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Emerging fuel impact on engine lubrication and lubricating oil condition in marine low- speed and medium-speed engines

Lubricants

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ABSTRACT

This paper discusses the influence of emerging fuels such as biofuel, methanol, and ammonia, on marine engine lubrication and used oil analysis, in the context of regulations aimed at reducing greenhouse gas emissions.

The shift towards alternative fuels is driven mainly by the need to comply with IMO's and European stringent emission reduction targets. Each fuel type presents unique lubrication challenges that might affect engine performance and maintenance.

Used oil analysis is a critical component in monitoring engine health. The introduction of new fuel types necessitates the development of modified analytical techniques to accurately assess the lubricating oil condition and especially the fuel dilution and impact on a variety of used oil parameters. Most engine operators today rely on routine laboratory analysis that are based on decades of experience on fossil-based fuels. However, the applied methods and limits should be questioned today, are not intended for these new emerging fuels and can in some cases impact negatively the engine performance and maintenance intervals.

Adapting used oil analysis for engines operating on emerging fuels is essential for optimizing engine performance and avoiding engine downtime and maximizing the engine maintenance intervals and oil drain intervals. Ongoing research and development will play a pivotal role in achieving these objectives.

Besides the laboratory testing, this paper looks at actual oil performance impact in real life engines operated on a variety of emerging fuels and compared with more traditional fossil-based fuels. The field case combines engine big data extractions with fuel and lubricant oil analysis in an intersecting way, providing a unique way to extract learnings from multiple data source angles.

1 INTRODUCTION

With a need to decarbonize the marine industry, new fuels with a lower carbon footprint are being explored. For decades marine engines have been burning residual and distillate fuels. Marine engine lubricants of today enable the use of such fuels. Specific lubricant formulations have been developed to cope with the corrosiveness caused by these high sulphur fuels and to keep combustion by-products either in suspension or allowing some contaminants to be removed by filters or centrifuges. Therefore, used oil analysis has always been an important measure to ensure the vessel's reliability. The new fuels entering the marine market, may have a specific impact on the combustion and by-products being formed. This paper looks back on the early experience using some of these fuels and highlights some watchpoints.

2 QUANTIFYING EMERGING FUEL CONTAMINATION IN LUBRICANTS AND THEIR IMPACT ON OPERATION

When operating internal combustion engines, there is always some degree of interaction between the fuel used and the lubricating oil. This is caused by raw fuel leakages or via unburned combustion by-products.

Each individual fuel may pose its own set of lubrication challenges. Quantifying the fuel contamination is therefore essential to understand the impact on the lubricating oil parameters and ensure reliable engine operation.

Several methods have been historically developed to quantify conventional fuels. However, these are not necessarily suitable for other fuel types.

Fuel contamination in diesel engine oil is typically quantified using gas chromatography (GC) or Fourier Transform Infrared Spectroscopy (FTIR). However, other lubricating parameters may also be affected, such as viscosity, oxidation, wear protection, corrosion, etc. These parameters provide an indirect means to see the impact of the fuel interaction with the lubricant.

This paper mostly focuses on FAME biofuel contamination in oil and methanol, as these are the currently available fuels where the engine technology is readily available.

2.1 Biofuel (FAME) contamination in lubricants and impact on operation

The adoption of FAME as a component of marine fuels is driven by stringent emission regulations and environmental sustainability objectives.

FAME (Fatty Acid Methyl Esters) is a generic term for biodiesel which is mostly produced from recycled cooking oils and renewable oil sources. Marine medium and low speed engines can burn FAME with little to no adjustments and can be blended in any ratio with either distillate fuel (MGO/MDO), VLSFO (Very Low Sulfur Fuel Oil) or HSFO (High Sulfur Fuel Oil). This makes it an ideal drop-in solution for shipowners to lower their vessels' carbon footprint without any heavy CAPEX investments.

Today there is already a considerable amount of good experience with running marine engines on FAME; although it is mostly at a ratio of 20-30% blended in a conventional marine fuel. On low-speed engines where fresh new lubricant is injected and burnt, no impact has been observed so far. However, on four-stroke medium speed engines where the lubricant is continuously exposed to combustion by-products and potential internal raw fuel leakages, the impact of using FAME seems to be larger.

2.1.1 Impact on used oil four stroke medium speed engines

The below case further elaborates on earlier test work initially discussed in Cimac Busan CIMAC paper 423 – "Marine engines lubrication within a broad fuel landscape & impact on exhaust aftertreatment systems," [1] and adds on some longer-term experience in medium speed engines operated on extended periods using both distillate fuel and 100% FAME.

The test engine accumulated 7,005 running hours under the B100-FAME biofuel test phase. However, just before the EOT inspection, at 17,699 main engine running hours, the vessel switched to regular low Sulphur Diesel fuel.

This case study aims to provide a comprehensive analysis of the lubricant impact when using biofuels, (FAME, B100) on three marine MAN 8L27/38 4-stroke engines, with a focus on the operational experience and impacts observed during the extensive testing of the Chevron HDAX® 9700 lubricant.

Besides the focus on used oil analysis, this study shows the results of the engine inspections, highlighting the wear and cleanliness performance of engine components when operating on biofuels compared to conventional Marine Diesel and EN590 automotive grade diesel.

This case study provides further insights into the practical implications of using FAME in marine engines, offering real-world operational data and findings that demonstrate FAME fuels working effectively in marine applications. Furthermore, it highlights some operational challenges and watchpoints.

2.1.1.1 Understanding the fuel

The fuel type and properties have a direct impact on the used oil condition and longer-term trends reflected in the used oil analysis.

To understand the impact of the FAME operation on the engine oil condition, it is important to understand how the used oil condition was impacted when operated on more conventional fuels. In this case, the engines were operated on Marine Diesel (MDO) according to ISO 8217 specification and EN590 ultra-low sulphur diesel (ULSD) which is the current standard for all automotive diesel fuel sold in the European Union member states and other European countries. This grade of fuel is also called (ULSD).

Fuel parameters	Units	EN590	MGO	Bio Diesel
Density	kg/m^3	820 – 845	Max. 890	860 – 900
Viscosity at 40°C	mm^2/s	2.0 – 4.5	1.4 – 6.0	1.9 – 6.0
Sulfur Content	% m/m	Max. 0.001	Max. 1.0	Max. 0.0015
Flash Point	°C	Min. 55	Min. 60	Min. 93
Cetane Index	-	Min. 51	Min. 40	Min. 47
Water Content	ppm	Max 200	Max. 0.3	Max. 0.05
Ash Content	% m/m	Max. 0.01	Max. 0.01	Max. 0.02
FAME Content	% V/V	0.1 – 11.9	<0.1 – 2.51	83.37 - 100
Micro Carbon Residue	% m/m	Max. 0.15	Max. 0.2	Max. 1.3
Pour Point	°C	-33 to -6	-30 to +3	-24 to +12
Cold Filter Plugging Point	°C	-26 to -6	-23 to 13	+4 to +8
Acid Number	mg KOH/g	Max. 0.56	Max. 1.38	Max 0.91

Table 1 shows the fuel parameters of different fuel types used during the case study 1 on medium speed engines

In the case study extended periods of operation on distillate fuels and FAME's, with periods of alternation were documented. This makes it exceptionally suitable to study the impact of the fuel type on the lubricant condition.

One of the fuel parameters not captured in ISO 8217 that deviated the most in this case study is Simulated distillation (SIMDIS) according to the *ASTM D7169 standard / Determination of the boiling point of petroleum fractions*. This method typically applied on heavy hydrocarbon mixtures, provides a boiling point distribution at 10%/50%/90% recovery using gas chromatograph (GC). The sample components are separated based on their boiling points as they travel through the GC column. The retention time of each component is recorded.

When comparing the distillate fuels (MGO, EN590) to the B100 (FAME), the 10%/50%/90% recoveries show a much wider spread for the distillate fuels, indicating these fuels are blended with multiple feedstocks where lighter fractions are present and can evaporate at lower temperatures. However, the B100 (FAME's) show all 3 results closer to each other, indicating similar feedstocks are used in the production of the fuel.

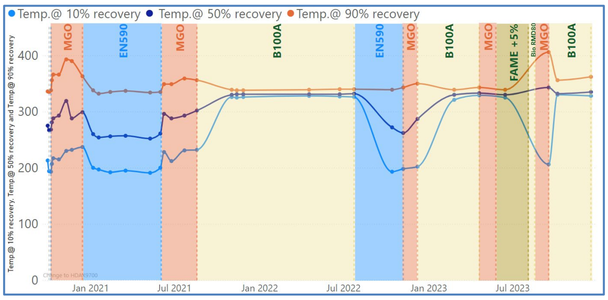

Figure 1 depicts the Simulated distillation (SIMDIS) according to the ASTM D7169 standard: "Determination of the boiling point of petroleum fractions"

2.1.1.2 Impact on used oil analysis

Lubricating oil samples were taken throughout the test program and a long-term trending was established. Below chapters described the impact of running extended periods on FAME versus MDO and EN590 conventional distillate fuels. The samples from main engine #1 were analyzed in more depth, while engines #2 and #3 were followed up with routine used oil analysis.

2.1.1.2.1 Lube Oil viscosity

All 3 main engines saw a similar trend of decreasing lubricant viscosity in the periods when operated on B100 (FAME), versus periods of operation on distillate fuel (MDO/MGO).

Figure 2 shows the viscosity @40°C trending of all 3 engines when switching between B100 FAME and MGO/EN590

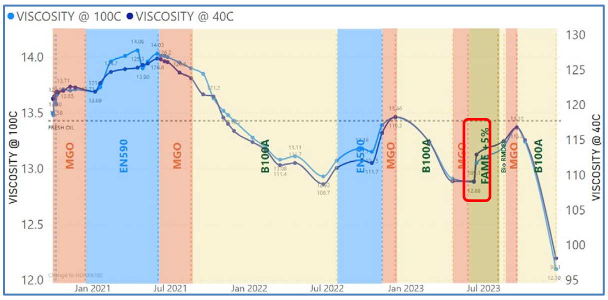

Figure 3 shows the viscosity trending at 40&100°C of Main engine #1 when switching between B100 FAME and MGO/EN590

The above graph (Figure 3) includes the reference line of fresh oil viscosity (@100°C). All B100 test periods show a clear viscosity drop, even beyond the fresh oil value, and at some points surpassing the minimum viscosity level recommended by the engine builder. In June 2023, there was a significant increase in viscosity level due to the replacement of 950 liters of oil in the sump tank, marked in red on Figure 3.

The lubricant viscosity drops each time when switching to B100 FAME. The entry of unburned biodiesel through raw leakages, or blow-by due to incomplete combustion, leads to a noticeable thinning of the oil.

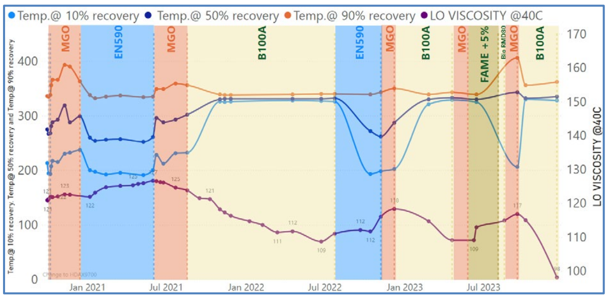

Figure 4 displays the viscosity trending at 40°C of Main engine #1 compared to the SIMDIS distillation graphs of the fuel.

FAME consists of more polar molecules with lower volatility and higher boiling points compared to hydrocarbons in EN590 and MGO fuels. This low volatility prevents biodiesel from evaporating once it enters the crankcase.

Distillate fuels (MGO/EN590) are clearly blended fuels with a widespread range in the SIMDIS distillation results. In addition, the lighter more volatile hydrocarbons in EN590 and DMA tend to evaporate more readily, causing less persistent dilution and minimal impact on oil viscosity drop.

As biofuel dilution is clearly impacting the difference in viscosity behaviour of the used engine oil, focus has been put on identifying a method to quantify the amount.

Several laboratory test methods have been developed over time to determine the dilution of fuel into lubricants. However, as we will face significant changes in new fuels sources, it is imminent that we ensure appropriate methods are applicable for these new future fuels & blends.

As this case study is on FAME contamination and investigation of impact on lubricant viscosity drop, this was investigated first.

2.1.1.2.1.1 By Fourier Transform Infrared Spectroscopy

A well-established potential method is determining (bio) fuel content by Fourier Transform Infrared Spectroscopy (FTIR or IR)

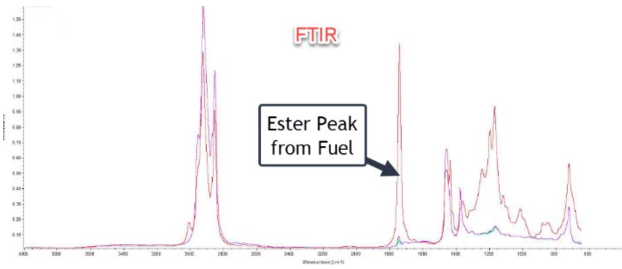

Figure 5 shows the FTIR spectrum from FAME fuel and used lubricant. The ester peak is clearly showing.

The figure above shows the spectra of the biofuel FAME sample versus the used oil samples. The ester peak from the fuel is very dominant and some smaller peaks in the used oil can be observed.

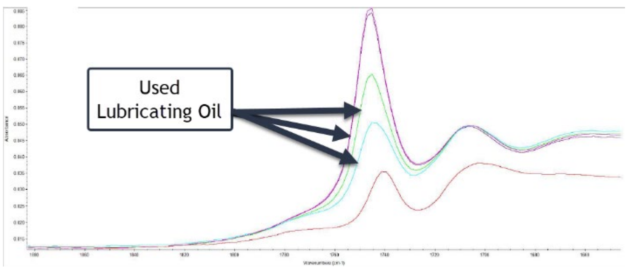

Figure 6 is zooming in on FTIR from fresh oil and used oils contaminated with FAME, showing the consistent ester peak originated from the FAME

Zooming out on the critical wavelength around 1740 cm-1, some peak is visible in the fresh oil range as well, originated from the fresh lubricant.

Taking this into account, a model was made to estimate the quantity of FAME contamination to the lubricant.

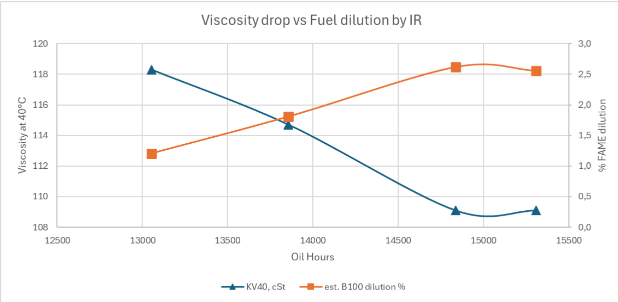

Figure 7 clearly shows the viscosity drop vs Fuel Dilution measured by FTIR

The prediction method established shows a good correlation with the viscosity loss observed in the field. However, some caution needs to be considered as (1) only a small population was used with one type of biofuel and one specific lubricant.

2.1.1.2.1.2 By Gas Chromatography

This method uses gas chromatography to simulate distillation and determine the boiling range and was applied to determine the boiling point distribution of FAME. The applied method is comparable to ASTM D7398 [3], where the temperature range was extended so that heavy samples (FAMEs with high boiling points or with long straight chain hydrocarbons) could be analysed.

The study was performed on a single lubricant sample from the case study that had seen extended FAME operation, and yet after being switched back to distillate fuel, the viscosity was restored. The sample corresponds to the first datapoint on Figure 7 above (Oil viscosity KV40°C=118.3Cst)

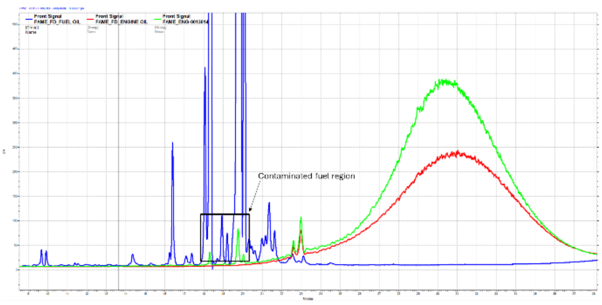

Figure 8 depicts the overlayed chromatograms Fresh Lube oil with Used Lube Oil and Biofuel B100 FAME sample

Looking at the above chromatogram, the FAME Biofuel (BLUE) has its characteristic elution fingerprint peaks (14 – 22 mins).

These peaks do not exist in the fresh engine oil (RED) but some of these peaks in the above region, such as those around 18.3 mins, 19.8 mins and 20.1 mins, are visible in the used engine oil (GREEN).

The peaks on the used engine oil enclosed in the rectangular box are referred to as contamination fuel. However, these peaks may have two sources:

(1) residual species from the biofuel, which can be taken as an indication of biofuel dilution or contamination in used engine oil.

(2) degradation species from engine oil over its service, which, if corroborated, cannot be taken as biofuel dilution or contamination.

Peaks between 22.5 ~ 23 mins cannot be taken as bio-fuel indicators as they are also occurring in fresh and used engine oils.

Mass % of the contaminated fuel in the used oil sample was found to be 0.89 wt%.

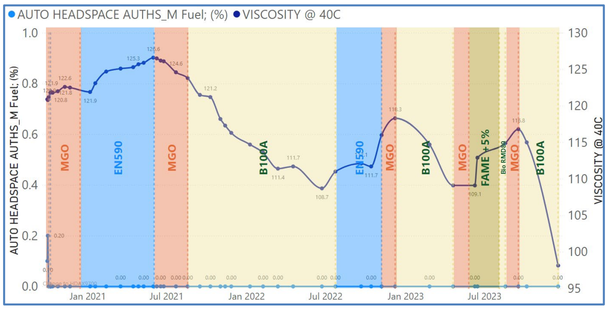

Figure 9 illustrates the viscosity trending at 40°C of Main engine #1 compared to the HS-GC fuel dilution measurement not picking up any fuel dilution during viscosity drop on FAME.

Additional analysis was done with Gas Chromatography (GC). However, this time method DIN 51454 [2] was applied. In general, different fuels have different boiling points, making it possible to determine different fuels present in the fuel. This method is applicable for petrol, diesel, FAME, + FAME-diesel-mixes, vegetable oil and paraffinic diesel. However, the challenge applying this standard method is that the fresh oil also has lighter fractions. Therefore, it is possible that during GC fuel detection, the lighter fractions from the lubricant itself will also be detected. Overtime these lighter fractions from the lubricant can (partly) evaporate, which means the lubricant part will be also present in the results. Therefore, the method was slightly adjusted, and the fresh oil impact was not considered.

Two independent labs were used to evaluate this method on the field samples. Lab1 provided the total fuel contamination (FAME + Diesel), whereas Lab2 differentiated the diesel part from the FAME part. For both labs the new oil values were deducted.

The analysis of Lab1 indicate a clear trend. As the fuel dilution value increases, the Viscosity at 40°C decreases. This inverse relationship suggests that higher concentrations of FAME in biofuel correlate with lower viscosity at 40°C. The data for biofuel samples show a consistent pattern, highlighting the significant impact of FAME content on fuel viscosity.

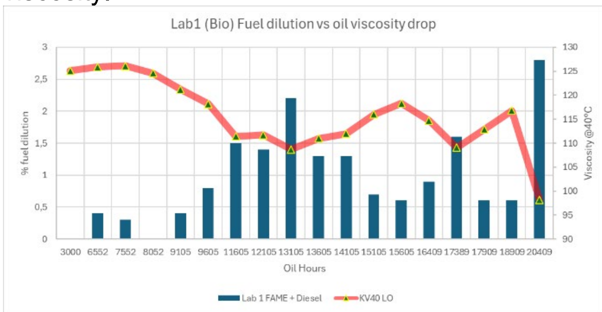

Figure 10 shows the results from Lab1 fuel dilution results vs oil viscosity

The analyses of Lab2 reported separated values for diesel and FAME, however FAME values reported below 0.5% were reported as <0.5%. Therefore, these cannot be added up to straightforward compared to Lab1 Results.

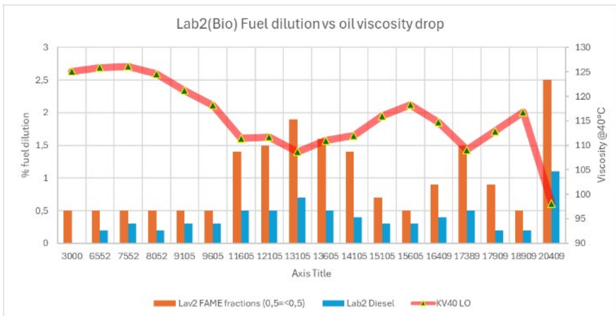

Figure 11 show the results from Lab2 fuel dilution results vs oil viscosity. Periods where viscosity shows a downward trend are operations on biofuel

2.1.1.2.2 Flash Point

Measuring the flash point is often considered as a measure to determine fuel contamination. However, as lighter fractions often evaporate before the oil sample is taken, the higher remaining fuel fractions often don't trigger an alarmingly low flash point measurement. In this field case the ASTM D92 COC method did not serve as early warning system to predict the viscosity drop caused by (bio)fuel dilution.

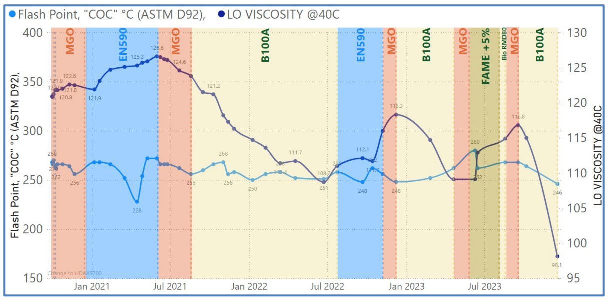

Figure 12 shows the relationship between the flash point vs oil viscosity

2.1.1.2.3 BN retention and TAN

In the realm of marine engineering, particularly for four-stroke engines running on various fuels, monitoring the Total Base Number (TBN) of lubricating oils is crucial. TBN is a measure of an oil's alkalinity, which helps neutralize acids formed during combustion, thus preventing corrosion and wear. Different methods are employed to measure TBN, each with its specific applications and advantages.

The ASTM D2896 method is widely used for determining the total base number (TBN) of new oils and ensuring that used oils in service have sufficient alkalinity to neutralize acids formed during combustion. This method employs a strong acid, perchloric acid, which ensures that both strong and weak bases in the oil are neutralized,

ASTM D4739 uses a weaker acid, hydrochloric acid to measure the oil's alkalinity. This method is mostly used on engine oils operated in an environment that produce weaker acids, mostly from oxidation only. Unlike ASTM D2896, ASTM D4739 focuses on neutralizing only the strong bases, ignoring the weaker ones that can interfere with the results. This makes it more suitable for tracking how much of the oil's alkalinity is left after use. Within ASTM D4739, there are two approaches: (1) measuring TBN at buffer pH3 and (2) at the well-defined inflection point. The buffer pH3 method measures TBN until the pH reaches 3. This provides a quick result but might miss some strong bases, giving lower TBN values. Therefore, this is good for routine checks. For more detailed analysis, the well-defined inflection method is better to understand how much alkalinity is left in used oils. When dealing with biofuels like FAME, which can be more acid, it's crucial to monitor TBN closely to prevent engine damage.

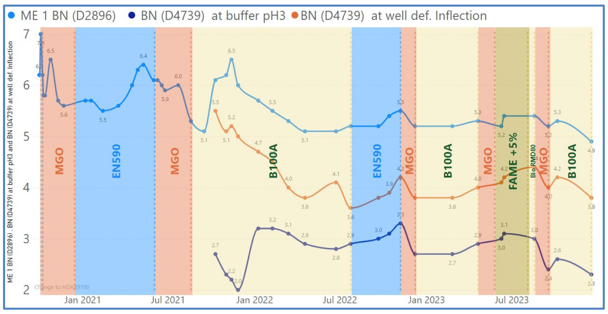

Figure 13 depicts the TBN measurements during the field trial

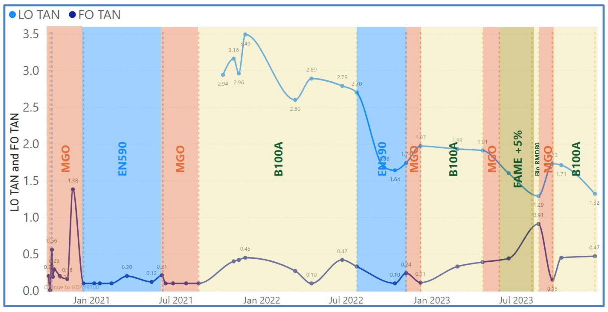

Figure 15 depicts the TAN of the used oil during the field trial

For the field case study samples, applying the more commonly used D2896 method was sufficient to guarantee safe and reliable operation of the engines. The D4739 at buffer PH3 follows a similar trend. D4739 at well defined inflection does not add much value in this case.

2.1.1.2.4 Oxidation, Nitration and TAN

Oxidation and nitration levels are low throughout the test period, starting with a gradual buildup of oxidation at start, and levelling out irrespectively with maybe a slightly higher level triggered during FAME burning, compared to running on distillate fuels.

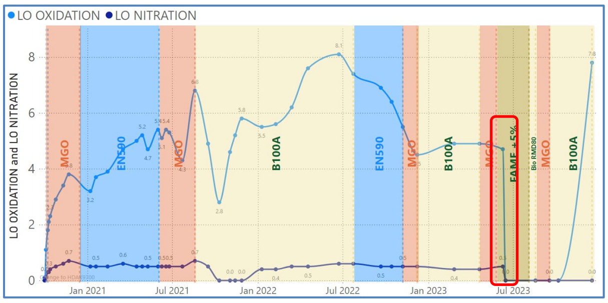

Figure 14 depicts the Oxidation and Nitration during the field trial

In June 2023, there was a significant drop in oxidation levels due to the replacement of 950 liters of oil in the sump tank (red box on graph).

The Total Acid Number (TAN) measurement in used oil appears to remain unaffected using both conventional as biofuels, indicating that fuel type does not significantly influence TAN levels.

Neither did Acid Number measured in the biofuel indicate any severe levels (see table 1).

2.1.1.2.5 Wear Metals

The concentration of wear metals in the used oil appears to remain unaffected whilst using different fuels, indicating that fuel type does not significantly influence wear metal levels.

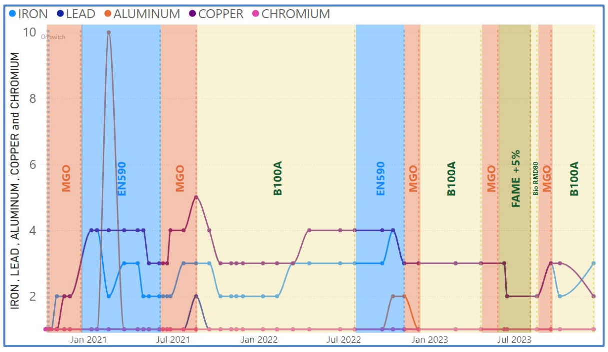

Figure 16 depicts the Wear metals during the field trial

2.1.1.2.6 Contamination

During the test period, a significant spike in sodium levels was observed. This increase was attributed to a cooling water pump seal leakage. Once the leakage was identified and repaired, the sodium levels gradually returned to normal.

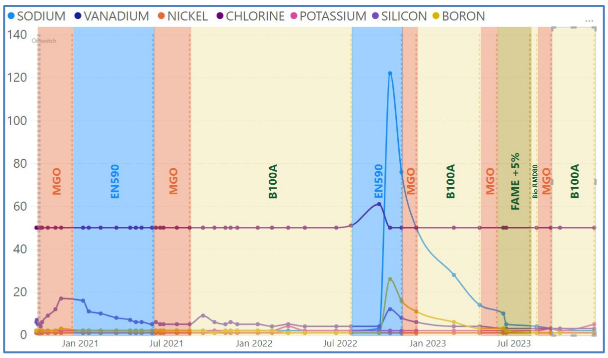

Figure 17 depicts the contaminants in the used lubricant during the field trial

In addition to sodium, silicon levels also showed notable but minor spikes, where the first peak could be traced back to an improper installed viledon filter on the turbo charger inlet. This was a dredging environment, where sand-mist is common. Nevertheless, there was no significant correlation between silicon levels and wear metals.

Apart from the sodium spike, all other contaminant levels remained below the OEM limits.

2.1.1.2.7 Water

During the test period, a minor increasing trend in water contamination was observed. However, no alerting levels were reported. The spikes in Sodium and Boron, believed to be linked to a cooling water pump leakage, were not reflected in the water content as shown in Figure 13, proving the proper function of the LO Purifier. On board, there is an Alfa Laval S305 LO Purifier maintaining a throughput of 1200 liters per hour and separation temperatures of 92°C in port and 97°C at sea.

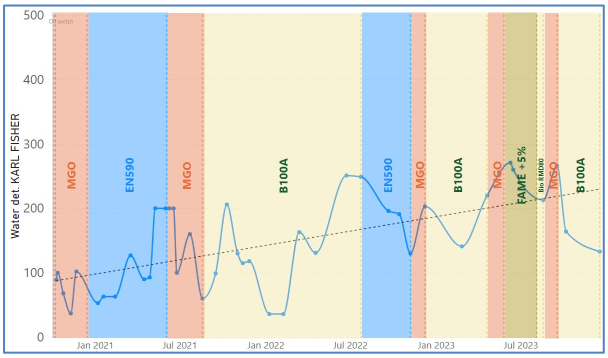

Figure 18 shows the water contamination in the used oil samples

2.1.1.2.8 Soot and insolubles

Low levels of soot have been observed throughout the testing program. However, this is in line with expectations as the installation is equipped with a lube oil centrifuge purifier designed to remove soot and contaminants from the oil in service.

Most routine labs today measure soot content by Infrared (FTIR). The method applied on the samples in the study are determined at 3800 cm-1, which correlates with *ASTM D4055: Test Method for Pentane Insolubles by Membrane Filtration*.

The second method applied is Thermogravimetric Analysis (TGA) to measure the amount of soot in a sample. TGA is a technique that measures the change in weight of a sample as it is heated over time. This method helps quantify the soot content by observing the weight loss that occurs when the soot burns off at high temperatures

TGA and SOOT by IR (3800 cm-1) values do not show a clear and consistent relationship with the different fuel types. The values for TGA soot and SOOT LOAD by IR fluctuate without a distinct pattern that correlates directly with the fuel type.

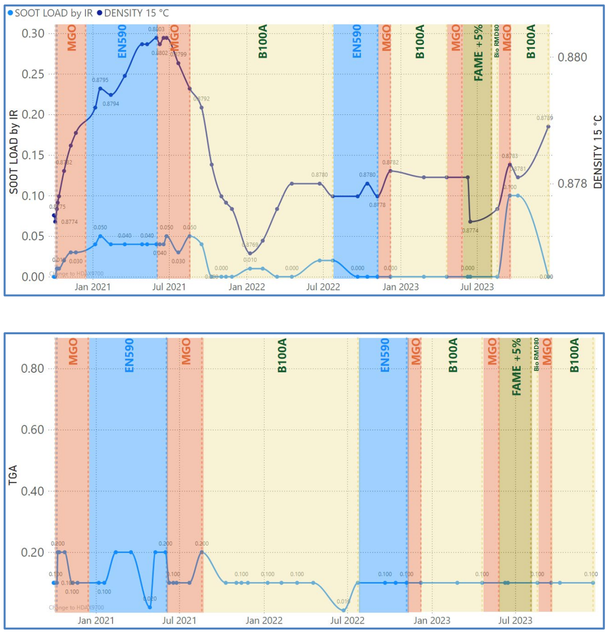

Figure 19 shows the soot by IR & TGA vs Density in the used oil

Lubricating oil density can provide some insights into the condition of used oil and its soot load, but it is not the most direct or comprehensive method for such assessments. The density of lubricating oil can change due to contamination, oxidation, and the presence of soot. An increase in density might indicate the presence of contaminants or degradation products. Soot particles, which are primarily carbon, can increase the density of the oil.

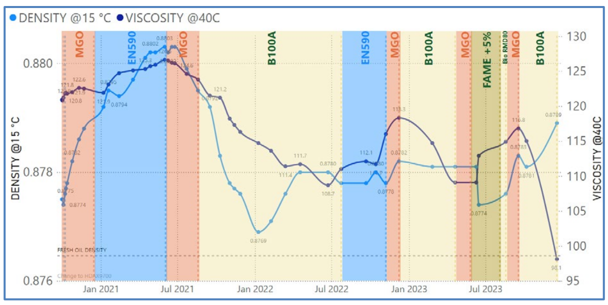

Figure 20 shows the LO Viscosity and Densityof the used oil

2.1.1.3 Inspection results

Besides the focus on the used oil analysis, the engine condition was inspected at regular intervals and cylinders 6 and 7 of engine #1 were overhauled at start and end of test. Borescope inspections were performed at regular intermediate inspections. The crankcases and storage tank were cleaned and filled with the test lubricant. The test engine accumulated 7,005 running hours under the B100-FAME biofuel test phase. However, just before the EOT inspection, at 17,699 main engine running hours, the vessel switched to regular low Sulphur Diesel fuel.

The end-of-test inspection on biofuel revealed similar low wear on the critical engine components as when running on distillate fuel. The engine maintained high cleanliness levels in the camshaft and crankcase compartments with moderate and easily removable deposits on pistons and valves. Again, very comparable to the distillate fuel operation prior to the biofuel test phase.

Cylinder Heads: During the FAME test phase, the rocker arm deck and cylinder head cover (cold areas of the engine) were found to be clean with no sludge formation. The discoloration observed on the Rocker Arm deck has been present since the engine was new. It is residual preservation material since engine build.

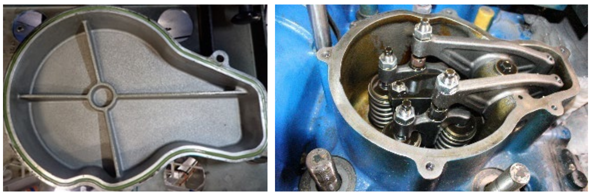

Figure 21 shows the clean condition of the cylinder Head Cover and Rocker Arm at FAME EOT

Low wear on the valve seats and seals, indicating good overall condition and effective sealing. There were minor deposits observed on the valves and in the intake and exhaust ducts.

Figure 22 shows the good condition at end of test on FAME operation

The fire face showed moderate deposit, and smooth ash deposit on the valves indicating normal appearance.

Figure 23 shows minimal deposit formation at end of test on the cylinder Head fire face

Pistons: The inspection of the pistons revealed very good condition at FAME EOT. Although both piston crown tops showed moderate white deposit buildup, primarily concentrated at the outer rim with nearly no deposits at the center of the crown, the deposits were soft and could be easily removed. This appearance was similar to the piston crowns found at the EOT on Diesel operation, where the deposits were also moderate but harder to remove. The condition observed with the FAME fuel operation is acceptable and appears normal, with the deposits not affecting the engine's performance or maintenance intervals.

Figure 24 shows the comparison of the piston crown top on Diesel (picture on the left hand side) and FAME operation (picture on the right hand side)

The piston top lands exhibited overall good condition. Minimal deposits were observed on piston #6, while piston #7 had a slightly higher amount of buildup, indicating normal cylinder to cylinder variation. The ring grooves and ring lands found with no or minimal deposits. These deposits were soft, sticky, and easily removable with a cloth.

Figure 25 shows the excellent cleanliness of the pistons condition at the end of test on FAME

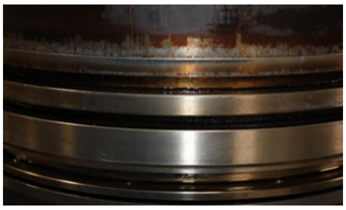

Figure 26 shows the very clean piston ring grooves and ring lands condition at end of test on FAME

Piston Rings: The piston rings were nearly clean on the backside, with both pistons showing good condition of running surfaces. These conditions were comparable to the previous distillate fuel test.

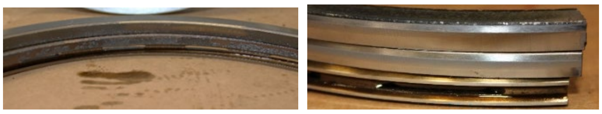

Figure 27 shows the clean condition of the piston rings appearance at end of test on FAME

Cylinder Liners: The inspection of the cylinder liners revealed a clear and open honing pattern, indicating minimal wear and good overall condition. Both liners showed some light discoloration, primarily due to cooling water leakage during the removal of the cylinder heads.

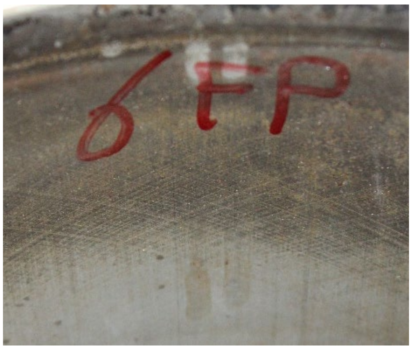

Figure 28 shows the close-up on Cylinder Liner #6 surface at TDC, at FAME end of test

Camshaft and Crankcase compartment: The inspection revealed exceptional cleanliness in both, the camshaft space and the crankcase. After running on biofuel, both areas maintained a very high level of cleanliness, comparable to the prior distillate fuel operation.

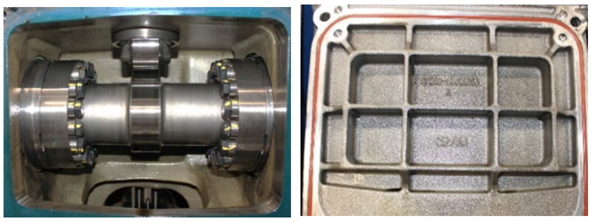

Figure 29 displays the camshaft compartment cleanliness

Figure 30 displays the crankshaft compartment

After the biofuel FAME EOT inspection (the data presented above) in January 2023, the engines, particularly engine #1, continued to be monitored. One year after the FAME EOT inspection, in December 2023, the final inspection was carried out. From the FAME EOT in January 2023 until December 2023, the engine accumulated an additional 4,500 operational hours, during which the vessel alternated between different fuels, including MGO, EN590 and biofuels from differences sources and suppliers. In total, the engine ran an additional 3,124 hours on Biofuels during this period. The final inspection, conducted in December 2023, was an additional check to assess the engine's condition after the extended operational period with different fuels. During this inspection, no pistons were pulled and instead, Cylinder Head #7 was removed, and a borescope inspection was performed on Cylinder Unit #6. The data collected from this final inspection is presented as additional findings to complement the initial FAME EOT inspection results already discussed in this paper, providing a comprehensive understanding of the engine's performance and condition after running on various fuels over the year.

The cold parts of the engine appear to remain at the same exceptional condition.

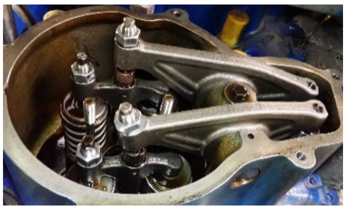

Figure 31 show the condition of the Rocker Arm at end indpection

Figure 32 shows the condition of the Camshaft & Crankcase at the end inspection

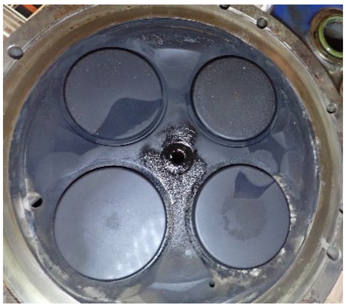

Figure 33 shows the cylinder Head Fire Face

Minor deposits developed on the fire face and valves, which is within acceptable limits and did not impact the overall performance or operation of the engine.

The piston crown tops showed moderate white deposit buildup, primarily concentrated at the outer rim with nearly no deposits at the center of the crown. The deposits were soft and could be easily removed

Figure 34 Piston Crown Top #7

Borescope inspection of Unit #6 revealed good condition of the combustion chamber components. Neither excessive deposit nor wear was observed.

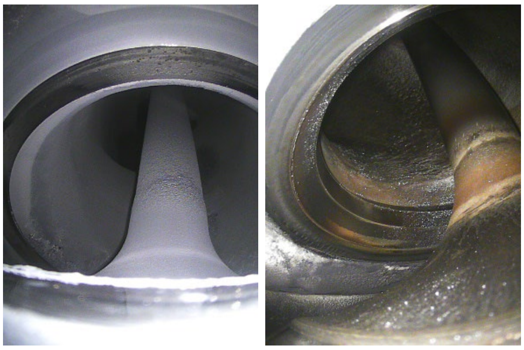

Figure 35 shows the condition of the intake and Exhaust Valves oservied by endoscope

Figure 36 shows the condition of the piston crown top and Cylinder Liner surface at TDC, observed by endoscope

The frequent changes between conventional distillate fuel types and biofuels did not impact the general condition of the engines much. The lubricant in use; Chevron HDAX® 9700 was able to keep the engine components clean and controlled wear without compromising engine durability and performance.

2.2 Methanol contamination in lubricants and impact on operation

As Methanol (MeOH) has a different boiling point (MeOH 64,7°C) compared to FAME (345°C to 365°C) / Diesel (344°C), the DIN 51454 method will not pick up any MeOH in the (used) oil. In this case a specific In House Method (IHM) Head Space Gas Chromatography (HS-GC) was established to detect the MeOH in the used oil.

2.2.1 Methanol contamination in four stroke medium speed engines

At the time of writing of this paper, no data is available.

2.2.2 Methanol contamination in two stroke low speed engines

2.2.2.1 Impact on system oil as crankcase oil

In this case study the focus was on the Methanol impact on the system oil of marine 2 stroke engine. The system oil in the 6G50ME-C9-LGIM engine ensures lubrication, cooling, cleaning of engine components and hydraulic actuator fluid. The oil circulates from the sump, through the pump, filters, and coolers, and is then distributed to various engine parts. The LO purifier continuously cleans the oil, removing impurities and water. The average temperature of system oil during operation ranges between 60°C and 70°C, and in the Sump Tank between 50°C and 60°C. The boiling point of Methanol is 64.7°C in ambient conditions.

As there is minimal to no contact between the MeOH and the crankcase oil, the focus of this program was put on the segregated sealing oil system, that is intended to have possible interaction with the MeOH. [4]

2.2.2.2 Impact on system oil as Sealing Oil

The sealing system uses the same system oil however in a parallel segregated system. The sealing oil supply unit is installed on the engine to prevent methanol leakage in the methanol injection system. In the Fuel Booster Injection Valve for Methanol (FBIV-M), sealing oil prevents the mixing of system oil as hydraulic & sealing fluid and methanol. The used sealing oil is then drained and recirculated to a separate tank within the sealing oil unit. The sealing oil consumption during this program was approximately 0.135 g/kWh.

Sealing oil samples were taken from December 2022 to October 2023, accumulating approximately 6,000 MERH of which 3,500 MERH engine ran on methanol. This study was to perform a more comprehensive analysis of the methanol impact on the sealing oil. The focus on sealing oil came because it should be less contaminated with other contaminants compared to system oil, thus reducing external factors that could disturb the methanol impact study.

2.2.2.2.1 Viscosity of sealing Oil

The viscosities at 40°C & 100°C maintain consistent levels, with a slightly increasing trend with both remaining in an expected range. The levels of MeOH in the lubricant were at very low levels, hence no impact in viscosity was seen.

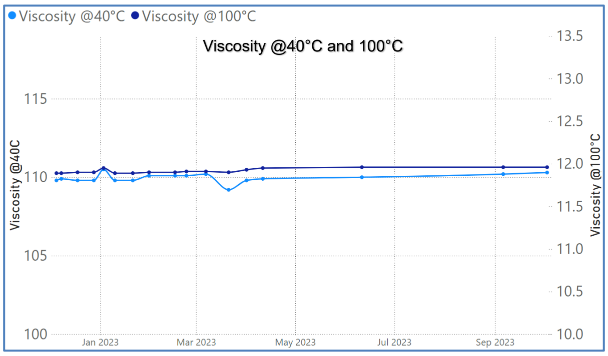

Figure 37 depicts the viscosity @40C and Viscosity @100C trends

2.2.2.2.2 Density of sealing Oil

Density @15°C shows a stable and slightly increasing trend, showing minimal load on the lubricant from contamination and oxidation.

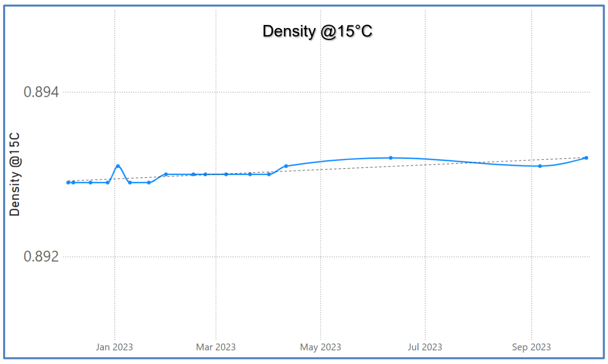

Figure 38 displays the sealing Oil density@15C

2.2.2.2.3 TBN of sealing Oil

TBN is typically measured by ASTM D2896 for marine systems oils. ASTM D4739 was applied in addition as it uses a weaker acid, hydrochloric acid to measure the oil's alkalinity. This method is mostly used on engine oils operated in an environment that produce weaker acids, mostly from oxidation only. Within ASTM D4739, there are two approaches: (1) measuring TBN at buffer pH3 and (2) at the well-defined inflection point.

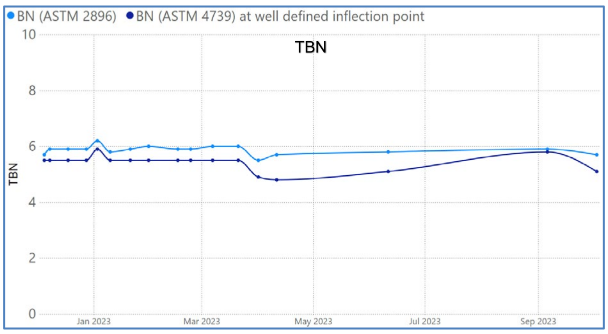

Figure 39 shows the TBN trend observed

TBN test method D4739 at pH3 was found to be less effective and was left out. More consistent results were obtained with D2896 and D4739 at well-defined inflection point. The BN level remained constant.

Overall, the ASTM D2896 method was found sufficient for use in this application.

2.2.2.2.4 TAN of sealing Oil

Apart from i-pH, TAN was investigated as a commonly used method to determine the Total Acid Number. TAN gives a broad measure of all acid components, where i-pH focuses on the strength of the acid only. No significant increase was observed.

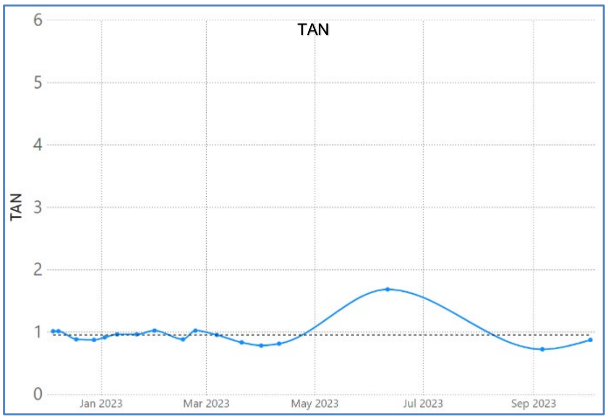

Figure 40 depicts the TAN Sealing Oil trend

2.2.2.2.5 I-pH of sealing Oil

The i-pH method is used to measure the strength of acids in lubricants, which is crucial for understanding their corrosive potential. Unlike the Total Acid Number (TAN) method, which measures the amount of acid, the i-pH method directly measures the strength of the acids present. This distinction is important because a small amount of strong acid can be more corrosive than a large amount of weak acid.

This method is not generally applied on marine oil. However, it was considered when dealing with methanol as a fuel.

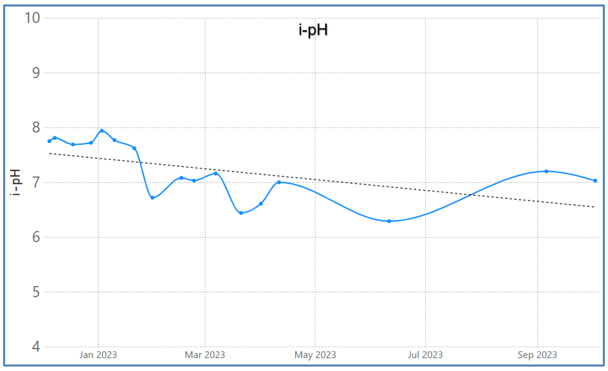

Figure 41 shows the i-pH Sealing Oil trend

A low i-pH value typically indicates a high concentration of strong acids in the lubricant, which can be more corrosive. Generally, an i-pH value below 4 is a concern, suggesting significant amounts of strong acid.

The observed measurements indicated a good level of corrosion protection.

2.2.2.2.6 Wear metals of sealing Oil

X-ray Fluorescence was used to determine the concentration of the metals. No wear metals were detected.

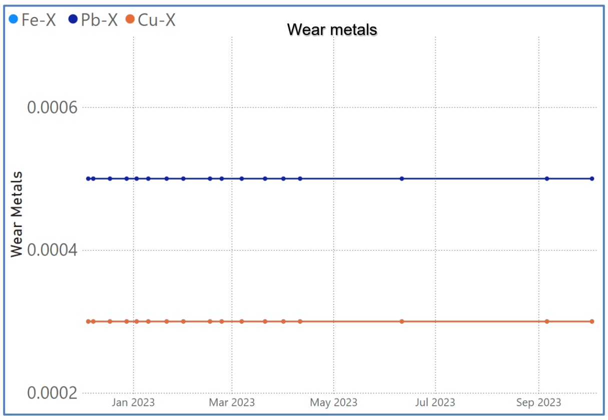

Figure 42 displays the measured wear metals in the sealing oil

2.2.2.2.7 Water contamination in sealing Oil

Water concentration in the sealing oil throughout the monitoring program remained below the 500 ppm (0.05 m/m%).

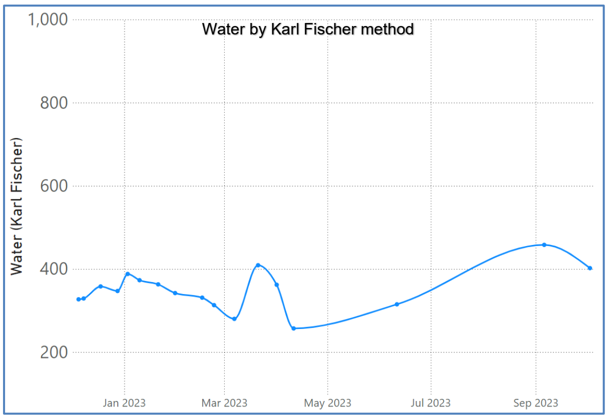

Figure 43 shows the trend of Water contamination in the Sealing Oil by Karl Fisher method

2.2.2.2.8 Lab inhouse method for MeOH detection

Headspace Gas Chromatography (HS-GC) is used to detect Methanol (MeOH) in the used oil. This technique is particularly effective for volatile compounds like MeOH. The volatile compounds are analyzed in the gaseous phase above the liquid sample.

A sample vial containing a fixed amount of used oil is heated to a constant predetermined temperature in the compartment of the headspace until equilibrium is obtained between the liquid and the gas phases. A defined amount of headspace gas is automatically withdrawn with a gas tight syringe and injected onto the column of the GC. The light hydrocarbons (e.g. MeOH) are identified and quantified using reference compounds. This data makes it possible to calculate the MeOH present in the used oil at a specific temperature. The calculation is based on the individual flammability limits of the components that are stated in technical references.

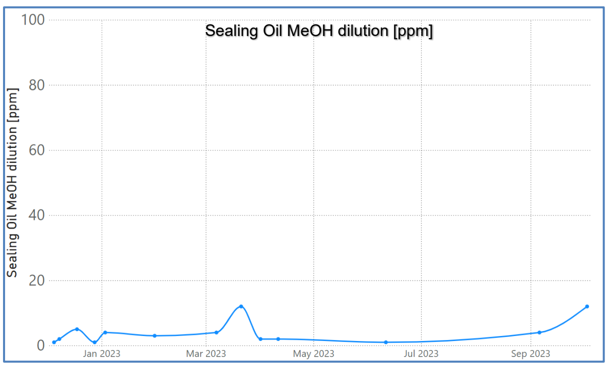

Figure 44 Shows the results found with a Lab inhouse method for MeOH detection in used oil - Sealing Oil

The amount of MeOH found in the sealing oil was very low.

2.2.2.3 Methanol impact on cylinder drain oil

The ongoing monitoring program focused on a vessel with a 6G50ME-C9-LGIM main engine, currently at approximately 10,800 Main Engine Running Hours (MERH). Initially, the vessel used Taro® Ultra 100 (BN100, SAE40) until 2,400 MERH, after which it switched to Taro® Ultra Advanced 40 (BN40, SAE50). The vessel operates at an average load between 55-70%, and as of February 26, 2024, at 6,000 MERH, the oil feed rate was optimized to 0.8 g/kWh. The vessel has accumulated 8,500 MERH on MeOH, which accounts for 79% of the total engine running hours, with the remaining 21% on primarily VLSFO and some LSMGO. A port inspection at 8,300 running hours revealed proper running-in of the Alu coat on most of piston rings. Overall, the units showed very good condition.

Figure 45 picture shows the good piston condition at 8300 running hours, taken during scavenging port inspection

2.2.2.3.1 Residual BN in Drain oil

Until July 2023 the engine was operated on 100BN Cylinder Oil with residual fuel. This caused some BN consumption prior to the start of monitoring program. After July 2023, engine was moved to methanol and 40BN cylinder oil. The methanol operation has only had a minimal impact on BN depletion. The black vertical line on the graph indicates the cylinder oil change from 100BN to 40BN.

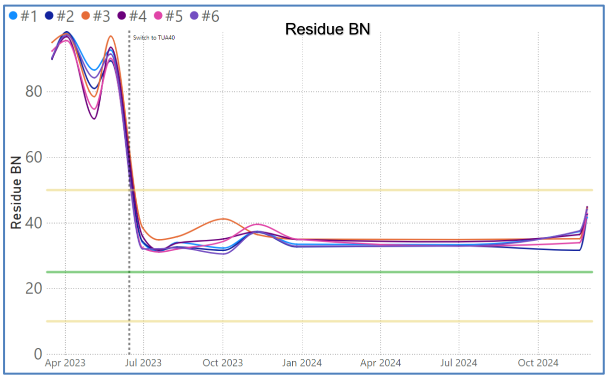

Figure 46 shows the measurements of the residual BN

2.2.2.3.2 Iron in Drain oil

Overall, low iron levels were measured. The optimized feed rate contributed to maintaining this condition.

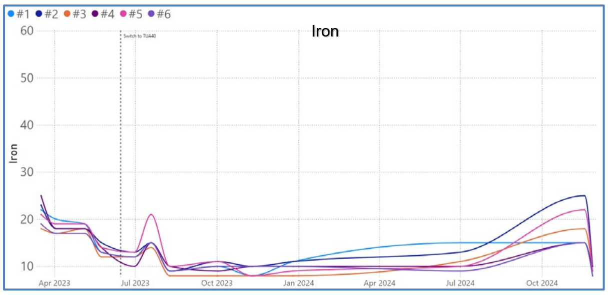

Figure 47 shows the low Iron trend in the drip oil samples

2.2.2.3.3 Water in Drain oil

The engine is equipped with a water mix system to lower the NO_x emissions when running on IMO Tier III mode. The operating concept adding water to methanol serves a purpose to lower the combustion temperature and therefore reducing NO_x. There is approximately up to 40% water mix with Methanol. The water content in the drain oil was monitored in relation to the water-mix in use. Some spikes of water were detected, which in the period where the system was applied. The blue vertical liner on the graph below indicates when the system was in use.

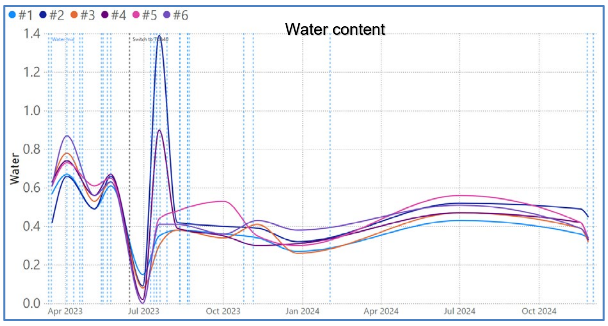

Figure 48 shows the water content in drip oil samples

However, no clear correlation can be made. All observed water levels are low and acceptable. No adverse effects were observed by port inspections and monitoring of wear metals.

2.2.2.3.4 Viscosity in Drain oil

The viscosity in the drip oils show a normal trend. A slight increase in viscosity was observed beyond June 2024, which is likely related to the lowering of the feed lube oil rate and (pilot) fuel impact, hence causing less dilution and higher exposure to oxidation and combustion by products.

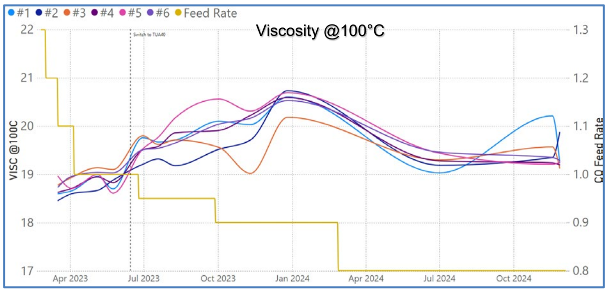

Figure 49 shows the viscosity @100C trend in drip oil samples

3 CONCLUSIONS

Long term operation with biofuel FAME B100 on MAN 8L27/38 medium speed had no negative consequences on the engine performance as such. However, during each operation on biofuel, a significant drop in viscosity was observed that needs to be carefully monitored to remain within OEM limits.

FAME biofuel Dilution can be detected with gas chromatography.

Methanol operation was followed up on several - LGIM engines, of which one discussed in this paper. Methanol can be used effectively as a marine fuel in these two stroke low speed engines, without compromising engine cleanliness and performance compared to VLSFO operation.

4 DEFINITIONS, ACRONYMS, ABBREVIATIONS

FAME: Fatty Acid Methyl Ester

FBIV-M: Fuel Booster Injection Valve for Methanol

HDAX® 9700: Chevron lubricant designed to cope with multifuel as distillate fuel, natural gas, biofuel, methanol, etc...

HS-GC: Head Space Gas Chromatography

IHM: In House Method

MDO: Marine Diesel Oil

MGO: Marine Gas Oil

OEM: Original Equipment Manufacturer

VLSFO: Very Low Sulfur (residual) Fuel

5 ACKNOWLEDGMENTS

The author wishes to thank SGS Belgium NV and all the Chevron colleagues who were involved in the development of this paper.

6 REFERENCES AND BIBLIOGRAPHY

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[2] DIN 51454: Testing of lubricants - Determination of fuel content in used engine oils - Gas chromatography method.

[3] ASTM D7398: Standard Test Method for Boiling Range Distribution of Fatty Acid Methyl Esters (FAME)

[4] MAN Energy Solution publication: "The methanol fuelled MAN B&W LGIM engine"

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