Performance and emissions of a medium-speed engine driven with sustainable options of liquid fuels

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Performance and emissions of a medium-speed engine driven with sustainable options of liquid fuels

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Abstract

Energy production and transport are major global contributors of greenhouse gas emissions. Both sectors should reduce their use of fossil energy sources. Pollutant emissions must also be reduced without jeopardizing energy efficiency, reliability, and profitability. The internal combustion engine will dominate in marine and power plant applications for a long time because it offers high energy density, efficiency, durability, and the ability to respond rapidly to load changes. Ever-tightening emissions legislation encourages development of new solutions for engine-driven power. One example is exploring the use of alternative fuels in large engines. Low-carbon liquid fuels with high energy density are ideal for applications working far from any infrastructure. This study evaluated how three liquid fuel alternatives perform in a medium-speed engine. One new fuel was a circular economy-based marine gas oil (MGO). The second novelty was a blend of renewable naphtha and low-sulfur light fuel oil (LFO). Neat LFO served as the baseline fuel. The study started with thorough fuel analyses, including the fuels' ignition properties. Then, a medium-speed engine was driven with each fuel by using similar engine settings and without exhaust aftertreatment. The results indicate that the thermal efficiencies were almost equal for all fuels at all studied loads. No notable differences were observed in the heat release curves. The naphtha/LFO blend produced slightly increased HC emissions at low loads but showed the lowest HC at full load. NO_x emissions were very similar with all fuels. MGO and naphtha/LFO blend usually emitted fewer ultrafine exhaust particles than LFO. Methane and nitrous oxide emissions were always very low. Overall, both novel fuels could be adopted for medium-speed engines.

Introduction

Energy production and transport are major contributors to global greenhouse gas (GHG) emissions. Both sectors should make drastic reductions in their use of fossil energy sources. At the same time, their pollutant emissions must be reduced without jeopardizing high energy efficiency, reliability and profitability.

In road transport, particularly in urban areas, electric and hybrid propulsion is likely to expand [1]. However, the internal combustion engine (ICE) will most probably dominate in marine, hybrid power plant and non-road applications for a long time because it has so many attributes. It provides high energy density and thermal efficiency, strength, durability, the ability to burn various fuels, rapid response to load changes, and affordability. The ICE also continues to improve as a result of better combustion, exhaust aftertreatment, and control systems. [1, 2-8]

Nevertheless, increasingly stringent emissions legislation encourages development of new solutions for engine-driven power. One example of this is exploring the use of alternative fuels to mitigate emissions from large engines. Low-carbon liquid fuels must become part of the energy agenda because sustainable liquid fuels will be needed for a long time to satisfy global growth in energy demands. The superior energy density of liquid fuels is ideal for applications working for long periods, far from any infrastructure. In addition, biofuels gradually are becoming economically attractive. [8-15] Local and cost-effective fuels also increase the self-sufficiency of energy generation. Thus, various liquid fuel alternatives potentially play an important role in flexible power generation and in marine and heavy-duty non-road applications.

Engine business, universities and research institutes have investigated many fuel alternatives in different engines over recent decades. The feedstock palette is enormous. Fuels originating from waste or residue are preferred since their GHG emissions are low. [15-23] In addition to renewable alternatives, power and engine companies are interested in condensates or side streams of oil and gas production. The aim is to use side streams for on-site power in oil and gas fields and stop flaring: the World Bank has set a global target to eliminate routine gas flaring by 2030. [24] The adoption of surplus fuels with low octane numbers may also become an important topic [8].

Synthetic residue-derived fuels are already very high-quality drop-in fuels [8, 25]. The worldwide share of renewables in transport is, however, still very limited [26]. Rohbogner et al. (2019) assume that the distillate fuel pool is not large enough to serve road transport, aviation and marine [27]. Therefore, there is interest in generation of new, low-sulfur liquid fuels for medium-speed engines. The most tempting of these new fuel options are those that are less processed and more cost-effective [15, 27-29] However, fuel flexibility is also an important issue because in future applications, engines must be able to switch between fuels. [30]

Meeting the ambitious CO_2 reduction targets in shipping appears to be possible only using CO_2-neutral fuels, assuming such fuels could be produced in a cost-effective and energy-efficient manner. Synthetic paraffinic hydrocarbon fuels are one such option. They would be easy to use in existing ship engines: an important issue, given that the typical life cycle of a ship is 25-30 years. [1]

Renewable naphtha offers a route towards decarbonizing. In general, naphtha is one of the fuels that would make it easier for engine manufacturers to fulfil the regulatory requirements of reducing both greenhouse gas and criteria pollutants from diesel engines. Naphtha is suitable for mixing-controlled combustion. It is also less energy-intensive at refinery level than conventional diesel fuel if the naphtha is refined from crude oil, which is still the main production method. [31-34]. Naphtha has also produced promising results in new combustion concepts such as partially premixed compression ignition (PPCI) and low-temperature combustion (LTC). It has enabled recalibration of the engine for lower NO_x because soot formation has decreased considerably. [31] Consequently, use of naphtha in CI engines has aroused interest in recent years.

Naphtha is particularly advantageous when it has been manufactured from renewable sources. In this study, naphtha was derived from crude tall oil (CTO) extracted during wood pulp production [35]. Neat naphtha has a low cetane number (CN) and viscosity [36]. Therefore, and because of its so far limited market availability, renewable naphtha worked as a blending bio-component in low-sulfur light fuel oil (LFO) in the current study. A previous study with a high-speed engine had also shown that the engine does not need any modification when fueled with a naphtha-LFO blend [37].

The other test fuel of the present study, marine gas oil (MGO), seems to be an increasingly common shipping fuel, especially inside emission control areas (ECAs) and within EU ports. MGO is a feasible alternative in those special regions because heavy fuel oil engines need an exhaust scrubber to meet their sulfur emission regulations.

Circular-economy based MGO is an environmentally friendly MGO option because its present feedstock, waste lubricating oils (WLOs) are considered to be a hazardous waste [38, 39]. Recycling potential energy feedstock is a step towards more sustainable solutions. EU countries are encouraged to recycle WLOs. As a result, recycling of WLOs is said to have increased to 75–85% and there is an EU-wide target of 100% collection of waste oils [39, 40].

Promoting the adoption of new and more sustainable alternative fuels requires a large amount of research about those fuels, their blends with conventional fuels, and engine experiments, as shown for instance in [28, 29]. Responding to this demand, the present study evaluated the performance of two liquid fuel alternatives in a medium-speed engine, intended for marine applications and on-shore power generation. One fuel was a blend of renewable naphtha and low-sulfur LFO and the other a circular economy-based MGO. Neat low-sulfur LFO served as the baseline fuel. In the experiments, a medium-speed engine was driven with each of the three fuels. At this first stage of the project, all fuels were studied using similar engine settings and without adopting any exhaust aftertreatment.

Experimental setup

Fuels

The renewable naphtha was a product of a manufacturing process of hydrotreated vegetable oil (HVO). Both products are based on CTO extracted during wood pulp production. Sulfur-free paraffinic naphtha is chemically pure hydrocarbon [35]. The manufacturing process has several phases, as illustrated in Figure 1. The hydrotreated raw fuel consists of mid-distillate diesel components in addition to lighter naphtha components that are separated by fractionation. [37]. UPM of Finland delivered the naphtha for this study. The fuel is produced in Lappeenranta, Finland.

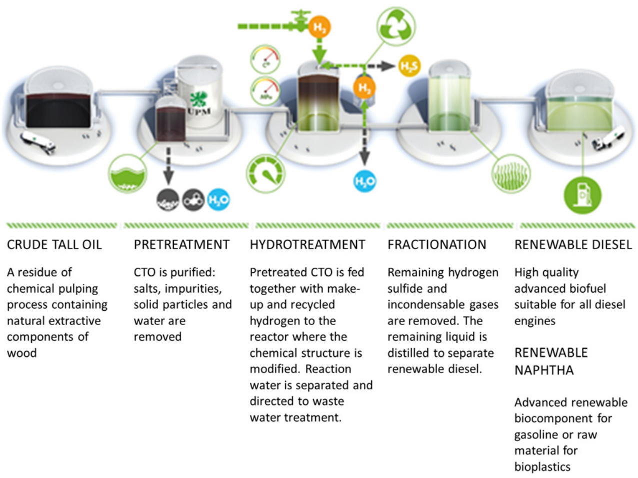

Figure 1. Manufacturing process of renewable naphtha [after 37].

Naphtha's low CN and viscosity may lead to a lengthened ignition delay (ID) and retarded start of combustion [36]. The investigated naphtha did indeed show a prolonged ID and late combustion start in a combustion research unit [41]. Consequently, and because of its expected limited availability, renewable naphtha was used as a blending bio-component in low-sulfur LFO. The blend contained 26 vol.-% of naphtha. This mixing ratio was chosen on the basis of the observed favorable combustion results of a 20/80 vol.-% blend in a pre-study with a high-speed engine [42].

The second studied alternative fuel, MGO, was a circular-economy based pilot product. It was the light fraction of the hydrotreaters of the regeneration process of used lubricating oils. With its low sulfur content of less than 100 mg/kg, MGO seems to be a feasible option for marine and on-shore power applications. The company STR Tecoil delivered MGO to our university. [43, 44]

Table 1 lists the fuels' main characteristics. As shown, the properties of MGO and LFO were very similar. MGO, however, had a slightly higher sulfur content but a shade lower contents of aromatic compounds, less favorable lubricity and slightly lower CN than LFO. Naphtha-LFO blend showed lower viscosity, density and CN than pure LFO but a shade higher contents of aromatics. However, its sulfur content was low and lubricity beneficial.

The methods, used for fuel analyses were the following:

- kinematic viscosity, EN ISO 3104/ASTM D7042
- density, EN ISO 12185/ASTM D7042
- cetane number, EN 15195
- sulfur content, EN ISO 20884/EN ISO 20846
- carbon content, ASTM D5291
- hydrogen content, ASTM D5291
- aromatics, EN 12916
- lubricity, EN ISO 12156-1

Ash contents are based on the information provided by the fuel suppliers. Lower heating values were calculated based on the fuel elementary analyses.

Table 1. Fuel specifications

	LFO	MGO	Naphtha-LFO	Unit
Kin. viscosity at 40 °C	3.1	3.7	1.8	mm^2/s
Density at 15 °C	836	838	809	kg/m^3
Cetane number	58	54	52	-
Sulfur	6	30	4.5	mg/kg
Carbon	84.5	84.8	85.0	wt.-%
Hydrogen	13.4	13.7	13.8	wt.-%
Total aromatics	16.8	15	18	wt.-%
Polyaromatics	1.4	1.3	1.6	wt.-%
Ash	< 10	< 10		mg/kg
LHV	43.2	43.3	43.5	MJ/kg
Lubricity	350	484	335	µm

Figure 2 depicts the distillation curves for the studied fuels. Due to the light fractions of naphtha, the distillation of the naphtha-LFO blend started already at approx. 50 °C and ended at 350 °C. MGO distilled at quite high temperatures, ranging from approx. 240 °C to 330 °C. For LFO, only two points were available. They indicated that LFO distillation was similar to MGO's, but the temperature range was probably larger, but only by a slight amount.

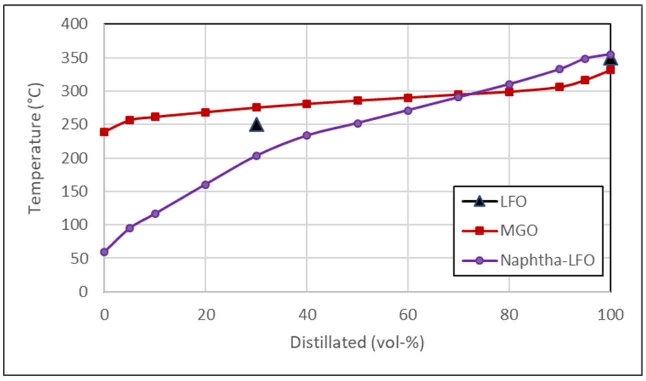

Figure 2. Distillation data for the experimental fuels

Engine and loading

The experimental engine was a medium-speed Wärtsilä engine, intended for power plants and marine applications. The engine is turbocharged and the charge air is cooled by water before entering the cylinders. No exhaust gas aftertreatment was adopted.

The engine was driven at a constant speed of 1000 rpm and loaded by an ABB alternator. The produced electricity was fed into the grid of the local energy company. The engine specification is given in Table 2. The maximum engine output was set at 640 kW for the full-load measurements in the current study. Experimental measurements were also performed at four partial loads, corresponding to 75, 50, 25 and 10% of the full load. The load points followed those of the test cycle D2 of the ISO 8178-4 standard.

Table 2. Specification of the experimental engine

Swept volume/cylinder	8.8 dm^3
Cylinder number	4
Bore	200 mm
Stroke	280 mm
Compression ratio	16
Number of valves	4
Speed	1000 rpm
Shaft power output	640 kW

Analytical procedures

The experimental setup's measurement system comprised proper pressure and temperature sensors along the air and exhaust paths. Intake air flow was determined by means of an air nozzle and fuel flow with a scale and watch. Engine management software, supplied by the engine manufacturer, gathered the sensor data and followed the engine control parameters. Additionally, several analyzers were included for combustion and emissions analyses. Table 3 lists those instruments.

Table 3. Measuring equipment

Parameter	**Instrument**	**Technology**
Cylinder pressure	Kistler KiBox®	
Exhaust HC	J.U.M. VE7	HFID
Exhaust NO_x	Eco Physics CLD 822 M h	Chemiluminescence
Exhaust CO, CO_2	Siemens Ultramat	NDIR
Exhaust O_2	Siemens Oxymat 61	Paramagnetic
Exhaust particle number	TSI EEPS 3090	Spectrometer

The emissions instruments were calibrated before and after the measurements. The engine was allowed to stabilize before taking the parameter recordings. The temperatures of cooling water, charge air in the manifold, and the exhaust upstream of the turbine had to be stable. – Figure 3 shows a diagram of the experimental setup [45].

Results

Combustion

Figure 4 depicts the heat release rate (HRR) versus the degrees of crank angle (deg) for all fuels at 75% load. The premixed peak of the naphtha-LFO blend was a shade higher than that of MGO and LFO. The initial combustion followed well the differences in CN: the lower the CN, the higher the premixed peak. In general, however, combustion progressed in a very similar manner with all fuels.

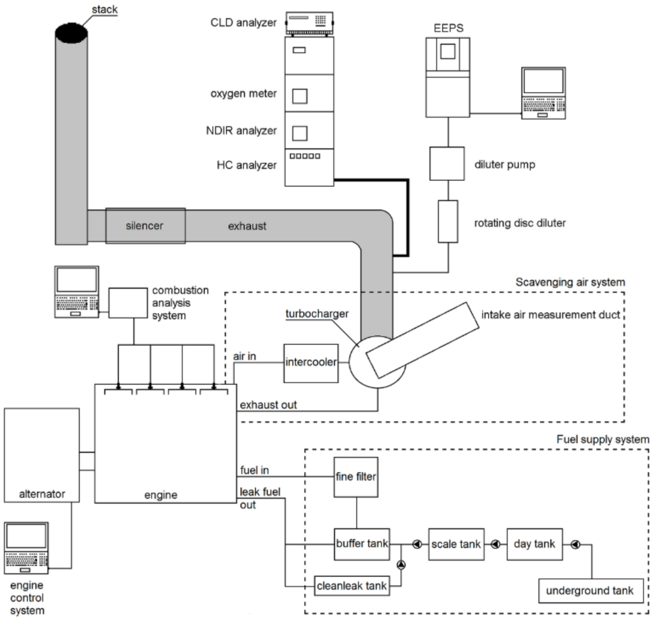

Figure 3. Experimental setup [45]

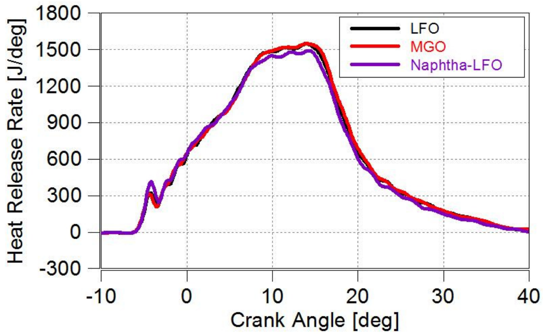

Figure 4. Heat release rate versus crank angle at 75% load for the studied fuels

Figure 5 illustrates that 50% of all fuels had burned at very similar crank angles (CA) at each load. The CA values were different at various loads since the injection timing was different, as shown in Figure 6. At half and lower loads, the timing was 9° CA before top dead center (bTDC) while at higher loads, the timing was advanced.

Finally, Table 4 lists the crank angles at which 50% of each fuel had burned at 75% load. As shown, the average values of 100 consecutive engine cycles are very close to each other for all fuels and the standard deviations vary from 1.8% (LFO) to 2.5% (blend).

Efficiency

Figure 7 shows that the brake thermal efficiency (BTE) of the engine was very similar when fueled with different fuels. At full load, the BTE was 40 to 41% and at half load 36%. At many loads, the BTE seemed to be a shade higher with LFO and the blend than with MGO. The differences were, however, within the measurement accuracy. The LFO result at 25% load was, quite evidently, wrong.

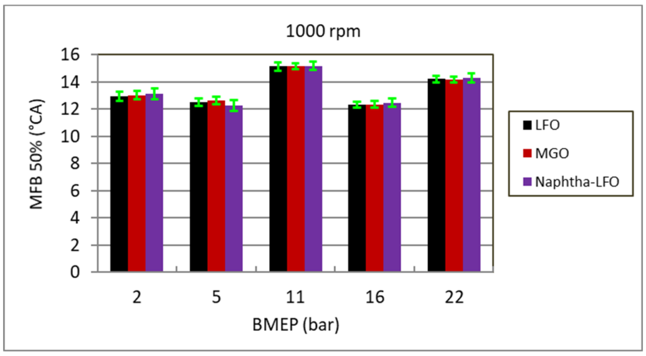

Figure 5. Crank angles for 50% mass fractions of burned fuel (MFB) at various engine loads

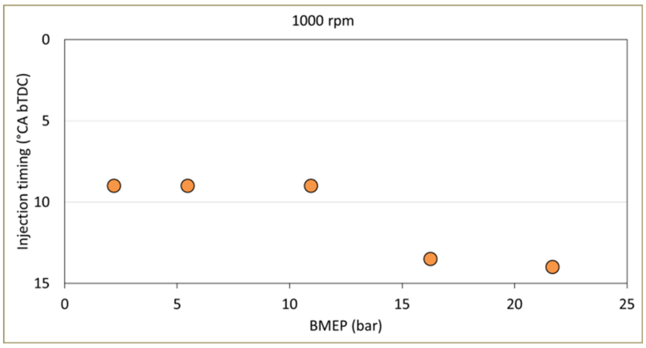

Figure 6. Injection timing at different loads

Table 4. Crank angles for 50% mass fractions of burned fuel at 75% load. Avg, average for 100 consecutive cycles; Stdev, standard deviation.

	Avg	Stdev	Unit
LFO	12.3	0.22	° CA
MGO	12.4	0.24	° CA
Naphtha-LFO	12.5	0.31	° CA

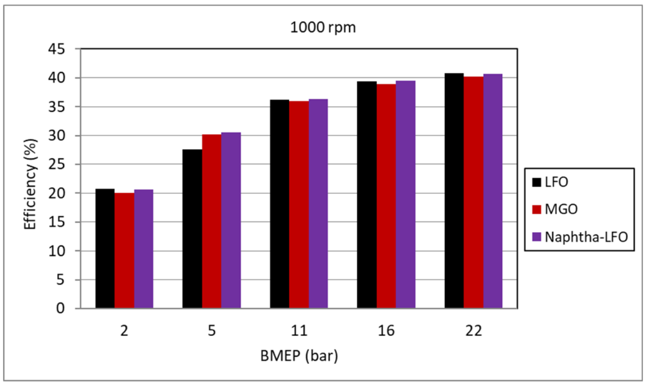

Figure 7. Brake thermal efficiency of the engine at different loads for various fuels

Emissions

Gaseous emissions

Figure 8 shows brake specific NO_x emissions were high with the engine settings that were used, reaching slightly more than 14 g/kWh at full load. Every fuel emitted very similar NO_x emissions, although MGO was slightly higher at high loads and slightly lower at low loads than LFO and naphtha-LFO blend. Again, one can see that some problems had occurred with LFO measurements at 25% load.

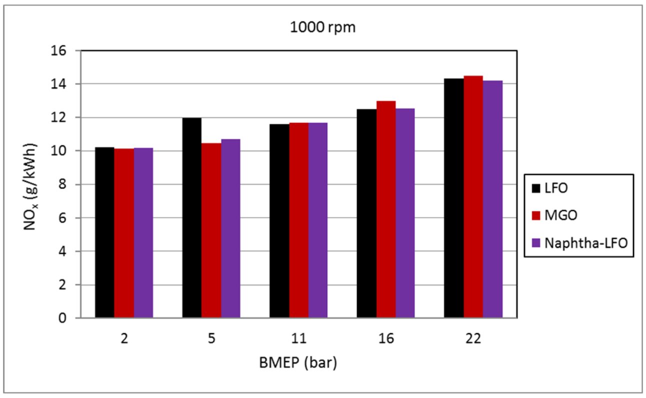

Figure 8. Brake specific NO_x emissions against engine load with the studied fuels

Figure 9 illustrates total hydrocarbons (HC), showing all fuels produced very similar HC emissions, except at the lowest load. At this point, HC emissions with the blend were highest, approximately 17% above the baseline LFO. Light fractions of naphtha with low boiling points may have resulted in increased over-leaning and higher HC at this very low load [28]. The opposite result was seen at high loads, where naphtha-LFO produced the lowest HC emissions. Reactivity conditions are beneficial at high load, even for lower-cetane fuels.

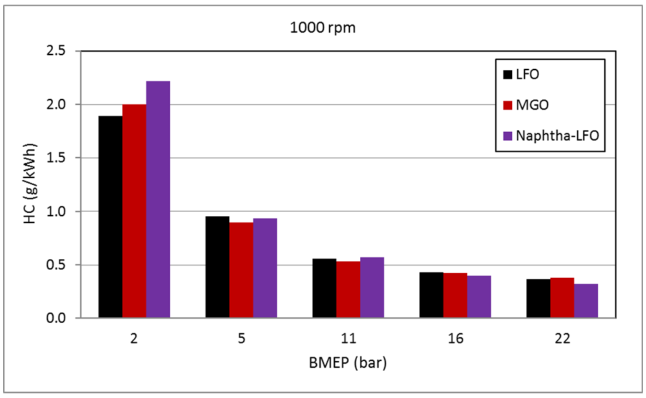

Figure 9. Brake specific emissions of total hydrocarbons as a function of engine load for different fuels

Carbon monoxide (CO) emissions were very similar for all fuels within the load range of 50 to 100%, Figure 10. At lower loads, the results varied slightly but the differences were not significant. At 10% load, MGO emitted slightly more CO than LFO (+10%) and the blend (+14%). At 25% load, the blend also resulted in the lowest CO, MGO showing the highest, 24% higher than the blend.

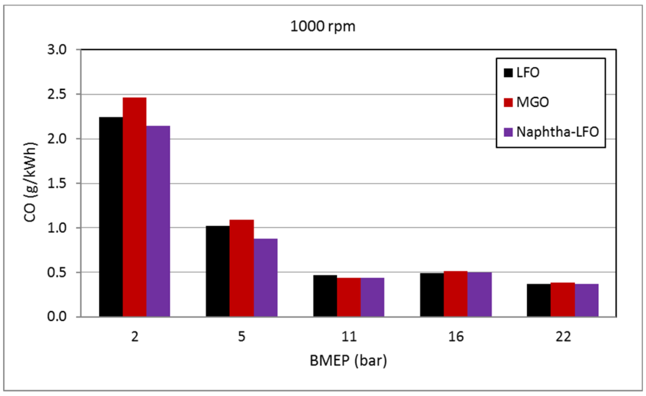

Figure 10. Brake specific CO emissions versus engine load for the studied fuels

Figure 11 depicts the calculated cycle-averaged emissions. NO_x emissions were almost equal for MGO and LFO (12.3 g/kWh) while the blend resulted in slightly lower NO_x of 12.1 g/kWh. In terms of HC, MGO's 0.56 g/kWh was the lowest whereas LFO showed the highest or 0.58 g/kWh. The blend's CO was the lowest, 0.56 g/kWh, while MGO produced the highest, 0.61 g/kWh.

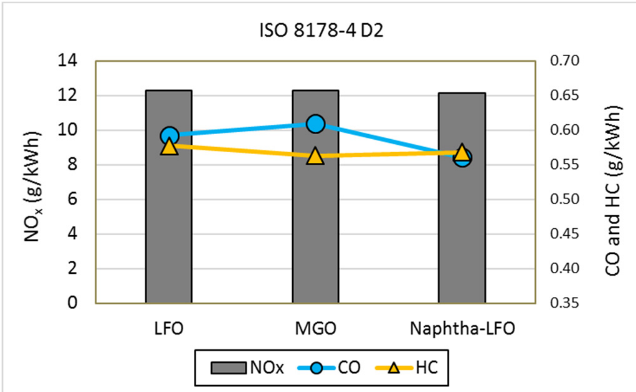

Figure 11. Calculated cycle-averaged brake specific emissions for the studied fuels

From the GHG viewpoint, emissions of methane and nitrous oxide are also important. Figure 12 illustrates the wet exhaust methane contents at various engine loads. Methane decreased with increasing engine load. Naphtha-LFO blend emitted lower CH_4 content than LFO and MGO, especially at high loads. However, CH_4 contents were generally very low, at below 5 ppm.

Figure 13 shows that the wet exhaust contents of nitrous oxide were also very low, well below 1 ppm at all loads. The highest recorded content was slightly higher than 0.5 ppm, within the measuring accuracy of the FTIR analyzer. No clear trend was detected between the fuels.

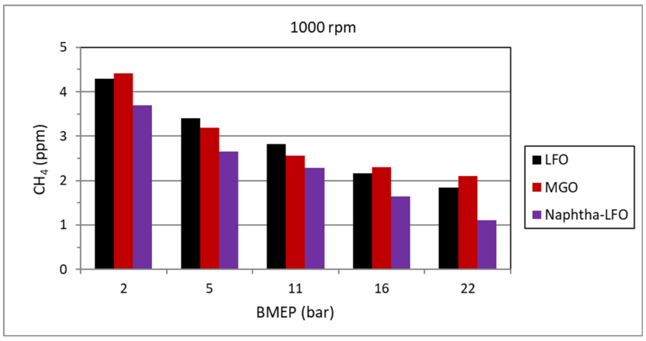

Figure 12. Wet exhaust methane contents versus engine load with different fuels

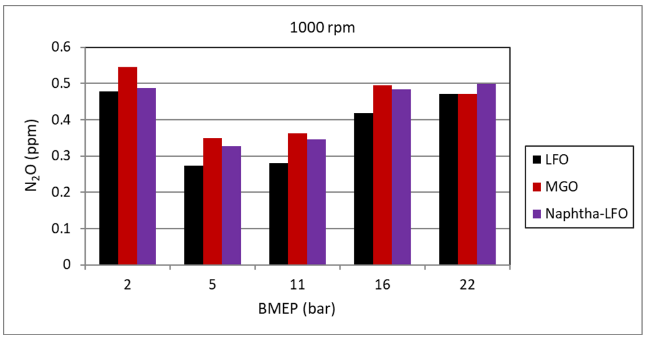

Figure 13. Wet exhaust contents of nitrous oxide against engine load with various fuels

Particulates

The exhaust did not contain high numbers of nucleation mode particulates but the accumulation mode peaks were usually higher by two orders of magnitude than those of nucleation mode tops [45]. Up to 75% load, the size distributions peaked within the size range of 30 to 50 nm, as illustrated for 75% load in Figure 14. At full load, the peak of every fuel moved towards larger particles, up to approximately 80 nm.

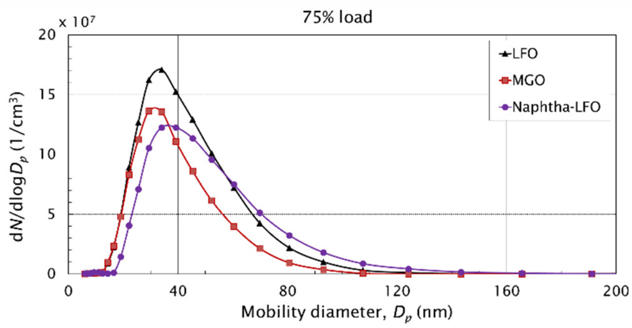

Figure 14. Exhaust particle size distributions for different fuels at 75% load (after [45])

Figure 15 depicts the total particulate number (TPN) within the size range of 5.6 to 560 nm. At low loads, TPN was the lowest with MGO and highest with LFO. From 50 to 100% load, MGO and naphtha-LFO blend generated almost similar TPNs, both clearly lower than LFO. It is apparent that blending naphtha with LFO resulted in a clear reduction in particulate number.

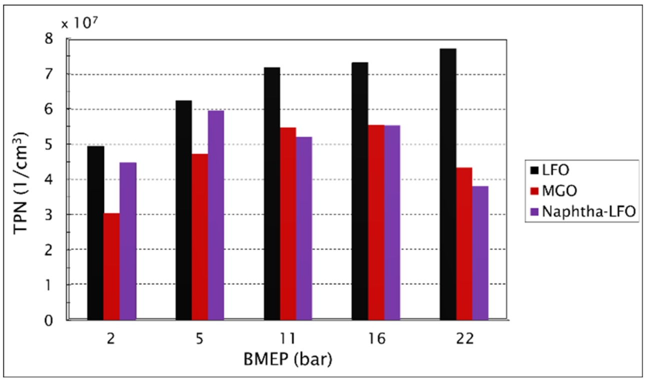

Figure 15. Total particulate number (TPN) of exhaust within the particle size range of 5.6 to 560 nm (after [45])

Discussion

The use of the studied blend of renewable naphtha and LFO was pioneering. There are few publications available on the use of this type of blend in medium- or high-speed engines. Some results, however, do exist. Hissa et al. (2019) detected that a slightly weaker naphtha-LFO blend (20/80 vol.-%) burned as favorably as LFO in a high-speed diesel engine [42]. That result supports the observations of the present study.

Niemi et al. (2019) reported that the same 20/80 vol.-% blend in the same engine resulted in almost similar BTE and NO_x but somewhat higher CO (+9%) and HC (+26%) emissions than neat LFO [37]. In some respects, the results of the present study were in line with that of [37]. With the current slightly stronger blend (26/74%), the engine efficiency and NO_x emissions were again almost equal for naphtha-LFO and neat LFO. Unlike in [37], however, the blend's cycle-weighted CO was now lower than LFO's by 5% and HC was almost similar.

Ovaska et al. (2019) detected that the weaker naphtha-LFO blend (20/80%) reduced the number of exhaust particle above 50 nm at rated and intermediate speeds [46]. In the present study, the blend also reduced particulates. Together with its competitive CO and HC performance, the blend's improved particulate results may be explained by favorable mixture formation. The boiling point has an important role in the fuel evaporation rate [47] and high volatility plus low viscosity improve mixture formation. Most likely, naphtha's higher volatility promoted fuel-air mixing. Combined with naphtha's low aromatic content, this probably led to the reduction in the number of particulates with the blend. [31] Chang et al. (2013) also detected that naphtha improved the particulate/NO_x trade off when operating the engine in the relevant drive cycle [32].

It must be noted that naphtha has some special properties that affect its usability. Siviö et al. (2019) detected that the naphtha-LFO blend (20/80%) had improved cold properties relative to neat LFO, so no specific measures are needed for fuel pumping and filtering. On the other hand, the blend had a very low flash point that calls for particular consideration of safety aspects during both storage and use. [44] Rules applied to methanol-fueled ships can also be feasible for the safe use of naphtha [48], since the flash point of methanol is approx. 12 °C, close to that of current naphtha and its blend (approx. 10 °C).

Additionally, the low boiling temperature of some naphtha compounds may necessitate sufficient backpressure in the fuel return line of the injection system [32]. The lubricity of the naphtha-LFO blend in the current study was close to that of the baseline LFO so the blend should not harm lubrication of injection pumps lubricated by fuel.

As a whole, the results of the present study showed that the blend worked beneficially at all loads. So, the blends of naphtha and conventional fuels offer a realistic way to improve the sustainability of maritime and power generation applications.

Viollet et al. (2014) also examined the role of naphtha and considered that future compression ignition engines will use, for example, low-quality gasoline such as naphtha fuels. The authors speak about fossil naphtha and suggest that using it in the gasoline compression ignition (GCI) concept has several advantages. It would mitigate anticipated demand imbalance between heavy and light fuels and offer diesel-like efficiency at lower cost [49]. Our university will, however, continue to focus primarily on renewable naphtha. It will be studied in the planned combustion concept project investigating Reaction Controlled Compression Ignition (RCCI), a field in which our staff already has experience [50].

As with renewable naphtha, there are also only few engine results available for circular-economy MGO. Gabiña et al. (2019) evaluated the suitability of an alternative fuel produced from waste oils for an actual marine diesel engine. However, the fuel had considerably higher kinematic viscosity than our MGO (21 mm^2/s vs. 3.7 mm^2/s) and slightly higher density (+15%) and CN (57 vs. 54). Accordingly, the fuel was preheated to reduce its viscosity before injection into the cylinders. The tested fuel proved to suit the engine well as regards combustion and emissions. Combustion differences were insignificant when compared with diesel fuel oil (DFO) and efficiencies were almost equal for both fuels. The MGO produced from waste oils emitted less NO_x than DFO, whereas CO was slightly higher but still low. As a whole, this alternative fuel derived from waste lube oil was suitable for use in medium-speed marine diesel engines. [2]

Ovaska et al. (2019) observed that circular-economy MGO generated high TPN at all loads at rated speed in high-speed engine tests, most probably due to its higher sulfur content. MGO was, though, favorable in terms of HC and CO emissions. Cycle-weighted HC was only two thirds of that with LFO. CO was 15% lower with MGO, while NO_x emissions were similar. Smoke as filter smoke number (FSN) was negligible for both fuels [46]. Hissa et al. (2019) also reported on a beneficial emissions performance of the same MGO [42]. Unfortunately, the viscosity and CN of the MGO in the batch used in the studies [46] and [42] were clearly higher than those of the present study's MGO. The density was also slightly higher. Therefore, the results of [46] and [42] are not completely comparable with the results at hand.

In the present study, the MGO results of engine combustion, efficiency and most of the emissions were quite similar to those recorded with baseline LFO. The TPN was even lower. Regarding performance, the studied MGO proved, thus, to be a suitable fuel for the investigated medium-speed engine. For long-term use, the only issue may be MGO's lubricity since it was slightly above the maximum, allowed for automotive diesels (484 vs. 460 μm) [51].

Conclusions

The current work studied how two liquid fuel alternatives operate in a medium-speed diesel engine, intended for marine applications and on-shore power generation. One fuel was a blend of renewable naphtha and low-sulfur LFO (26/74 vol.-%) and the other a circular economy-based MGO. Neat low-sulfur LFO formed the baseline fuel. All three fuels fueled the engine in the experiments, one after another. The engine speed was constant and the investigated parameters were recorded at five loads. In this preliminary project, the engine settings were similar for all fuels and the experimental setup did not include any exhaust aftertreatment.

Based on the conducted measurements, the following conclusions could be drawn:

- All fuels burned in a very similar, efficient way. The ignition delay followed coherently the differences in the CN, with the naphtha-LFO blend showing a slightly longer ID than the other fuels. However, the 50% burned fraction of each fuel occurred at almost equal crank angles at all loads.
- All fuels resulted in very similar brake thermal efficiencies of the engine at any given load. The variation was within one percentage point at each load.
- The brake specific NO_x emissions were also quite similar at each load with all fuels. The cycle-weighted emissions, calculated according to the ISO 8178-4 D2 cycle, were a shade lower for the blend (12.1 g/kWh) than for MGO and LFO (12.3 g/kWh).
- There was also little difference in CO emissions: the cycle-averaged brake specific CO ranged from 0.56 to 0.61 g/kWh for all fuels. MGO led to slightly higher CO than the other fuels because it emitted slightly more CO at low loads. The blend showed the lowest CO.
- The cycle-weighted brake specific HC emissions ranged from 0.56 to 0.58 g/kWh. MGO's result was the lowest and LFO's the highest. At an engine load of only 10%, the blend emitted 17% higher HC than the baseline LFO.
- The wet exhaust contents of the heavy GHG emissions, methane and nitrous oxide, were very low at all engine loads for all fuels. Methane was always below 5 ppm and nitrous oxide below 0.6 ppm.
- The number of nucleation mode particulates was drastically lower than the number of accumulation mode particles with all fuels at all loads. Up to 75% load, the size distributions peaked within the size range of 30 to 50 nm while at full load, the peak moved towards larger particles. At low loads, the TPN within the size range of 5.6 to 560 nm was the lowest with MGO. From 50 to 100% load, MGO and naphtha-LFO blend generated broadly similar TPNs, clearly lower than with LFO. Blending naphtha with LFO gave a clear reduction in particulate number.
- All in all, the studied circular-economy MGO proved to be very suitable for the medium-speed engine. Combustion, performance and emissions were quite close to those obtained with low-sulfur LFO. The lubricity should be slightly improved, however. – A share of 26 vol.-% renewable naphtha in the naphtha-LFO blend resulted in very similar engine combustion, performance and emissions to LFO. The blend's very low flash point will require specific protocols during storage and use.

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Abbreviations

BTE	brake thermal efficiency
bTDC	before top dead center
CH_4	methane
CLD	chemiluminescence detector
CA	crank angle
CN	cetane number
CO	carbon monoxide
CTO	crude tall oil
deg	degrees crank angle
DFO	diesel fuel oil
ECA	emission control area

EEPS	engine exhaust particle sizer
EU	European Union
FTIR	Fourier-transform infra-red
GHG	greenhouse gas
HC	total hydrocarbons
HFID	heated flame ionization detector
HRR	heat release rate
ID	ignition delay
ICE	internal combustion engine
ISO	International Standard Organization
LFO	light fuel oil
LHV	lower heating value
LTC	low-temperature combustion
MFB	mass fraction burned
MGO	marine gas oil
N_2O	nitrous oxide
NDIR	non-dispersive infra-red
NO_x	oxides of nitrogen
PPCI	partially premixed compression ignition
Stdev	standard deviation
TPN	total particle number
WLO	waste lubricating oil