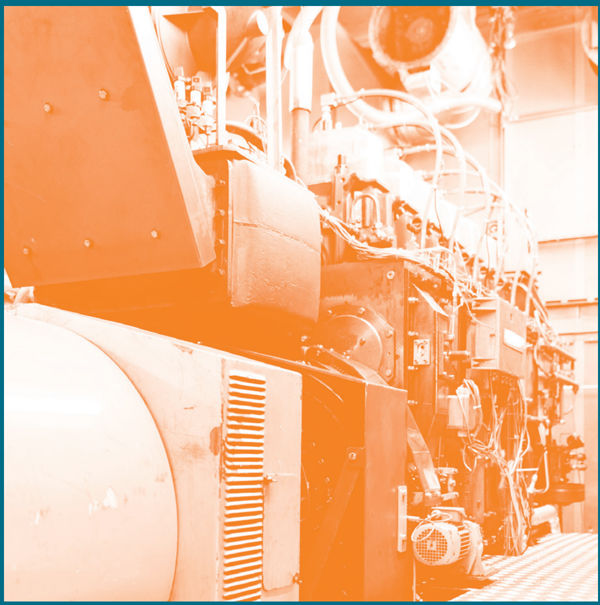
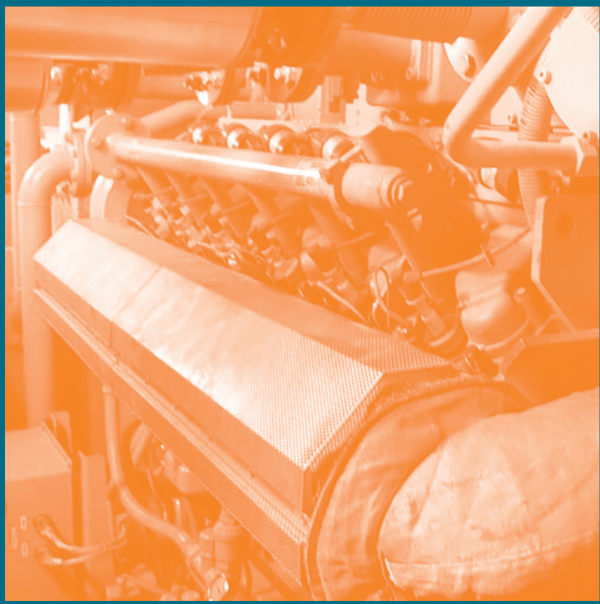
7th Large Engine Symposium 2022
The Future of Large Engines VII

Novel Technology and Fuel Options: The Route to Clean Shipping





Book of Abstracts

Bert Buchholz (Editor)
and 75 co-authors

Foreword:

Climate change and the need for rapid and drastic reductions in CO_2 emissions is presenting international shipping with new challenges. The contribution of shipping to global CO_2 emissions is approximately 2.7%. Considering the fact that more than 90% of the world's raw materials and consumer goods are transported by ship, this share appears to be comparatively small and proves the efficiency of shipping as a means of transport. However, the sum of these emissions is about as high as the CO_2 emissions for the whole of Germany, which highlights the need for a drastic reduction. The shipping branch has reacted to meet the challenge, setting a first and clear signal with the IMO Greenhouse Gas Strategy in 2018. The European Commission has since furthermore introduced its own plans to decarbonize the EU maritime sector with the FuelEU Maritime proposal of 2022.

The choice of fuel used is the most important key to CO_2 neutral shipping. As electric propulsion systems are only viable for small ships and short distances, synthetic fuels (E-Fuels or Power to X / PtX fuels) will play a key role. Green hydrogen, produced using renewable energy sources will provide a basis for these. Due to hydrogen's low volumetric energy density, further synthesis steps are required to produce PtX fuels which boast good storage capabilities, high total efficiencies and high compatibility with marine engines. Intense scientific research is necessary in the coming years in order to examine the suitability and effects of the use of the different PtX fuels in terms of environmental impact, safety, net value added and their effect on propulsion technologies and infrastructure, which in turn will enable founded strategic decisions. In addition, even approaches to the application of CCS technologies on board ships are already being discussed and developed today.

Concepts for reducing greenhouse gas emissions and harmful emissions resulting from shipping available in the short and mid-term time scales should not be forgotten whilst this research is being carried out. The potentials of LNG as a clean fuel for shipping should be quickly and thoroughly exploited. The advantages of LNG in terms of pollutant emission are invaluable, especially in avoiding environment conflicts in harbours and coastal regions. A rapid and sustainable solution to methane slip is however critical in the survival of LNG and dual fuel technologies, without which LNG's greenhouse gas reducing potential cannot be fully exploited. This will gain relevance as the production of synthetic methane or SNG offers the chance of a CO_2 neutral future while continuing to use and develop currently existent technologies and infrastructure and allowing easy integration into the current fleet of ships.

The fuels with 0.5% sulfur content introduced in 2020 will be a challenge for the branch for some time. Problems with fuel handling on board, mixing incompatibilities and the reliable operation of engine components and exhaust after-treatment systems have to be overcome. Fuel norms and parameters to be monitored need to be further developed in order to correctly evaluate the ignition characteristics, combustion behavior and emission performance of these fuels. At the same time, new possibilities arise for desulphurization technologies.

Against the backdrop of the challenging and dynamic world of the marine engine branch, the Rostock Large Engine Symposium offers a platform for the international exchange of ideas between researchers, developers, manufacturers and users. This symposium transcript showcases the content of the 7th Large Engine Symposium in Rostock which took place on the 15th and 16th of September 2022. This event was jointly organized by the University of Rostock's Chair of Piston Machines and Internal Combustion Engines and FVTR GmbH.

I would like to express my sincere thanks to all participants who have contributed to this edition of the conference transcript and to the success of this 7th RGMT – Rostock Large Engine Symposium. Special thanks also go to our guests, whose support was particularly important for the success of this symposium. I also wish to thank the companies Robert Bosch GmbH, Schaller Automation Industrielle Automationstechnik GmbH & Co. KG, MET Motoren- und Energietechnik GmbH and Kistler Instrumente GmbH for their support in sponsoring the participation of 9 students in the Large Engine Symposium.

My special thanks go to all the employees of the Chair of Piston Machines and Internal Combustion Engines (LKV, University of Rostock) and of FVTR GmbH involved in the preparation of this symposium. I thank them for their dedication, creativity and optimism in the many organizational and administrative tasks required for this year's symposium. Without their commitment the 7th RGMT – Rostock Large Engine Symposium in September 2022 would never have been possible.

Rostock, September 2022 Bert Buchholz

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Schedule Day 1: Thursday, 15th September 2022

TIME	TOPIC	SPEAKER	COMPANY
09:00	Opening	Prof. Bert Buchholz	LKV, University of Rostock
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	General Framework	Klaus Heim	Winterthur Gas & Diesel Ltd.
09:15	Welcome Address	Claudia Müller	Federal Government Co-ordinator for Maritime Industry & Tourism
09:30	The maritime energy transition and the large engine industry	Peter Müller-Baum	VDMA
10:00	Power-to-X - Enabler for decarbonization in high power applications	Dr. Daniel Chatterjee	Rolls-Royce Solutions GmbH
10:30	Coffee Break		
	Session 2:	Lead	
	Methanol as Marine Fuel	Dr. Daniel Chatterjee	Rolls-Royce Solutions GmbH
11:00	Methanol as a viable fuel option to drive carbon-neutral shipping	Prof. Gunnar Stiesch	MAN Energy Solutions SE
11:30	ABC's DZ Dual Fuel Methanol engine	Ewout De Wilde	ABC
12:00	Methanol injection systems for large 4-stroke engines	Ingmar Berger	Woodward L'Orange GmbH
12:30	Lunch		
	Session 3:	Lead	
	Developement Trends for Injection Equipement	Prof. Gunnar Stiesch	MAN Energy Solutions SE
13:45	Powering a greener future: the OMT injector enables high-pressure direct injection of ammonia and methanol	Dr. Marco Coppo	OMT – Officine Meccaniche Torino SpA
14:15	Development and Simulation of "High Pressure Gas-and/or hydrogen DI-Injectors" for large bore internal combustion engines	Erich Vogt / Bernd Niethammer	DUAP AG / ITAZ GmbH
14:45	Injection technologies for alternative fuels	Jens-Olaf Stein	Robert Bosch AG
15:15	Coffee Break		
	Session 4:	Lead	
	GHG-neutral Ship Operation	Dr. Michael Willmann	Woodward L'Orange GmbH
15:45	Development of a GHG-neutral combustion concept exemplified by methanol	Dr. Martin Theile / Martin Drescher	FVTR GmbH
16:15	Hydrogen as a fuel – a cruise ship operator perspective	Malte Zeretzke	Carnival Maritime GmbH
16:45	Transition to new marine fuels in shipping – The ship operators view	Sebastian Ebbing	VDR
18:00	Boat Tour		
19:30	Social Evening Event		

Schedule Day 2: Friday, 16th September 2022

TIME	TOPIC	SPEAKER	COMPANY
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		Prof. Kai Herrmann	FHNW
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	System Requirements of New Fuels	Prof. Kai Herrmann	FHNW
09:00	Ammonia as a Fuel – the role for catalytic components	Dr. Joseph McCarney	Johnson Matthey
09:30	Research approaches and methods for future fuels and lubricants in marine applications	Dr. Fanny Langschwager	LKV, University of Rostock
10:00	Coffee Break		
	Session 6:	Lead	
	Marine and Stationary Energy Systems	Dr. Marco Coppo	OMT SpA
10:30	Upgrade of lean-burn gas engines to future hydrogen admixture in the natural gas grid	Dr. Marco Schultze	Caterpillar Energy Solutions GmbH
11:00	Optimization of the HyMethShip system using the simulation platform LEC ENERsim	Dr. Nicole Wermuth	LEC GmbH
11:30	The low-speed two-stroke engine in a hybrid setup: The engine designer's approach to system integration	Stefan Goranov	Winterthur Gas & Diesel Ltd.
12:00	Lunch		
	Session 7:	Lead	
	Fundamental Research in Injection Technologies for Alternative Marine Fuels	Prof. Andreas Wimmer	TU Graz
13:15	AmmoniaMot – Experimental investigations of an ammonia dual-fuel combustion process for decarbonization of the maritime sector	Karsten Stenzel / Harald Arndt	WTZ Roßlau / Neptun Ship Design
13:45	Comparison of pilot fuel ignited premixed ammonia vs. methane dual-fuel combustion	Silas Wüthrich	University of Applied Sciences and Arts Northwestern Switzerland (FHNW)
14:15	Fundamental combustion studies on alternative fuels for low-GHG ships	Dr. Satoshi Kawauchi	National Institute of Maritime, Port and Aviation Technology (MPAT), Japan
14:45	Coffee Break		
	Session 8:	Lead	
	Wear Detection & Reduction Measures	Dr. Christian Reiser	WTZ Roßlau GmbH
15:15	Combination of physical and virtual sensors for the condition-based monitoring of large engine sliding bearings	Dr. Horst Brünnet	Schaller Automation Industrielle Automationstechnik GmbH & Co. KG
15:45	From severe wear to a lifetime of 32,000 running hours: Field study on valve spindles in lean-burn gas engines	Jan-Peter Edelmann	Märkisches Werk GmbH
16:15	Closing Words	Prof. Bert Buchholz	LKV, University of Rostock

Hosts: FVTR

Your host, the FVTR GmbH...

is pleased to welcome you to this year‘s RGMT. Just as new technological developments in the field of maritime energy transition are noticeably spreading, we have also further developed the conference and look ahead to welcoming you at the new venue in the Yachthafen Residenz Hohe Düne.

Climate neutrality, CO_2 and pollutant emissions, new maritime fuels, energy transition, digital twins, ... these are just some of the buzzwords of the topics that will accompany us over the next two days at the conference and probably also your company in the coming years. As a partner of the maritime energy transition always aiming for perfecting energy conversion, FVTR GmbH is pleased to offer you an exchange platform for your topics. We are looking forward to exciting technical discussions and presentations. It‘s good to have you here.

Martin Theile & Martin Drescher

Dr.-Ing. M. Theile

Dipl.-Ing. M. Drescher

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FVTR GmbH

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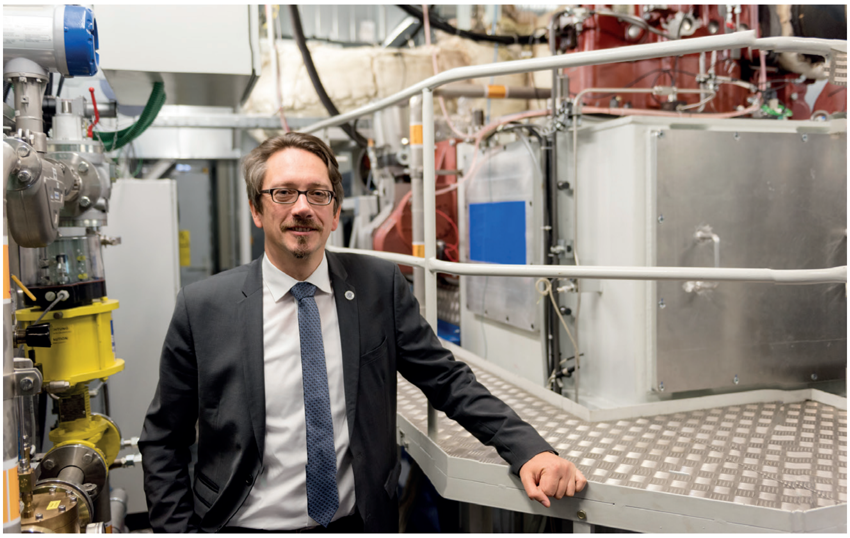
Your Host, the LKV…

is pleased to welcome you as a guest at the 7th RGMT. With a record number of participants and an exhibition that has grown once again, we see that the maritime energy conversion also faces you and your company with exciting tasks. Together with you, we would like to take the path towards a climate-neutral shipping in the coming decades.

That is why we have literally taken up the cause of the maritime energy conversion. With significantly expanding experimental opportunities at the Rostock research site in the future and a strong energy industry in northern Germany, my team and I are looking forward to exciting projects and sustainable technologies for our industry.

Your Prof. Dr.-Ing. Bert Buchholz



Prof. Dr.-Ing. Bert Buchholz

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LKV

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The maritime energy transition and the large engine industry

Peter Müller-Baum (VDMA)

At present, unfortunately the global energy transition is unable to keep pace with the goals of the Paris climate protection agreement. This also applies to the shipping industry. Yet the industry accounts for around 2.5 percent of global CO_2 emissions, and transport volumes at sea continue to rise. The good news is that the shipping industry can make a significant contribution to fight climate change. But it must act quickly and decisively because the Maritime Energy Transition must not fail. Direct electrification and hybridization will probably continue to work for shipping only to a limited extent and rather in niche applications, although there are some encouraging examples. However, the internal combustion engine will certainly continue to play a key role in the future. However, we must succeed in quickly replacing fossil fuels with CO_2-neutral alternatives. Given the enormously long innovation cycles in the maritime industry, this is a major challenge.

LNG is already being increasingly used, and new ships are being ordered with dual-fuel engines so that LNG can be used in addition to traditional fuel. The future lies in synthetic fuels, where energy is stored in form of chemical bonds. If the used energy carriers are produced based on green hydrogen, ships will be CO_2-neutral or even CO_2-free.

At present, synthetic LNG, ammonia and methanol are the fuel options most talked about. The Pros and Cons are intensively discussed at international level, and on the long run the market may decide which technology and which fuel is the best option. For the time being, however, to start the market ramp up also regulatory measures are necessary. The different ideas and proposals by IMO, the EU (Fit-for-55 package, in particular FuelEU Maritime), as well as national governments (with a variety of hydrogen strategies) are neither consistent nor necessarily expedient.

The presentation will cover and compare these regulations, including a European PtX-Roadmap for the maritime industry. It is intended not only to present facts and figures, but also proposals that might be discussed with the conference participants.

Power-to-X - Enabler for decarbonization in high power applications

Dr. Daniel Chatterjee (Rolls-Royce Solutions GmbH)

Defossilization of high-power applications represents a challenging task as complete electrification often is not possible in most cases. One promising option for the reduction of greenhouse gas emission of high-power applications are renewable electricity-based fuels, so called e-fuels including hydrogen, that are produced by Power-to-X (PtX). While e-fuels are not an economically viable option yet, a market ramp-up is expected after 2030, evoked by ambitious CO_2 reduction targets and decreasing prices due to scale-up of production sites. PtX enables the coupling of the electricity and mobility sectors and allows the usage of existing infrastructure for the transportation of renewable fuels globally.

The potential of e-fuels produced with PtX is covered in the first part of this paper. The global projected demands of e-fuels as well as the efficiencies of different fuel options (well-to-wake) are identified and shown for high power marine applications. Furthermore, production costs of e-Fuels are analysed and the implications of the location and its suitability for renewable energy harvesting is assessed globally and represented by a harvesting factor. The second part of this publication showcases promising alternative new propulsion technologies that are developed for e-fuels, like methanol combustion engine and fuel cell as well as their respective challenges. Besides the overall market potentials, the work also demonstrates a pathway from economic production of renewable fuels to the usage of the e-fuels in high-power maritime powertrain.

Methanol as a viable fuel option to drive carbon-neutral shipping

Prof. Gunnar Stiesch (MAN Energy Solutions SE)

Methanol is a viable fuel candidate for marine applications to meet the stringent emission regulations and ambitious greenhouse gas reduction goals from international organizations, e.g. the International Maritime Organization (IMO) and the EU. Due to its liquid state at ambient conditions, the alcohol is easier to handle compared to the gaseous alternatives, ammonia and hydrogen.

Already in 2016, the first MAN B&W 2-stroke dual-fuel methanol engines, the S and G50ME-C LGIM, entered the world fleet.

More than 120.000 service hours have been logged in the meantime. The first 23 ordered 2-stroke methanol engines have been installed on vessels carrying methanol as a cargo, whereby an easy fuel supply and a straight forward business case can be achieved. In 2021 a major step was made by A.P. Møller-Mærsk ordering methanol engines both for a 2.100 TEU feeder and later for additional 8+4 times 16.000 TEU container vessels, all to be operated on green carbon neutral methanol. This has changed and further intensified, the interest in methanol from the maritime industry. At MAN Energy Solutions, these orders called for the development and design of the large G95ME-LGIM engine, initially intended for large and very large container vessels, but in the future also applicable to the ULCC segment. And in order to accommodate the extended market interest in methanol engines also for other vessel types, MAN is rolling out the LGIM technology to further engines in its 2-stroke engine program: a G80 engine is currently under development, and 70 and 60 bore engines are considered depending on market interest.

Similar as for 2-stroke engines, methanol is now gaining much more attention also for typical 4 stroke engine applications, in order to enable operation on carbon-neutral fuels. Therefore, the development of methanol 4-stroke engine applications both as propulsion and as auxiliary systems is in progress. Typical 4-stroke applications are characterized by a larger variety of boundary conditions and requirements. Studies on different combustion processes and injection systems have been carried out to identify and select the optimal solution for the relevant applications, considering both new build and retrofit solutions.

This paper provides an insight into powering vessels on carbon-neutral green methanol as part of MAN Energy Solutions' decarbonization strategy. Details on engine and fuel gas supply system design as well as flexibility and safety aspects are presented and display the progress achieved in the development of methanol burning engines.

ABC's DZ Dual Fuel Methanol engine

Ewout De Wilde (ABC)

ABC's DZ engine family (1-4MW at 1000rpm) is widely used and has proven itself in diverse applications. The majority are diesel engines, however also several biofuel versions and LNG Dual Fuel versions are in the field. Recently, a Hydrogen Dual Fuel engine is introduced and full aftertreatment (SCR+DPF) was added to comply with EU stage V limits - whatever fuel is used.

The latest addition to the DZ engine family is the Methanol Dual Fuel version. The development, test results and first field application will be described in this paper.

The origin for the development was the need for an engine that has the potential to meet and exceed the IMO 2050 GHG reduction target, specifically for those applications where hydrogen storage is impractical in terms of space requirements. Additionally, it was a must to be able to retrofit existing DZ diesel engines.

Based on these requirements a low-pressure port fuel injection system was chosen and first SCE testing was performed with available components. Based on these results, several engine components and settings were improved to increase the substitution ratio and decrease emissions. The improvement was again validated on the SCE. To limit the number of iterations on the SCE, separate component testing of injectors was performed, and mixture formation was simulated with CFD.

Based on these SCE results, a multicylinder configuration was determined and an 8-cylinder prototype was build. The results of these tests will be discussed as well as the aftertreatment setup to reach different emission legislations.

Finally, an outlook is given on the first application for ABC's methanol engines: within the EU funded project "Fastwater", a Tug from Port of Antwerp will be retrofitted to methanol dual fuel operation. The necessary changes to convert the existing DZ diesel engines will be described.

Methanol injection systems for large 4-stroke engines

Ingmar Berger (Woodward L'Orange)

The fuel properties of methanol allow a wide range of feasible combustion concepts from spark ignited otto-cycle concepts with port fuel injection (PFI) or direct injection (DI) to diesel-like high pressure dual fuel (HPDF) concepts. The best choice is strongly depending on the target application.

Woodward L'Orange (WLO) has developed a whole family of high-pressure dual fuel injectors in recent years. The main advantages of the HPDF concept are the high efficiency, power density and the inherent redundancy of the engine concept with its 100% diesel capability. The well-established 3-1 nozzle design will be complemented by a 1-1 nozzle design that allows a more robust and economical injector design.

While HPDF injector concepts rely on hydraulic actuation, for single fuel engines the goal is to have direct solenoid actuated fuel injection systems to reduce system complexity on the engine.

PFI injectors are designed to inject the methanol with relatively low rail pressures of 10-50 bar. Therefore, the nozzle concept needs to be optimized for atomization at low pressures. Swirl nozzles are one promising concept to achieve this goal. Methanol PFI can offer an attractive path to retrofit existing engines to allow a smooth transition to low carbon combustion engines.

For solenoid driven DI methanol injectors, the main challenge is to integrate the methanol injection system along with the spark plug. Arranging the spark plug preferably in the center of the cylinder head the injector must be placed at the periphery of the combustion chamber. Hence, WLO has designed a long and slim nozzle, which requires minimum space at the bottom end of the cylinder head. For larger injection pressures of several hundred bar the atomization concept can remain pressure based like for conventional injectors. For smaller injection pressures however, a swirl atomizer offers better atomization results and is therefore used below 50bar.

For WLO's DI and PFI injector family a whole range of solenoids is established, ranging from solenoids similar to those currently used in WLO's Diesel injectors up to high power solenoids that are capable of actuating directly driven Methanol injectors for large engines.

Design examples for the different injector types will be discussed.

Powering a greener future:
The OMT injector enables high-pressure direct injection of ammonia and methanol

Dr. Marco Coppo (OMT – Officine Meccaniche Torino SpA)

The ambitious targets adopted by the International Maritime Organization to reduce the amount of greenhouse gases emitted by the marine transport sector forces the industry to look for new ways of powering vessels. While propulsion system electrification is feasible on short range voyages, where frequent battery recharging is possible, it becomes impractical for ocean going vessels, where chemical energy storage in fuel molecules and its conversion into mechanical energy through an internal combustion (IC) engine still represents the most feasible solution.

In order to make vessel operation with IC engines sustainable and achieve net-zero CO_2 propulsion, the engines should be operated with carbon-free fuels, such as ammonia, or synthetic or e-fuels that are produced from renewable power and CO_2, such as methanol. This requires the development of dedicated fuel injection systems due to the nature of such fuels, which are toxic, have low lubricity, low vapour pressure and can promote corrosion.

The paper explains the design issues and choices related to the development of high-pressure injection systems capable of operating with ammonia and methanol, presenting the architecture of a fuel-actuated common rail injector prototype developed by OMT, and how it was used to study and optimise combustion concepts for such fuels.

The injector was developed and tested first with water on an injection test rig, to simulate the physical characteristics of such fuels and identify potential wear issues. All the materials chosen were tested for compatibility with methanol and ammonia, and a summary of the findings is reported here.

First insights about fuel spray propagation and mixture formation were obtained by testing the injector on an optically accessible, constant volume chamber filled with heated inert gas, with a mixture of Schlieren and Mie scattering measurement techniques.

The OMT injector, fitted with three different nozzles designed to achieve the same injection rate for operating pressures ranging from 600 to 1300 bar, was used for the single cylinder research engine investigation as part of the COMET Center LEC EvoLET conducted by LEC, OMT and other company and university partners. The focus of this test campaign was to study the combustion process of diesel-ammonia and diesel-methanol dual fuel engine operation where a separate diesel injector was used to supply fuel for the diesel pilot ignition.

The paper concludes with the presentation of the first results of the experimental campaign on combustion optimisation, and an overview of the lessons learned about operating such fuel injector with ammonia and methanol.

Development and simulation of "high pressure gas-and/or hydrogen DI-injectors" for large bore internal combustion engines

Erich Vogt (DUAP AG), Bernd Niethammer (ITAZ GmbH)

Gas-hydrogen mixtures as well as pure hydrogen has long been considered as a future fuel in large size transportation powertrains (incl. marine applications), due to its ability to eliminate carbon-based emissions (e.g., greenhouse gases) and to achieve a high energy efficiency. Furthermore, hydrogen can be produced out of renewable energy sources.

In the internal combustion engine industry, several technologies have been developed up to now, in order to reduce the carbon emissions. One of the possible ways is the use of low- or zero-carbon content fuels, such as natural gas-hydrogen blends, up to pure hydrogen. Hydrogen as an energy carrier and used as main fuel is a promising option due to its carbon-free content, wide flammability limits and fast flame speeds. Utilizing hydrogen direct injection has been proven to be a promising solution, to fulfill the carbon emission targets and future legislation requirements in many countries.

During the second half of the 20th century, hydrogen fueled Internal Combustion Engines (ICEs) were mainly demonstration projects and was focused on automotive applications. Advanced methods and new materials for hydrogen storage (e.g., high pressure storage, up to 700 bar), production (e.g., solar thermo-chemical processes) and usage (e.g., high pressure direct in-cylinder injection). These developments have catalyzed the revival of global interests towards incorporating hydrogen as an energy carrier in large size powertrains.

One of the major obstacles in commercializing of hydrogen DI or Dual-Fuel DI engine, is the lack of commercially available gas- and/or hydrogen-injection hardware.

The cooperation of the project partners will lead to a common development and production of new types of gas and/or hydrogen high-pressure DI injectors up to 350 bar, for large engines with a displacement of 4 to 40 liters per cylinder.

The overarching goal of this program is an economic, durable and sustainable gas- and/or hydrogen-injector design for accelerating the shift to zero-emission power in shipping, as well as in heavy-duty road vehicles and off-highway machines.

This paper will provide an overview of the development, simulation analysis and knowledge stage of gas- and/or hydrogen-DI-injectors use in internal combustion engines, under various engine operation modes and strategies, to achieve short injection times as well for load amounts and the idle volumes.

Keywords: High Pressure, DI (Direct Injection), Natural Gas, Hydrogen, Internal Combustion Engine

Injection technologies for alternate fuels

Jens Olaf Stein (Robert Bosch AG – Business Unit Large Engines)

The Paris climate goals against global warming pushes the industry and society into action. Large engines make a significant contribution of 5 -7 % of the world-wide CO_2 emissions. Consequently large engines are forced to reduce their greenhouse gas and CO_2 emissions significantly. The application areas of large engines are Construction and Industry, Power Generation, Marine and Railways. Large engines are because of several reasons difficult to replace by batteries and fuel cells. That is the reason why CO_2 neutral or even CO_2 free large engine applications are already in development to achieve the greenhouse gas emission goals for 2030, 40 and 50. Pilot applications will enter the market even by 2022 and the ramp up of new technologies will happen prior to 2030. CO_2 emission reduction can be fulfilled by improved engine and vehicle efficiency, by carbon capture and storage technologies and by bio- and e-fuel applications. This paper shows the application options for bio- and e-fuels in large engines.

Due to the fact that electrolysis based drop in fuels (e-Diesel, e-Kerosine,) have a low production efficiency, relatively high production costs and will be very likely occupied by off highway and airplane applications, alternative fuels will be required. Today hydrogen, ammonia, methane, methanol and ethanol seem to be the most promising alternative fuels for large engine applications. The physical and chemical parameters of these fuels differ a lot from Diesel and natural gas. Differences in viscosity, lubricity, density, energy density, vapor pressure, evaporation energy, flash point, flame-ability, ignition energy, cetane number, octane number and flame propagation require significant adaptions at the fuel injection/admission system as well as the combustion system.

All alternative fuels require individual mixture preparation and combustion systems for best fuel consumption and lowest exhaust emissions. The capability of retro fit and dual fuel use has to be considered in all concepts. The paper is showing the application areas and pros and cons of different mixture preparation systems for the alternative fuels of large engines.

Development of a GHG-neutral combustion concept exemplified by methanol

Martin Theile, Martin Drescher (FVTR GmbH)

Alternative fuels seems to be a possibility to reach the goal of climate neutrality and a cleaner shipping. In particular, „power-to-X concepts“ (PtX), in which fuel production is realized with the use of renewable energies, offer a real opportunity to avoid greenhouse gas emissions. However, when using novel fuels, various challenges may occur which have to be solved.

For methanol, as an example of a possible e-fuel, compared to conventional fuels, the lower calorific value, the high enthalpy of vaporization, the changed requirements for material compatibility and the different safety aspects must be considered. To address all those aspects an approach and methodology has been established. Such a workflow for a combustion process development is shown in the following paper.

In the first step, CFD analyses are used to determine the injection parameters. These include the nozzle's geometric structure, hole number, spray angle, flow rate and the evaporation and mixture behaviour of the spray. Subsequently, additional experimental investigations are carried out to validate these data on the component test bench before using the injectors on the engine. Further, the suitability and material compatibility of the pump and other fuel system components could be tested on separate test benches. The experience gained in this process provides considerable help in the subsequent investigations on the engine test bed.

The methanol project covered various injection and combustion strategies. These can be divided into port fuel injection as a homogeneous mixture formation process and direct injection. Direct injection was applied as a homogeneous, partially homogeneous and diffusive combustion process using the optimized nozzles and the flexibility of the common-rail technology. Diesel injection was used as the ignition source in all cases. The different processes were compared in terms of efficiency, emissions, combustion cycle variations, ignition behaviour and degree of substitution. Based on the results obtained, further investigations were carried out using the diffusion combustion process and a maximum methanol injection pressure of 2200 bar. Thus, methanol rates of 98.5 % energetically could be achieved. Finally, to demonstrate a 100% GHG-neutral combustion process, the diesel fuel required for ignition can be replaced accordingly. Suitability of e-fuels for substituting the pilot ignition are discussed on the example of HVO and OME.

Hydrogen as a fuel - a cruise ship operator perspective

Malte Zeretzke (Carnival Maritime)

Carnival Maritime as the operator of AIDAs and COSTAs cruise ship fleets is heading towards GHG neutrality till 2040 and a first "zero emission ship" in this decade. Hydrogen is considered having a key role for the associated roadmap and for the marine energy transition as such. However, many challenges along the entire value chain from the production to the utilization on board will have to be overcome to allow large oceangoing cruise vessels to be operated on global itineraries. This includes technology, timelines, regulations/politics, operational flexibility, production volumes and not least the economics behind the novel energy carrier. One key element for a ship operator will be the storage of hydrogen on board. While storage conditions and volumes of pure hydrogen, especially for long haul itineraries is imposing massive technology challenges. Hydrocarbons or ammonia as a storage medium for hydrogen might be an attractive option, allowing to implement an ambitious green cruising strategy by starting today.

Exhaust gas aftertreatment for future large engine fuels

Dr. Daniel Peitz (HUG Engineering AG)

Efforts for defossilization of the large engine industry are ramping up, but still there is no clear winner in terms of the future fuel: Hydrogen (H_2), Ammonia (NH_3), Methanol (MeOH), Methane (CH_4) or other liquid diesel fuel substitutes are all under consideration. The origin of the fuels should be either biological or synthesized using renewable energy to avoid a shift from consuming direct fossil energy to their indirect use. However, carbon capturing technology must be mentioned as an exception to enable still use of fossil primary energy sources, provided the fossil carbon balance can be closed.

In terms of specific pollutant emissions, each of the above fuels comes with intrinsic challenges and potentials. The injection and ignition technology utilized for their combustion largely determines the emission profile, becoming the starting point for any exhaust gas aftertreatment. The other main factor are the future emission limits on global, transnational, national and regional levels, defining the goal to be reached. Moving from start to finish line, there are specific obstacles for the various fuels in discussion and, hence, different paths one can take, each with peculiarities along the way.

In this contribution, Hug Engineering will highlight the characteristics of different future fuels and combustion concepts in terms of aftertreatment possibilities and restrictions. Many of the statements are still general in their nature, as exhaust gas conditions and compositions are not fully known for all scenarios. However, some conclusions where solutions will be available considering today's technology and where significant challenges remain can be made already due to the experience in niche applications in which exhaust gas aftertreatment has been already combined with alternative fuels or in which ambitions for outperforming legal clean air requirements exist. Also, there are many ongoing research activities exploring various engine setups for far from today's fuels disclosing also exhaust gas composition.

Most likely we will continue to see no single fuel being the solution for all large engine applications and their use cases, thus, from an aftertreatment view we will need to work on all the specific challenges in parallel, be it NO_x for all high-pressure fuel injection concepts, laughing gas from NH_3 combustion, formaldehyde from methanol combustion or methane slip from gas combustion. Additionally, we need to continue reducing all kinds of particulate emissions, including ultrafine particles which cause the strongest local health effects. The optimum arrangement of dedicated components dealing with these and other pollutants is also an important topic due to the possible interactions.

Exhaust gas aftertreatment as well as engine development will see more varieties than in the past decades, interaction and collaboration between the two will become even more crucial. Therefore, we are happy to present our considerations about this topic at the large engine symposium.

Ammonia as a fuel – The role for catalytic components

Dr. Joseph McCarney (Johnson Matthey)

Ammonia is an interesting option for a "fuel of the future". Zero carbon at the point of use it has potential for low carbon emission across its lifecycle. Though its energy density is half that of diesel, it is many times that of compressed hydrogen and is an option to store and transport renewable hydrogen in a liquified form. Ammonia may be used directly as a fuel to generate power in boilers, turbines, engines and fuel cells.

Aspects of ammonia combustion are challenging. Some may be resolved via blending with other fuels e.g. hydrocarbon based (including bio and e-fuels) and hydrogen. Blends with hydrogen (where ammonia is cracked to provide an ammonia/hydrogen mix) are particularly interesting as they maintain the possibility of low carbon emissions. Emissions from ammonia fuelled processes may contain NO_x, NH_3 and N_2O – all of which need to be controlled.

Engine controls with improved system designs will help limit the formation of undesirable emissions but catalyst components are expected to play a crucial role in both the processing of ammonia prior to combustion and in the after treatment of NO_x & NH_3 (via SCR) and the reduction of N_2O. With a GHG equivalency of ~300, controlling N_2O emissions to very low levels is a critical factor for these applications. In this paper we review options to control these emissions and outline the experience gained from the Nitric Acid Industry on abating N_2O and compare key differences with engine emissions such as temperature of operation, oxygen levels and water content.

Dr. Fanny Langschwager (LKV, University of Rostock)

Within the marine market, heavy fuel oil (HFO) has been the number one fuel for decades, with the need for cheap energy sources outweighing environmental concerns. To achieve the climate policy goals (reducing GHG emissions in shipping), large quantities of CO_2-neutral fuels will be needed in the future. In 2018, the IMO (International Maritime Organization) set out its strategy for reducing ship-based greenhouse gas emissions in its resolution MEPC.304(72), signalling that CO_2 emissions are to be reduced by 40% by 2030 and by 70% by 2050. Due to their comparatively long lifecycles, ships and their propulsion systems built in 2025 will still be in service well after 2040. Thus, the key to achieving these ambitious targets appears to lie in the decarbonisation of fuels. Although approaches to optimize the ship design (EEDI=Energy Efficiency Design Index) itself and the way the ship is operated (EEOI=Energy Efficiency Operational Indicator) lowers the fuel consumption, a 100% CO_2-free shipping will just be possible with the use of a carbon free or carbon neutral fuels in the future.

Besides this shipping is one of the largest emitters of sulfur oxides and CO_2. Since 2020, ocean-going vessels may only use fuels with a maximum sulfur content of 0.1 ma.-% when operated within Sulphur Emission Control Areas (SECAs). The current IMO regulation limits the sulfur content in fuel in the open sea to 0.5 ma.-%. In the short term, therefore, new low-sulfur marine fuels are needed that make shipping more environmentally friendly.

This requires further significant changes in marine fuels, which have to be implemented quickly. Large-scale production of synthetic carbon-neutral fuels is still costly and not mature for current applications. The volume structure in maritime shipping and competing sectors such as aviation, stand in the way of timely and widespread use of such fuels. Under these circumstances, biogenic fuels such as pure vegetable oils, biodiesel (FAME), hydrogenated vegetable oils (HVO) and biomethane (LNG) can be used as alternative solutions to bridge the gap until PtX fuels become available.

Another focus of research is on tailor-made lubricants for internal combustion engines operating with future PtX fuels, such as ammonia and methanol. These fuels have very poor lubrication properties. In addition, water is produced in large quantities during hydrogen combustion, which leads to severe stress on the lubricating oil, far beyond the levels known from engines running on fossil hydrocarbons. Similar fuel-specific problems are being investigated in relation to hydrogen, methanol and NH_3 engines.

Following the currently visible developments in power generation and power storage in Germany, the conversion of electricity into gas seems to be an innovative objective with currently available technologies. The vision for the future is to temporarily store the electricity generated from the overproduction of renewable energies in the form of hydrogen and, if necessary, to use it for electricity generation by combustion in a lean burn gas engine with high efficiencies.

The requirements for CHP units driven by lean gas engines are very diverse and will continue to increase. Due to their high level of development, they succeed in meeting these requirements. They have high efficiencies for economical plant operation and at the same time can be used flexibly to compensate for fluctuating energies from wind and photovoltaics and provide static and, if required, dynamic support for the power grid.

The addition of hydrogen generated with surplus electricity to the natural gas grid can thus contribute to the decarbonization of electricity generation in natural gas CHP plants. Lean gas engines can be reliably operated with admixtures of hydrogen. Tests on the test bench have shown that hydrogen admixtures of up to 25 % to natural gas can be handled by the MWM engines of Caterpillar Energy Solutions GmbH with approximately the same performance and efficiency. In addition, the applicable safety standards are met. The reliability and durability of the products expected by the customer will be similar to natural gas engines.

Transoceanic shipping is the backbone of international trade and is responsible for around 3 % of anthropogenic CO_2 emissions. The IMO reduction targets for greenhouse gas emissions call for fossil-free and innovative technology solutions that require optimal design and integration into the overall propulsion system. The use of renewable, and in particular low flashpoint fuels, poses challenges for the port infrastructure and requires the buildup of renewable fuel supply chains, while the onboard installations face the challenge of ever-increasing complexity, amongst others the coupling of multiple energy forms such as electricity, fuel and heat, additional storage systems and the optimal control of hybrid ship propulsion. Design and optimization of such systems with multiple degrees of freedom necessitate sophisticated simulation tools, which consider both technological and economic boundaries.

In this paper the simulation platform LEC ENERsim is presented, which allows optimization of generic energy systems, from the early design phase to commercial operation. The simulation concept enables coupling of various energy system components such as sources, converters and storages. Under given technological and economic constraints, mathematical models are utilized to optimize both design and operation for custom target functions such as lowest costs or emissions.

A techno-economic assessment of the HyMethShip (Hydrogen-Methanol-Ship) system is performed using LEC ENERsim. The concept of HyMethShip uses onboard pre-combustion carbon capture to drastically reduce CO_2 emissions. By reforming renewable methanol to hydrogen in a membrane reactor, CO_2 is separated, liquefied and stored on board. Hydrogen acts as energy source for internal combustion engines, and engine exhaust heat is utilized to drive the initial reforming reaction.

The HyMethShip concept is evaluated for a RoPax ferry operating in the Baltic Sea, and possible optimal designs of the system are discussed. The model optimizes the system for a typical operational profile of a single voyage, intrinsically covering different maneuvering phases such as entry/exit of harbors and open sea navigation. Optimal design of hybrid system components includes battery sizing, electric drivetrain, intermediate hydrogen storage and CO_2 specific components like liquefaction and storage units. Reformer heat requirements are optimally aligned with engine waste heat potentials, and the need for backup thermal energy supply to enable sustainable hydrogen operation is evaluated. Different operation modes for dual fuel operation with methanol as backup fuel are evaluated.

The low-speed two-stroke engines are dominating the merchant marine sector as preferred prime movers. This is mainly due to their relatively high efficiency, reliability, and ease of maintenance and use.

Maturing technologies in the field of electrification have increased the pace of hybridising merchant ships with two-stroke main engines. The systems discussed in this paper consists of a dual-fuel main engine coupled with a shaft generator, battery, thruster, auxiliary generating sets, and an energy management system, interfaced with the controllers of all the energy resources and converters.

When efficiently integrated, especially on a control level, the system benefits are multifold. The fuel consumption and CO_2 emissions are reduced, while the level of redundancy is increased. In addition, the system spinning reserve capabilities are enhanced, which enables optimum output of the energy resources without the risk of a blackout. The transient behaviour of the machinery is also improved. Furthermore, efficient system integration can help enhancing functionality and prevent premature degradation of system components, as well as reduce fuel consumption, all of which can result from suboptimal integration.

This paper discusses some key challenges for designing two-stroke engine-based hybrid systems, especially when relatively larger shaft generators are required. This may restrict the power output of the shaft generator due to the engine's constrained operational field and limitations related to its transient load acceptance. Moreover, emphasis is placed on the importance of proper sizing of the electromechanical subsystems and the defined strategies for active control among them to fulfil system-wide optimisation objectives.

The methods employed at WinGD for designing and deploying such systems are explained in further detail using different case studies. These case studies provide evidence of significantly enhanced overall ship efficiency, including reduced fuel consumption and CO_2 emissions. Through choosing the optimum system configuration and control strategies, the usage of the main engine is maximised, leading to increased propeller efficiency. Among others, this is made possible by a shaft generator using the light running margin for electrical energy production. The CO_2 emissions are reduced by minimising the running hours of the auxiliary generating sets or by operating them within their optimal efficiency range due to an intelligently distributed system load. The control ensures safe no-auxiliary-generating-sets operation at sea passage, and optimal energy production for safe manoeuvring. Furthermore, for applications with controllable-pitch propeller, an advanced control enables safe manoeuvring without the necessity of online auxiliary generating sets.

AmmoniaMot – Experimental investigations of an ammonia dual-fuel combustion process for decarbonization of the maritime sector

Karsten Stenzel (WTZ Roßlau), Harald Arndt (Neptun Ship Design)

Maritime transport accounts for around 3 % of global energy demand and roughly 7 % of oil consumption. The goal of the International Maritime Organization (IMO) to reduce CO_2 emissions by 50 % until 2050 compared to 2008 can only be achieved by a massive shift to carbon-free fuels. Ammonia is an important energy carrier for the decarbonization of maritime shipping and is characterized in this context by good frame conditions for production, storage as well as infrastructure. Accordingly, the classification society DNV expects ammonia to have a share in the maritime fuel market of around 30 % by the year 2050.

The BMWK-funded project AmmoniaMot is intended to lay an important foundation for the establishment of ammonia in future four-stroke engines and for the maritime energy transition. To achieve this, the project partners Technical University of Munich, MAN Energy Solutions, Woodward L'Orange, Neptun Ship Design and WTZ Roßlau have come together to form a strong alliance. In the project, basic investigations are being carried out on a Rapid Compression Expansion Machine (RCEM). In the RCEM, Heat release rate (HRR) analysis, as well as simultaneous shadowgraphy (SG) and chemiluminescence (CL) imaging, are used to characterize the influence of different spray interaction angles on diesel-piloted ammonia spray combustion. Strong interaction with diesel is found to initiate ammonia combustion faster. In addition, long after end of diesel injection, an influence of diesel products on ammonia combustion is observed. These preliminary investigations provide an important basis for the subsequent single-cylinder tests at WTZ Roßlau. To carry out the studies for the combustion process development, a comprehensive ammonia periphery was designed and built in cooperation with Neptun Ship Design. This allows ammonia to be injected directly into the combustion chamber at a pressure of up to 500 bar and is to be further developed in the next step into a modularized, encapsulated fuel system for use on board ships. In addition, holistic solutions are being developed for the introduction of ammonia as a marine fuel. Accordingly, not only the engines but also safe fuel systems have to be considered, taking into account the tank facilities and the bunker requirements. In combination with the development of the corresponding regulations by the classification societies, this should create certainty in planning and enable the timely introduction of ammonia technologies in the field as well as the establishment of production facilities by the energy industry.

Comparison of pilot fuel ignited premixed ammonia vs. methane dual-fuel combustion

Silas Wüthrich (University of Applied Sciences and Arts Northwestern Switzerland (FHNW), Institute of Thermal and Fluid Engineering (ITFE))

In view of reducing greenhouse gas emissions the transition from fossil fuels to sustainable energy carriers is a prerequisite to keep global warming within tolerable limits. Since IC engines will continue to play a role in global energy strategies during a transitional phase, especially for large engine applications difficult to electrify, the use of ammonia as substitute fuel may be an approach for de-carbonization. However, its utilization needs research since ignition concepts and combustion properties still pose considerable challenges in view of reliable and efficient operation.

The optical engine test facility Flex-OeCoS has been successfully adapted enabling dodecane pilot fuel ignited premixed ammonia dual-fuel combustion investigations. It features IC engine relevant operation conditions such as pressures, temperatures, and flow (turbulence) conditions as well as adjustable mixture charge composition and pilot fuel injection settings. Thermodynamic heat release analysis in terms of ignition and combustion characteristics has been established. Simultane-ously applied high-speed Schlieren/OH* chemiluminescence measurements allow the examination of the combustion process.

Premixed ammonia dual-fuel combustion has been compared to methane combustion process. Ignition delay, combustion transition, and turbulent flame propagation as well as heat release characteristics have been investigated within variation of air-fuel equivalence ratio, start of pilot fuel injection, and other operation conditions. Different gas properties (lower heating value, air-fuel ratio) illustrate ammonia lower reactivity affecting heat release and flame propagation. Moreover, strong dependency on air-fuel equivalence ratio (energy content) and temperature conditions in terms of ignition delay, dual-fuel combustion transition, and corresponding heat release is present. The optical investigations confirm the thermodynamic analysis and promote assessment of pilot fuel evaporation, ignition, combustion transition, and flame propagation. Conclusions give insight into the thermo-chemical processes of ammonia pilot fuel ignited dual-fuel combustion.

Dr. Satoshi Kawauchi (National Institute of Maritime, Port and Aviation Technology (National Maritime Research Institute), Japan)

It is an urgent task for us to develop marine engines to burn zero-carbon fuels like hydrogen and ammonia to achieve the IMO target to reduce GHG (Green House Gas) from international shipping drastically. Also, low-carbon fuels like natural gas (methane) and methanol which act as a bridge between conventional crude-based fuel oil and above-mentioned zero-carbon fuels should be restudied. This paper covers the following four parts.

Part 1: As concept designs of low- or zero-GHG ships for 2050 planned by the Japanese projects, prototypes of hydrogen fueled, ammonia fueled, methanol fueled and LNG fueled ships are introduced. The roadmap and concept ships proposed by the projects will strongly encourage the researchers to develop the low- and zero-carbon fuels and marine engine systems for them.

Part 2: Current combustion studies on 'bridge fuels', natural gas (methane) and methanol are reviewed. Most of the data in the part 2 are obtained by a world-largest class Rapid Compression and Expansion Machine (RCEM) that simulates the combustion chamber of low- and medium-speed marine engines.

For the Otto-cycle type natural gas engines, 'pre-ignition' at a higher load is an issue to be solved. In this part, the pre-ignition phenomenon is visualized and it is reconfirmed that a leaner and more homogeneous mixture is a measure to avoid the pre-ignition.

On the other hand, the Diesel-cycle type diffusive combustion by a high-pressure natural gas injection has no problem of pre-ignition or knocking. In this part, a fundamental study on both the Otto- and Diesel-cycle type methane combustion is restudied. It would be also useful for development of the both type of hydrogen burning engines.

Methanol has potential as a liquid 'bridge fuel' and it is also possible that bio-methanol and e methanol would appear as zero-carbon fuels in the future. In this part, visual data on the diffusive combustion of methanol spray is analyzed and the reason why low-calory fuels like methanol burn rather better than gas oil is explained.

Part 3: A fundamental calculative study on the ammonia spray formation is introduced. Comparing to the other fuels, ammonia spray is further cooled by evaporation because of its higher latent heat. Combined with ammonia's inherently slow combustion rate, this temperature drop would make some low temperature region in the flame and possibly causes a negative-effect on combustion like N_2O (a strong GHG) formation. In this part, some measures to reduce the N_2O formation is dis-cussed according to the above-mentioned calculative study.

Part 4: This part presents a study of high-pressure injection and diffusive combustion of hydrogen for the Diesel-cycle type hydrogen burning engine development, which has not been studied extensively compared to the premixed lean-burn (Otto-cycle) type hydrogen combustion.

It is considered by a fundamental experiment injecting hydrogen at 30 MPa into piston-compressed air that hydrogen diffusive combustion can be controlled well by its time-based injection rate, that means the lower hydrogen injection rate would make a milder combustion.

Furthermore, it is clarified by visualization that hydrogen jet can be stably self-ignited by a high temperature of piston-compressed air. That will lead to the development of an absolute zero-GHG engine without any pilot fuel.

Combination of physical and virtual sensors for the condition-based monitoring of large engine sliding bearings

Dr. Horst Brünnet (Schaller Automation Industrielle Automationstechnik GmbH & Co. KG)

Condition-based monitoring as tool for preventive and predictive maintenance of large engines alongside with the proceeding digitalization path their way into operation routines. Hazardous operating conditions and damage initiation can be detected online and trigger maintenance actions. The early detection and differentiation of damage initiation enable the user to plan service actions, increase maintenance intervals and reduce costs. Sliding bearings play a vital role in the operation of rotating machinery. Conventional monitoring approaches such as bearing temperature measurement show significant drawbacks with respect to mounting effort and reaction time. As a result, damages are only detected in an advanced state of bearing degradation. Schaller developed a bearing monitoring system in cooperation with RWTH Aachen University capable of detecting the transition from hydrodynamic lubrication into mixed friction which gives an early indication of metal-to-metal contacts and therefore an initiating damage. This online condition monitoring system for sliding bearings – BEAROMOS 2020 –identifies different lubricating conditions and has the potential to evaluate the severity for the development of failures. This is achieved by measuring the thermoelectric voltage created by the temperature difference between bearing and crankshaft in case of solid body contact. A former conducted experimental study on a sliding bearing test rig with measurement of load, friction torque, temperature of lubricant and bearing and sliding velocity showed that the online condition monitoring system BEAROMOS 2020 could not only distinguish mixed friction from hydrodynamic lubrication but also indicate wear and damage earlier than a bearing temperature sensor.

In this study, experimental results from a fully instrumented single cylinder engine test bench are presented, where main bearing and big end bearing failures were selectively induced and the resulting thermoelectric signal was evaluated. The bearing specimen investigated were analyzed over lifetime: before operation, after running-in and after damage initiation. The results confirm the high sensitivity of the online condition monitoring system which can clearly distinguish between hydrodynamic lubrication and different wear conditions. The fast and dynamic response to mixed friction conditions especially in critical engine operation scenarios yields an important advantage over bearing temperature monitors. Additionally, a physical engine model has been developed for the single cylinder test bench engine Hatz 1D81Z in cooperation with Vir2sense with the help of manufacturer data and available engine measurement data. This model was adapted to build a virtual pressure sensor which could be integrated in the test bench control unit. In combination with the mixed-friction signal, the virtual pressure sensor has the potential to link the source of mixed-friction to the actual firing sequence without installing another physical sensor prone to wear. The combination of an early wear indication by the online bearing monitoring system and the isolation of the friction source to one engine compartment is the foundation for a new condition-based monitoring system for large engine bearings.

From severe wear to a lifetime of 32,000 running hours: Field study on valve spindles in lean-burn gas engines

Jan-Peter Edelmann (Märkisches Werk Gmbh)

Besides modern engine concepts resulting from tightening emission legislations, robustness in operation is key for the future of large bore engines. Motivated by the Paris and Glasgow climate agreements, today's engine developments shall entail the ambitious transition from carbon-based fossil fuels to carbon-neutral or zero-carbon fuels. The reliability of engine components is of essential importance in this context. In particular, gas exchange valves are in focus as they face highest thermal, mechanical and corrosive loads.

This work deals with a development of the tribological pair valve spindle/seat ring, which started at the analysis of severe valve wear and ended at a running time of 32,000 hours of newly designed components in the engine field. The field study comprises several valve designs which were tested on a constantly operated lean-burn gas engine (6 MW, 750rpm). Theoretical and experimental findings from recent years, which provided detailed insight into the tribosystem valve spindle/seat rings, triggered the material choice and material-related design. Both valve spindle and seat ring were regulary investigated at 4,000-hour intervals from the beginning of the test. Measurements of static valve lash as well as visual, geometrical and microscopical investigations were done to assess the wear behavior. Moreover, the engine performance was recorded to understand the impact of valve spindle and seat ring geometries on the intake manifold airflow.

The results reveal that the material, geometry, manufacturing process and load collective are key factors to mitigate the risk of severe valve wear. The field study demonstrates that a valve recession rate below 10 nm/hr on a large-bore gas engine is possible, thus enabling a valve lifetime of minimum 32,000 running hours. Furthermore, the design of the valve seating face (seat angle and seat width) affects the cylinder filling volume and contributes to improving the thermal efficiency of the engine.

This field study supports and complements latest material and tribological research on model and component scale. The analysis of dominating valve wear mechanisms, the individual material choice and adequate manufacturing processes contribute to increasing lifetime without losses of thermodynamic efficiency, thus securing engine reliability and robustness at increasingly drier operating conditions.

Notes

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