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Medium speed engine oils optimized for ultra low emission profiles

Lubricants

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ABSTRACT

Exhaust pollutants from marine engine operation, especially in vicinity of shores or in ports of densely populated cities remain a public topic. Particular focus is on cruise ships, ferries and vessels erecting and servicing the growing offshore wind renewable electricity industry. First vessels employing medium-speed diesel engines equipped with exhaust diesel particulate filters (DPF) in addition to a selective catalytic reduction (SCR) system are in service, reaching unprecedented low emissions for such engines.

Traditionally, trunk piston engine oils (TPEO) for medium-speed engines are monograde lubricants tailored mostly for either heavy fuel oil (HFO), distillate fuel or gas operation. For vessels aiming to fulfill ultra low emissions, fossil-based fuel loses relevance – instead, the aim to reduce CO2 emissions leads to considering (partial) substitution with lower CO2 footprint bio-, waste-derived or synthetic distillates. However, the engine lubrication system still by its general design has been engineered also considering high-sulfur HFO operation with elevated base number TPEO for corrosion protection. Alternatively, for gas engines the lubrication system design, if specifically adapted, tries to limit the amount of TPEO on the cylinder liner as released droplets may act as preignition source. Due to similar considerations, the amount of sulfated ash in gas engine lubricants is kept at much lower levels than for liquid-fueled engines, the absence of sulfur in the gaseous fuel also reduces the need for neutralizing additives in the lubrication oil significantly.

The ever-increasing requirements for the application of exhaust gas aftertreatment (EAT) systems and the shift away from HFO towards distillates requires dedicated TPEO developed for extended operation on distillate fuel with low sulfated ash levels. With distillate fuels, TPEO composition as much as their consumption become the dominating factor for ash accumulation in the DPF, which determines service intervals. Thus, low-ash oils can significantly extend time between overhauls, while improving general predictability for maintenance, hence the total cost of ownership for the operator may be lower, particularly if also combined with oil exchange procedures rather than “top up only” intentional consumption of lubrication oil. This correlation has been already experienced in several other engine applications previously, but industrial and marine engine builders have been more conservative in terms of lubrication oil choice so far.

Therefore, low-ash TPEO is benchmarked with reference oil through laboratory tests simulating the equivalent to 6,000 hours of engine lubrication oil consumption. In the test, a DPF is exposed to particle containing exhaust gas under controlled flow conditions. The impact on DPF performance is evaluated and compared with field data obtained from MW-size medium-speed engines using low-ash TPEO in combination with ECA-compliant distillate fuel on DPF-SCR aftertreatment systems. The results demonstrate benefits for operators, including extended intervals between overhauls and improved maintenance planning, highlighting the critical role of low-ash TPEO in achieving ultra low emission profiles.

MEDIUM-SPEED ENGINE OILS OPTIMIZED FOR ULTRA LOW EMISSION PROFILES

1 INTRODUCTION

Air pollution from marine engine operation remains a critical environmental and public health concern, particularly in coastal regions and densely populated port cities. Cruise ships, ferries, and vessels associated with the rapidly growing offshore wind industry are receiving increased attention due to their emissions. To address this, the first vessels utilizing medium-speed diesel engines equipped with diesel particulate filters (DPF) in combination with selective catalytic reduction (SCR) systems have entered service, achieving unprecedented low emissions for such engines.[1]

Traditionally, trunk piston engine oils (TPEO) for medium-speed engines have been monograde lubricants optimized primarily for either distillate, heavy fuel oil (HFO) or gas operation. However, as the maritime sector strives to meet increasingly stringent emission regulations, HFO is losing relevance. The push to reduce CO_2 emissions is leading to a shift toward lower-carbon alternatives, including biofuels, waste-derived fuels, and synthetic distillates. Despite this transition, marine engine lubrication systems are still designed around high-sulphur containing fuels that require high ash lubricants with elevated base numbers to counteract corrosion. In contrast, gas engine lubrication strategies focus on minimizing the risk of pre-ignition, resulting in lower sulphated ash levels and a reduced need for neutralizing additives due to the absence of sulphur in the fuel.

The dual challenge of integrating exhaust gas aftertreatment (EAT) systems and transitioning from HFO to distillates underscores the need for dedicated TPEO formulations with low sulphated ash content. In distillate-fueled engines, lubricant composition and consumption directly influence ash accumulation in the DPF, which in turn determines service intervals. By reducing ash deposition, low-ash lubricants can significantly extend the time between overhauls, enhancing operational predictability. While these advanced lubricants come at a higher cost, they have the potential to lower the total cost of ownership by improving maintenance intervals, particularly when combined with optimized oil exchange strategies rather than the conventional “top-up only” consumption approach. Although such lubrication strategies have been successfully adopted in other engine applications, the marine industry has remained relatively conservative in its approach. This study explores the impact of low-ash lubricants on DPF-equipped marine engines, highlighting their potential to optimize service intervals and long-term operational costs.

The main objective of this study is to showcase the potential benefits of low-ash TPEO in marine applications by benchmarking its performance against a reference oil under controlled laboratory conditions. Using a particle-containing exhaust gas flow setup, the oil consumption of a medium-speed engine was simulated over an equivalent of 6,000 operating hours. The impact on DPF performance was evaluated for a dedicated low-ash TPEO and compared to another oil. Furthermore, these results were validated against field data from MW-scale medium-speed marine engines operating on low-ash TPEO in combination with Emission Control Area (ECA)-compliant distillate fuels. The study demonstrates the overall benefits for operators, particularly in terms of extended time between overhauls and improved predictability for DPF maintenance.

2 EVALUATION APPROACH AND METHODOLOGY

The formation, deposition, and migration of ash within the DPF are complex processes influenced amongst other factors by engine condition, operation profile, fuel and lubrication oil type as well as their respective consumption. In consequence, ash accumulation on a test bench cannot fully replicate real-world conditions. However, real-world durability tests to study long-term ash accumulation are often impractical due to their high cost and extended duration. Therefore, accelerated ash loading methods are commonly used to generate ash deposits under controlled testbed conditions, even though combustion of lubricating oil in laboratory tests leads to an ash composition that may differ from that observed in real applications.

Several approaches exist for generating increased ash loads in the exhaust gas under laboratory conditions, [2] including:

- increasing the sulphated ash content in the lubricating oil,
- using a burner to generate ash by burning engine oil,
- injecting lubricating oil into the inlet manifold, or
- doping fuel with engine oil.

Each of these methods has advantages and limitations in terms of reproducing extended field operation and being easy to set up. As all may lead to an excessive or uneven ash distribution within the DPF, careful consideration of ash characteristics and test conditions is essential to ensure reliable and representative results.

For this study, the fuel-doping method was selected as the most suitable approach based on its feasibility, ability to achieve controlled ash distribution, and comparability with real-world engine operation. This method enables controlled ash generation while maintaining realistic thermodynamic exhaust gas conditions, avoiding as much as possible clogging patterns which would not typically occur in service.

The laboratory test setup was designed to replicate field operation of a medium-speed diesel engine equipped with a DPF. The test duration was based on an assumed DPF service life of 6,000 h before ash maintenance, and the filter was prepared accordingly. Thus, a comparison between laboratory results and field data from medium-speed marine engines could be made. The test parameters and assumptions are documented in Table 1.

Table 1. Assumed parameters of the accelerated laboratory experiment to represent field operation.

Parameter	Unit	Value
Engine load	%	85
Desired service interval	h	6000
Specific lubrication oil consumption	g/kWh	0.25
Ratio lubrication oil : fuel oil	-	1 : 14

Reference oil #1 for the laboratory experiment was chosen to be Chevron HDAX 9700, an SAE 40 medium-speed trunk piston engine lubrication oil with low levels of sulphated ash, phosphorus, and sulphur (low-SAPS) at an ASTM D874 sulphated ash content of 0.7 %. This lubrication oil was also chosen by Jan De Nul for the Voltaire, an ultra-low emission vessel (ULEV) equipped with ABC DZC medium-speed engines and a combined DPF+SCR aftertreatment system.

For comparison, two additional lubrication oils were considered: Test oil #2, a commercially available oil with a sulphated ash content of 1.45 %, and Test oil #3, which has a sulphated ash content of 0.5 %. The oils are listed in Table 2. Due to several encountered issues in the laboratory test setup, this contribution will only present results obtained with the Reference oil #1 and Test oil #2, additional data will be available at a later stage.

Table 2. Sulphated ash content of test oils according to ASTM D874.

Parameter	Unit	Value
Reference oil #1 (Chevron HDAX 9700)	wt %	0.7
Test oil #2	wt %	1.45
Test oil #3	wt %	0.5

In a prior study [5] it was concluded that doubling and even tripling the sulphated ash content of the engine oil results in still very similar ash morphology. Thus, maintaining a constant mixing ratio of the fuel oil and the lubrication oil, the amount of ash per test hour from combustion of the different test oils would vary, but relative comparison of the impact on DPF performance by the different oils would be possible.

As the accelerated ash loading experiment worked with lubrication oil enriched normal diesel fuel, the ratio of ash originating from the two sources shifted. In Figure 1 a comparison of the ash contributions by source for the different test oil candidates is provided.

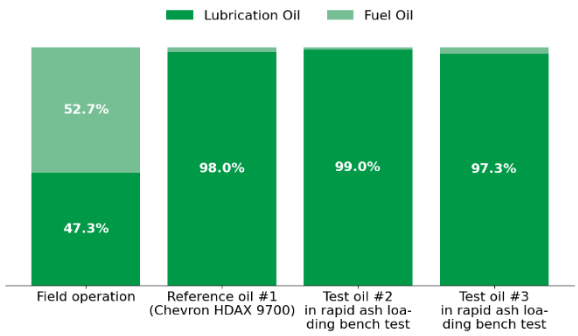

Figure 1. Origin of ash contributions for different test candidates under accelerated oil consumption in comparison to field operation.

For the experiments, a customized testing system for DPFs called Diesel Particulate Generator (DPG) by Cambustion Limited is utilized in combination with a standard Hug Engineering DPF cassette as installed in the field. A schematic of the test setup is visualized in Figure 2.

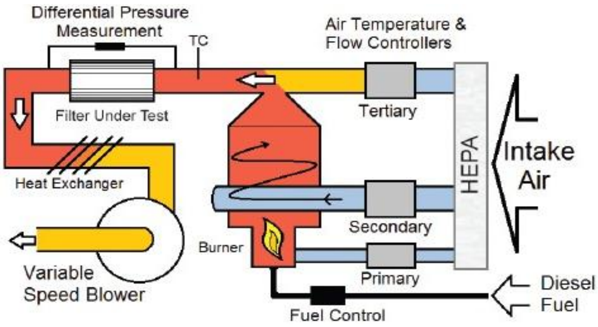

Figure 2. DPG test system utilized for accelerated DPF ash impact assessment [3].

The DPG system is capable of adjusting inlet mass flow, temperature and soot concentration over a wide range to replicate application-relevant operating conditions. Stable and reproducible soot generation is ensured by utilizing a diesel burner which operates at constant ambient pressure. Additionally, during the experiments, particle mass and number concentrations are continuously monitored both upstream and downstream of the filter to ensure accuracy and consistency in the measurements. The advantage of this setup, as depicted in Figure 3, is that it approximates the characteristics of a full-scale field DPF system, albeit in a reduced-size configuration. This ensures that key aspects such as sealing integrity and the materials surrounding the substrate are inherently included in the recorded data, reinforcing the desired comparability.

Figure 3. Test section of the DPG test system and the single DPF cassette reactor.

Although the setup is reproducing conditions comparable to field applications, it should be noted that the soot generated in the laboratory device is different in its chemical composition compared to combustion engine soot – engine soot is composed of a combination of elemental carbon and significant fractions of functionalized organic carbon, while the DPG's diesel burner flame soot tends to contain only minimum organic carbon fractions. In addition to these boundary conditions, the oxygen concentration in the open flow system at approximately 20 % is significantly higher than in lean burn engine exhaust gas. Furthermore, the thermal boundary conditions differ due to the use of a single cassette reactor instead of a multi-cassette system. Although the reactor is insulated, the absence of adjacent cassettes may affect heat dissipation and thermal gradients. These factors are carefully considered when evaluating the results to ensure a meaningful and accurate interpretation.

3 DIAGNOSTICS AND EXPERIMENT

To ensure accurate monitoring of filter functionality, a condensation particle counter (CPC) and a smoke meter (SM) continuously record particle emission data. The smoke meter has been specifically calibrated for the fuel-lubricant mixture to ensure precise measurement of the incoming soot-ash concentration.

To enable comparison with field data, additional measurements are taken on both the raw gas and clean gas sides using a micro soot sensor (MSS) and a high concentration-nano particle emission tracker (HC-NPET). Probe ports are shown in Figure 3. This parallel measurement approach enables the determination of filtration efficiency regarding two key aspects:

- Mass concentration of black carbon (measured via MSS).
- Particle number (excluding hydrocarbons) (measured via HC-NPET).

The latter is regulated in EU Stage V and Euro VI.

The assumed 6,000 h of DPF service life in terms of ash accumulation by the lubrication oil were represented on the DPG test setup by approximately 400 hours. In addition, a total of approximately 130 hours of DPF performance checks were run to assess the impact of ash loading in-between the ash loading cycles. The automated routine consisting of ash loading and DPF performance checks was combined to a measurement run cycle which was repeated 23 consecutive times thereby simulating the desired 6,000 h of field operation.

Analogous to the test protocol developed in a prior study [4], which was based on dosing control of oil into the engine's fuel supply system, the measurement run cycle considered different phases: the ash loading, which can be subdivided into a phase with formation of a soot cake at the DPF inlet and periodic active regenerations for soot oxidation, and DPF performance checks regarding the impact of collected ash. The measurement run cycle depicted in Figure 4 was arranged and provides a representation of how recorded parameters evolve during a measurement run.

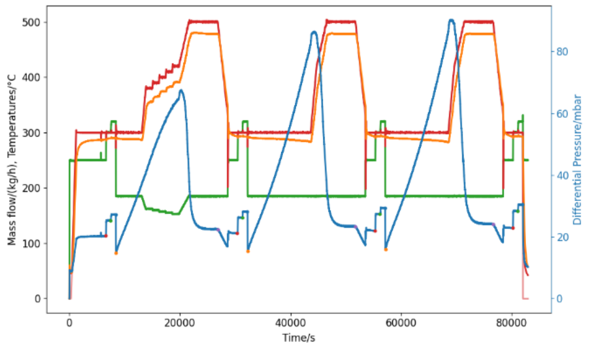

Figure 4. Measurement run cycle with ash loading and DPF performance checks for investigating ash impact.

Each measurement run cycle consists of flow and temperature variations, soot loading phases and regeneration phases in which the accumulated soot is catalytically burnt. Filtration efficiency regarding PM and PN is calculated over the entire loading period using the acquired measurement data from the CPC, SM, HC-NPET and MSS. Flow variations are conducted at the start of each test and after each regeneration under specific conditions. During regeneration the soot is fully oxidized, ensuring that only ash remains on the filter after each cycle. As ash is accumulated in the DPF with increasing test hours, the comparison of acquired backpressure data for these specific conditions provides a trend of the backpressure increase. A stepwise temperature increase routine was implemented to determine the onset of the catalytic soot burning temperature.

Overall, the following effects in terms of impact by ash accumulation were targeted by the DPF performance checks:

- backpressure increase,
- soot filtration efficiency, and
- changes in catalytic soot burn off temperature.

Two effects have to be considered as deviations from the field conditions regarding ash loading:

- ash mass flow: the ash mass flow in the experiment is significantly elevated compared to field conditions. It is an unavoidable effect of the accelerated ash loading of the DPF.
- soot-ash ratio during loading phase: the ratio of soot to ash accumulating during each loading cycle is lower than in real-world operation. This difference affects ash rearrangement during DPF regeneration when soot is burnt.

4 RESULTS AND DISCUSSION

As ash accumulates on the filter, it reduces both the filtration area and volume. Some areas of the filter become covered with a combination of soot and ash, while others are entirely covered with ash [6]. Consequently, the backpressure increases as more ash accumulates. One common type of ash distribution is the plug-type formation, where an ash plug develops at the end of the inlet channels. This plug effectively shortens the inlet channel, causing the soot cake to form more rapidly and with greater thickness for the same amount of soot collected, thereby leading to an increased pressure drop [4].

This pressure drop increase is displayed in Figure 5. The recorded differential pressure across the filter follows the methodology described in Chapter 3. The backpressure data was measured under specific flow conditions for each measurement cycle over the course of running hours and is plotted against the equivalent engine oil running hours.

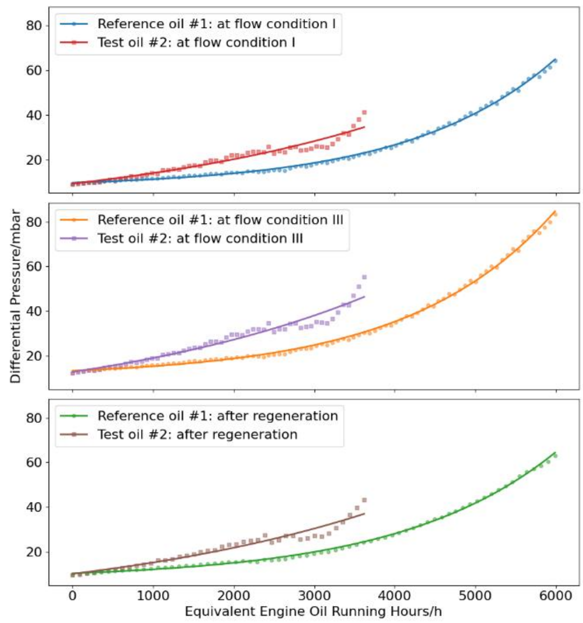

Figure 5. Evolution of differential pressure across the filter cassette at specific time steps for Reference oil #1 and Test oil #2.

For evaluation, the filtration efficiency was also considered. A data point is only included if the filtration efficiency exceeds 99 %. This condition is met after an initial sealing phase and remains consistent throughout the entire test, even shortly after regeneration.

In Figure 5 it is illustrated that for the Reference oil #1, the initial pressure increase is approximately linear but transitions into an exponential one as the loading continues. The exponential increase can be approximated by Equation 1:

$$A * e^{-B*x} + C. \quad \text{Eq. (1)}$$

The observed pressure increase is a direct consequence of the channel geometry, which is rectangular with a defined length. During regeneration, the oxidation process causes the soot-ash matrix to collapse. This collapse results in particle movement, with some particles being transported further downstream by the gas flow while few also migrate through the filter. Consequently, large portions of the channel wall that were previously coated with ash become exposed, while the moving ash accumulates in a compressed, concentrated form at the downstream end, forming an ash plug. This ash plug effectively shortens the functional length of the channel, contributing to the observed non-linear pressure increase.

When comparing the reference oil with Test oil #2, a linear pressure increase is again observed during the initial loading phase. However, the slopes of the idealized linear trends differ significantly, with Test oil #2 exhibiting a much steeper pressure increase. This can be attributed to the higher ash accumulation rate per unit time.

Assuming an idealized ash accumulation behavior, where deposited ash continuously forms a growing plug, the length of this plug increases after each regeneration cycle. The transition from a linear to an exponential pressure rise occurs with a steeper gradient, as illustrated in Figure 5, for example, by the red, purple and brown curves. Due to the higher ash content, as shown in Figure 1, slight irregularities can be observed in the brown curve, which are also reflected in the curve fitting. However, despite the discrete nature of the data, the exponential increase is clearly visible, even though it cannot be fully captured by the fit due to the relatively lower number of measurement points in the exponential phase compared to the linear phase.

As initially described, the filtration efficiency for BC and PN is continuously recorded. If this efficiency falls below a certain threshold, it is assumed that undefined boundary conditions are available, compromising the measurement data. A threshold below the described requirement is met at the last recorded measurement point, which is why the test was terminated at that stage.

While the accelerated oil ash loading of the DPF cassettes in the laboratory setup clearly indicated the advantage of the HDAX 9700 reference oil in comparison to the 1.45 % sulphated ash Test oil #2, from field observations it was up to this point not possible to have such a one-to-one comparison of otherwise identical conditions.

However, following the DPF systems installed onboard the Jan De Nul vessel Voltaire, which used ECA compliant ISO 8217 0.1 % sulphur DMA fuel in combination with Chevron HDAX 9700 lubrication oil, service intervals for the DPF in excess of 6,000 hours of engine operation could be confirmed without necessity for DPF ash maintenance – while particle filtration efficiency was proven onboard to remain > 98 %. These field observations reconfirm the value of low-SAPS lubrication oil in combination with DPF.

5 CONCLUSIONS

As the large engine industry is moving towards more stringent emission regulations, DPF usage will be more widespread. For medium speed engine operators, total cost of ownership in combination with predictability of their operations is essential. The use of low-SAPS TPEO designed to provide corrosion protection from sulphur containing fuels, while still providing low ash levels, has the potential to prolong operation before ash maintenance would be required on a DPF.

In the presented study, accelerated ash loading experiments were run on a laboratory setup for DPF in order to assess the impact of ash content for different lubrication oils. The reference oil Chevron HDAX 9700 could be confirmed to achieve extended DPF operation before reaching backpressure values equivalent to what was measured with a higher sulphated ash containing test oil with lower operating hours.

Follow-up of a DPF field installation onboard a vessel utilizing the identical reference low-SAPS lubrication oil product could confirm anticipated service intervals while maintaining ultra-low emission profiles.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

Latin

A, B, C	[-]	Fit parameters
x	[-]	Independent Variable

Abbreviations

CPC	Condensed Particle Counter
DPF	Diesel Particulate Filter
DPG	Diesel Particulate Generator
EAT	Exhaust gas aftertreatment
ECA	Emission Control Area
HC-NPET	High Concentration-Nano Particle Emission Tracker
HFO	Heavy fuel oil
SAPS	Sulphated ash, phosphorus, and sulphur
SCR	Selective Catalytic Reduction
SM	Smoke Meter
TPEO	Trunk piston engine oils
ULEV	Ultra-Low Emission Vessel

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