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The impact of alternative fuels on the requirements for future turbocharger generations

Turbochargers & Air/Exhaust Management

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ABSTRACT

The International Maritime Organisation's (IMO) ambitious target to reduce greenhouse gas emissions from international shipping by at least 20% by 2030 compared with 2008 levels, and the introduction of the Carbon Intensity Indicator (CII) rating as a tool to help achieve this goal, has led to significant interest in dual-fuel combustion engines.

These engines can burn high percentages of synthetic and carbon-neutral fuels when available, as well as conventional diesel fuels. To achieve fuel flexibility, these engines are equipped with adapted state-of-the-art turbocharging technologies. This means that these turbochargers are a compromise to meet the thermodynamic requirements of both types of fuels. The price of this fuel flexibility is a lower turbocharger and system efficiency.

In line with the IMO strategy, dual-fuel engines are likely to be a bridging technology to 100% net-zero emission engines powered by alternative fuels such as methanol, ammonia or hydrogen. This next generation of engines will place different demands on turbocharging technologies in terms of thermodynamics, boost pressure, corrosion resistance and other boundary conditions.

This paper examines the turbocharging requirements of internal combustion engines running on pure or blended alternative fuels and attempts to answer the question of when to choose a single-stage turbocharger and when to use a two-stage turbocharger. It also takes into account different boundary conditions such as modified oil parameters and advanced exhaust aftertreatment systems and shows their influence on the affected components.

To this end, the data collected from single-cylinder and dual-fuel engine tests is analyzed and supplemented by the lessons learned from the growing number of dual-fuel applications used in the field.

The results will provide an overview of the development targets for the future generation of turbochargers, which are essential to meet the IMO's greenhouse gas strategy to achieve net-zero emissions from international shipping by 2050.

1 INTRODUCTION

Kompressorenbau Bannewitz GmbH (KBB) has been developing and manufacturing turbochargers for large engines for more than 70 years. Since that time, the development of KBB's turbochargers has been driven by customer demand for higher pressure ratios and improved efficiency. In response to this demand, KBB introduced the 9th generation of turbochargers, the ST27-EP series, in 2017, achieving a pressure ratio of up to 6:1.

Following the introduction of the International Maritime Organization (IMO) Tier III regulations in 2016, engine manufacturers (OEMs) were compelled to enhance their engine performance, focusing more intently on nitrogen-oxide (NOx) emissions. Consequently, they adapted their strategies to control the charge cycle (e.g. Miller), which led to a significant increase in demand for higher boost pressures. [1]

Since then, IMO has changed its strategy and moved from regulating exhaust components like NOx or sulfur oxides (SOx) to rating the carbon footprint of the whole vessel. This new approach takes into account the design, energy management on board, and the carbon-equivalent emissions of the engines. Driven by this development, vessel owners have started to request engines that can use alternative fuels like methanol or ammonia, which might offer an improved footprint compared to conventional diesel. In response to this growing demand, OEMs have introduced dual-fuel engines, capable of running on various fuels.

This paper examines the impact of the introduction of alternative fuels on state-of-the-art turbocharging technologies and the upcoming turbocharger generations.

2 ALTERNATIVE FUELS AND THEIR IMPACT ON TURBOCHARGER THERMODYNAMICS

Dual fuel engines are a key-technology to achieve the targeted IMO regulations aiming for zero emissions by 2050. This technology offers significant potential for retrofitting existing fleets to operate on carbon-neutral fuel while providing shipowners with the flexibility to switch fuels based on price and availability.

On the other hand, tuning the engine and especially the turbocharger to work with the characteristics of both fuels is challenging and often results in a compromise at the expense of engine efficiency.

2.1 Methanol

Currently, methanol-fuelled vessels represent only ~1 % of the world fleet tonnage. However, the order books show a clear trend that methanol, alongside conventional and LNG-fuelled vessels, appears to become a more popular choice for customers, with order books showing a share of around 10% of tonnage ordered. [2]

Due to the short development time, most of the methanol engines available on the market are adapted diesel engines with modified fuel supply or built as dual fuel engines. In order to keep the complexity of combustion and fuel supply to a manageable level, and due to the lack of space on the cylinder head, several OEMs have decided to use port-fuel injection instead of direct injection. Although the majority of these projects are based on dual fuel engine concepts, the requirements for turbochargers for methanol engines can be derived.

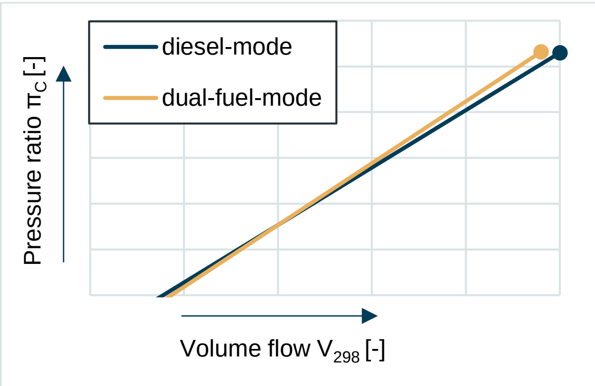


Figure 1 - Dual fuel engine operation line comparing methanol and diesel operation

As illustrated in Figure 1 the operational characteristics of a dual fuel methanol engine can be delineated in terms of two distinct lines. The data presented has been obtained from a single cylinder test bench, with the methanol injection facilitated via port fuel injection and the diesel injection accomplished through direct injection. The blue line in the figure delineates the conventional diesel operating line, while the other line indicates an operating line with a high methanol energy fraction (MEF). The share of methanol is calculated based on its energy equivalence to diesel. The volume flow has been standardised with regard to the diesel operating line.

Both methanol and diesel operation line overlap over a wide range of operating points. The dots indicate the 100 % load point. The pressure ratio required for diesel and methanol operation in this single cylinder configuration is at a comparable level. While the methanol combustion with high MEF operates with a slightly reduced air flow.

As demonstrated in Figure 1, a compressor optimised for diesel operation also performs very well in a methanol engine. However, there are differences between these two fuels that may have an impact on the turbocharging concept. The subsequent section will present a comparison of the properties of methanol and diesel.

Table 1 - Properties of methanol compared to diesel (MDO) [3], [4]

Fuel Type	MDO	Methanol
Density [kg/m³] @0 °C, 1,013 bar	~900	792
Lower Heating Value [MJ/kg], H_G	42	20
Air-Fuel Ratio [kg/kg], AFR_{stoich}	14.5	6.5
Calorific Value of The Fuel-air Mixture @ λ = 1 [MJ/m³]	3,74	3,97
Evaporation Enthalpy [kJ/kg]	260	1110
Min. Ignition Energy [mJ]	0,23	0,1

As demonstrated in Figure 1, a compressor optimised for diesel operation also performs very well in a methanol engine. However, there are differences between these two fuels that may have an impact on the turbocharging concept. The subsequent section will present a comparison of the properties of methanol and diesel.

Table 1 compares the properties of methanol and marine diesel oil (MDO). Methanol has a much lower calorific value, which means that more than twice the mass of methanol is required to equal the energy stored in one kilogram of MDO. This is a particular challenge when it comes to storing the necessary energy reserves on board a vessel. On the other hand, the mass of air required to burn one kilogram of methanol is almost half the air-fuel ratio (AFR) of MDO. This is due to the chemical composition of methanol, which already contains some of the oxygen needed to burn the fuel, so less additional air is required. And this property is equivalent to the energy gap, meaning that the inevitably higher fuel consumption doesn't result in a higher air mass flow compared to diesel.

The calorific value H_G of a combustible air-fuel mixture can be calculated by using the equation (1)

$$H_G = \frac{H_u * \rho_G}{\lambda * AFR_{stoich} + 1} \quad (1)$$

Where H_U is the lower heating value of the fuel, ϱ_G is the density of the air-fuel mixture, AFR_{stoich} is the stoichiometric air-fuel ratio and λ is the air-fuel equivalence ratio.

The lower stoichiometric air-fuel ratio of methanol compared to diesel results in a higher calorific value for a combustible air-fuel mixture, with a difference of approximately 6%. This lower air mass requirement for methanol combustion is accompanied by the necessity of injecting a greater quantity of methanol to achieve the same energy output as diesel.

The implementation of a port-fuel injection system to inject methanol poses challenges due to the limited time and available air for the injection of this higher fuel amount. To facilitate the filling of the cylinder with an air-fuel mixture, an increase in boost pressure is a viable option, particularly during full-load operation. At the same time, it is imperative to ensure that the permissible cylinder peak pressures are not exceeded. [5]

A further challenge is posed by the high evaporation enthalpy of methanol, which is four times higher than that of diesel. Achieving optimal evaporation of the fuel droplets within the limited timeframe is difficult. To address this, the cooling capacity of the charge air cooler is reduced, and the compression ratio of the cylinder can be increased. However, this higher evaporation enthalpy of methanol affects the exhaust temperatures of the engine.

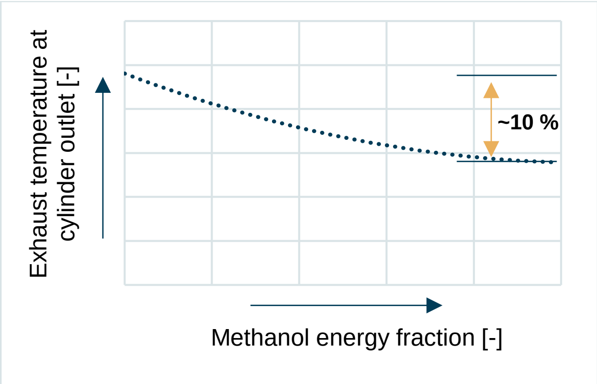


Figure 2 - exhaust temperature depending on methanol energy fraction

Figure 2 shows the different temperatures measured at the cylinder outlet of the single-cylinder engine at a constant load point with increasing MEF. The lowest temperature was reached at the highest methanol energy fraction. The difference between the exhaust temperatures of the load point without methanol and the highest level is in the range of 10 %.

This must be taken into account when selecting the correct turbine configuration. Especially for dual-fuel engines, the turbine specification can only be a compromise between an efficient set up for diesel or for methanol operation.

The combustion concepts of methanol may require compressor maps that are highly comparable to those of diesel specifications. Discrepancies are likely to occur in the turbine section of the turbochargers, where reduced exhaust temperatures are anticipated to exert an influence.

2.2 Ammonia

According to DNV's alternative fuels insight dashboard there are currently only 2 ammonia vessels in operation. But the order books for the next years show a growing number of ammonia fueled vessels. [2]

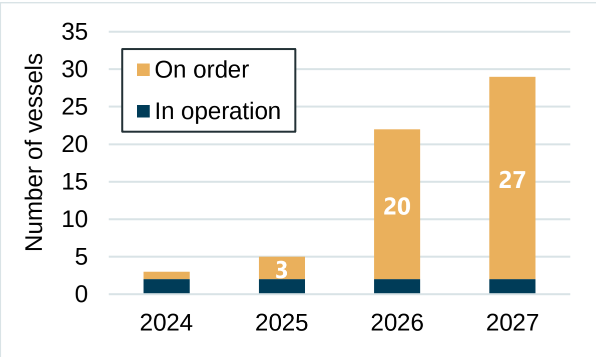


Figure 3 – number of ammonia vessels in operation and ordered [2]

Alongside methanol, ammonia is a promising alternative fuel that could support the strategy of the IMO to reduce CO2 emissions by a minimum of 40 % by 2030 compared to 2008 levels. Ammonia is notable for its carbon-free nature, resulting in no CO2 emissions during combustion. However, as illustrated in Table 2, the combustion of ammonia is more challenging than that of methanol. This is especially due to the high evaporation enthalpy and the high minimum ignition energy. Therefore, it takes more time to develop a working combustion concept. [4]

Table 2 - Properties of ammonia compared to diesel (MDO) [3], [5], [6]

Fuel Type	MDO	Ammonia
Density [kg/m³] @0°C, 1,013bar	~900	682 $_{(aq)\ -33°C}$
Lower Heating Value [MJ/kg], H_u	42	18.6
Air-Fuel Ratio [kg/kg], AFR_{stoich}	14.5	6.05
Heating value of the fuel-air mixture @ λ = 1 [MJ/m³], H_G	3.74	3.97
Evaporation Enthalpy [kJ/kg]	260	1368
Min. ignition energy [mJ]	0,23	8
Flame-velocity [m/s]	~0.8	0.067

In particular, the high ignition energy of ammonia is the main reason that many ammonia engine concepts use an additional fuel such as diesel or hydrogen to ignite the ammonia-air mixture. [4]

Therefore, and to provide a reliable fallback strategy, dual fuel engines are a viable platform for developing ammonia burning concepts. In addition to the ignition energy of ammonia, its high evaporation enthalpy poses a significant challenge. Achieving optimal ammonia vaporisation can be challenging due to the limited distances between the injection nozzle and the intake valve, thereby hindering the feasibility of high substitution rates for ammonia with port-fuel injection. This underscores the distinct advantages offered by direct injection systems for such applications.

A lot of initial investigations have been carried out to understand the combustion properties of ammonia and to determine the most effective way to use it as a maritime fuel. Especially, ammonia's very low flame velocity highlights its suitability for use in low and medium speed engines. As the development of ammonia combustion is still in progress, only limited data is available to determine turbocharger specifications. One possible scenario is shown in Figure 4.

The heating value of the ammonia-air mixture is higher than that of diesel, and consequently, less air is required to achieve the same energy output. Research results also indicate that the ammonia combustion process is most efficient when moderately lean, with a λ in the range of 1.2 – 1.8, while diesel combustion operates usually in a range of λ = 2 – 2.5. Consequently, the air flow must be reduced for the combustion of ammonia. [4]

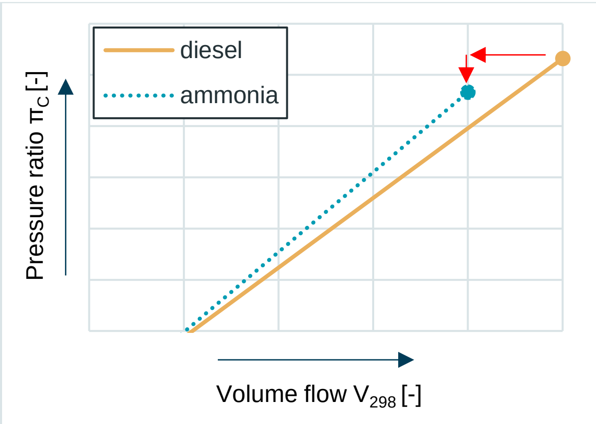


Figure 4 – comparison engine operation line ammonia and diesel operation

To assist the ignition of ammonia, it is recommended that the engine compression ratio is increased; at the same time, to keep the peak cylinder pressures within an acceptable range, it may be necessary to reduce the boost pressure at full load. [6]

Figure 4 illustrates the different operation lines of diesel and ammonia operation. The orange line indicates the diesel operation, while the blue line signifies the engine operation line adjusted for ammonia operation.

The boost requirements for methanol and ammonia combustion are comparable to those of diesel. The shown combustion concepts with port-fuel methanol injection and direct ammonia injection using diesel as a pilot fuel, are compatible with a state-of-the-art single-stage turbocharger without the need for significant modification. However, in certain instances, a two-stage turbocharging system may be the optimal choice. The following section will provide a detailed comparison of the advantages offered by both technologies.

2.3 Single- and two-stage turbocharging technologies for alternative fuels

Since the introduction of KBB's 8th generation of turbochargers into the market in 2013, customers have been able to choose between economical single-stage turbocharging technology and high-efficiency two-stage turbocharger solutions for increased boost pressures.

As outlined in section 2.1 and 2.2, the boost requirements for the combustion of alternative fuels can be met by both technologies. The most appropriate choice will depend on the specific application. Table 3 provides an easy overview showing the advantages of two-stage and single-stage turbocharging. In general, it can be summarised that applications with a focus on high power density or high load profiles should use a two-stage turbocharger system. The higher purchase and maintenance costs are amortised over the product lifetime due to the lower fuel costs resulting from the optimised system efficiency.

Table 3 - Comparison of the advantages of single- and two-stage turbocharging systems (cross=positive; circle=neutral)

	Single-Stage Turbocharging	Two-Stage Turbocharging
Pressure Ratio	+	+ +
Efficiency	+	+ +
Service Costs	+	○
Package & Space	+	○
Power Density	○	+
Total Cost Of Ownership	+	+

3 INFLUENCE OF ALTERNATIVE FUELS ON MATERIALS AND LUBRICATION

Beside the changed thermodynamics especially in the exhaust path of an engine, alternative fuels have also impact on the material of the turbocharger itself. Methanol and ammonia are recognised as corrosive substances, underscoring the necessity for careful material selection in such applications. Methanol, for instance, has been observed to be capable of compromising the integrity of sealing materials, such as fluoroelastomer-based compounds. Ammonia has also been observed to potentially damage materials containing copper, brass, aluminium, zinc, and magnesium alloys. [3], [6] The materials used in engines and turbochargers often exhibit excellent properties that meet their design requirements. However, they can present disadvantages in terms of corrosion resistance, as stable materials such as stainless steel tend to be more costly and might present disadvantages in meeting the design requirements.

In order to avoid unnecessary material changes, a comprehensive analysis was conducted in order to ascertain the potential avenues through which fuel and its constituent elements could come into contact with components of the turbocharger. Every component along such a path was checked in terms of corrosion stability against ammonia and methanol.

The lubrication system of the turbocharger is of particular importance. Given the critical function of the lubrication system in the turbocharger, and the fact that engine oil comes into contact with numerous components, it is vital to understand how ammonia and methanol interact with it.

3.1 Lubrication for alternative fuels

Engine oils are characterised by their unique formulations, which are meticulously engineered to satisfy the specific demands of engine manufacturers for various applications. In recent decades, there has been a notable evolution in the field of oil formulations, with a range of adaptations being made to suit a variety of fuels, blends, and applications. This adaptation process has involved the development of formulations suitable for heavy fuel oil (HFO), gas, biofuels, and low ash formulations for diesel particulate filters (DPF).

In particular, contamination of the engine oil with fuel can lead to wear and critical damage if a certain limit is exceeded and the oil is unable to perform its function. Due to the limited practical experience with ammonia and methanol, engine manufacturers have not yet specified possible fuel concentrations or defined acceptable levels of fuel contamination of the engine oil.

Turbocharger bearings share the oil supply with the rest of the engine and have to work with all the various oil formulations available on the market. To ensure the turbocharger's functionality and the bearings' resistance to corrosion, KBB has blended various oil samples with methanol and tested them with different bearing materials.

3.1.1 Oil blending tests with methanol

For blending tests three different oil types (EO) from various brands have been chosen that are in use for medium-speed engine applications since recent years. The properties of the used oil samples can be found in Table 4

Table 4 - Properties of the oil samples

	SAE grade (viscosity class)	Application
EO1	40	oil for medium speed diesel engines < 5 % sulphur content in fuel
EO2	40	Oil for medium speed engines running on HFO
EO3	40	Low ash oil for spark-ignited gas engines

All engine oils have been blended with pure methanol at two different temperatures, 60°C and 80 °C. After blending, the samples were placed on a shaker for 24 hours to ensure thorough mixing of the fluids and to simulate the rotation of the crankshaft. Following the mixing stage, the oil blend was extracted, and the density was measured. The change in oil density is an indicator of the methanol fraction that was blended into the engine oil.

Table 5 - visual inspection of the oil-blends

	~20 °C	60 °C	80 °C
EO1			
EO2			
EO3			

As shown in Table 5, the visual differences between the three engine oils are evident. The left column illustrates the oils without methanol at room temperature, while the other two columns depict the oil blends at temperatures of 60 °C and 80 °C, mixed with methanol. It is notable that sample EO1 changes from an amber colour to a milky colour at 60 °C. At 80 °C, the colour reverts to amber.

Similarly, sample EO2 undergoes a transition from a dark brown to a lighter brown at both 60 °C and 80 °C. Sample EO3 exhibits only slight changes, though less pronounced than those observed in EO1 and EO2.

Following a visual inspection, the oil samples were analysed for their methanol content. The results of this analysis are presented in Figure 5.

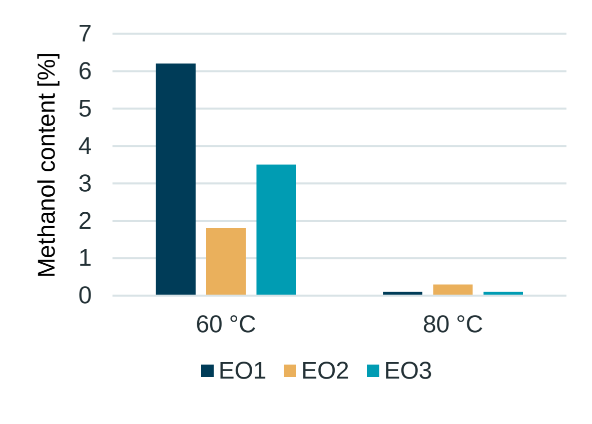


Figure 5 - methanol content after 24h mixing

The results demonstrate variation in the oil samples' capacity to store methanol. While EO1 and EO3 exhibited high methanol contents of 6.2 % and 3.5 % at 60 °C, only marginal amounts of methanol were found in the samples at 80 °C. Sample EO2 exhibited divergent behaviour, storing lower amounts of methanol at 60 °C and higher contents of ~0.5 % at 80 °C. In general, all samples demonstrate significantly lower methanol content at temperatures of around 80 °C. These findings suggest that increasing the oil temperature above or within a range of 80 °C may be a viable option to significantly reduce the methanol content of engine oil.

The objective of the oil-blending tests was to establish a critical oil-methanol blend for subsequent material and corrosion tests on affected components. Given that the boiling point of methanol is 65 °C, it is highly probable that the created scenario with a methanol share of 6.2 % in EO1 demonstrates a realistic worst-case scenario, particularly given that other oil samples would exhibit even higher methanol concentrations.

3.1.2 Blending oil with ammonia

Comparable to the blending tests with methanol, tests with ammonia have been carried out. Due to the different properties of ammonia an adapted blending and analysing set-up has been chosen. As ammonia is already vaporising at -33 °C, the blending process was conducted in a pressurised reactor. The ammonia was introduced into the reactor through the oil sample, enabling direct contact between the ammonia gas and the oil.

Unfortunately, the analysis method that had been selected for methanol could not be successfully transferred to ammonia. This was determined by the fact that measuring the density of the blend led to results that were not plausible and lacked repeatability. Consequently, a more complex analysis approach was adopted. Unfortunately, the results have not been available at the time of publication of this paper.

3.2 Corrosion and material compatibility

The objective of the oil blending tests outlined in Chapters 3.1.1 and 3.1.2 was to ascertain whether methanol or ammonia can contaminate engine oil with relevant concentrations. A secondary objective was to create realistic worst-case blends for material-testing purposes.

3.2.1 Corrosion tests with methanol

To ensure that the bearing material is resistant to corrosion caused by methanol, various material samples were tested, also the KBB standard bearing material. In order to determine whether different oil formulations have a significant effect on the corrosion behaviour, tests were carried out with EO1 and EO3, as they showed the highest methanol concentrations. The material samples have been stored for 26 days in a pressurised reactor at 60 °C and 10 bar pressure. To facilitate a better comparison of the results, reactors were also set up containing no material but oil and oil-blend samples.

Table 6 - visual inspection of the samples after 26 days

EO3 - oil only	EO3 - oil-methanol blend	EO3 - oil blend + material sample
		

Following a visual inspection of the samples after 26 days of testing, interesting results were observed. As shown in Table *6*, the pure oil sample has maintained its brown colour, while the blended sample of EO3 has changed to a light brown. This is in contrast to the blending test conducted in

Section 3.1.1, where there was minimal colour change. The sample containing the bearing material exhibits a milky hue. Due to technical issues, the density of the blended samples could not be measured after 26 days of storage, preventing the determination of the methanol content. A visual inspection of the EO1 samples showed comparable results.

The following Table 7 presents a comparison of the standard KBB-bearing material before and after the 26-day testing period.

Table 7 - comparison KBB standard bearing material before and after corrosion test with methanol

Bearing material sample before testing	Bearing material sample after testing
	

As shown on the left side of the table, the copper displays a light brown colour. Following the corrosion test with methanol, the sample exhibited a dark brown colouration. Despite cleaning, the dark brown discolouration persists.

In order to comprehend the effect of the methanol on the bearing material, it was necessary to cut the samples and subject them to further microscopic analysis.

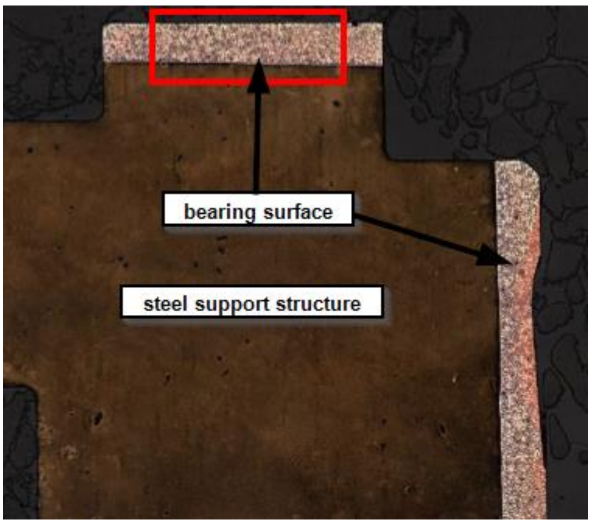


Figure 6 – section view of a bearing sample after methanol corrosion test

The section view of the bearing sample displays the steel support structure as dark brown, a result of the contrast agent employed. The copper alloy bearing material is observed to appear in a light brown hue. A more detailed view of the red framed area of the bearing surface can be found in Figure 7 below.

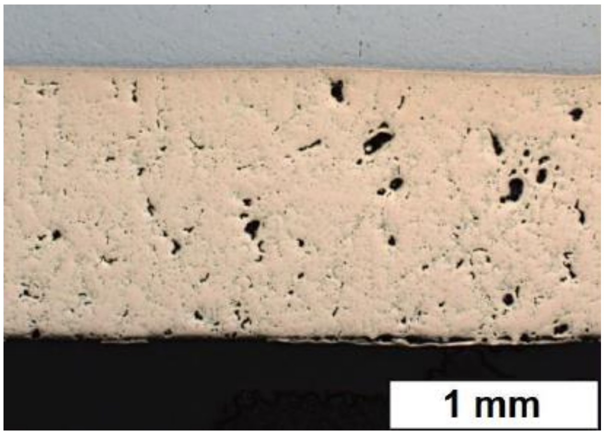


Figure 7 - Detail view of the copper alloy bearing surface

Upon microscopic examination, the steel support is revealed to be a black area, while the copper exhibits a light brown hue. The black spots visible between the copper are indicative of alloy components that have been embedded into the copper. The upper surface of the bearing is flat and closed, with no corrosion-related disruptions detected.

Beside the shown copper alloy that is used as one of the standard KBB bearing materials three additional materials have been tested. All materials have been found to demonstrate resistance against corrosion caused by methanol.

3.2.2 Corrosion tests with ammonia

Due to the delay in the analysis of the ammonia-blended oil samples described in Chapter 3.1.2, an alternative corrosion test with ammonia had to be conducted. The objective of this test was to evaluate the corrosion resistance of various bearing materials in the presence of ammonia.

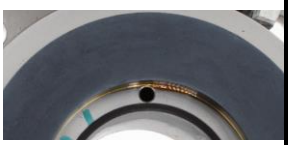
In order to achieve expeditious results and ascertain the potential of engine oil to protect the bearing material against ammonia, an extreme test was developed. The bearing samples were partially immersed in engine oil. Subsequently, the samples were placed within a pressurised reactor at 60 °C, into which a gas mixture consisting of 10 % air and 90 % ammonia was introduced. Following a 26-day test duration, a visual inspection of the samples was conducted.

Following the extreme test scenario, which overdraws realistic boundaries, all samples have shown indications of corrosion. For instance, Figure 8 demonstrates the presence of characteristic blue reaction products, which are typically associated with copper-ammonia reactions. A more thorough examination of the other samples reveals that some materials appear to exhibit higher levels of corrosion resistance compared to others.

Figure 8 - corroded copper alloy sample caused by ammonia

Table 8 presents a bearing sample from both sides: one side immersed in engine oil and the other side left unprotected. Minimal corrosion was exhibited by the side covered by a thin layer of oil, while the unprotected side displayed clear deep blue colours, indicative of cupper corrosion caused by ammonia.

Table 8 - comparison of bearing material with and without oil protection

Sample covered by engine oil	Sample without oil protection
	

The tested parts undergo some further visual inspection to determine how the corrosion affects the bearing structure. The results of this analysis have not been available at the time of publication of this paper.

Copper is an essential component of slide bearings in turbochargers. The results demonstrate the feasibility of incorporating copper-based alloys into ammonia-fuelled engines. Achieving a satisfactory bearing lifetime necessitates the selection of the correct alloy, in conjunction with a suitable engine oil.

4 CONCLUSION

Dual-fuel engines running on alternative fuels, such as methanol and ammonia, are a key technology in achieving the targeted IMO regulations. For vessel owners, they offer the potential to use carbon-neutral fuels where they are available and a fallback to conventional fuels if necessary.

For engine manufacturers and component suppliers dual-fuel engines using alternative fuels offer a great platform to gain experiences with the new fuel types and to optimise their engine concepts.

In terms of their properties ammonia and methanol differ from diesel. While the charge air requirements are comparable to diesel combustion the turbine-side needs slight adaptations which could be done for example by adjusting the turbine nozzle ring. Both concepts single- and two-stage turbocharging system are capable to deliver the charge air for alternative fuel combustion. The decision which concepts suits best can be done by taking into account other boundaries as application, budget, available space and of course efficiency and power output.

As methanol and ammonia are corrosive it is important to understand which components of the turbocharger might get in contact with the fuel and as a consequence to change these affected materials if they aren’t resistant. Within this paper it was shown that KBB standard bearing material is able to resist contaminated oil with methanol. Regarding ammonia resistance the results also show that KBB has suitable turbocharger bearing materials available that are able to achieve good component lifetimes. Especially when the oil-material selection was done properly.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFR Air Fuel Ratio

DPF Diesel Particulate Filter

EO Engine Oil

HFO Heavy Fuel Oil

H_G lower heating value of the air-fuel mixture

H_U lower heating value

IMO International Maritime Organization

KBB Kompressorenbau Bannewitz GmbH

LNG Liquified Natural Gas

MEF Methanol Energy Fraction

MDO Marine Diesel Oil

NOx Nitrogen-Oxides

OEM Original Engine Manufacturer

SOx Sulfur-Oxides

λ Air-Fuel Equivalence Ratio

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