited or pilot ignition systems. Even sensitive physics like ignition by electrical spark and knock phenomena, near wall or end-gas, can be accurately predicted. This capability offers the advantage to design highly optimised natural gas engine components such as pistons, intake ports, precombustion chambers, fuel systems and ignition systems. With this simulation technology, the authors have developed a CFD combustion simulation that enables to predict the auto ignition of lubricating oil that takes place prior to the intentional ignition event. This is a very useful designing tool not only to investigate more about the mechanism of this abnormal combustion and countermeasures but also to make careful optimisation of engine parameters to avoid auto-ignition of lubricating oil. This paper aims at describing the fundamental physics of lubricating oil auto-ignition by comparing the experimental observations with the results obtained with an advanced combustion modelling technology and CFD code.

Technical challenge for the two-stroke premixed combustion gas engine (pre-ignition behaviour and overcoming technique)

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Emission legislations are gradually strengthened for marine engines. A gas engine fueled with LNG is in the spotlight due to simplify an exhaust gas aftertreatment and reduce GHG emission. Two-stroke slow-speed engines are preferred for propulsion of large vessels due to high power, slow speed, and high reliability. Unfortunately, most commercialised gas engines have been four-stroke medium-speed engines due to technical difficulties of two-stroke slow-speed gas engines. To realise the two-stroke slow speed premixed gas engine, a technological breakthrough is needed. The new concept of two-stroke slow speed premixed gas engine is verified by engine test with one-cylinder modified to gas engine configurations from a normal two-stroke slow-speed diesel engine. In this engine test, a pre-ignition phenomenon is observed under specific conditions, which occurred at higher mean effective pressure. Pre-ignition leads to high maximum cylinder pressure and high NOx emission due to uncontrollable ignition timing by pilot fuel injection. In a combustion chamber of reciprocating engines, the lubrication oil is indispensable to maintain sliding condition between piston and cylinder liner and existing. This paper shows that the influence of cylinder lubrication oil on pre-ignition is realised by in-cylinder visualisation with a high speed camera and endoscope. Luminescence intensity and the number of auto-ignition flames are reduced by reduction of cylinder lubrication oil. In addition, this paper describes the effects of temperature, equivalence ratio of pre-mixture, and characteristics of lubrication oil on ignition behaviour from fundamental test results. This fundamental test is carried out by rapid compression and expansion machine (RCEM). RCEM can simulate the high temperature and high pressure condition of the actual engine. The fundamental test results show that the temperature reduction technique is not enough to avoid the pre-ignition because the auto-ignition temperature of lubrication oil is similar to the ignition temperature of pilot fuel. However, lean pre-mixture reduces ignition probabilities of pre-mixture induced by auto-ignition of lubrication oil. Moreover, this pre-mixture can be ignited by micro pilot fuel in this lean pre-mixture condition. In this suitable condition, it is possible to avoid pre-ignition and misfire. This paper clarifies that controlling the premixture equivalence ratio within the suitable condition is important for stable operation of the two-stroke premixed gas engine without pre-ignition caused by auto-ignition of the lubrication oil.

Continuous development of Tier III SCR for large two-stroke diesel engines

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The details of the SCR development at MAN Diesel & Turbo are presented. This is both concerning the catalyst application, the requirements of the engine control system and identified challenges in connection with the SCR application. Furthermore, the first costs and operating costs are considered, and the influence of reducing agent is discussed from both a technical and an economic point of view. An alternative mixer application for the next generations of SCR systems is also described, and finally suggestions for different NOx sensor strategies are summarised.

Development of marine SCR system for large two-stroke diesel engines complying with IMO NOx Tier III

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Engine designers and builders are striving to establish reliable and economical measures to have their engines meet the IMO NOx regulation Tier III, which is coming into force in 2016, requiring a drastic level of NOx reduction from ships and needing in fact a different technology from those for previous Tiers I or II. In order to provide ships with main engines complying with contemporary regulations even in/after the year 2016, Hitachi Zosen Corporation, who is not only an engine builder but also a catalyst manufacturer as well as an SCR manufacturer well-known in land applications, has developed a marine SCR system for large two-stroke diesel engines in collaboration with MAN Diesel & Turbo, an engine designer leading the market. The concepts of the system are:
• Urea SCR
• SCR located upstream turbine
• SCR operated on ordinary HFO. This paper presents mechanism and features of the system and test results from the testbed and the sea trial. Main themes are how such an SCR system works on a large two-stroke diesel engine running on HFO, of which exhaust gas generally is low temperature and contains a considerable amount of sulphur oxides, and how such an engine is controlled even in low load and/or transient conditions. The system ensures always high enough exhaust gas temperature to do SCR of high sulphur exhaust gas without utilising any extra heating device, which consumes extra fuel, by making use of a cylinder bypass. In low load conditions, a part of the scavenging air bypasses the cylinders and SCR line through the cylinder bypass line, and hence hot exhaust gas to the SCR. In transient conditions, the SCR bypass is controlled so as to charge the cylinders with an appropriate amount of scavenging air as necessary. This makes engine’s quick acceleration possible. All these functions are automatically controlled. A number of various tests were performed not only in the SCR research laboratory but also with an actual product engine equipped with the SCR system on a testbed at Hitachi Zosen’s engine factory in order to confirm that its technology was applicable also to marine-use and to optimise it for marine application. After the successful tests on the testbed, both the engine and the SCR system were transferred for installation on a newly built ship, on board which the SCR system were intended to be field-tested in service, with the geometrically same SCR arrangement as well as the same control system as those for the testbed. The sea trial was performed to confirm that the engine with SCR functioned correctly and safely even in an actual ship system, and to measure and record its initial conditions prior to the vessel’s delivery. During the sea trial, transient responses were tested in various cases, e.g. accelerations, decelerations, manoeuvrings and ahead/astern, and confirmed them as expected. Similar to the testbed results, 80% of NOx reduction ratio was achieved, and IMO’s E3-cycle value of NOx emission was confirmed to be less than 3.4 g/kWh, which is the limit for low speed engines, also in the sea trial.

High-pressure SCR at large diesel engines for reliable NOx-reduction and compliance with IMO Tier III standards

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The ammonia SCR technology is an efficient instrument for denitrification of exhaust gases and therefore an approved technology to comply with the IMO Tier III limits (within ECAs). It is successfully used in the on-road sector as well as in several maritime and stationary large diesel engine applications. The operation of large diesel engines with highly efficient TC systems (e.g. two-stroke engine with single-stage TC or four-stroke engines with two-stage TC) however shows very low exhaust gas temperatures downstream the TC turbines. At the SCR system, these boundary conditions not only lead to low reaction rates of the nitrous oxides with the reducing agent ammonia but also cause unwanted side reactions of sulphur oxides contained in the exhaust gas with the ammonia. The formation of ammonium sulfate can lead to a blocking of the SCR monolith and therefore to a decrease of reactivity up to a complete deactivation of the system. Those effects not only occur when running on residual oils with increased sulphur contents but already by operation on distillate fuels of higher quality with a sulphur content of 0.1%. SOx-scrubbing upstream the SCR system would result in further decreased temperatures, which will further intensify the loss of reactivity. Approaches to solving this problem have to provide higher temperature levels of the exhaust gases at the inlet of the SCR-system. An efficient solution is presented by placing the SCR upstream the turbine of the TC system or between the turbines (in case of two-stage TC). The SCR operation would benefit from the higher exhaust gas temperature levels and an energy consuming reheating of the exhaust gases can be avoided. This would require a rearrangement of the exhaust gas system to accommodate the SCR catalyst and the dosing unit for the reducing agent upstream of the last turbine stage. In opposition to known and already in-use SCR systems, which are placed behind the TC turbine, the effects of the increased pressure levels at the pre-turbine position on the SCR system and on the reaction kinetics are still widely unknown. Therefore, the effects on the ammonia storage capacity, the chemical conversion rates as well as on the SCR system itself are investigated experimentally. A synthesis gas test bench and a single cylinder research engine with a CR injection system are used for the analyses. Both test benches offer the opportunity to adjust the operation conditions equal to those upstream the TC turbines of large diesel engines. Here, the exhaust gas temperatures, the composition and especially the pressure level are of main interest. At the synthesis gas test bench the parameters temperature, pressure and space velocity are varied and the effect of those boundary conditions on the SCR system are studied systematically. The results from the synthesis gas test bench are compared with measurements using real exhaust gas at the externally turbocharged single cylinder research engine. Here, the exhaust gas back pressures are also adjusted similar to a pre-turbine application of the SCR. Additionally, the influence of particle loaded exhaust gas is taken into account. The chosen catalyst samples are honeycomb structures with oxides of vanadium, wolfram and titanium, which is typically used in maritime applications and conventional arrangements of the SCR system downstream the TC. The research focuses on improving the basic understanding of the SCR system and the effects of the operation conditions upstream the turbine of the TC on its behaviour. Within the paper the results of the experimental investigations as well as the analysis of the storage behaviour and the reaction kinetics of an ammonia SCR system installed upstream the TC turbine of IMO Tier III compliant large diesel engine will be presented and the potential of this approach will be discussed.

Development of Niigata new gas turbine pump drive unit CNT-4002MN

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Niigata Power Systems Co., Ltd. (NPS) has developed the CNT-4002MN gas turbine unit for pump drive with an output 4,000 PS, which was launched in 2010. This unit reaches an output of 4,000 PS by making two shaft gas turbines with an output of 2,000 PS each to one output shaft through the reduction gears. In this paper, the feature of the specification of the gas turbine unit for this pump drive, the running performance, the start control, and other characteristics are described. The main engine of the pump drive unit is the NGT2BM gas turbine, and it consists

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of a gas generator turbine, which is installed on the two-stage centrifugal compressor and two-stage axial flow turbine and power turbines which is installed on the one-stage axial-flow turbine. The rotational speed of the output shaft can be changeable in 700-1000 min-1, and the waste water pump can be applied for various usages for another and a mechanical drive. For the load change while running, the full digital controller device is doing the fuel control and to stabilise the rotational speed of the output shaft of two set of two shaft gas turbines. Additionally, the prolonged running of one minute until the emergency power supply can be secured, even during a black-out while running, is possible. Moreover, it is possible to drive the re-ignition while stopping and rapid starting. In recent years, the urbanisation of the river surrounding area is advanced, and the importance of measures against flood in these regions increases in Japan. It is expected that this unit can make the best use of features of the gas turbines such as light and small, large scaled power, low NOx, low noises and the low vibrations, and contribute to the flood control measures in the region as well as in the urban area where the installation requirement is severe.

**Modelling ship energy flow with multi-domain simulation**

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Ship energy efficiency is becoming more and more attractive to shipowners, builders and researchers due to the increasingly high fuel cost and the accumulatively strict international maritime rules. It is especially evident for modern ships with complex power plants including mechanical, electrical and thermo-hydraulic systems. Marine engines, as the heart of ship power plant, play a key role in the fuel energy utilisation. But, even for a very efficient marine engine, only less than 50% fuel energy can be converted to useful work. The other over 50% of fuel energy is mainly taken away in a form of heat energy by engine cooling water system and exhaust gas system during the combustion process. Practically, quite many methods, such as waste heat recovery, have been already developed to enhance the total efficiency of ship power plants. However, there still is not a clear and thorough understanding of the operating efficiency of different processes due to their complexities, which is specifically true for the steam powered systems. In this paper, a new method is introduced to model the ship energy flow for thoroughly understanding the dynamic energy distribution of the marine energy systems. Due to the involvement of different physical domains in the energy processes, the multidomain simulation method is employed to model the energy flow within Matlab/Simscape environment. The energy processes are described as multi-domain energy flow as function of time. All the main energy processes are to be modelled as subsystems only at a general and system level, and to be built as simple but comprehensive as possible to facilitate the simulation interaction among different main subsystems. For each subsystem, the developed model contains rather simple description of the energy processes involved. The operation and load profiles from real operation data can be given as inputs to examine the dynamic energy balance during the operation. The simulation results have positively shown the feasibility and reliability of the energy flow simulation method. The developed energy flow simulation method could further help people better monitor the ship energy flow and understand ship energy systems. More importantly, it could give some valuable insights into how to design an energy-efficient ship power plant and how to operate the vessel efficiently. Furthermore, it could be easily utilised to test and verify new technologies, and hence to find possible ways to improve the energy efficiency of both the existing and new built ships.

**Carbon and fuel reduction at sea and ports - development of a new cogeneration concept with ship engine exhaust heat driven cooling generation/ storage system**

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Jonathan Heslop, Newcastle University, UK
Tony Roskilly, Newcastle University, UK

Although international shipping is the most carbon-efficient mode of commercial transport, it was still estimated to have emitted 870 million tonnes of CO₂ in 2009. Part of the emission is generated by ship auxiliary engine that produces electricity for refrigeration and other electric devices on board, while large amount of exhaust heat from ship propeller engine is wasted without further utilisation. Through applying new technologies, thermal energy management work can be done on waste heat recovery and utilisation on board and, in turn, achieve carbon abatement of shipping. Based on a RoRo ship travelling regularly in the northern Atlantic Ocean, a ship propeller engine heat-driven refrigeration and cooling storage system is developed in terms of the transport schedule of the ship. The thermally activated absorption refrigeration saves about 40 kW from the auxiliary engine. The ice-slurry cooling storage system releases cooling at ports while the propeller engine heat is unavailable, therefore the overall refrigeration system generates zero carbon emission at ports, which could meet the most stringent policy in some emission controlled areas. The estimated annual emission reduction on this RoRo ship is about 1,176.85 tonnes of CO₂, if the new system is applied.

**The Bosch electronic diesel control system for medium- and high-speed engines**

Gerhard Rebichler, Robert Bosch AG, Austria
Christoph Kendlbacher, Robert Bosch AG, Austria
Martin Bernhaupt, Robert Bosch AG, Austria

EPA Tier IV, IMO Tier III and EU3b emission limits require complex systems of fuel injection-, air- and exhaust gas treatment. The Bosch control units for engine management in the commercial vehicle and off-highway market are designed to meet the requirements of the legislation on further emissions. It is obvious to use this available technology for the medium- and high-speed engine applications. Building on the success of the Bosch automotive engine control units and sensors, Bosch has developed an engine controller and a set of sensors for industrial and maritime applications. The commercial vehicle ECU SW and HW platform includes complex functions for fuel balance control, exhaust gas recirculation, exhaust gas treatment, multi-fuel injection control, fuel pressure control, engine position management, engine speed governors, multi ECU systems and diagnostic functions, etc. which are the basis for the newly developed Bosch maritime electronic diesel control platform. Modularity and flexibility of the ECU SW and HW is a key criterion to cover all medium- and high-speed engine variants optimally. Multi ECU systems for engine variants up to 16 cylinders (two ECU1s) are available and up to 24
individual functions, e.g. twin air flow and fuel pressure control for high-speed engine applications. This technical paper will describe the Bosch electronic management system into the Rexroth ship automation system is developed. Pre-compliance tests have been performed and the final compliance test is in preparation. In cooperation with Bosch Rexroth an interface for the integration of the ECU engine control module into the Rexroth ship automation system is developed. This technical paper will describe the Bosch electronic engine management system components for the medium- and high-speed engine applications.

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**Room A**  
**Fundamental Engineering – Thermodynamics 1**

**Optimal utilisation of air- and fuel-path flexibility in medium-speed diesel engines to achieve superior performance and fuel efficiency**

Alexander Knall, MAN Diesel & Turbo SE, Germany  
Gunnar Stiesch, MAN Diesel & Turbo SE, Germany  
Markus Friebel, MAN Diesel & Turbo SE, Germany

With the development of common rail fuel injection systems, variable geometry turbochargers, variable valve timing and combustion feedback systems, medium-speed diesel engines offer substantial control flexibility with the potential of significantly improving performance, fuel economy, emissions and thus customer value. Engine performance - traditionally governed solely by the mechanical system - is increasingly dependent on the interaction of the flexible subsystems and their proper control. This paper seeks to demonstrate the benefits offered by variable airpath control in combination with a fully flexible common rail fuel injection system. System interactions and optimisation are analysed and performed with design of experiment (DoE), response surface modelling and constraint merit functions. Above mentioned method is applied to design custom-tailored medium-speed engine maps for constant speed generator, controllable pitch as well as fixed pitch propeller operation. Engine performance data are obtained via engine dynamometer experiments augmented with analytical simulations. With constant speed generator operation, it is shown that through optimising the engine calibration in accordance with the typical load profile thereof, specific fuel oil consumption is reduced by several grams without related engine hardware changes. The potential of applying engine control maps specifically tailored to the mode of operation, e.g. fast steaming, slow steaming or manoeuvring, the operation is assessed and the potential quantified. This so-called multi-mapping approach allows for improved performance and reduced emissions over the entire operating regime of the engine. In addition to steady state operation, benefits in transient response are demonstrated by means of optimised air- and fuel-path control. Particularly load rejection and smoke emissions are substantially improved over conventional, mechanically rigid systems. Lastly the affect of Tier III exhaust gas treatment solutions - selective catalytic reduction (SCR) to reduce NOx and or scrubbers to capture SOx - on engine performance is investigated. It is shown that Tier III exhaust gas treatment systems may adversely affect engine performance through increased exhaust gas backpressure and the requirement of elevated exhaust gas temperatures. By means of optimally adjusting the engine control to the new boundary conditions, it is demonstrated that engine performance and efficiency can be restored to Tier II levels.

**Analysis and optimal design on air intake system of controllable intake swirl diesel**

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Xiaobo Li, Harbin Engineering University, China  
Gongmin Liu, Harbin Engineering University, China  
Xiaoli Yang, Harbin Engineering University, China  
Xiaoxiao Niu, Harbin Engineering University, China

Choosing one marine controllable intake swirl diesel as the research object, this paper does some calculation and analysis on the intake flow field by using a 3D flow field analysis software, obtains the swirl ratio and the flow coefficient of the target diesel in different valve lifts and intake baffle angles, and finds that the intake swirl of the diesel has a two-stage characteristics, namely the value of the swirl changes from high to low. On the basis of the calculation and analysis of the diesel air intake system flow field, this article completes the structure optimisation design of the diesel intake, and gets the laws of the swirl ratio and the flow coefficient influenced by the structure of the diesel intake. At the same time, this paper verifies the calculating results through using the steady flow test of the diesel air intake system, and ensures the accuracy and reliability of the diesel air intake system calculating analysis and design optimisation.

**Investigation of extreme mean effective and maximum cylinder pressures in medium-speed diesel engines**

Peter Elts, Technical University Braunschweig, Germany  
Claude-Pascal Stoeber-Schmidt, Technical University Braunschweig, Germany

The current level of mean effective pressure (mpc) of medium-speed diesel engines is 25 to 28 bar. Maximum pressure (pmax) is about 230 bar. At the Technical University Hamburg Harburg, a research engine with a mpc of 40 bar and a pmax of 350 bar has been operated successfully with good results. This led the authors to investigate what can be expected when operating at even higher pressures. In a theoretical study the mpc of a 320mm bore medium-speed engine was increased up to 80 bar. A zero dimensional cycle simulation program was used for the calculations. Compression ratio, stoichiometric air ratio, valve timing and mechanical efficiency were kept constant. Several strategies concerning combustion and turbocharging efficiency (etaTC) were investigated. Some results: With a constant etaTC of 70% and constant rate of heat release (ROHR) an increase of mpc above 60 bar is not possible, because the scavenger pressure difference becomes negative. Specific fuel oil consumption (sfo) increases slightly. The exhaust temperature before turbine (TbT) rises significantly. With constant ROHR and a constant ratio of pressure before turbine and charge air pressure a mpc of 80 bar is possible. TbT decreases slightly, sfo decreases by 5%. The required etaTC is above 80%. Thermal load of course increases significantly. In all cases the required charge air pressure (pch) and pmax rise approximately proportional to mpc. For a mpc of 80 bar, the first reaches 15 to 16 bar and the latter 750 to 800 bar. Using a jet mixing model, two strategies for injection and combustion were investigated. In both the injection duration was kept constant. If the nozzle area is increased proportional to the injected fuel mass, the ROHR is unchanged and so are the operating data. The nozzle hole diameters become very large so smoke problems have to be expected. Injection pressure rises only moderately. If the nozzle area is increased...
The ME-GI concept is based on a diesel-type combustion process of a gas jet that is injected into the combustion chamber with high pressure between 150 and 315 bar depending on engine load. The ignition of the gas is ensured by the injection of a small amount of diesel oil prior to gas injection - the pilot injection. This paper describes the ME-GI concept and its implementation on a dedicated test engine as well as on a production type engine. Furthermore, it also presents performance and emission results from a subsequent optimisation effort. Successful development of the ME-GI concept required a suitable research facility platform for thorough investigations and engine tests. Therefore, it was decided to retrofit an electronically controlled two-stroke low-speed marine diesel research engine, 4T50MEX, to gas operation. Retrofitting the research engine to gas operation required the development and installation of gas engine components as well as the development of a new control and safety system, which is added to the standard electronic control system. Before adopting all new components and software to the research engine, preliminary tests were carried out on a one-cylinder gas test rig in order to verify the functionality and reliability of the ME-GI concept. The establishment of the gas research platform also required considerable preparations in order to achieve authority approval of the gas supply installation, which was established according to EU’s ATEX regulations (e.g. Directive 94/9/EC, concerning equipment and protective systems intended for use in potentially explosive atmospheres). The ATEX regulations required for example risk analysis, zone classification plans and education of engineering staff. The engine tests performed can be divided into two groups. Firstly, the ME-GI engine is benchmarked directly against operation on liquid diesel oil. This benchmark confirms a significant reduction in NOx emission. The NOx reduction exceeds 25% on average, which is consistent with simple theoretical estimates based on adiabatic flame temperature equilibrium NOx predictions, where the main driving force is a lower flame temperature due to a higher stoichiometric air amount for methane compared with diesel. Secondly, in order to explore the possibility of even further optimisation of the ME-GI concept a more elaborate study, applying theory from Design of Experiment (DoE) as well as Response Surface Methodology (RSM), is conducted, in which parameters related to the gas injection system are included as well. It is demonstrated that the ME-GI concept offers potential SFOC savings of 3-6 g/kWh in the part load range (below 85% engine load). The engine test data are furthermore supplemented with results from optical diagnostics.

**High-pressure natural gas injection (GI) marine engine research with a rapid compression expansion machine**

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Daisuke Tsuru, Kyushu University, Japan
Hiroshi Tajima, Kyushu University, Japan
Koji Takasaki, Kyushu University, Japan

The use of natural gas as fuel for vessels is a highly promising solution to meet the challenges of technical compliance requested by upcoming CO2, SOx, NOx and soot emission regulations. In gas injection (GI) engines, gas sprays burn as diffusive combustion without knocking or misfiring. The thermal efficiency is high because a high compression ratio, equal to diesel engines, can be applied. However, unlike lean burn gas engines, an additional device, such as an EGR or SCR system, is required to meet IMO Tier III NOx regulations. In order to analyze and understand the combustion processes of such potential concepts to reduce emissions, a rapid compression expansion machine (RCM) with relevant dimensions of marine engines has been developed at

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**A fundamental study on improvement of ignition behavior of low ignitability fuel with pilot injection**

Satoshi Kawauchi, National Maritime Research Institute, Japan
Masahide Takagi, National Maritime Research Institute, Japan

New regulations of the IMO, introducing drastic reductions in fuel sulphur content, allow 0.1% sulphur in fuels used in ECAs, starting from 2015. Together with the worldwide situation of decreasing fuel resources, the introduction of alternative fuels complying with future regulations of marine diesel fuel displays decreasing fuel resources, the introduction of alternative fuels fuel sulphur content, allow 0.1% sulphur in fuels used in ECAs, New regulations of the IMO, introducing drastic reductions in A fundamental study on improvement of ignition system.

**The MAN ME-GI engine: From initial system considerations to implementation and performance optimisation**

Lars Ryberg Julussen, MAN Diesel & Turbo, Denmark
Stefan Mayer, MAN Diesel & Turbo, Denmark
Michael Kryger, MAN Diesel & Turbo, Denmark
Kyushu University. The RCEM is utilised as a research model for
gi engines. An electronically controlled high-pressure gas injec-
tion system enables injection pressures of up to 50 MPa. Diesel
pilot sprays in dual-fuel mode as well as glow plugs are used for
ignition. Air conditions in the cylinder at the gas injection are
about 10 MPa and 550 °C, simulating a current gi engine. In
a first series of experiments, a cylinder head with a cubic shaped
 clearance volume and an observation view of 200mm in width
and 50mm in height is applied to analyse the spray combustion.
In the experiments, pure methane, the main component of natu-
ral gas, is used. At first, the gi combustion is compared to the
diesel spray combustion. As a result, rates of heat release for gi
diesel combustion are comparable, while the emissions de-
crease by using gas. However, the direct photos taken with 20’000
fps show a different flame behaviour between the two fuels. Such
differences in the flame characteristics are examined in detail ap-
plying the ‘laser shadowgraph’ and the ‘BDL (back diffused laser)’
optical techniques. Furthermore, in order to meet IMO Tier III
NOx regulations, the oxygen content of the intake air is reduced
as a good approximation for an exhaust gas recirculation (EGR)
system. As expected, the brightness of the flame decreases and an
NOx reduction of 75% in 17% O2 can be achieved. For a second
series of experiments, a cylinder head with a cylindrical clearance
volume is newly developed to allow different swirl velocities and
an observation view over the whole 240mm in diameter window;
the side injection system corresponds to a common two-stroke
engine. Injection nozzles with different numbers of injection
holes are tested, applying different injection pressures, and multi
flames are visualised. In conclusion it can be stated that experi-
ments with the RCEM help to determine emission influencing pa-
rameters and optimisation potential, to visualise and to analyse
phenomena that have not been simulated yet.

Improvement of dual-fuel-engine technology for
current and future applications

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Torsten Baufeld, AVL List GmbH, Austria

Currently a renaissance of dual-fuel engines can be experienced in
the large-bore engine markets. For a very long time, this technol-
y was in use only in stationary power generation application,
where the market shares decreased clearly during the last decade
due to the strong improvements on pure gas engine performance
values and the extension of the pure gas engines to higher output
ranges with large medium-speed engines. In addition to the pre-
vious sole land-based usage, several mobile applications are now
opening further markets for large-bore dual-fuel engines. These
applications are marine main propulsion (e.g. LNG carries, cruise
liners) and auxiliary usage (e.g. container vessels) as well as rail
traction purposes (e.g. long-haul locomotives). The main drivers
for the increased interest in DF engines are lower fuel costs in
comparison with the expensive HFO or diesel fuel and the op-
portunity to reduce especially the NOx emissions enabling a ful-
fillment of upcoming emission legislations. Furthermore, natural
gas could be a high-potential low-sulphur fuel as requested for a
lot of mobile engine applications very soon. The typical second-
ary liquid fuel beside gas - which has been disadvantageous in
stationary DF applications very often - enables as back-up fuel
a very reliable mobile operation. In marine usage a DF engine
facilitates a fulfillment of the IMO emission regulations inside
and outside an ECA just by switching the mode between gas and
diesel operation. The challenges of the mobile applications are
often very variable speed operation, fast load response requirements,
changing gas qualities and reliable engine operation even under
difficult operating conditions. Due to the typical two operational
modes (gas operation and diesel operation) of DF engines several
compromises must be made in engine design (e.g. compression ratio,
piston bowl shape, valve timing, etc.) as well. This leads
currently to disadvantages with respect to efficiency and power
density. With regard to the before mentioned topics, AVL inves-
tigated the dual-fuel engine technology by systematic medium-
speed single-cylinder engine testing. A wide variety of parameters
were evaluated and the operational borderlines were explored.
Based on the gained results, a short-term outlook with today's DF
engine technology will be defined. AVLs future perspective of DF
engine technology will be created as well enabling the definition
of required mid-term developments.

Solutions for meeting low emission requirements in
large-bore natural gas engines

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Across the entire natural gas engine industry, operators and
OEMs are faced with increased expenses and the deterioration
of engine performance as they struggle in meeting the mandated
lower emission levels. In the sector of large-bore engines, greater
than 250mm, the field is populated by two combustion strate-
gies aiming at meeting lower emissions. A significant percentage
of large-bore, low-speed engines, use two spark plugs per cylin-
der to enhance the combustion rate. The remaining population of
to achieve stable engine operation at NOx emission levels below 500 mg/Nm3 (1.0 g/bhp-hr). In the case of
large-bore, low-speed engines currently using conven-
tional spark plugs, it is possible to avoid the costs associated with the
conversions to fuel-fed precombustion chambers by simply re-
placing the conventional spark plugs with specially designed pas-
sive prechamber spark plugs. These highly effective designs are ob-
tained with the latest technology in computational flow dynamic
(CFD) that uses the CONVERGE detail chemistry CFD software.
Results from engine testing indicate that specially designed passive
prechamber spark plugs achieve stable engine operation at NOx
emission levels below 500 mg/Nm3 (1.0 g/bhp-hr). In the case of
engines that already have a fuel-fed precombustion chamber, low-
er emissions can be achieved with the use of a passive prechamber
spark plug in place of the conventional spark plug to form a two-
stage precombustion chamber operating with significantly leaner
mixtures. The flame jets emerging from the passive prechamber
spark plug compensates for the slower flame propagation rates
associated with lean prechamber combustion. The optimum de-
sign of the two-stage precombustion chamber, the amount of fuel
required, the fuel injection timing and the spark discharge char-
acteristics are also determined with the latest technology in com-
putational flow dynamic (CFD) that uses the CONVERGE detail
chemistry CFD software. An electronic fuel control valve provides
the amount of fuel required at the correct timing. Furthermore, an
ignition system with a tunable high energy spark discharge wave
form achieves the desired combustion stability while maintaining
a long plug life. Engine test results from this system indicate stable
engine operations at NOx emissions levels below 250 mg/Nm3
(0.5 g/bhp-hr). The solutions demonstrated in this paper provide
PM emitted from diesel engines has harmful effects on human respiratory organs. Consequently, a severe restriction on its emission amount has been implemented and various PM reduction devices have been developed for cars. However, these PM reduction devices which utilise a catalyst are not applicable to ships. This is because HFO used for ships contains a large amount of sulphur. PM from marine diesel engines is composed of dry soot, soluble organic fraction (SOF), and sulfate. Regulations for decreasing the sulphur content in the fuel have been proposed by IMO. Implementation of these regulations will reduce the amount of sulphur in fuel from 3.5% to 0.5% globally by 2020 or 2025, and from 1.0% to 0.1% in ECAs by 2015. Reducing the sulphate content will decrease the total amount of PM emission from ships significantly, but the amount of dry soot and SOF emissions will remain the same. In this study, a basic experiment to investigate the effects and reproductions of a PM reduction filter for marine diesel engines was conducted. And then, a newly developed diesel particulate filter (DPF) with a regenerator was connected to the exhaust line of a high-speed marine diesel engine, and the effects of PM reduction and engine performances were investigated. The outlines of the experiments are as follows:

- **Effect of DPF on PM reduction**: To clarify the effect of PM reduction by DPF, the filter material used for DPF was installed between the PM sampling probe set in the exhaust line of the test engine and the dilution tunnel. The components of PM were compared for the cases with and without the filter material. The engines used for the experiments are the low-speed marine diesel engine (7,722 kW) of the training ship Seiun Maru, which uses HFO and the high-speed marine diesel engine (103 kW) of the laboratory of the National Fisheries University, which uses gas oil and marine diesel oil (MDO).
- **Effective temperature and time for filter regeneration**: Various temperatures were investigated for a given time in order to determine the optimum temperature for filter regeneration in DPF. The collected elements on the filter were placed into a furnace at a given temperature and the time required for regeneration was recorded.
- **Effect of the newly developed DPF on PM reduction**: The DPF with a regenerator was connected to the exhaust line of a high-speed marine diesel engine, and the effect of the device on PM emission and engine performance was investigated.
- **Regeneration of DPF**: To remove PM on the filter, the DPF equipped with a heating apparatus and the filter was developed. The DPF was installed in the exhaust line of the engine, and an experiment on the regeneration of DPF was conducted. As a result, for practical applications of DPF for marine diesel engines, the following must be satisfied:
  - A comparison of the experimental data demonstrates that most of the dry soot can be removed by the DPF, but SOF and sulphate remain. This is because the required high temperature for the passage of the exhaust gas through DPF causes SOF and sulphate to become like gases.
  - The optimum temperature for assuring a complete regeneration within the first few minutes at a minimum electric power is determined to be 650°C. Temperatures lower than 650°C result in longer regeneration times, which is insufficient. Temperatures higher than 650°C may lead to shorter regeneration times, but the cost for the required electric power increases.
  - Though most of the dry soot and some of the SOF and sulphate in PM can be removed by DPF, it has been known that specific fuel consumption deteriorates by 3% when the exhaust gas pressure increases by 10-kPa interval.
  - PM can be removed by heating the filter to 650°C or more. As a result, a continuous regeneration of the DPF becomes possible without the need to change the filter.

### Development of DPF (diesel particulate filter) with a regenerator for marine diesel engines

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**Verification testing of the L-ccrt(tm) particulate control system on an NREC 3GS218 genset locomotive**

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Steven Fritz, Southwest Research Institute, USA
Paul Anderson, Johnson Matthey ECT, USA
Jose Ramirez, Johnson Matthey ECT, USA
Saji Pillai, Johnson Matthey, USA
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The Air Quality Improvement Program (AQIP), established by the California Alternative and Renewable Fuel, Vehicle Technology, Clean Air, and Carbon Reduction Act of 2007 (California Assembly Bill (AB) 118, Statutes of 2007, Chapter 750), is a voluntary incentive programme administered by the California Air Resources Board (CARB) to fund clean vehicle and equipment projects, research on biofuels production and the air quality impacts of alternative fuels, and workforce training. Within the AQIP are Advanced Technology Demonstration Projects, with the purpose of helping accelerate the next generation of advanced technology vehicles, equipment, or emission controls which are not yet commercialised. On May 28th, 2010, the City of Los Angeles Harbor Department and the Port of Long Beach jointly submitted a proposal to CARB for AB118 AQIP Advanced Technology Demonstration grant funding to demonstrate a Tier IV locomotive DPF retrofit system on a 2,100 HP genset switcher locomotive. The project partners included Johnson Matthey, Inc, the technology provider, and Union Pacific Railroad, which will use the retrofit system on a switching locomotive operating in the San Pedro Bay Ports. The test locomotive used for this project was UPY27755, an NREC model 3GS21B, originally manufactured in July 2007. This locomotive uses three diesel-engine driven generator sets (Gen Set 1, 2, and 3) to provide power to the locomotive traction motors. The locomotive was moved from the Los Angeles operating fleet of Union Pacific Railroad and sent to SwRI Locomotive Technology Center (LTC) in San Antonio, Texas, for installation and testing of three Johnson Matthey's Diesel Particulate Filter (DPF) retrofit systems, L-CCRT™. The JM L-CCRT™ system consists of a flow-through diesel oxidation catalyst (DOC) in front of a catalysed soot filter (CSF) coated with an oxidation catalyst. The system catalytically oxidises engine derived NO to NO₂, and that NO₂ continuously oxidises soot trapped in a catalysed wall flow filter. This continuous soot removal prevents the occurrence of excessive exhaust gas back pressure on the engine. The locomotive was modified to fit the three JM DPF housings, in place of the standard mufflers for each of the three engines. While the DPF housing is roughly the same footprint as the muffler, the DPF housing is taller than the stock muffler. As part of the modifications of the locomotive, the roof sections over the engines were modified to accept the taller DPF housing. After degreasing the L-CCRT™ systems for 20 hours...
NOx, SOx, and particulate matter (PM). For NOx and SOx, the harmful exhaust gas emissions from marine diesel engines are Atsuto Ohashi, National Maritime Research Institute, Japan
Tatsuro Tsukamoto, Tokyo University Of Marine Science And Technology, Japan
Hidetsugu Sasaki, Tokyo University Of Marine Science And Technology, Japan
Tadashi Makino, Furugen And Makino Lab. Inc, Japan

Newly developed diesel particulate filter for marine diesel engine – electrostatic cyclone DPF
Muneckatsu Furugen, Furugen And Makino Lab. Inc, Japan
Tadashi Makino, Furugen And Makino Lab. Inc, Japan
Hidetsugu Sasaki, Tokyo University Of Marine Science And Technology, Japan
Tatsuro Tsukamoto, Tokyo University Of Marine Science And Technology, Japan
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The harmful exhaust gas emissions from marine diesel engines are NOx, SOx, and particulate matter (PM). For NOx and SOx, the IMO Tier II regulation went into effect in January 2011, and the regulation is strengthened in Tier III. On the other hand, for PM, an action to reduce the sulphur content of fuel oil is adopted for the nonce. Because MDO and HFO are used as fuels in marine diesel engines, large amount of PM is emitted. However, for marine diesel engines, a practical use of the diesel particulate filter (DPF) is not realised at present. The authors have developed an electrostatic cyclone DPF to reduce PM emission in diesel exhaust. This DPF consists of an electrostatic precipitator (ESP) and a cyclone precipitator (Cyclone). The ESP is arranged in the upstream position, and the Cyclone is arranged in the downstream position. A mechanism of the PM collection in the electrostatic cyclone DPF is as follows: The ESP can collect fine particles, and the Cyclone can collect large agglomerated particles. When the thickness of deposited PM, which is collected on the collecting plate of the ESP, becomes excessive, the deposited PM falls automatically away from the collecting plate. And then the fallen deposited PM is easily collected into the dust box of the Cyclone. An advantage of the electrostatic cyclone DPF is in a structure without the PM clogging both in the ESP and the Cyclone; therefore this DPF is basically maintenance-free equipment.

Experiments: The PM collection test with the DPF was investigated by using two types of marine diesel engines, i.e., the low-speed two-stroke engine (3UIC33LSII-ECO, 1,275 kW, 162 rpm) and the medium-speed four-stroke engine (MU323DGSC, 257 kW, 420 rpm). Two types of fuels – MDO with a sulphur content of 0.07% and HFO with a sulphur content of 2.2% – were used for the tests. The DPF was installed in the exhaust line of the engines, and PM mass concentration and PM particle size distribution were measured. PM mass concentration was measured with the dilution tunnel system, and PM particle size distribution was measured with the Scanning mobility particle sizer (SMPS).

Results:
- The electrostatic cyclone DPF can reduce PM emission by more than 90%. The DPF has high collection efficiency not only for soot but also for sulphate and soluble organic fraction (SOF) in PM;
- The PM collection efficiency for HFO was higher than that for MDO; therefore it was confirmed that the DPF is applicable to marine diesel engines operated with HFO;
- The majority of the PM particle has a diameter of less than 500 nm, and the PM collection efficiency for particles smaller than 100 nm, which are especially harmful for health, is greater than 95%;
- As the electrostatic cyclone DPF shows high collection efficiency, an exhaust gas processing system which can reduce PM, SOx and NOx will be realised by the application of the DPF.

The proposed exhaust gas processing system consists of the DPF, the scrubber and the EGR system. The scrubber is arranged in the downstream position of the DPF. The exhaust gas from which PM and SOx was removed through the DPF and the scrubber is used as EGR gas. As a result, PM, SOx, and NOx can be reduced by this system. Because only SOx and NOx are included in the exhaust gas passing through the scrubber, the proposed system has an advantage that the wastewater disposal in the scrubber is easy. The authors believe that the proposed exhaust gas processing system is appropriate for the marine diesel engines.

Study on DPF technology to meet China’s IV emissions regulations
Deng Yulong, Weichai Power Company, China
He Fuchen, Weichai Power Company, China
Zhang Suying, Weichai Power Company, China
Wang Fengshuang, Weichai Power Company, China
Miao Lei, Weichai Power Company, China

Particulate emission from diesel engines is one of the most important pollutants in urban areas. How to reduce the PM emission is becoming a key topic in internal combustion engine study area. A DPF (diesel particulate filter) is a great way to reduce PM. The article studies on DPF and burner system’s performance and the technology to let the engine meet China IV emission by using the system. Conclusion: DPF system is high efficient to reduce PM. Using burner regenerator can avoid many troubles on DPF system considering the high sulphur fuel in China. The DPF and burner technology have good promise in urban technology.

Wednesday May 15th / 15:30 – 17:00 Room D
Integrated Systems and Electronical Control
Piston Engines, Gas and Steam Turbines & Applications – Energy Management and Control Systems

Model-based techno-economic assessment and optimisation of marine waste heat recovery options
Nikolaos Kakalis, Det Norske Veritas, Greece
George Dimopoulos, Det Norske Veritas, Greece
Iason Stefanatos, Det Norske Veritas, Greece

Waste heat recovery (WHR) is a promising solution for the efficient, cost-effective and environmentally friendly power generation onboard oceangoing vessels. Nowadays, there is a renewed interest in these systems due to persistently rising fuel costs, market volatil-
ity, environmental concerns and stringent emissions regulations. In this landscape, the marine powerplant complexity increases significantly under machinery space and weight limitations, multiple safety and operational constraints, new technologies and fuels, and inherently higher capital costs. To address simultaneously such issues, a techno-economic approach able to take into account the design, operation and control of the entire integrated marine energy system throughout its mission profile is required. In this paper, we present the techno-economic assessment and optimisation of waste heat recovery options for an aframax tanker, a cape-sized bulk carrier and an 8,000-TEU container ship, via mathematical modelling and simulation techniques. Representative models of the integrated energy system of each vessel have been developed using a modular library of reconfigurable component process models suitable for design, performance and transient operation analyses. To account for the interrelations of design, operability and transient operation between the prime mover and heat recovery subsystems, detailed models of a diesel engine, turbocharger, power and steam turbine, various heat exchangers and auxiliaries were used. The component models have been calibrated and validated using measured data. Capital cost functions for the waste heat recovery components have been employed along with operational cost data to evaluate and optimise the net present value (NPV) of the energy system subject to technical, operational, safety, space and weight constraints. This assessment and optimisation has been performed taking into account typical mission profiles for each of the vessels considered. The techno-economic assessment and optimisation results indicate that there is clear potential for the waste heat recovery systems for the selected ships. However, the best-suited configuration and savings potential are strongly related to the specific ship type and size. The efficiency gains and operability of the WHR system also vary with the powerplant load demands. This study identified the minimum attainable load for WHR system operation for each ship. In addition, sensitivity analyses on fuel prices and capital costs have been performed and the range of economic viability of the WHR has been identified. Through this model-based approach complex integrated systems can be successfully and timely investigated providing effective decision support to system designers, integrators and owners/operators.

Next generation of engine control systems
Alexander Levchenko, Heinzmann, Germany

The increasingly more stringent legislation with regard to pollutant emission presents engine manufacturers and operators with great challenges. Irrespective of whether the required standards are met within the engine itself and/or with different exhaust aftertreatment concepts, we can no longer do without state-of-the-art control units that operate discretely in the background. The number of electronic regulated components on combustion engines will continue to increase in the future. This in turn increases the integration effectively regulated components on combustion engines will continue to increase in the future. This in turn increases the integration of state-of-the-art exhaust standards in diesel engines is the CR injection technology including the control system. More and more complex actuation algorithms, combined with calculation-intensive methods for the compensation of injection-system component tolerances and long-term drift, require powerful hardware and optimised software operating times, that when used together enable not only emissions to be reduced, but also compensates for the wear suffered by the injection system components. Special attention was paid to both the simple connection ability to the various exhaust aftertreatment components, as well as the actuation of VVT, EGR and WG. Dual-fuel applications are also gaining more and more in significance. To this end, the new Heinzmann control system provides a basis both for actuation on the diesel side and a comprehensive range of auxiliary and exhaust gas components. Here, too, our platform solution provides ideal integration of components with each other while the final result achieves maximum efficiency with regard to the diesel-to-gas conversion rates and reliable operation. Nowadays, next to pure functionality, it is the ease of configuration and use friendliness that are of major significance. Remote support options and fast link-up to superordinate systems is another important factor, which enhances the appeal of the control system. While opening up brand new options for developing individual service solutions and products.

Energy management for large-bore, medium-speed diesel engines
Robert Kudicke, Technische Universität München, Germany
Georg Wachtmeister, Technische Universität München, Germany
Alexander Knaff, MAN Diesel & Turbo SE, Germany
Gunnar Stiesch, MAN Diesel & Turbo SE, Germany

In an environment of ever rising fuel prices and stricter emission regulations, manufacturers of large-stroke medium-speed diesel engines need to discover new ways to reduce the fuel oil consumption and the overall costs of their systems. As fuel efficiency has always been the major goal, those engines convert a big percentage of the chemical energy into mechanical energy. Unused fuel energy leaves the combustion chamber as waste heat and enthalpy of the exhaust gases. This paper will focus on the engine’s heat transfer from the combustion chamber into the surrounding parts and the cooling system. For a better understanding of the cooling systems, a research project with MAN Diesel & Turbo SE and the Institute of Internal Combustion Engines at the Technische Universität Muenchen was initiated. The overall goal is to analyse and understand the heat transfer from its origin during the combustion via the engine block and cooling system to the environment. With the introduction of two-stage turbocharged engines the heat load and the complexity of the cooling systems will increase. The knowledge of the cooling system’s behavior is essential, to face this challenge in the near future. An analysis of three large-bore diesel engines with a similar cylinder geometry and shaft power showed three different topologies of the cooling system. From this analysis the following question was deduced: Why are different topologies used and what are the technical advantages and drawbacks of each system? The cooling and lubrication oil systems are crucial for a safe operation of the engine. However, there exists a trade-off between fuel consumption on the one hand and safety on the other hand. Smaller coolant and oil flow rates require less pumping power but at the same time the maximum heat load of the cooling system is reduced. A deeper knowledge about the system’s behaviour will
help to further close the gap to the optimum of the trade-off in the future. For the simulation two different tools are used in this project. The engine is modelled and simulated in GT-Suite (Gamma Technologies Inc.). For the cooling system Dymola (Dassault Systems) based on the open multi-physical modelling language Modelica is used. Different cooling systems for large-bore medium-speed diesel engines were modeled, simulated and analysed. The simulations were validated using measurement data provided by MAN Diesel & Turbo. The results of the simulation at different stationary load points considering the application (marine propulsion, power generation, etc.) and environmental conditions (e.g. temperature and humidity) are discussed. The paper will show the influence of the topology of the cooling water and lubrication oil systems on heat exchanger and pump size. At high temperatures energy can be used more efficiently and heat exchanger surface areas can be reduced. But the temperature level also affects the engine’s heat transfer. So the influence of the cooling water and lubrication oil temperature on the friction and the heat transfer from the cylinder to the cooling fluids needs to be taken into account. The effect of different temperature levels will be shown in a variation of the coolant and lubrication oil temperature. A profound understanding of the components, their dependencies and interactions is important for a system optimization. With this knowledge it will be possible to further reduce safety factors, the dimension of heat exchangers and to use smaller pumps. This will improve the overall system’s efficiency.

New approach for ECS software development
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Ingo Koops, AVL Software and Functions GmbH, Germany
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Christian A. Roduner, AVL Software and Functions GmbH, Germany

The future emission legislation for marine applications stipulates a considerable reduction of nitrogen oxide pollutants. In 2016, the IMO will enact the emission standard Tier III for ECAs, while engines operated at open sea will have to meet the less stringent emission level Tier II. Dual-fuel engines provide the possibility to run in different propulsion modes that are suitable for the permitted emission levels. On open sea, a dual-fuel engine can be operated IMO Tier-II compliant in diesel mode with cost-efficient heavy fuel oil. In ECAs, dual-fuel engines run on natural gas to fulfill the upcoming emission regulation IMO Tier III. The operation and interaction of diesel and gas mode result in complex control structures for dual-fuel engines. In each propulsion mode, the engine shall provide a reliable operation with an excellent transient behaviour. At the same time, engine durability and safety aspects may not be neglected. Hence, the development of an engine control system (ECS) for dual-fuel engines represents a notable challenge. Generally, the development process for engine control systems includes the elaboration of control software, which has to be tested and calibrated on engine test bed. This proceeding contains two major drawbacks. First, the availability of prototype engines is limited especially at the initial development phase. Second, engine test bed operation is expensive and increases the overall costs for the engine development. In this paper, AVL shows a possibility to improve the development process of ECS software. Therefore, a close interaction of the tools Simulink from The Mathworks and AVL’s BOOST RT is used to set up a simulation environment. BOOST RT provides the plant model of the engine. Its thermodynamics and flow characteristics are simulated in the time domain using steady and unsteady 0D and quasidimensional component models. Responsiveness of engine sensors as well as the behaviour of actuators is also included in the BOOST RT model. ECS control concepts are modeled in Simulink. The BOOST RT interface in Simulink allows a model-in-the-loop (MiL) simulation of ECS software and engine plant model. Furthermore, BOOST RT is capable of generating a surrogate of the engine plant model. This also can be done for a part of the model and in combination with the remaining crank angle resolved model. Thus, the computing time can be tailored for real-time applications on a hardware-in-the-loop (HIL) test bench considering also slow computers or complex models. On Simulink side, auto code and flash tools are used to implement the control functions into the target ECS hardware. As a consequence, a HIL simulation of the control functions running on the ECS hardware is set up to test and calibrate the ECS application software. In summary, the coupling of BOOST RT and Simulink allows a validation of ECS control functions in an early engine development phase. Engine test bed time can be reduced through the use of control functions with a relatively high maturity level and calibration efforts are minimised by pre-parameterised application datasets. The advantages of this improved development process will be shown by means of chosen engine control functions used in diesel and gas mode of a dual-fuel engine.

Poster Sessions Wednesday May 15th
Session 7
Development of a New Electronically Controlled Cylinder Lubrication System
Y. He, Wuhan University of Technology, China

Extending Oil Life in Natural Gas Engines
F. Girshick, Infineum, USA

Development of Gas Engine Oils for Corrosive Gas Service
A. Baker, Infineum, USA

Fibre Optic Sensor for Online Monitoring of Oil Film Pressure in Engine Main Bearing
H. Ronkainen, M. Kapulainen, A. Hokkilaen, I. Stunts, S. Varjus, R. Turunen, S. Nyyssonen, J. Halme, VTT, Finland

Energy Efficient Gas Engine Lubrication
K. Tillier, ExxonMobil, USA, B. Murphy, GE Energy, USA

A Study on Wear Progress of Engine Bearing under Mixed Lubrication Condition
T. Sano, Daido Metal Co., Ltd., Japan

“Black Sludge” in TPEO & Evaluating Sulphonate & Salicylate Detergents on Asphaltenic Dispersancy
J. Piao, J. Zhang, J. Yu, T. Feng, PetroChina DaLian Lube Oil R&D Institute, China

Lubrication & Friction Mechanism Research of Laser Surface Texturing Technology on Cylinder Liner of Diesel Engine
B. Yin, Y. Liu, Jiangsu University, China

Session 5
Simulating the Combustion & Near-Wall Flame Extinction of a Methane Gas IC Engine by Employing a Zonal Cylinder Model
A. Kadke, G. Hennigsdorf, Friedrich-Schiller University, Halle-Wittenberg, Germany

Combustion & Exhaust Emissions Characteristics of Pilot-Ignited Engine Fueled with Digestor Gas
E. Tomita, N. Kawahara, Y. Sunada, Okayama University, Japan, M. Kondo, Mitsu, Japan

Development of an Ethanol E100 Combustion Engine
J. Fernandez de Landa Magarin, Dresser-Rand, Spain

Session 4
Study on Acoustic Characteristic & Noise Control Measure of Marine Diesel
J. Wang, Shanghai Marine Diesel Engine Research Institute, China

Influence of EGR Rate on D30 Impure DME/Diesel Engine Performance Combustion & Emissions
T. Wang, D. Wang, Taiyuan University of Technology, China

Feasibility Research of Biomass Energy Applied in Internal Combustion Engine
Z. Gao, D. Mei, Z. Wang, P. Sun, Jiangsu University, China, Y. Yuan, Nantong University, China, G. Elsbett, Guenther Elsbett Technologie, Germany

Study of Simulation & Experiment on Engine Emissions with DME & Non-Standard Diesel Blended Fuels
X. Yuan, T. Wang, F. Guo, Taiyuan University of Technology, China
Comparison of PM Emission from DME & Diesel Engine
S. Liu, J. Huang, Y. Wei, Xian Jiaotong University, China

Theoretical Study & Experimental Investigation on Augment High-Pressure Common Rail System
Q. Guangyao, C. Haoling, Naval University of Engineering, China

Exhaust Emission Control of Mitsubishi UE Diesel Engine
K. Imanaka, N. Hiraoka, A. Miyagami, M. Sugihara, Mitsubishi Heavy Industries, Japan

Horst Harndorf, University of Rostock, Germany
Jean Rom Rabe, University of Rostock, Germany
Martin Drescher, FVTR GmbH, Germany

Session 9
Modelling & Control of a Fuel Cell & Micro Gas Turbine Hybrid Power System for Ship Application
J. He, P. Zhizhong, D. Cledland, University of Strathclyde, UK

The Exergy Analysis of Marine Diesel Engine Waste Heat Recovery System
Z. Wang, Harbin Engineering University, China

The Design & Implementation of the Hardware In-The-Loop Simulation Comprehensive Test Bench of High-Pressure Common Rail Electronic Control System for Large Low-Speed Marine Diesel Engine
G. Wang, J. Yang, Y. Yu, Z. Wang, C. Shu, Wuhan University of Technology, China

Development of Medium-speed EUP Electronically Controlled Diesel Engines

Development of Electronic Fuel Injection Controller of High Power Locomotive Diesel Engine
M. Guan, Z. Cai, S. Han, CNR, China

Modelling & Simulation Research of Electro-Hydraulic Speed Governing System of Diesel Engines
E. Song, Harbin Engineering University, China

The Study of Real-Time Simulation Model on Marine Diesel Engine
J.H. Li, CSIC, China

Thursday May 16th / 08:30 – 10:00 Room A
Fundamental Engineering – Thermodynamics 2

Hydraulic measures to improve common rail injection system performance – impact of injection rate shaping on emissions of a medium-speed diesel engine
Christian Fink, University of Rostock, Germany
Martin Drescher, FVTR GmbH, Germany
Jean Rom Rabe, University of Rostock, Germany
Horst Harndorf, University of Rostock, Germany

The introduction of IMO Tier III in 2016 demands a reduction of NOx emissions by 75% compared with IMO-Tier II. This cut in emissions is only to be achieved by applying new technologies to ship diesel engines. One promising option to reduce emissions by engine internal measures is the introduction of exhaust gas recirculation (EGR). In order to control particulate emissions as well as fuel consumption, this technology can only be applied when significantly improving the fuel injection system at the same time. The presented work focuses on the impact of injection rate shaping on the emissions of a medium-speed diesel engine. The approach is based on the idea to generate very specific injection rates, which are referred to have a positive effect on engine emissions, by simple hydraulic considerations. Therefore, the existing common rail injection system of the medium-speed research engine 1 VDS 18/15 has been modified and extensively tested. The engine measurement results show that injection rate shaping significantly influences engine emissions. In certain points, reductions of particulate emissions of up to 70% compared with a reference set-up were achieved at constant NOx while even providing advantages in indicated engine efficiency. It is shown that especially at 50% load conditions a RAMP-like injection rate offers the highest potential. On the other hand, no advantage is detected for the given conditions at 75% engine load. These results are confirmed by cylinder pressure traces showing how rate shaping influences the premixed and diffusive combustion phase. Based on the engine results it has to be stated that hydraulic measures to control injection rates can have a considerable potential to reduce engine emissions. The possibility to influence the combustion process by applying injection rate shaping allows a fundamental analysis of combustion parameters with respect to emission generation. The presented work thus provides an important basis to improve the understanding of emission generation processes in large diesel engines.

Research on heat transfer performance and temperature field inspection methods of cylinder head
Zhang Ping, Naval University Of Engineering, China
Ouyang Guangyao, Naval University Of Engineering, China
Lv Jianming, 91852 Troop Of Navy In Shanghai, China
Liu Qi, Naval University Of Engineering, China

Taking a high-power density (HPD) diesel engine as the research object, the characteristics of heat transfer is analysed and HTIC influences on temperature of cylinder head are ascertained by orthogonal experimental designing method. Secondly, a new method of inspecting thermal faults inner cylinder head, based on temperature parameters is put forward. Experimental and numerical results have proven that when comparing with normal and abnormal cylinder head, under the same heat transfer conditions, for resistive crack inner cylinder head, the area temperature values near the crack change obviously. The maximum difference in temperature is -267.9°C. Finally, on the base of LM inverse heat conduction problem solving method, a general programme to identify inner HTC of complex object based on surface temperature is developed and applied in identifying heat transfer condition on firedeck of cylinder head. The results are validated by experimental values and the error is less than 1%, which meets the practical engineering requirements and will give a theoretic and technical gist for a new method to make sure three-dimensional temperature field of cylinder head based on surface temperature values.

Acoustic source characterisation of medium-speed IC engine exhaust system
Antti Hynninen, VTT Technical Research Centre of Finland, Finland
Mats Abom, KTH Competence Centre for Gas Exchange, Sweden
Hans Boden, KTH Linne Flow Centre, Sweden
Esa Nousiainen, Wärtsilä Finland Oy Power Plants, Finland
Matias Aura, Wärtsilä Finland Oy Industrial Operations, Finland

Due to the tightening demands concerning the environmental noise, knowledge of the sound generation of internal combustion engines (IC engines) is of great importance. The exhaust noise of an IC engine travels from the source via transmission path, exhaust system, to the outside environment. When designing the elements used in IC engine exhaust systems, e.g. silencers or catalytic converters to reduce the exhaust emissions, including noise, the acoustic source characteristics of the IC-engine must be known. The studied audio frequency range can be divided into the...
low frequency plane wave range and high frequency non-plane wave range. The low frequency plane wave range acoustic source characteristics of an IC engine can be determined accurately by using for example process simulation software and acoustic multi-load methods. If the diameter of the studied duct is small as in automotive systems, the low frequency plane wave range source characterisation might be enough. When studying noise from a medium-speed power plant or marine IC engine, the duct diameters are large and therefore the acoustic source characteristics in the high frequency nonplane wave range are also important. The goal and inner wall is to estimate the range of acoustic source data of a medium-speed IC engine exhaust system can be determined in the low frequency plane wave range and also in the high frequency non-plane wave range using engineering practices and acoustic power based methods. In this study the source characteristics are determined based on simulations and measurements, then the low- and high-frequency source characteristics are combined in a way that allows them to be used in multiport simulations.

The effect of piston structure parameters on the lube oil consumption

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Jun Wen, Chengdu Galaxy Power Co, Ltd, China
Lizhong Shen, Kunming University of Science and Technology, China
Zhentao Liu, Zhejiang University, China

Based on the measurement of temperature filed of piston and cylinder sleeve, the dynamic model of 2D25 diesel piston assembly was established. The effect of piston structural multi-parameters and single parameters on lube oil consumption was analysed by orthogonal experimental design method and conventional method, and the single parameters, including the radial clearance between piston skirt, piston head and cylinder inner wall, and piston pin offset. The results indicate that the radial clearance between piston skirt and cylinder inner wall has the greatest impact on the lub-oil consumption, followed by the piston head radial clearance and the piston pin offset. The convex position of piston skirt profile, stiffness and ovality of piston skirt had little impact on the oil consumption. The lub-oil consumption had little change with the radial clearance between piston skirt and inner wall from 0.06mm ~ 0.09mm, but the lub-oil consumption increased rapidly when the radial clearance between piston skirt and inner wall was at the range of 0.09mm ~ 0.15mm. The lub-oil consumption had a little increment with the piston head radial clearance. The lub-oil consumption was the lowest when the piston pin offset to main bearing surface was 0.5mm, and the lub-oil consumption was increasing with piston pin offset to main bearing surface was increasing, but the range was not obvious.

Service experience of MAN B&W two-stroke diesel engines – an update

Stig Baungaard Jakobsen, MAN Diesel & Turbo, Denmark

After the introduction of the Tier II versions of the MAN B&W M-range of two-stroke diesel engines, around 85% of all new orders are specified as electronically controlled ME/ME-C/ME-B types. This trend is covering all engine sizes; however the trend is most dominating for large-bore engines (80, 90, 98) where nearly 100% of all orders are specified in electronic controlled versions. It is therefore of extreme importance that the ME engines have reached a matured development status and this paper confirms that this is indeed the case. Today, the ME engine concept is widely accepted among major shipowners and the benefits of electronic control is seen more and more as the concept is enhanced with features as auto-tuning, integrated control of exhaust bypass, variable turbine area turbochargers, turbocharger cut-out and in the near future (Tier III era) integrated control of exhaust gas recirculation, water in fuel emulsion and SCR. An update of service-related issues on the electrohydraulic control will be given. The continued change in economics for shipping following the worldwide financial crisis starting in autumn 2008 has called for continued focus on extreme low continuous load operation of several types of vessels. This focus started for large container vessels operated down to 10% load continuously. However, now it also becomes relevant for other ship types like tankers and bukers. An update on service experience will be given, including service experience with ‘high-pscv tuning’ as retrofit. Lower design speed for newly ordered ships has called for new engine types in various types of vessels applying larger diameter and more efficient propellers. For large container vessels, about 8,000 - 14,000 TEUs, the S90ME-C engine in Mark 8 and Mark 9 versions have become new industry standard. An update on service experience with this new application of the well-proven S90 engine, formerly predominantly specified for VLCC propulsion, will be given. The trend of applying lower propeller revolutions on various ship types has also called for the introduction of the ultra-long stroke G-type engine series. Early service experience of these engines will be given. Common for both the ME/ME-C and the MC/MC-C engine series is the well-documented possibility to do condition based overhaul (CBO) with average time between overhauls (TBOs) of 32,000 hours and above. For tankers, this opens up the possibility to do only major overhauls at dockings with five years interval. Many shipowners do now have the experience with CBO. Development of a new piston ring package for small bore engines (50 bore and lower) has made it possible also to enjoy extended time between piston overhauls on these engine types. The so-called POP (Port On Plane) top piston ring will also be introduced.

Diesel engines optimisation and fuel savings

Magnus Karlsson, Stolt Tankers BV, The Netherlands

The aim of this paper is to present how to achieve a reduction of fuel oil consumption and maintenance cost through optimisation of diesel engines. Furthermore, the paper will also handle combustion-related problems of Marpol Annex VI emission Tier I, low NOx settings of diesel engines and diesel engine optimisation in general. All presented cases are real and are backed up with real combustion diagrams, measurements and calculations carried out during performance and energy audits onboard Stolt Tanker’s vessels by the author of this paper. The author has as well attended several factory acceptance tests for diesel engines. A diesel engine combustion analyser instrument is used when carrying out the performance tests of diesel engines onboard vessels. Based on the results from the combustion diagrams achieved from the combustion analyser and other relevant performance data, the diesel engines are optimised for improved performance. The work process in the combustion diagrams will be explained and also how the diagrams should look like to achieve the most efficient combustion. The paper will show examples of diesel alternator engines with Marpol Tier I low NOx emission settings. The paper reveals that newly installed diesel engines on vessels optimised in compliance with low NOx emission limitations
can be poorly optimised and therefore in a state of combustion unbalance. The paper shows that it is possible to optimise these poor factory-adjusted diesel alternator engines to achieve a more efficient combustion and thereby a reduced fuel oil consumption and maintenance cost and still comply with the low NOx emission limitations. One special case of wrongly designed diesel alternator engines in compliance with low NOx emission limitation installed on the new vessels in the fleet is presented. In connection to this special case an older diesel alternator engine was optimised to make it possible to compare the design of the fuel injection in the two engines. Furthermore, there will be examples of optimisation of older diesel engines that do not need to be in compliance with Marpol Tier I low NOx regulation, both a two-stroke main engine and a four-stroke diesel alternator engine. The author believes that the paper can be enlightening for both shipowners and engine makers.

**Design and field experience of Hyundai-Wärtsilä two-stroke RT82 family engine**

Jang Ho Kim, Hyundai Heavy Industries Co, Ltd, South Korea  
Byoung Gi Kim, Hyundai Heavy Industries Co, Ltd, South Korea  
Sang Lip Kang, Hyundai Heavy Industries Co, Ltd, South Korea  
Bai Young Kim, Hyundai Heavy Industries Co, Ltd, South Korea  
Ju Tae Kim, Hyundai Heavy Industries Co, Ltd, South Korea  
Bo Soo Kim, Hyundai Heavy Industries Co, Ltd, South Korea

Since an official shop test of proto camshaft-controlled Hyundai-Wärtsilä RTA82C engine was carried out in April 2008 at Hyundai Heavy Industries Co, Ltd (HHI-EMD), more than 90 sets of the RT82 family engine (RTA82C, RTA82T, RT-flex82C and RT-flex82T) are in service with very good service feedback to date. Accumulated service hours of the 8RTA82C engine, which entered into service firstly in the RT82 family engine, is exceeding approximately 25,000 hours. Design improvement on fuel injection and hydraulic pump system, common rail supply system etc. was performed, through sufficient validation tests, in order to provide economical, reliable and prolonged times between overhauls for shipowners. Through enhanced product care activities, aforementioned design modifications have been introduced accordingly on newbuildings. Measurement of optimised engine performance, stresses and temperatures measurement of all major components for IMO Tier II emission regulations on RTA82C as well as RTA82T engines was carried out successfully, and it was confirmed that all of design philosophy met the market demands. Verification test of increased waste heat recovery system (WHRS) bypass ratio and fuel actuated saeless technology (FAST) injector was successfully performed on the 7RT-flex82T engine at the test bed of HHIEMD in very close cooperation with Wärtsilä Switzerland Ltd. According to the test result, shipowners can be offered more competitive and economical engine operating conditions. This paper presents the latest market trend, design improvement and field experience of the RT82 family engine. Also, proactive activities of HHIEMD satisfying market demand will be described.

**Condition-based maintenance of the two-stroke propulsion engine**

Oyvind Toft, BW Fleet Management AS, Norway  
Henrik Roßted, MAN Diesel & Turbo, Denmark  
Per Samuelsson, Federal Mogul Gothenburg AB, Sweeden  
Tormod Opsahl Linnerud, Det Norske Veritas, Norway  
Tormod Opsahl Linnerud, Det Norske Veritas, Norway

The typical time between overhaul of two-stroke main engine cylinder units has been in the range of 10,000 to 15,000 hours. This has been regarded as best practice in the shipping industry for the last three decades - a practice that has ascertained safe and reliable operation. The development of design and material technology in this period has lead to significantly higher outputs, improved reliability, lower emissions and higher cost efficiency. Examples are improved designs of the turbocharger, combustion chamber, bearings, fuel system, lubrication system and piston rings. There may still be challenges in certain areas, but all in all the gains have been considerable. At the same time ship operators have increasingly been challenged by their business partners as well as the public at large to operate within ever larger safety margins. Amongst others, this has implied that even planned overhauls requiring disabling of the main engine when the ship is in service, becomes increasingly difficult - especially for any kind of tanker vessel. For a long time, there have been restrictions in place hindering overhauls when alongside at terminals. This restraint has recently also been imposed by authorities of some of the most strategic anchorages. Disabling main engines commonly requires standby tugs in these areas thereby increasing costs for overhauls to a large degree, and many operators see this as shrinking opportunities to carry out planned maintenance in a cost-effective way. To mitigate this situation attempts have been made to operate main engines from ‘dock-to-dock’, i.e. at five-year intervals, which requires about 30,000 hours between overhauls. This would entail several advantages. Clearly, planning, lead time for acquiring spare parts, availability of assistance etc. would improve the quality of work and perhaps also reduce spare part costs to some degree. Furthermore, the time loss would become reduced. The results from the aforementioned tests have been encouraging to the degree that one could think of main overhaul intervals of even up to ten years, which would require safe operation for up to 60,000 hours. Largely prolonged service periods as well as the trend towards higher engine outputs would call for changes to the specifications for some highly loaded key components whose service life is not always predictable. A section of this paper explains the specific challenges for piston rings. Various types of coating on the running face and on the side face are now state of the art for the high efficient two stroke engines. The design of the ring groove plays also an important role if one wants to achieve running hours of approximately 60,000 hours. The hard chromium plating used today might not always be the right choice. New coatings in the piston grooves besides on the piston rings may be a necessity. Further, as the engine designers have come up with more and more powerful engine versions, demand on the piston rings has increased. Additionally, a more prolonged TBO together with the new SECA regulation will have an important influence on the ring design for the future. The exhaust valve spindle is another example where heavy duty material may be required to withstand the stress and fatigue imposed by such long service time. Since costs for overhauls when the ship is docked tend to increase somewhat due to yard assistance and increased costs for heavy duty components, the proposition to carry out overhauls at alternate dockings becomes much more interesting as cost efficiency would increase sharply and more than outweigh operating costs associated with current practices. The paper reports on results obtained with two MAN B&W 6 S 60 MC-C engines and discuss requirements to components and operational procedures. Furthermore, an outline of a maintenance programme based on condition monitoring to achieve ten-year intervals between main overhauls for two-stroke main engines is proposed.
**SCR is an established technology and has been used to remove acidic NOx emissions from the exhaust gases of engines, boilers and other combustion processes for over 50 years. The first SCR demonstration on a ship engine was conducted more than 30 years ago and since then over 500 vessels have installed SCR technology. Today, SCR is considered a proven, commercially available technology capable of removing 95% or more of NOx in an exhaust gas. As such, it is expected to be one of the major technical options capable of meeting IMO Tier III standards. Whilst there has been considerable success in the application of marine SCR, the experience in the field is mixed and contrary messages have emerged. As part of the IMO NOx review, the International Association for the Catalytic Control of Ship Emissions to Air (IACCSEA) committed to sponsoring an independent review of field experience of marine SCR. A database comprising most of the shipping SCR installations was compiled and a representative sample was surveyed. In this paper we propose to explore the following findings from the dataset and survey:**

- The extent to which SCR has been applied to a wide range of engineering types, utilising different fuels (of differing sulphur content) and operating over a range of engine conditions over the past 30 years;
- The major problems that operators have had with SCR and a description of how these issues were managed, resolved or mitigated;
- An outline of the most important lessons learnt that may be applicable during and after the transition to IMO Tier III.

**First operational experiences with a combined dry desulphurisation plant and SCR unit downstream of a HFO-fuelled marine engine**

Ralf Juergens, Couple Systems GmmbH, Germany

In December 2011, Couple System successfully managed the commissioning of a dry scrubber (DryEGCS) in combination with a SCR catalyst. The application consists of an engine test bed on which marine diesel engines up to an output of 24 MW are running. The exhaust gases of the HFO-fuelled engine are fed into the dry scrubber, named DryEGCS, where the exhaust gas is cleaned off of SOx in a magnitude of more than 99%. Particles are removed in excess of 90%. The temperature of the exhaust gas is maintained and represents the optimum temperature for the reduction of NOx by the SCR catalyst. The SCR process requires the injection of ammonia, which in this case is done in the form of an aqueous ammonia solution. The installed SCR system is one of the largest systems operated downstream of a marine diesel engine. The combined DeSOx and DeNOx system meets all present and future IMO regulations including a potential PM regulation. The entire system is monitored by a continuous monitoring system according to scheme B (MEPC.1849). The paper includes a full technical description as well as operational data.

**Urea SCR system for pollution control in marine diesel engines**

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Hiroyuki Kamata, IHI Corporation, Japan
Hayato Nakajima, IHI Corporation, Japan
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Kouji Moriyama, Diesel United Ltd, Japan
Kenji Goto, Japan Marine United Corporation, Japan

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**Field experience of marine SCR**

Johnny Briggs, IACCSEA, UK
Joseph McCarney, IACCSEA, UK

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**Testing SCR in high-sulphur application**

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Raimo Turunen, VTT Technical Research Centre of Finland, Finland
Hannu Vesala, VTT Technical Research Centre of Finland, Finland
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NOx and SOx emissions from ship exhausts are limited by IMO ship pollution rules. NOx emission limits are set for diesel engines depending on the engine maximum operating speed. Limits are set globally (Tier I and Tier II) and in addition for emission control areas (Tier III). Tier III standard is dated to 2016 and is expected to require the use of emission control technologies. SCR is an available technology capable of meeting this requirement. This technology uses a catalyst and ammonia for the reduction of NOx to elemental nitrogen. On the other hand, SOx limits require the use of lower sulphur level fuels or aftertreatment systems, like scrubbers, to decrease SOx emissions. Scrubbers might become popular as they allow the use of inexpensive heavy fuel oil. The sulphur is usually considered as poison to catalysts. In SCRs, a V2O5 catalyst has been widely employed due to its high activity and sulphur tolerance. Even so, sulphur-related challenges do occur. At high temperatures, the SO3 can result in an unwanted visible plume, while at low temperatures, the SO3 can react with the ammonia to form ammonium sulphates, which deposit on and foul the catalyst. This brings certain requirements for the SCR optimisation in high sulphur applications. Ships utilise large engines, which require large catalyst volumes to deal with the emissions. Installations to large engine applications can be difficult and testing rather complex. Only minor (or none) tuning of the parameters is possible in real applications. In this study, a slipstream emission control test bench is utilised to test smaller SCR units with a proper exhaust gas from a medium-speed diesel engine. The test bench has an advantage of easily tuned and controlled parameters (like temperature and exhaust flow). A heavy fuel oil with a sulphur content of 2.5% is utilised as test fuel. Two different SCR catalysts with a volume of 40dm3 are tested using engine loads of 100%, 75% and 50%. In addition, different exhaust gas flow rates and temperatures, adjusted according to scheme B (MEPC.1849). The paper includes a full technical description as well as operational data.

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**Aftertreatment – SCR Experience**

Thursday May 16th / 08:30 – 10:00 Room C

Schiff&Hafen | Ship&Offshore | May 2013

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Tier III emission control of the IMO requires the substantial reduction of NOx emissions from marine diesel engines. Tier III is expected to require a dedicated NOx emission control technology such as the selective catalytic reduction. Our experiences of an onboard catalyst test in an exhaust gas of heavy fuel oil (HFO) and the subsequent development and evaluation of the urea SCR system are described in this paper. The preliminary catalyst test was conducted by the slipstream type reactor mounted onto a marine diesel engine which was fueled by high-sulphur HFO. Onboard durability test showed that the honeycomb-structured SCR catalyst suffered from the deposition of the mixture of soot and oil mist contained in the exhaust gas and deactivated readily. The deactivation was more severe at lower operational temperatures. This experimental test suggests the importance of the reduction of the soot and oil mist in the exhaust gas to prevent the possible deactivation of the SCR catalyst. Subsequent development and evaluation of the urea SCR system was performed by the exhaust gas of the low sulphur marine diesel fuel at the test bench of the works. The system consisted of the afterburner to maintain the specific temperatures of the exhaust gas, the aqueous urea injection system, and the honeycomb-structured SCR catalysts. The dimensions of the piping and the reactor were designed to achieve a uniform distribution of urea with assistance of a computational fluid dynamics (CFD). The diesel particulate filter (DPF) was installed as a potential option to reduce the particulates upstream of the SCR catalyst. The urea SCR system was operated at temperatures between 270°C and 350°C and at the ratio of equivalent NH3 and NOx between 0.4 and 0.95. The performance test has successfully proven that the system can reduce NOx efficiently according to the stoichiometric ratio of NOx and urea injected. The experimental results were confirmed to be essentially consistent with the CFD calculations. Online gas analysis revealed that urea decomposition proceeded by sequential steps. Urea injected into the exhaust piping thermally decomposed into isocyanic acid and ammonia. Isocyanic acid was further decomposed by hydration and formed ammonia over the catalyst. Unreacted ammonia was detected downstream of the SCR catalyst, however, it was nominal concentration. Both the afterburner and DPF was confirmed to reduce the soot as well as oil mist in the exhaust gas. Particularly the DPF can eliminate more than 80% of the total amount of the soot/oil mist mixture. The emphasis can be placed on the importance of the appropriate setting of the operational parameters such as residence time of the exhaust gas in the catalyst and its temperature.

**Thursday May 16th / 08:30 – 10:00**

**Room D**

**Component and Maintenance Technology**

**Filter and Crankshaft Development**

**Influence of filtration on component lifetime of common rail injection systems**

Stefan Schmitz, Boll+Kirch Filterbau GmbH, Germany

Heavy fuel oil is filtered by automatic back-flushing filters. The pressure rating of modern common rail systems is rising and the wear of abrasive impurities in the oil got an increased and no more acceptable influence on the components lifetime. Thus the engine manufacturers are developing more robust systems whilst the filtration should follow the higher requirements on filtration efficiency. The paper will summarise the experiences with new filter applications.

**Fatigue strength of super clean solid type crankshafts**

Ryota Yakura, Kobe Steel, Ltd, Japan

Tomoya Shinozaki, Kobe Steel, Ltd, Japan

With recent trend towards higher output and compactness in marine and power generator engines, the solid type crankshaft used for the four-cycle diesel engine is demanded to have higher fatigue strength. It is well known that fatigue strength is influenced by non-metallic inclusions responsible for the fatigue crack initiation. Fatigue strength can be improved by reducing the amount and size of non-metallic inclusions. The non-metallic inclusions are mainly sulphide and oxide. Therefore, a super clean steel making process has been developed to reduce sulphur and oxygen by vacuum ladle refining furnace. In order to confirm the material qualities of the steel manufactured by the super clean steel making process, the fatigue test on RR-forged crankshaft was carried out. As a result, it is confirmed that fatigue strength of super clean steel has been improved by at least 10% compared with that of conventional steel. In the conventional steel, as for K factor in the fatigue strength calculation formula specified in IACS UR M53, K=1.05 is given for CGF (Continuous Grain Flow) forging crankshaft. By reducing the amount and size of non-metallic inclusions, fatigue strength has been improved by 10% or more compared with conventional steel. This result shows that safety margin would be maintained at the same level with present state after K-factor raises up to 1.15 for super clean steel. Therefore, designed fatigue strength may be improved about 10%. On the other hand, in the fatigue of high strength steel, some cases in very high cycle (more than 10,000,000 cycles) fatigue region are reported in recent literature. Nevertheless, one study for very high cycle fatigue behaviour of low alloy steel used for solid type crankshaft is not enough. Therefore, the investigation for very high cycle fatigue property of super clean and conventional steel has been carried out. In the very high cycle fatigue test of up to 1,000,000,000 cycles, fatigue fracture did not occur in both steels. It was confirmed that the difference of fatigue strength between super clean steel and conventional steel is maintained in a very high cycle region. From this result, it became clear that the super clean steel has a high fatigue strength and high reliability in both the conventional (less than 10,000,000 cycles) fatigue region and very high cycle (more than 10,000,000 cycles) fatigue region.

**Adjustable tuned mass damper concept for diesel generator**

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Antti Maekinen, ABB Oy, Finland

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A tuned mass damper is a well-known concept that can be used to reduce undesired oscillation of structures. However, in structures where the dynamic properties are difficult to estimate, a traditional mass damper needs to be designed very carefully to make it work properly. For these kinds of structures, an adjustable tuned mass damper (ATMD) is an effective vibration control tool. In this study a simple concept for the ATMD was studied based on a leaf spring and moving mass. The moving mass was located in the middle of
On the design of a single cylinder engine for enhanced functional and reliability validation

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The increasing global demand for power generation and transportation presents a significant opportunity to the world’s large engine producers, but presents a key question regarding the protection of our environment and preservation of our natural resources. Meeting these challenges require the introduction of higher efficiency and cleaner engines to the market that extend the known boundaries of performance whilst ensuring product reliability. The successful delivery of these new engines with competitive time to market demands a leap in development philosophy and method. This paper presents the design approach for a single-cylinder engine that in close combination with a powerful analysis process enables the significant reduction of development cost and duration, whilst substantially enhancing the fundamental reliability achieved in new product development. Traditionally single cylinder engines have been applied to the early life evaluation of combustion processes. As such the flexibility in configuration, greater refinement in test control and measurement, reduced costs of prototype parts and operation, and reduced test facility demands have accelerated the development of ever cleaner and more efficient combustion systems. Coupled with assessment of the combustion process there has existed the opportunity for the preliminary durability assessment of certain performance related components. This has been promising in particular due to the much reduced overhead in operation. However, there remains a substantial and unrealised opportunity in the application of single-cylinder engines to the accelerated validation of multi-cylinder engine function and reliability. In this paper, the authors present this opportunity and the approach to deliver both class-leading functionality and reliability. At first the boundary conditions for operation representative of a multi-cylinder engine may be established through the coupled use of multi-cylinder and single-cylinder engine simulations. The gas exchange processes that influence cylinder filling and trapping of residual fractions, charge motion, and transport of emissions may be determined such that early stage confirmation of the boosting exchange processes and component thermal loading, lubrication and friction. Secondly, the architecture of the single-cylinder engine is created such that the maximum commonality with engine hardware may be achieved. Evidently this would include the replication of bore and stroke, but also deck height, connecting rod length and cylinder bore offset. Ensuring the use of common big end bearings and entire valve train geometry will then enable not only the use of common cylinder head and piston assemblies, but also connecting rod, liner and all valve gear. The development of rapid prototyping methods which align with production design materials and manufacturing processes ensures the seamless transfer of designs to the production supply chain. Thirdly, and with the foundation of representative components operating under representative conditions, it becomes possible to significantly extend the validation of both function and reliability. With precise measurement of temperature, pressure and strain, the thermal and mechanical performance of components may be confirmed. Further, with representative thermal and mechanical loading, and component deformation and dynamics, the performance of the piston and cylinder liner systems, valve train kinetics, and rotating and reciprocating friction may be confirmed. Perhaps most significantly, early stage validation may be obtained for predictions of component and system reliability, which include analysis of high and low cycle fatigue correlated to thermo-mechanical performance analyses and infeld warranty data. The application of such a design and analysis philosophy at the early pro-approach to advanced manufacturing methods and supply chain management, delivers significant functional and reliability validation of engine design before committing to multi-cylinder engine hardware. The possibility to deliver new, reliable and more environmentally friendly engines is therefore realised.
day's OPEs the scavenging is controlled by pistons. Whereas the OPE presented is operated as four-stroke-engine by arrangement of hydraulically shifted liners undisturbed by scavenging holes or gaps so that the pistons with their rings are shielded against crossing any in- or outlet-ports. Therefore, all the modern engine technology to increase mileage, reduce oil consumption, wear and emission can be implemented in this OPE technology presented. So this design combines the advantages of an opposed piston principle with the benefits of the classic engine technology for technical and economic progress. A first prototype has been tested successfully, demonstrating also the mechanical function of shift liners without problems and showing very low friction losses for the shift liners. The wall thickness of these liners can be kept low - like conventional dry liners - as they are supported by the surrounding cylinder, leading to low oscillating liner masses during shifting. The inand outlet ports are located near the pistons top dead centre area and are opened and closed by the upper end of the shift liners like valves, which are closed by spring forces and opened by hydraulic actuation. Different to conventional OPEs, there are no distinct exhaust or intake pistons and thermal load is nearly equally distributed on both pistons. The hydraulic system shares the lubrication oil with the engine, avoiding leakage problems and providing a simple oil circuit. The presented design also offers two different modes of combustion technologies: Injection from the outer combustion chamber edge towards the chamber centre (from cold to hot), or injection from above the combustion chamber centre towards the chamber walls (from hot to cold). For the first mode one or more injectors are positioned around the cylinder, providing the chance for multi-nozzle injection in different time and quantities. For the second mode, the cylinder inner wall must be considered as a virtual cylinder head with all same geometric dimensions as for a classic combustion chamber, but including injection completely rotated by 90°. It provides state-of-the-art conditions like well-developed common engines today in production, but requiring only one injector for two pistons. As no piston rings are crossing the in- and outlet ports, the presented engine is aiming for very big gas flow sections - not interrupted by window lands or port ribs - so far much bigger than conventional multi-valve technique could allow for - with the result of better cylinder filling and less dynamic gas flow losses. As the shift liners are hydraulically actuated a variable valve timing can be easily achieved, as well as a complete cylinder cut-off in multi-cylinder engines.

Application of a sensor system based on linear Raman scattering for in-situ determination of mixture composition of natural gas at the supply line of a dual-fuel driven diesel engine

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A sensor system for the online control of the natural gas composition is presented. The system is based on the principle of linear Raman scattering and allows the determination of all natural gas components within a measurement time of 30 seconds. The sensor will be described and characterised in terms of accuracy and reproducibility. Moreover, first measurements at the supply line of a two-stroke marine engine will be presented.

Structural vibration challenges of marine diesel and gas engines

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Controlling structural vibration of marine engines continues to be a challenge as specific power increases and versatility is in demand. Modern diesel and gas engines should be capable of running both as propulsion engines with variable speed and generator set engines with fixed speed. For both applications, load response is of paramount importance. The same engine platform is normally used for applications using diesel, gas, propulsion and genset engines with several cylinder numbers. Finding a design solution for the rotating shaft system and the structural block system, which works well for all combination, is a task that needs consideration of many influencing factors. As vibration level is influencing engine reliability and life, it is important to choose a design solution with low vibration levels. However, for obvious production and service reasons, the number of shaft and block variants should be kept to a minimum, often requiring that the same solution should be capable of sustaining all engine applications. The paper discusses how modern multi-body simulation tools may be used to evaluate different solutions for both the shaft and the structural system, and takes the influence of the participating systems into consideration. In particular, it is discussed how various firing orders will give different possibilities for torsional tuning of the shaft system. For marine variable speed applications it is important that the engine can be tuned to run comfortably over the whole speed range both with regard to shaft torsional vibrations and engine structural vibrations. It is shown that different firing orders cause large influences to the X- and H-moment of the engine block structure. Measures to avoid resonance at critical eigenfrequencies are also discussed.

The new FEV single cylinder engine family, the efficient tool for engine development

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Medium-speed engine development is facing big challenges regarding mechanical and thermal loading due to future market demands as well as reduced NOX, HC, CO and particulate emissions without drawbacks in fuel consumption/CO2-emissions, engine reliability and cost. Depending on the engine size and the application (e.g. marin propulsion, gen-set or rail) and under consideration of different fuels, (e.g. distillate, heavy fuel oil, gas, alternative fuels) a variety of measures like flexibility in the injection system combined with increased injection pressure and variable valve timing will have an impact on the engine development. Two-stage turbo charging and waste heat recovering as well as possible exhaust gas recirculation (EGR) and exhaust aftertreatment systems will have to be considered. In order to investigate these different functional features, even before a new multi-cylinder engine will be available, a single-cylinder test engine is the most efficient tool to support these developments. Not only combustion-related issues can be investigated but also several cylinder individual mechanical and thermal-load related questions can be tested. Such single-cylinder engine investigations will shorten development time and cost, and will improve engine reliability right from the start of a
market introduction of a new engine family. The paper will give an overview about the bore and stroke range, which can be covered by the single-cylinder engine family as well as a detailed description of the engine family capabilities, features, and modularity. A further part of the paper will be the introduction of the variety of investigations that can be done by such a single-cylinder engine. Finally, the development of cost- and time-saving potential by the use of single-cylinder engine testing will be evaluated.

Onboard fuel oil cleaning, the ever neglected process how to restrain increasing cat-fine damages in two-stroke marine engines
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Remains of cat fines in the fuel oil entering the engine account for a considerable part of the wear of the combustion chamber components in two-stroke engines. The attempt to lower the amount of cat fines in fuel oil bunkers by the ISO 8217:2010 to maximum 60 ppm has however not lowered the global average content. On the contrary, increased use of ECA fuel has lead to a significant increase in the number of cat fines-related engine wear situations. Cat fines entering the engine create wear by means of so-called three-part abrasion. The sliding surfaces made of cast iron are the most sensitive, as the cat fines has a tendency to embed into natural porosities of the cast material structure and create wear on the counterpart. Thereby cylinder liners, piston ring grooves and piston rings become the most affected components of two-stroke engines. It is rare that cat fine-related damage is seen on the fuel equipment due to the high hardness of those components. Recent statistic, involving 165 high cylinder and piston ring wear cases, where replica technique have been used detecting cat fine particles embedded in the liner surface, showed cat fines being the reason in 86% of the cases. This investigation has also shown that even small cat fine particles below 10 micron contribute to the wear. Analysis results of the HFO bunkered in most of the high wear cases showed that the vessels in question had bunkered fuel oil with a high amount of cat fines as fuel oil within the limits of the ISO 8217:2005 specification. Consequently, the cause of the high wear may be found in either too low separation efficiency on board, by settling and accumulation of cat fines in the different tanks on board or a combination of both. This highlights the need of an approved method specifying separator size and efficiency, e.g. certified flow rate (CFR) or similar methods. It also calls for regular checks of the onboard separation efficiency, e.g. by participating in a fuel system check (FSC) programme. Commercial methods such as cat fines size distribution (CSD) screening add an extra dimension by evaluating the particle size of the cat fines. A severe cat fines attack has been monitored by measurements of cylinder liner and piston ring wear through online drain oil analysis. The results showed that the wear dropped from an extremely high to normal level few days after the supply of cat fines had stopped by changing of fuel and after manual cleaning of the tanks. The conclusion is that cat fines damage over a long period of time is the result of a continuous flow of cat fines led to the engine, and that the wear is not stopped until manual cleaning of a contaminated system (including settling and day tanks). Proper lay-out of tank and pipe connections of the fuel oil cleaning systems on board can prevent cat fines accumulation by continuously cleaning the tank bottoms. This in connection with optimised flow rate through the cleaning system, taking advances of the fact that marine engines mostly is operated at part load, may give a significant improvement of the cleaning efficiency. New systems including settling- and day tank lay-out, recirculation pipe connections with flow measuring device and dynamic control of the separator supply pumps are presented in the paper. Technologies, such as FSC, CSD, LinerScan and Cat Guard, have been used in combination with ‘COCOS Engine Diagnostic System’ to evaluate the correlation between cat fines concentration and engine wear rates as well as the need to improve the fuel cleaning efficiency onboard. The paper will demonstrate that the risk of cat fines related wear can be significantly reduced by ensuring optimised fuel system treatment, by introducing a new fuel cleaning system layout, by automatic control of the cleaning flow rate and by intensified monitoring of the fuel treatment efficiency.

Propulsion system (dis)integration
Piet Kloppenburg, Techno Fysica, The Netherlands

Over the years, propulsion systems have become more sophisticated and complicated. In spite of regular updates of class rules and regulations to cover the present state-of-the-art technology, upgrading of international standards, QA/QC procedures and supervision of production and assembly by end users, regular failures occur that lead to excessive wear, loss of functionality up to total lack of propulsion. Besides the lack of system thinking, one of the key factors is the introduction of electronic control of several functions on separate engines, as fuel injection, valve control, cylinder lubrication, condition monitoring etc. and on complete propulsion systems consisting of several engines and propulsors where different operational modes can be chosen. Replacing mechanical functions by electronic control absolutely increases the flexibility of systems regarding tuning them for specific applications and for a specific goal (for instance fuel-optimised versus emission-optimised) with a single push of a button or completely automatic.

The advantages are clear: more flexibility, more accurate control, higher load limits, lower fuel consumption and emissions over the load range than on mechanically controlled systems and higher redundancy, for instance if a camshaft fractures on a mechanically controlled engine it stops while on an electronically controlled engine, one cylinder is shut down when a failure occurs and it keeps on running. The disadvantages are also becoming clear in daily practice:

• There is a responsible party for the entire system, being the shipyard or self-appointed system integrator, but often there is no competent party with total knowledge of, control over and interest in system integration that covers electronic systems, mechanical systems and the interaction between them.
• There is a lack of understanding what the effect of actions by electronic systems can be on the mechanical integrity of these governed systems because electronic and software engineers and mechanical engineers are worlds apart: they often do not understand each other even if they communicate at all.
• The different parties that deliver controls for a propulsion system (engine-related controls, power management systems, DP systems) have no intimate relationship, i.e. the communication is limited to exchange of protocols and wiring diagrams and does not involve the effect of the combined overall control system on the mechanical load of the propulsion installation.
• During sea trials, the measurements performed are limited so that especially dynamic effects due to interaction between separate components and/or systems that can lead to failures or excessive wear are not recognised.
In this paper several cases of disintegration of propulsion systems in practice will be discussed. The examples range from fracture of propeller shafts through rupture of rubber elastic couplings to repeated damage of bearings and unworkable situations due to unstable behavior of control systems. Each case is discussed in detail and the damage mechanism as well as the consequences from an operational point of view will be presented as well as the measurements and calculations necessary to determine the root cause. Factors of influence on the development of the damage or wear mechanism for each case will be presented. A procedure to prevent the encountered damages and unwanted interaction between components in a system and detect them in an early stage will be proposed.

Systematic Evaluation of performance of vlcc engine, comparing service monitored data and thermodynamic model predictions
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The general practice in ship engine performance monitoring is to record important engine parameters (i.e. pressures, temperatures, speeds etc.). Some shipping companies include cylinder pressures and shaft torque recordings. Periodically, data is collected in a service report form and forwarded to headquarters for further processing and evaluation. Whilst most marine diesel engines are fitted with some type of condition monitoring, the thermodynamic performance evaluation systems used in the aerospace and process industries, have not been widely used in performance assessment of marine diesel ship propulsion and auxiliary engines. One reason is the complexity of the diesel engine process requiring sophisticated thermodynamic models. This paper presents the procedure applied for shipboard engine performance evaluation, using a thermodynamic model to generate reference data. The model, which requires some detailed geometric information for each specific engine, was initially calibrated using the shop tests data and validated for accuracy using the sea trials data and early service data of the specific engine. Then, the recordings from monthly in-service performance reports were compared with simulation predictions for the same operating conditions. Any important differences between obtained (measured) and expected (simulation) values may point out to component or process problems. Thus, in cases where the deviations in the various engine operating parameters exceeded a limit of 3%, the cause was investigated. In some possible operating conditions of a ship dictated by market parameters, no prior operating data was available. Also presented in the paper are results of simulations using the validated model of the specific engine at very low loads (<20%), to predict engine performance, prior to actual operation.

After treatment – Specific Aspects
Thursday May 16th / 10:30 – 12:00
Room C

After treatment systems for marine applications: practical experience from the perspective of a classification society
Fabian Kock, Germanischer Lloyd, Germany

Recently, the Marine Environmental Protection Committee (MEPC) of the IMO adopted guidelines addressing additional aspects to the NOx Technical Code 2008 with regard to particular requirements related to marine diesel engines fitted with SCR systems. Following these guidelines, a combined engine and SCR may be tested separately in cases where the combined system can neither be tested on a test bed due to technical and practical reasons nor an onboard test can be performed fully complying with the test requirements detailed in the NOx Technical Code 2008. The certification procedure to be processed in such instances has been referred to as the scheme B approach. In particular, starting from January 1st 2016, when the third stage of emission limits for NOx (Tier III) shall apply to newbuildings when operating in an ECA, the new guideline and the scheme B approach will impose a strong challenge for engine and SCR manufacturers, ship operators and certifiers (recognised organisations / classification societies) from a technical and operational point of view. Germanischer Lloyd (GL), acting as a recognised organisation for more than 90 flag states, has a strong interest in a lean and inviolable introduction of the legislation imposed by IMO. Thus, GL has started to accompany and supervise the design and installation of marine diesel engines fitted with SCR systems applying the scheme B approach at an early stage on a number of pilot installations in order. Moreover, GL’s accredited laboratory for Exhaust Emission Measurement and Chemical Analyses has long lasting experience in measuring the exhaust gas emissions from marine diesel engines fitted with SCR systems on board vessels, which have to follow the Swedish NOx tax regulation and therefore has a deep insight into the long-term in-service experience SCR manufacturers and ship owners have with this kind of systems. This presentation aims to introduce latest experiences in measuring, survey and certification of gaseous emissions from marine diesel engines fitted with SCR. The presentation evaluates technical solutions for exhaust gas aftertreatment systems from the perspective of a classification society with a strong focus on its technical, operational, organisational and administrative challenges. In particular, the applicability of the new ‘Scheme B’ approach provided by IMO concerning the combined certification of engines and SCR systems tested separately is examined critically on the basis of a number of practical examples.

Simulation-based development of the SCR spray preparation for large diesel engines
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In order to fulfill the requirements of the IMO Tier III regulation, either a combination of internal engine technologies or external measures are required. Exhaust gas aftertreatment by Selective Catalytic Reduction (SCR) is a proven technology that basically allows any engine to fulfill the IMO-III regulation. The design of compact SCR systems remains a significant challenge for the developer. Besides a high efficient NOx-conversion on the catalysts, the main issue is the efficient spray preparation including the injection of a urea-water solution and the distribution of the reducing agent ammonia, generated by a thermolysis reaction. The uniformity of the ammonia at the catalyst inlet is decisive in order to achieve highest levels of Nox reduction and to avoid deposit formation. Therefore well adapted designs are mandatory to fulfill the system targets concerning emissions, durability and cost effectiveness. Due to the complex physical and chemical phenomena involved in the spray injection, CFD simulations are performed to...
provide valuable insight on the system behaviour. This assists the development in early phases of the development and enables an efficient optimisation. Development time and costs are therefore reduced. The paper provides a survey over the physical and chemical models which have been developed for the description of all relevant phenomena involved in the spray preparation, including the spray evaporation and the thermolysis, the spray-wall interaction and the wall film formation. The developed models have been implemented into a commercial CFD code and validated by experimental investigations of the individual effects. The developed methods have been applied for the investigation of the spray preparation and ammonia uniformity in SCR-systems as well as to evaluate the risk of deposit formation. The paper shows the CFD-aided development of an ultra-compact inter-turbine SCR system for a medium-speed ship engine fulfilling IMO-III and describes the applied methods. The emphasis of the investigations was the optimisation of the ammonia uniformity at the SCR-catalyst. Furthermore the spray behaviour and the risk of deposit formation in the exhaust pipes have been evaluated. Based on the results of the CFD-investigations and on the design of the SCR-System, engine tests will be performed to prove the performance of the SCR-systems under real life conditions.

**Emission monitoring – development of predictive emission monitoring**

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Markus Loevholm, Wärtsilä, Finland

Emission monitoring plays a key role in the trend towards lower emissions. Regulators want to ensure that the set emission limits are followed and need a means of monitoring the performance of the installations. Emission control technology, such as SCR, use emission measurements in order to tune the process to the correct operating point. In addition, record keeping and reporting of emissions e.g. in annual reports is a means of providing visibility and importance to emissions. Exhaust gas from diesel engines has proven challenging for emission monitoring systems. Even systems developed for use in harsh conditions, such as in coal-fired power plants, often do not perform adequately when measuring from diesel engines operating on heavy fuel oil. Cold-dry systems where the exhaust is cooled down to remove moisture and acidic components typically require frequent attention in long-term continuous operation. In-situ systems as well as hot-wet extractive systems require less maintenance, but are typically more costly. This article will discuss experimental investigations of emission monitoring technology. Even systems developed for use in harsh conditions, such as in coal-fired power plants, often do not perform adequately when measuring from diesel engines operating on heavy fuel oil. Cold-dry systems where the exhaust is cooled down to remove moisture and acidic components typically require frequent attention in long-term continuous operation. In-situ systems as well as hot-wet extractive systems require less maintenance, but are typically more costly. The emphasis of the investigations was the optimisation of the ammonia uniformity at the SCR-catalyst. Furthermore the spray behaviour and the risk of deposit formation in the exhaust pipes have been evaluated. Based on the results of the CFD-investigations and on the design of the SCR-System, engine tests will be performed to prove the performance of the SCR-systems under real life conditions.

**Total marine diesel emission control technology using nonthermal plasma hybrid process**

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Masashi Kawai, Osaka Prefecture University, Japan
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Tomoyuki Kuroki, Osaka Prefecture University, Japan

The regulations governing marine diesel engine NOx emission in the IMO emission standards have become more stringent. Because it is difficult to fulfill these requirements by means of combustion improvement alone, effective aftertreatment technology is needed to achieve efficient NOx reduction. Here, we propose an effective PM and NOx simultaneous reduction aftertreatment system that employs a nonthermal plasma (NTP) hybrid process. Compared with selective catalytic reduction (SCR), the proposed technology offers the advantage of treatment at a low temperature of less than 150 °C, without the use of urea solution and harmful heavy metal catalysts. Firstly, laboratory-scale experiments are performed with a stationary diesel generator (YDG200VS-6E, YANMAR Co, Ltd, Japan) (specifications: single cylinder; rotating speed, 3600 rpm; and maximum output power, 2.0 kW). Marine diesel oil (MDO, sulphur = 0.067 mass%) is used as a fuel. The system mainly consists of a marine diesel engine, an adsorption chamber containing adsorbent pellets that can adsorb/desorb NOx in an exhaust gas by controlling their temperature, an NTP reactor, and a diesel particulate filter (DPF). Whole exhaust gas flows to the system at 300 NL/min. The afttreatment comprises (a) adsorption, (b) desorption, and (c) cooling processes. In the adsorption process, an exhaust gas first passes through a DPF, where particulate matter is removed. Subsequently, the gas is cooled by an air-cooling radiator and then passes through an adsorption chamber where NOx is removed by adsorption. The mass flow rate of these gases is measured at the exit of the chamber by a NOx analyser. The clean gas then flows out of the system. In the desorption process, the exhaust gas first passes through a heat exchanger integrated into the adsorption chamber, where it heats the adsorbent pellets to induce thermal desorption of NOx. Simultaneously, N2 gas is supplied to the pellets at 10 NL/min. Then, NOx is eluted. The NOx + N2 gas is subsequently reduced to N2 using the NTP reactor. The NOx concentration is measured after the confluence of the exhaust gas and the reduced gas. In the cooling process, the remaining NOx in the pellets is desorbed by introducing air into the adsorption chamber at 50 NL/min with the help of the residual heat. The desorbed NOx is recirculated into the intake of the engine to enhance total NOx reduction. Based on the measured NOx concentrations and the power consumptions for NTP generation, adsorbed NOx in the adsorption process, and desorbed NOx and treated NOx in the desorption and cooling processes are found. Considering these obtained values, the energy efficiencies upon NOx removal are calculated and the performance of the system is evaluated.

**SUMEBore – the powder-based cylinder running surface coating solution contributing to emission reduction**

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Peter Ernst, Sulzer Metco AG, Switzerland
Rising fuel prices and more stringent requirements in the field of exhaust emissions, such as NOx, PM and carbon dioxide are significantly increasing the pressure on the manufacturers of internal combustion engines of all categories to find, evaluate and apply technologies that contribute to a reduction in these emissions. As a result, interest in cylinder inner diameter surface coatings has risen considerably in the last three to four years, and particularly in the SUMEBore coating solution from Sulzer Metco. Such coatings are applied by a powder-based atmospheric plasma spray (APS) process. The APS coating process is extremely flexible and can also process materials to which wire-based coating processes do not have access. Particular advantages become obvious when coatings are necessary made from high chromium containing steels, metal matrix composites (MMCs) or pure ceramics. The compositions of the coatings can be tailored to the specific challenges in an engine, e.g. preventing excessive abrasive wear, scuffing issues or corrosion attack caused by bad quality fuels and/or high exhaust gas recirculation rates (EGR). Cylinder liner surfaces from trucks, diesel locomotives and marine propulsion, gas engines for power generation and gas compression have been coated with such materials over the past four to five years in small and large series production. These engines have been tested successfully. Most of the tested engines achieved significant reductions of lubrication oil consumption (LOC), one of them in excess of 75%, reduced fuel consumption, very low wear rates and corrosion resistance on the liner surfaces, when compared with the currently uncoated cylinder surface (baseline). The paper will introduce the APS coating technology for ID cylinder surfaces and as an example will highlight the coating of cylinder surfaces in a 4,000 hp EMD 16-710G3 locomotive two-stroke diesel engine. Details of the application of a corrosion resistant MMC coating will be shown, together with results obtained with the Da Vinci DALOC measurement technique in an engine test where the lubricant oil consumption was accurately quantified at four steady-state operating conditions typical of North American freight locomotive and which clearly showed the significant contribution of the liner ID coating to reduction of LOC. In addition, the paper will give an example of an industrialised, fully automated SUMEBore coating equipment installed at a European truck OEM, for the APS cylinder surface coating of up to 250,000 cylinder liners for a truck engine.

**Challenges for cylinder liner development**

Per Ronnedal, MAN Diesel & Turbo, Denmark
Hirofumi Yamamoto, Toa Koki Co Ltd, Japan
Takayuki Goto, Mitsui, Japan

The two-stroke crosshead low-speed diesel engine has been a preferred prime mover in the merchant marine for almost a century. Although its basic working principle has not been changed, the demand for even higher power, produced at the lowest possible fuel consumption, from a machine occupying a minimum of space, has constantly increased the demands to its cylinder liner. This relates to both the thermal and mechanical loading, and the tribological behaviour under ever changing conditions. This paper gives a view on the development in loading on the cylinder liner as one of the main engine components to which it has developed over time. Special attention is given to the recent development as a result of the high focus on specific fuel oil consumption, and the thereby introduced changes in the combustion conditions. New application of advanced analysis method for acid attack on the running surface of the cylinder liner is demonstrating how the new operating conditions will affect the behaviour of the cylinder conditions, and in consequence the cylinder liner. Countermeasures of design and operational measures will be presented and service examples will illustrate the validity of the conclusions and countermeasures. As for the increased mechanical loading of the cylinder liners, two main new designs will be demonstrated:

1) One new design relates to the mechanical design of the cylinder liner, and how this design is able to withstand the increased pressure from the diesel process. The cylinder liner consists of a so-called ‘strong back’ consisting of a steel bandage shrink fitted to the upper part of the cylinder liner. The increased strength of the steel in comparison with the cast iron material thus results in a higher load capability. Service experience of several years of operation is presented for reliability confirmation.

2) The other design feature allowing an increased pressure is based on development of a new material application: the so-called CGI or Compacted Graphite Iron. This application has been developed in tight cooperation with the Japanese cylinder liner manufacturer Toa Koki. The paper describes the production technique applied to achieve a stable yield. The merit in terms of mechanical properties of the CGI is shown. Tribological test data will be presented, and finally service experience will be shown for a number of different engines. In summary, it will be illustrated how modern diesel engine process and application affects the cylinder liner, and how these effects are overcome.

**Development of new generation long life piston ring coating for two-stroke large-bore marine diesel engines**

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Takeshi Yamada, IHI Corporation, Japan
Yoshiyuki Umemoto, Diesel United, Ltd, Japan

Large-bore marine diesel engines equipped as main propulsion on oceangoing large vessels like container ships and crude oil tankers are supposed to possess very high reliability. One of the main factors that affects the reliability of the main engines is the stable sliding of piston rings and cylinder liners. IHI Corporation and Diesel United have jointly conducted numerous basic experiments and tests on wear monitoring between piston rings and cylinder liners, and measurements of oil film thickness between piston rings and cylinder liners of main engines on vessels in commercial operation. The results obtained so far are utilised in clarifying the abnormal sliding mechanism between piston rings and cylinder liners that is hereafter referred as scuffing, and in developing effective cylinder lubrication methods that may be effective in preventing the scuffing. These activities have lasted almost ten years. The findings obtained clarified the following phenomenon. The scuffing is closely related to hard particles contained in the fuel oil (FCC), and to changes of engine operating conditions, typically the engine speed. Poor lubrication of piston rings and cylinder liners to be caused by the above mentioned effect is clarified to induce the scuffing. Research results obtained during the period have clarified that the development of cylinder lubrication systems is quite effective in avoiding the poor cylinder lubrication. Furthermore, it is also important to develop the piston ring coating that may prevent the rapid growth of the scuffing phenomenon even when the poor cylinder lubrication is initiated, and that make the piston rings strong enough as to be immune to the presence of FCC on the sliding surfaces. Meanwhile, some shipowners prefer to have longer overhauling intervals matching with dry-dock interval due to economic reasons. The scuffing resistance of piston rings and cylinder liners
become extremely lowered when the piston ring coating is worn out in recently developed, advanced engines, which have a higher output. Therefore, the life of the piston ring coating is required to be longer than the dry-dock intervals. Chromium ceramic coating is used as the piston ring coating that has relatively high reliability. However, further improvements with respect to the piston ring coating lifetime and scuffing resistance are required to be realised for satisfying the market demands. The present paper reports about the development of a new generation coating for piston rings. The first step of the development is to clarify the sliding characteristics and the sliding mechanism of conventional plasma sprayed Mo coatings and chromium ceramic coatings. Plasma sprayed Mo coatings have a high scuffing resistance with inferior coating life. Chromium ceramic coating films possess a longer coating life than the plasma sprayed Mo coatings with lower scuffing resistance than the Mo coatings. Numerous basic studies and various measurement results obtained on operating ships in the present investigation have yielded a concept for new coatings that should have superior scuffing resistance than the Mo coatings, and longer coating life than that of chromium ceramic coatings as targets of the development of the new coatings. The developed coatings are subjected to laboratory tests that indicated that the coatings possess excellent properties. Namely, the developed coatings possess the scuffing resistance of about 1.8 times that of conventional chromium ceramic coatings, and the coating life has been prolonged more than 4.3 times than that of the conventional chromium ceramic coatings. Furthermore, the developed coatings are confirmed to possess the same order of attacking property against the cylinder liners. Test conducted on operating ships have confirmed the same order of the coating life and superior sliding property as obtained at the laboratory tests. Thus, the actual applicability of the developed coating for main engines of operating vessels has been demonstrated.

**Design optimisation in the solution of piston ring sticking and carbon deposit**

Lingyu Zhu, Weichai Power Yangzhou Diesel Engine Co, Ltd, China

High oil consumption and blow-by rates are often related to piston ring sticking and carbon deposit. Engine tests were carried out and test results were analysed to investigate and verify factors and correlations of the problems. Designs of cylinder block and head water jacket were optimised and the combustion system was improved in the solution of piston sticking and carbon deposit. The results of the engines with an improved design are quite satisfactory.

**Poster Sessions Thursday May 16th**

**Session**

**Simulation Study on the Overall Performance Optimization for 4190 Series Marine Diesel Engine Based on AVL Boost Software**

J. Huang, Y. Qiao, Z. Yin, Jimei University, China

**The Influence of Intake Charge Temperature on Combustion & Emissions of Dual-Fuel HCCI Combustion Engines**

M. Fahti, M. Mersalim, DESA, Iran, R. Khoshbakhti Saray, Sahand University of Technology, Iran

**Comparison of Torsional Vibration Measurement Techniques**

W. Hendrick, K. Janssens, L. Britte, LMS International, Belgium

**Influence Factors on Preload Deformation & Structure of Cylinder Line**

Y. Bi, L. Shen, J. Lei, D. Jia, Y. Xu, Kunming University, China

**Session 11**

**Experimental Study on the Method for T.D.C. Determination of a Medium-speed Marine Diesel Engine**

X. Wu, H. Zhang, L. Ren, Y. Tian, F. Gu, Shanghai Marine Diesel Engine Research Institute, China

**An Attempt to Recompute ECN in the FCA Instrument**

L. Vedala, S. Chandrasekharam, R. Visveswaran, Viswa Lab, USA

**Active Vibration Isolation for a Diesel Engine Generator in Marine Application**

T. Yang, J. Du, M. Zhu, X. Liu, Z. Liu, Harbin Engineering University, China

**Shipping under Hard Pressure in Challenging**

J. Erdmann, NBS Niedereiche, Germany

**Session 6**

**Numerical Simulation on Spray Atomisation Characteristics & Mixing Performances for SCR System in a Marine Diesel**

Z. Yuanping, Z. Song, Harbin Engineering University, China, G. Lin, Jiangsu Nuclear Power Corporation, China

**Investigation on Marine Exhaust Gas Desulphurisation by Seawater Scrubbing**

W. Hong, Harbin Engineering University, China

**Selective Catalytic Reduction of NOx with NH3 over TiO2.9Mo.1O2-6 Nanocomposites Catalysts Prepared by Solution Combustion Synthesis**

B. Guan, H. Lin, L. Zhong, W. Dong, Z. Huang, Shanghai Jiao Tong University, China

**Experiment & Modelling of Urea Spray Impingement & Deposit for Diesel SCR**

L. Hua, T. Yang, Y. Zhao, S. Shuai, Tsinghua University, China

**Effects of Particulate Oxidation Catalyst on Particulate Matter emitted from Diesel Engine**

X. Feng, Y. Ge, X. Han, L. Hao, J. Tan, L. Yu, J. Guo, Beijing Institute of Technology, China

**Session 8**

**Energy Efficient Hydraulic Systems for Large Engines**

S. Fischer, Bosch Rexroth, Germany

**Development & Application of a Monitoring & Fault Diagnosis System for Marine Diesel Engines**

Y. Yu, J. Yang, Wuhan University of Technology, China

**A Method for Determination of Filter Blocking Tendency of Residual Bunker Fuels**

S. Ghosh, A. Talukder, R. Visveswaran, Viswa Lab, USA

**Clean Energy with DUAP Fuel Injection – Results & Further Developments**

M. Gutierrez, A. Marti, E. Vogt, DUAP AG, Switzerland

**The Research & Development on Parts Performance Improvement for Internal Combustion Engine**

C. He, Shanghai Golston Shipping Fittings Co. Ltd., China

**Evolution & Characterisation of the Friction Condition Transition of Chrome-Plated Cylinder Liner & Two Typical Piston Rings**

W. Jianping, China North Engine Research Institute, China

**The New Machining Method of Connecting Rod Spherical Surface**

X. Rongrong, D. Zongjiang, X. Shao, X. Hou, P. Zhou, Ningbo China

**Development Design of Crank Oil Seal**

Q. Liu, Ningbo, China

**Session 12**

**Study of Total Energy Utilizing for Biogas Power Generation-Cogeneration based on the Energy Efficiency Analysis**

S. Li, CNPC Jichai Power Equipment Company, China, S. Bai, Q. Zhang, G. Li, Shandong University, China
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