The HyMethShip Project: Innovative Emission Free Propulsion for Maritime Applications

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Abstract

The HyMethShip project (Hydrogen-Methanol Ship propulsion using onboard pre-combustion carbon capture) is a cooperative R&D project funded by the European Union's Horizon 2020 research and innovation program. The project aims to drastically reduce emissions while improving the efficiency of waterborne transport. The HyMethShip system will achieve a reduction in CO_2 of up to 97 % and practically eliminate SO_X and particulate matter emissions. NO_X emissions will fall by over 80 %, safely below the IMO Tier III limit. In this paper the HyMethShip concept is introduced and the combustion system development for an engine capable of operating with hydrogen as well as methanol is described. Selected measurement results from single cylinder engine testing are presented and their usage for the multi-cylinder engine development is outlined. Additionally, some issues that might accelerate or hinder the concept application for commercial shipping are presented.

1. Introduction

Transoceanic shipping is very important for international trade and has high energy efficiency per ton and kilometer. Much of the transport work occurs close to land and densely populated areas. Emissions of sulfur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM) from shipping have been identified as having a negative impact on health and the environment. Regulations of maritime emissions have been introduced, albeit ones that are less demanding and come into effect much later than those for land-based transport. In 2017 less than 3 % of global CO_2 emissions were attributed to shipping (Figure 1).

Due to the efforts in other sectors to reduce CO_2 emissions and the projected growth of global shipping, the contribution of maritime transport to global CO_2 emissions is going to increase significantly. The EU "White Paper on Transport" from 2011 [3] set a goal of a 40 % reduction in CO_2 emissions from EU maritime transport in 2050 as compared to 2005. The International Maritime Organization adopted a resolution in April 2018 [6] to reduce GHG emissions by at least 50 % by 2050 compared to 2008. In order to meet these goals, there is a need to consider new fuels and innovative technology solutions. The HyMethShip project (Hydrogen-Methanol Ship propulsion using on-board pre-combustion carbon capture) aims to drastically reduce emissions and improve the efficiency of waterborne transport at the same time. Compared to the next best available marine engine technology, i.e. methanol combustion and post-combustion carbon capture, the HyMethShip system is estimated to show more than 40 % higher system efficiency (Figure 2).

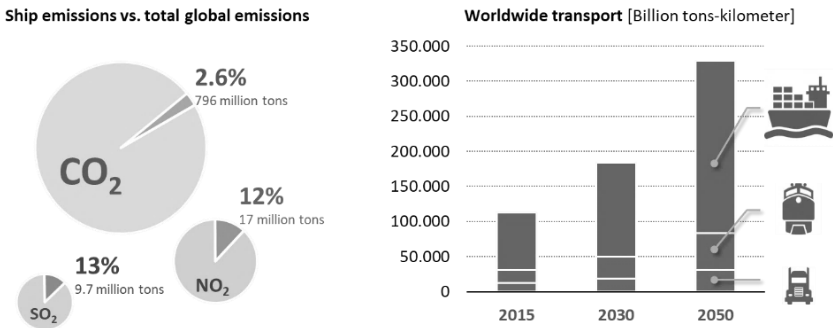

Fig. 1 Emissions and development of global transport [8]

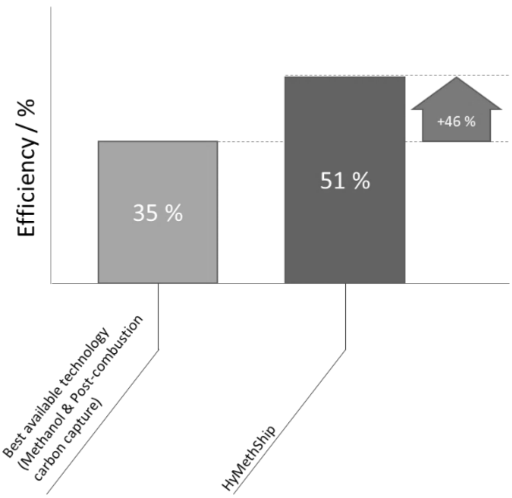

Fig. 2 Efficiency estimation for best available technology (methanol & post-combustion carbon capture) vs. HyMethShip (pre-combustion carbon capture)

The HyMethShip system innovatively combines a membrane reactor, a CO_2 capture system, a storage system for CO_2 and methanol as well as a hydrogen-fueled combustion engine into one system (Figure 3). The proposed solution reforms methanol to hydrogen, which is then utilized in a conventional reciprocating engine that has been upgraded to use multiple fuel types and is specially optimized for hydrogen use. The HyMethShip system targets a reduction in CO_2 of more than 97 % and will practically eliminate SO_X and PM emissions. NO_X emissions will be reduced by more than 80 %, significantly below the IMO Tier III limit. The HyMethShip system eliminates the need for complex exhaust gas aftertreatment, which is required for conventional (HFO/MDO) combustion systems to achieve equivalent SO_X, NO_X and PM levels. The drastic CO_2 reduction is a result of using renewable methanol as the energy carrier and implementing pre-combustion CO_2 capture and storage on the ship. The renewable methanol fuel bunkered on the ship is ideally produced on-shore from the captured CO_2, thus closing the CO_2 loop from the ship propulsion system.

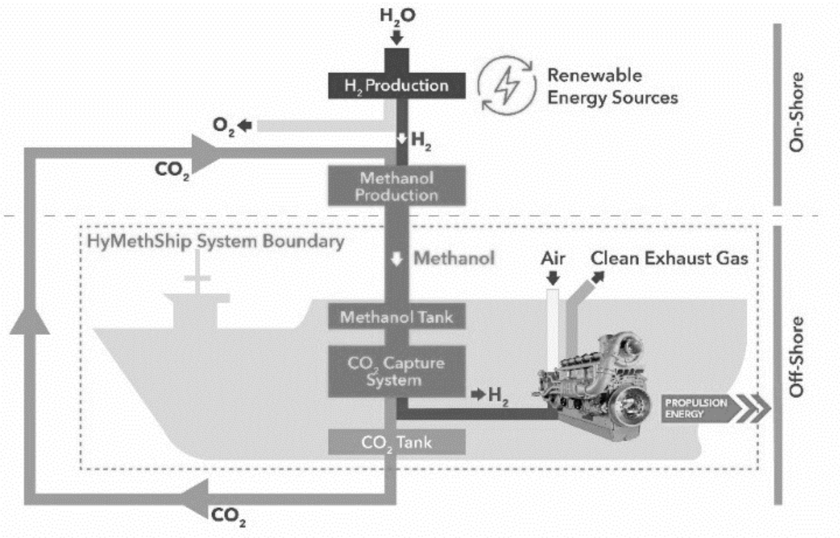

Fig. 3 HyMethShip concept [15]

HyMethShip's overall efficiency entitlement is estimated to be approx. 51 % as outlined in Figure 4:

- Methanol bunkered on board of the vessel and steam are reformed to hydrogen using waste heat from the engine. During the reforming process thermal dissociation of water at high process temperatures inside the membrane reformer produces additional hydrogen molecules, resulting in a surplus energy of more than 12 percentage points:
  $CH_3OH + H_2O \rightarrow CO_2 + 3\ H_2$ (Eq. 1)
- The combustion engine operating with an estimated efficiency of 47 %

generates losses in the range of 60 percentage points based on total hydrogen energy content. About 75 % of the engine's waste heat is used to provide the process temperatures required by the carbon capturing system.

- Two percentage points of the generated mechanical energy are used to produce electricity for the pumps and auxiliary devices in the CO_2 capture system.

Due to the methanol reformation the fuel energy available for engine combustion is higher than the methanol energy content that could be used for direct methanol combustion.

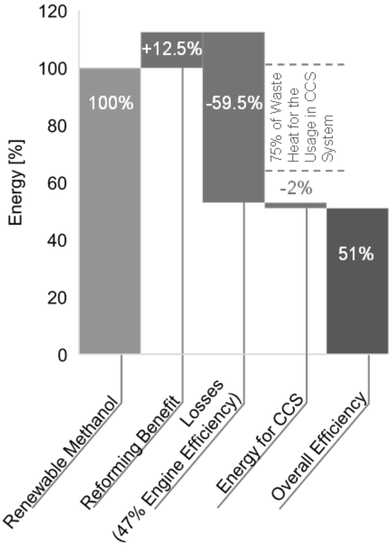

Fig. 4 Estimation of HyMethShip system efficiency

Within the HyMethShip project the individual technology components will be developed and build, and the combined system will be validated on an on-shore technology demonstrator with an engine in the range of 1 to 2 MW. The aim of this sub-project is the combustion system development on a single-cylinder engine (SCE), the definition of operating ranges and operating conditions that fulfill all engine and system requirements and the provision of all data required for the turbocharger system layout of the multi-cylinder engine (MCE). At first the requirements that the HyMethShip system and maritime regulations pose on the engine will be laid out and feasible engine solutions will be described. The methodology for the SCE combustion system development will be explained, followed by selected experimental results. Finally, some thoughts on the HyMethShip adoption challenges by vessel owners or operators will be given.

2. Marine propulsion system requirements

The requirements for marine propulsion systems are driven by safety regulations and emission legislation. Alternative energy carriers, such as hydrogen and methanol are relatively new to the marine industry and as such specific maritime regulations do not presently exist or are undergoing deliberations at the IMO. Some guidance can be provided by the "International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels" (IGF Code) [7] that was written with LNG in mind and the "Draft Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel" that was published in 2018. The IGF Code demands redundancy of fuel supply and specifies that fuel supply systems shall be arranged with full redundancy and segregation all the way from the fuel tanks to the consumer, so that a leakage in one system does not lead to an unacceptable loss of power of the vessel.

The propulsion system of the HyMethShip concept employs a reciprocating internal combustion engine that is already state-of-the-art for marine applications. The main energy source for the engine will be hydrogen generated by the methanol reformer but in order to fulfill the redundancy requirements the system will be designed to allow operation with a conventional liquid fuel as well. This operating mode can also satisfy vessel power demand during start-up / warm-up of the reformer and the CO_2 capture system.

Methanol back-up	Diesel back-up
+ Only methanol tanks required + Transient operation / maneuvering with lower (soot) emissions + Lower compression ratio feasible for H_2 operation + Lower emissions in nearly all operating conditions	+ Transient capability not limited by knocking combustion
- Energy storage system might be required to address transient power requirements - Formaldehyde emissions from methanol combustion might require an oxidation catalyst - Transient capability might be limited by knocking combustion	- Methanol & diesel tanks required on vessel - Logistic in harbor more difficult - Higher compression ratio / compromise required

Table 1: Methanol vs. diesel back-up operation

Currently existing dual-fuel engines for marine propulsion use diesel combustion for redundancy. HyMethShip can employ a similar concept with diesel back-up operation and standard hydrogen operation with diesel pilot ignition. In the latter hydrogen is injected into the intake ports or directly into the cylinder during the intake stroke or early in the compression stroke. A small amount of diesel fuel is injected into the cylinder late in the compression stroke and auto-ignites due to high temperatures of the hydrogen-air mixture. From the ignition centers a flame propagates through the combustion chamber consuming the homogenous hydrogen-air mixture. The diesel fuel fraction depends on the operating conditions and varies between 1 and 5 % in steady-state operation. In order to reliably inject these small quantities of fuel medium speed engines incorporate a pilot injector in addition to the main diesel injector, while for high speed engines wide-range injectors are in development [9].

The HyMethShip concept will also allow a different kind of dual-fuel engine where methanol combustion is used for redundancy. In that case a spark ignition system will be used for hydrogen as well as for methanol combustion. In steady-state hydrogen operation no second fuel is required. There are advantages and drawbacks for both back-up fuel options (Table 1). The advantages of a concept using methanol combustion for redundancy instead of diesel combustion lie in reduced emissions of NO_X, SO_X and particulate matter and potentially reduced tank space requirements since no bunkering of diesel is required. The drawbacks could be reduced transient capabilities if knocking combustion occurs and the fact that methanol combustion is not considered an established technology in maritime applications yet and ship operators might be hesitant to accept this new technology. There are, however, various pilot vessel projects in progress that utilize methanol as the main fuel source and evaluate engine combustion as well as methanol bunkering and storage options [1][2][11][12] [13]. The engine performance will be evaluated within the HyMethShip project. Vessel power requirements, operational patterns and available space will determine which back-up fuel will finally be selected.

For international marine applications the emission limitations contained in the "International Convention on the Prevention of Pollution from Ships" apply. MARPOL Annex VI sets limits on NO_X emissions with the Tier II / III standards that were introduced in 2008 [4][5]. NO_X emission limits are set depending on the engine maximum operating speed. While Tier II limits apply globally, Tier III standards only apply in NO_X Emission Control Areas (ECA). Engine emissions are tested on various ISO 8178 duty cycles, with duty cycles E2 and E3 applicable for various types of propulsion engines. HyMethShip will fulfill the more stringent NO_X limits for ECA and target duty cycle NO_X emissions of less than 2.0 g/kWh.

Apart from legislative requirements the engine also has to fulfill requirements that are specific to the HyMethShip concept. Engine waste heat, particularly from the exhaust gas, will be used for the methanol steam reforming process adding further demands on the combustion system development. Mixture stoichiometry, compression ratio and combustion phasing will have to be adjusted in order to provide adequate exhaust enthalpy to the reformer while at the same time protecting the exhaust valves, exhaust turbine and the exhaust system from excessive heating.

The transient performance of the HyMethShip concept is determined by the transient performance of the individual system components – combustion engine, reformer and carbon capture system – and by the interaction between the sub-systems. A high transient capability of the combustion engine is insufficient if the reformer is incapable of delivering the required increase in hydrogen mass flow rate. In an early performance assessment, the transient vessel power requirements are defined for one specific use case – a ferry operating in the North Sea / Baltic Sea – and various layout options for transient operation are evaluated [10][14]. In this study the combustion of methanol / hydrogen mixtures is considered in order to evaluate the potential of methanol addition for transient performance.

3. Test set-up and procedures

The definition of the combustion system started with 0D combustion and 1D performance simulations taking previous experience with hydrogen combustion in large engines into account. Variations of excess air ratio (EAR) and ignition timing combined with varying compression ratios and inlet valve closing (IVC) timings were performed in the GT Power simulation environment. The engine configuration fulfilling the vessel power and emission requirements as well as the lower and upper exhaust gas temperature limit of approximately 500 °C and 650 °C, respectively, was chosen for the experimental investigations. A preliminary operating range for the testing was defined, as well as the exhaust back pressure for the selected operating conditions based on the turbocharger efficiency.

Moreover, 3D CFD simulations of the hydrogen injection and the mixture formation in the intake port and the combustion chamber were performed to determine injection strategies and hydrogen fueling nozzle design. For this investigation, boundary conditions from 1D engine simulations were used. Various nozzle design variants were evaluated based on the achievable in-cylinder mixture homogeneity. Injection timing variations allowed to define the latest possible end of injection (EOI), the timing at which no fuel remains in the intake port after IVC. The 3D CFD simulation themselves will be subject of a future publication.

The experimental investigations were carried out on a high-speed 4-stroke single cylinder research engine. An open chamber configuration with centrally located spark plug and a compression ratio in the range of typical special gas applications was chosen. The engine features a single camshaft with early intake valve closing before bottom dead center (BDC). Modified serial components were used for fuel admission into the intake port (hydrogen and/or methanol) and the combustion chamber (methanol). Further details of the engine configuration can be found in Table 2.

Rated speed	1500 rpm
Displacement	≈ 6 dm^3
Compression ratio	Adjustable by modifying the piston geometry
Valve timing	Miller valve timing with early IVC, adjustable by modifying cam lobe profile
Number of inlet and exhaust valves	2/2
Swirl/tumble	≈ 0/0
Charge air	Provided by external compressors with up to 10 bar boost pressure
Hydrogen supply	Port injection, up to 10 bar
Methanol supply	Direct or port injection, up to 200 bar
Ignition system	Modified standard system
Balance of inertia forces	Lancaster mass balance for first and second order inertia forces

Table 2: SCE technical specifications

All engine fluids including cooling water, lubricating oil, fuel gas and charge air temperature are controlled to ensure well-defined and reproducible testing conditions. In lieu of a turbocharger, an air compressor upstream of the engine and a flap in the engine exhaust system are used to adjust intake and exhaust manifold pressures. A flush mounted piezoelectric cylinder pressure transducer enables real-time calculation of the IMEP of each cycle. Additional measuring instruments are shown in Table 3.

Quantity	**Instrumentation**
Air mass flow	Emerson Micro Motion CMF300
Hydrogen mass flow	Emerson Micro Motion CMF050
Methanol mass flow	Emerson Micro Motion CMF010
Charge air humidity	Vaisala HMT 338
Charge air temperature	Resistance temperature sensor PT100
Charge air pressure	Piezoresistive pressure sensor
Cylinder pressure	AVL piezoelectric transducer QC34C
Exhaust gas temperature	Thermocouple type K
Exhaust gas pressure	Piezoresistive pressure sensor
Exhaust gas emissions	V&F HSense, IAG FTIR, AVL AMA i60

Table 3: SCE measurement instrumentation

For the SCE investigations the main influencing parameters EAR and ignition timing were varied for selected indicated mean effective pressures (IMEP) at a fixed engine speed of 1500 rpm. For hydrogen operation EAR was varied in range of 1.8 – 3.0, while EAR for methanol operation was kept below 2.0. The boost pressure was adjusted to achieve the target EAR for a given IMEP, while the exhaust back pressure was adjusted according to the 1D simulation results. Based on the simulation results EOI for methanol was set to gas exchange top dead center (TDC), and for hydrogen 90 CAD after TDC. Maximum injection duration was 400 CAD for methanol and 80 CAD for hydrogen.

In addition to tests with either hydrogen or methanol fueling, tests with mixtures of the two fuels in different energetic shares were performed.

4. Results and discussion

An overview of the measurement results with hydrogen operation and the workflow applied to identify the feasible operating range is shown in Figure 5 where operating points are plotted in ignition timing vs. boost pressure maps. The size of the markers represents the coefficient of variation of IMEP (COV), larger circles indicating higher COV et vice versa, whereas the indicated efficiency is indicated as a gray scale level that ranges from black (lowest efficiency) to white (highest efficiency). The envelope of a point cloud, representing the operating range for a certain engine load, is plotted as a dashed line.

In Figure 5a all measurement points with good combustion stability are shown. As expected, operating points with higher boost pressure, i.e. higher load and/or higher EAR, and earlier ignition timing, i.e. earlier combustion phasing, show higher indicated efficiency. The opposite applies for lower boost pressure and late ignition timings. At low boost pressure, i.e. low engine load, the efficiency is low as well, independent of ignition timing.

Applying the NOX duty cycle limit (Figure 5b) leads to discarding of operating points with early ignition timing or low boost pressure – which leads to lower EAR which in turn results in higher combustion temperature and therefore higher NOX emissions – at a certain engine load.

Figure 5c shows the effect of the upper exhaust gas temperature limit of 650 °C on the operating areas: only two points with late ignition timing are omitted, i.e. all other operating points already have an exhaust gas temperature below the limit.

The use of the lower exhaust gas temperature limit of approximately 500 °C yields Figure 5d. Operating points in an area of early ignition timing and high boost pressure result in low exhaust gas temperature and are therefore neglected. The envelopes in Figure 5d represent the operating areas of the engine at different loads. When operating in these the set goal of a stable combustion and low emissions as well as required exhaust gas temperature is ensured.

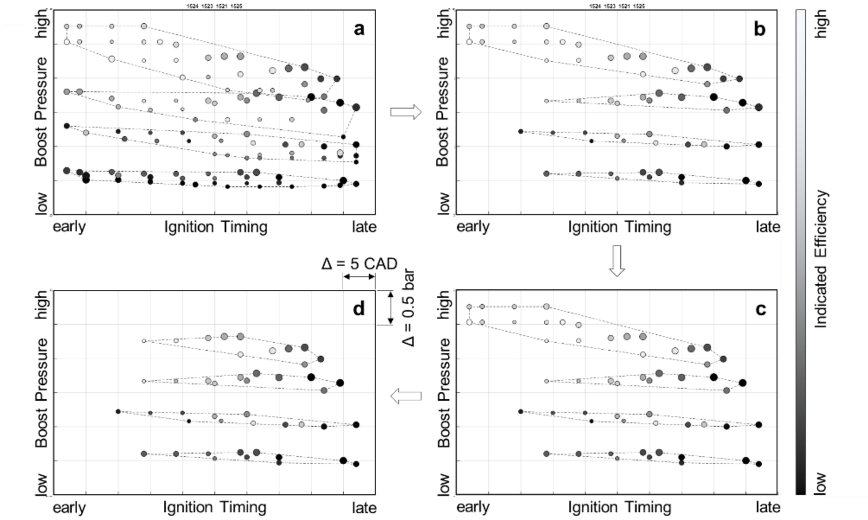

Fig. 5 Workflow for hydrogen operating range identification

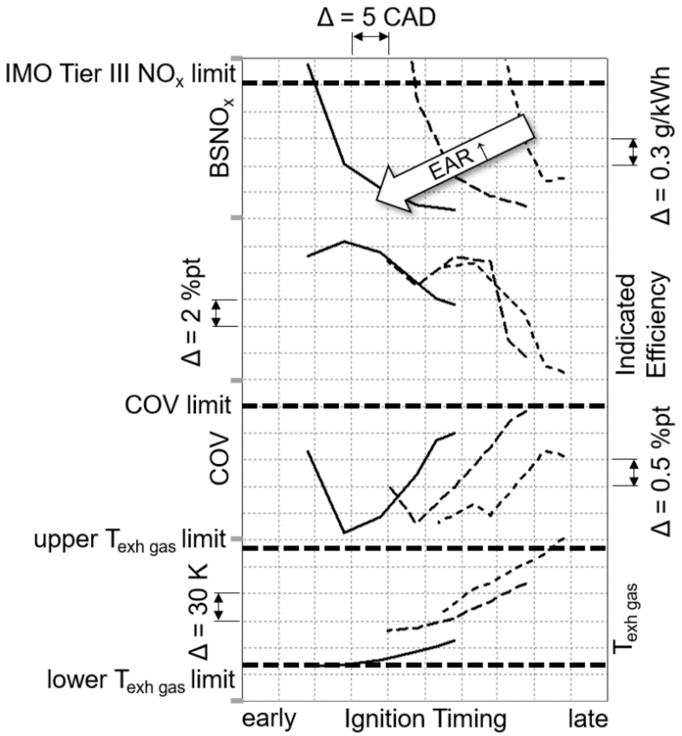

Fig. 6: EAR variation for hydrogen operation at nominal load

For a better understanding of the HyMethShip specific limitations an EAR variation for hydrogen operation at nominal load is shown in Figure 6. The limits of BSNOX, COV and exhaust gas temperature are plotted as thick dashed lines. With increasing EAR at constant ignition timing NO_X emissions as well as exhaust gas temperature drop significantly. Operating conditions with high EAR and early ignition timing that are favorable for high efficiency and still fulfill emission targets are approaching the lower exhaust gas temperature limit. Combustion stability is not influenced significantly by EAR and therefore does not limit the feasible EAR range.

The same procedure as for defining an operating range for hydrogen operation was used for methanol operation. The outcome can be seen in Figure 7a in the lower left gray shaded area. The selected operating points are plotted together with those of Figure 5d. Methanol operation in general was characterized by lower combustion stability in comparison to hydrogen operation, indicated by the larger markers. Moreover, combustion stability is mostly independent of EAR and ignition timing in comparison to hydrogen operation where ignition timing had a strong impact on combustion stability. Earlier ignition timing than for hydrogen operation was required throughout the load range.

Figure 7a also shows the advantage of using methanol as a second fuel for transient operation. Boost pressure requirements for medium load hydrogen operation and high load methanol operation are very similar. This is due to the lower stochiometric AFR as well as the lower needed EAR for methanol operation. Therefore, switching from hydrogen to methanol fueling at a constant boost pressure results in an increase in engine load, et vice versa.

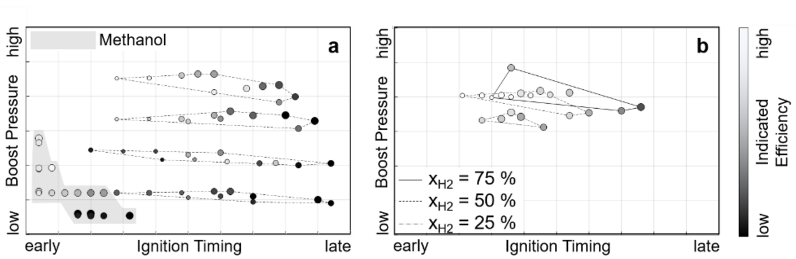

Fig. 7: Operating ranges for methanol and hydrogen operation (a) and dual fuel operation (b)

The operating ranges for various fuel mixtures at nominal load are plotted in Figure 7b. The solid envelope represents a high energetic share of hydrogen while the dashed and dash-dotted envelope represent a medium and low energetic share of hydrogen, respectively. At constant load with decreasing amount of hydrogen, i.e. increasing amount of methanol, the needed boost pressure drops which is in line with the previous made observations. Combustion stability was not influenced by this dual fuel operation; COV and therefore marker size did not change significantly compared to single fuel operation.

5. Conclusions and outlook

The HyMethShip concept has the potential to drastically reduce greenhouse gas emissions as well as pollutant emissions of ship propulsion systems. The final system design will depend on the particular vessel requirements, like transient performance or space considerations, and can incorporate a diesel-type or a gas-type combustion engine.

In this study the spark ignition combustion concept was validated in an SCE environment and the operating ranges for hydrogen and methanol combustion were established. The feasibility of engine operation with a hydrogen-methanol mixture was confirmed and will allow improved transient operation in the MCE. In a next step of the project the established data base will be used for the layout of the turbocharger and the boost pressure control system of the MCE which has to be flexible enough to allow methanol as well as hydrogen operation. The operating strategies for steady-state and transient operation will be developed and optimized, taking NO_X duty cycle emission limits into account. Finalizing the operating strategy for the MCE will be an iterative process where the methanol steam reformation and its impact on exhaust gas temperature and enthalpy requirements have to be considered as well.

Before the HyMethShip concept can be used in standard shipping applications there are a number of issues that need to be addressed by the shipping industry, including port infrastructures, methanol production and future regulations. CO_2 receptables or CO_2 grids need to be available in ports and guidelines for CO_2 discharge developed. Safety guidelines for vessels using hydrogen as a fuel need to be developed. For low well-to-wake emissions and a closed CO_2 lifecycle, it is desired that methanol is produced with recycled CO_2, e.g. from HyMethShip, and renewable power. Although the technology for renewable methanol production exists, nowadays the bulk of methanol produced world-wide uses natural gas as a feedstock. Shipping of methanol as cargo is ubiquitous but methanol bunkering as a propulsion fuel is not standard in ports and procedures for safe operation are in development. Methanol bunkering barges are currently not available in most ports making implementation of HyMethShip most likely in applications where the vessel can return to the home port for bunkering.

6. Acknowledgements

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7. Abbreviations / acronyms

AFR	Air fuel ratio
BDC	Bottom dead center
BSNO$_X$	Break specific NO$_X$ emissions
CAD	Crank angle degree
CO_2	Carbon dioxide
COV	Coefficient of variation
EAR	Excess air ratio
ECA	Emission Control Areas
EOI	End of injection
GHG	Greenhouse gas
HFO	Heavy fuel oil
IMEP	Indicated mean effective pressure
IMO	International Maritime Organization
IVC	Intake valve closing
MCE	Multi-cylinder engine
MDO	Marine diesel oil
NO_X	Nitrogen oxides
PM	Particulate matter
SCE	Single-cylinder engine
SO_X	Sulfur oxides
TDC	Top dead center

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