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Qualification of Pyrolysis Oil from Cashew Nut Shell Press Cake as Marine Biofuel

Fuels - Alternative & New Fuels

Jan Seidl-Zelenka, NORDEN A/S

Jakob Bejbro Andersen, MASH Makes A/S
Robert Bank, Forschungszentrum für Verbrennungsmotoren und Thermodynamik Rostock GmbH
Krishna Hara Chakravarty, MASH Makes A/S
Federica Conti, NORDEN A/S
Henrik Røjel, NORDEN A/S

ABSTRACT

The paper illustrates the efforts and investigations to qualify a pyrolysis oil from cashew shell press cake (POCC) as a drop-in marine fuel.

Biodiesel (FAME, fatty acid methyl esters) of different grades is already well established as a marine drop-in fuel. However, environmentally sustainable feedstock supply for FAME production is limited, with consequences on availability and price projected for the future. Thus, there is a need to develop and establish drop-in biofuels from other, more abundant and sustainable feedstocks such as waste and residue biomass.

Novel biofuel grades, e.g., derived through processes like pyrolysis and hydrothermal liquefaction, can have properties that distinctively differ from both fossil derived fuels and biodiesel which results in challenges associated with their use in internal combustion engines. In order to derisk using this fuel on-board marine vessels, a rigorous testing program has been set up which will be further explained.

As part of the validation program, blends of the POCC with VLSFO have been tested using a 3l research engine. This single cylinder engine is externally charged, equipped with a common-rail injection system and allows operating on various fuels and blends. For this testing an E2 test according to ISO8178 is performed after engine warm-up and switching to the test fuel. At each load point several measurements are taken and a variation of injection parameters, such as rail pressure, is done. The results of the test blends are compared to baseline measurements on conventional VLSFO only. Overall, the testing revealed the suitability of the POCC in blends with VLSFO as both engine performance and combustion stability have been satisfactory and emissions were similar to the baseline.

The paper is rounded up with a summary of trialing the bio blend on one auxilliary engine of a Capesize dry-cargo vessel. The trial results comprise of real-world performance and emissions data as well as initial findings on the influence of the fuel on the injection equipment. It could be shown that the overall engine performance was satisfactory, and NOx emission were within the regulatory limits. Within the accumulated running hours, the bio blend did not cause excessive deposit build-up or wear to the relevant engine components.

1 INTRODUCTION

The shipping industry has begun transitioning from solely burning fossil fuels to reducing greenhouse gas (GHG) emissions by utilizing fuels derived from renewable feedstocks, such as biofuels and e-fuels. This shift is necessary because maritime transport significantly contributes to total anthropogenic GHG emissions and is supported by international and regional regulations, such as FuelEU Maritime and the IMO's GHG Strategy.[1],[2]

The global fleet today consists of approximately 109,000 vessels over 100 gross tons.[3] The majority of these vessels are powered by liquid hydrocarbon fuels from fossil sources, while only a small portion (about 2,000 vessels [4]) use alternative fuels. Potential candidates for low-GHG emission fuels include renewable methane, renewable methanol, and renewable ammonia. However, to utilize these fuels, new vessels must be built or existing vessels retrofitted to ensure the machinery can convert the fuel into propulsion and auxiliary energy, and to meet strict safety requirements due to the properties of these fuels. Despite this, a significant share of newbuild vessels is still designed for conventional fuels.[4] Consequently, given the current fleet composition, the share of conventional vessels in newbuilding programs, and the expected lifespan of ships exceeding 20 years, forecasts for the fuel mix towards 2050 indicate that conventional, mono-fuel engines will account for 30% to 40%.[4],[5]

To immediately impact the GHG emissions of the fleet of conventional vessels, drop-in fuels that do not require significant modifications to a vessel's machinery, fuel storage and supply systems are necessary. These fuels also need to reduce GHG emissions on a well-to-wake (WtW) basis.

This paper discusses the steps taken to assess a novel biofuel, pyrolysis oil from cashew shell presscake (POCC), for its suitability as a marine drop-in blendstock. It briefly describes the production and upgrading process of POCC, followed by results from land-based assessments of performance, emissions, and impact on engine components using a single cylinder research engine (SCE). Finally, POCC was tested in a real-world environment on an auxiliary engine of a Capesize bulk carrier in commercial operation. The paper presents results from performance and emission measurements, along with observations on the formation of deposits on engine components and wear.

2 BIOOIL FROM PYROLYSIS OF CASHEW SHELL PRESSCAKE

Today, liquid drop-in biofuels are increasingly used in maritime transport. Most of these biofuels are second-generation biodiesel or fatty acid methyl ester (FAME) derived from waste feedstocks such as used cooking oil, food waste, or palm oil mill effluent. Biodiesel is typically supplied to the marine fuel market following quality standards EN 14214 [6] or ASTM D6751 [7], which are also required for compliance with the marine fuel standard ISO 8217:2024 [8]. Residues from FAME end-distillation can be blended with standardized biodiesel to serve as a cost-effective alternative. Since 2023, the Unified Interpretation of MARPOL Annex VI has allowed the use of biofuel blends up to pure biofuel, as long as no modifications are made to NO_x Technical Code critical components or settings.[9]

However, since standardized biodiesel can also be used in the on-road transportation sector, competition for the feedstock is high. Additionally, the feedstock for biodiesel production can be used to produce sustainable aviation fuel, further increasing cross-sectoral competition.

Consequently, the maritime transport industry has been seeking alternative feedstocks to produce sustainable drop-in biofuel.

2.1 Cashew as a feedstock

A potential alternative feedstock for biofuel production is the non-edible shell of cashew nuts (Anacardium occidentale). In 2023, the worldwide production of cashew nuts with shells totaled approximately 3.93 million tonnes, with more than 70% remaining as waste that can be used as feedstock for biofuels.[10] Major producing countries include Ivory Coast and India, followed by Vietnam, Tanzania, Indonesia, and Brazil. The processing of cashew nuts, however, happens predominantly in Vietnam and India. In 2022, the global collection of used cooking oil totaled approximately 14 million tonnes, with 11.4 million tonnes used to produce fuels.[11] As mentioned earlier, feedstocks that can be used for biodiesel, renewable diesel, or sustainable aviation fuel are experiencing cross-sectoral competition, indicating that the availability of cashew shells as feedstock for biofuel is significant.

The shell itself contains a dark and viscous liquid known as cashew nut shell liquid (CNSL), which can be extracted through various methods, such as mechanical or solvent extraction.[12] The main components of CNSL are anacardic acid, cardol, and cardanol. The quantitative distribution of these components varies depending on the extraction process. Various upgrading techniques can be applied to maximize the CNSL's cardanol content and furthermore improve its blendability with fossil fuels, such as marine gas oil (MGO) or very low sulfur fuel oil (VLSFO). However, there remains a risk that the fuel blend may be unstable, or that secondary reactions between the biofuel and conventional fuel could lead to excessive sludge formation or polymerization.[13] Other studies have investigated upgrading CNSL to a pure biofuel.[14]

After extracting CNSL from the shell, the presscake can be used as fuel in biomass-fired power plants. Alternatively, pyrolysis of the cashew nut shell presscake has been investigated to further upcycle the waste. Pyrolysis is the process of heating material in the absence of oxygen, producing three products: biochar, biooil, and pyrolysis gas. Biochar is being studied as a renewable alternative to coal [15] or for soil enhancement and as a permanent carbon sink[16]. Pyrolysis gas can be used for internal process heat demand or to generate electricity in gas-fired engine generators. The relative proportions of biochar, biooil, and pyrolysis gas produced depend on the process parameters and the feedstock's composition.

Figure 1. Cashew nut shell presscake after extraction of cashew nut shell liquid as feedstock for the production of pyrolysis oil and biochar.

MASH Makes produces biochar and biooil from cashew nut shells in small, modular units that can be set up close to the production sites where cashew nuts are pealed and CNSL is extracted from the shells, reducing the effort and associated emissions from transporting the feedstock to the plant. The biochar is certified under the European Biochar Certificate (EBC) scheme and sold as a soil amendment, while credits are claimed for carbon removal.

The biooil production is ISCC certified and the raw biooil has a GHG emission reduction potential of around 94% compared to the EU RED baseline of 94 g CO_{2e}/MJ.[17] POCC has similar chemical and physical properties to technical grade CNSL. At the same time characteristics that are different from CNSL result from the pyrolysis process. Thus, it requires further upgrading to qualify as a bio-blendstock for marine fuels. Issues such as the stability of blends with fuel oil and diesel oils, and the tendency to polymerize under high-temperature/high-pressure conditions, need to be addressed.

A promising, proprietary upgrading pathway, mainly relying on a thermo-chemical process, has been found. This process avoids the use of costly catalysts or hydrogen, improves blendability, and removes unsaturated bonds in the aliphatic side chain of the cardanol molecules, which are identified as the root cause of the polymerization tendency [18]. Furthermore, the upgrading process changes the molecular composition, partly retaining the phenolic groups, but with shorter aliphatic sidechains as well as pure aliphatic molecules. However, as not all of the components of the POCC are converted in the upgrading process, components such as cardanol remain part of the fuel.

3 LAND BASED PERFORMANCE AND EMISSIONS TESTING

To assess the suitability of POCC as a blendstock for marine fuels, a test campaign was conducted at FVTR in Rostock. This campaign included an analysis of the fuel's bulk parameters, simplified tests to predict the behavior of the fuel in a ship's fuel handling system, and an evaluation of the fuel's performance and emissions characteristics by testing it in a single-cylinder research engine, compared to pure VLSFO. In the following section, the results on the POCC's stability and tendency to form deposits in the fuel injection equipment will be compared to other organic oils based on the work published in Bank et al. 2024 [13].

3.1 Fuel quality

The properties of pure POCC are shown in Table 1 alongside those of VLSFO 0.5%S, which was used as both the reference fuel and fossil blendstock in the test. Additionally, selected parameters of the blend consisting of 20% by mass POCC and 80% by mass VLSFO 0.5%S are presented. It is observed that pure POCC complies with the limits set out in ISO 8217:2024 Table 3, except for the water content. Its density falls within the range of residual fuel oil, while its viscosity is comparatively low. POCC has advantageous cold flow properties, with a pour point of -36 °C. Furthermore, POCC appears to have high stability and does not cause copper corrosion. The VLSFO has properties resembling a refinery straight-run with relatively high viscosity, suggesting it was not highly blended to meet the sulfur limit of a VLSFO. The certificate of analysis also showed a high aromaticity of 63.4 wt.%. Due to the chemical characteristics of POCC, which includes phenolic components, the high aromaticity of VLSFO suggests good compatibility with POCC.

Table 1. Selected fuel quality parameters of the individual fuel components POCC and VLSFO, as well as the B20 blend used in the land-based testing on a single cylinder research engine.

Parameter	Unit	B100 POCC	VLSFO 0.5%S	B20 POCC/VLSFO
Density @ 15 °C	kg/L	0.9539	0.9486	0.9647
Kinematic Viscosity @ 50 °C	mm^2/s	14.02	277.7	106.8
Sulfur Content	wt %	<0.03	0.47	0.38
Pour Point	°C	-36	21	na*
Flash Point	°C	67	>120	na*
Water Content	vol %	0.8	<0.1	0.2
Micro Carbon Residue	%(m/m)	0.61	8.1	na*
Potential Total Sediment	%(m/m)	<0.01	0.01	na*
Ash	%(m/m)	0.016	0.02	na*
Sodium	mg/kg	<1	12	na*
Vanadium	mg/kg	<1	4	na*
Aluminium + Silicon	mg/kg	<15	38	na*
Calcium	mg/kg	<3	4	na*
Zinc	mg/kg	<1	4	na*
Total Acid Number	mg KOH/g	0.89	0.08	na*
Lower Calorific Value	MJ/kg	37.85	na	na

…parameters not explicitly tested; results can be assumed to be the weighted average of the results of the two blend components

Heavy oils are pre-cleaned in a purifier system where they are exposed to water and higher temperatures. A laboratory test was developed to understand the behavior of the fuels in the purifier system. This involves adding water to the fuel, sufficiently mixing the fuel and water phases, and then centrifuging them.[13]

Some novel biofuel grades, such as those derived from cashew nut shell liquid, tend to form stable emulsions with water when added, for example, in a vessel's purifier system.[13] Therefore, the B20 blend was also centrifuged with water in the laboratory. By centrifuging the samples, the aqueous (bottom) and fuel phases (top) are separated. To check for sludge or gel formation, the sample containers can be turned upside down, as shown in Figure 2. While other, more problematic biofuel types form a very stable emulsion, creating a separating layer in the sample container, the B20 blend (second from the left) remained stable. From the coloring of the aqueous phase at the bottom of the vial (top row of pictures), we can see that some of the blend's components still mix with the water.[13] Based on this test, it can be assumed that no increased sludge formation behavior is expected in a purifier.

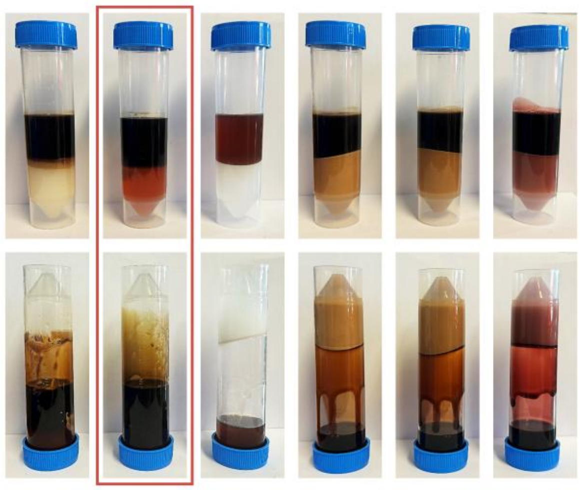

Figure 2. Results from sludge formation testing by centrifuging with water. Comparison of MASH Makes POCC with other organic oils. MASH POCC upgraded is second sample from left. [13]

POCC is highly aromatic due to its phenolic components, as described above. Previous studies have shown that when these phenolic fuels are blended with more paraffinic fuels, such as MGO, the unsaturated bonds in the biofuel tend to polymerize and create solid sludge that cannot be dissolved again.[13] This behavior might lead to excessive clogging of the fuel supply system of an engine when the supply is switched from the biofuel to MGO before stopping the engine.

To test the behavior of the B20 blend regarding this type of chemical aging, the blend was further diluted with road-grade diesel. However, no sludging was detected.

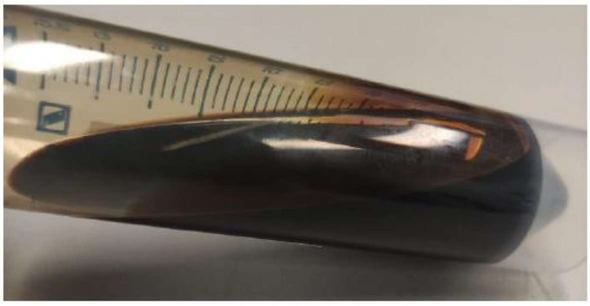

Figure 3. Compatibility/mixing stability of B20 POCC/VLSFO blend with diesel fuel.

Overall, the pre-testing of the fuel in the laboratory did not reveal any abnormal properties that would exclude this blend from being subsequently tested in the single-cylinder research engine.

3.2 Facility and method for land-based testing

A single-cylinder research engine, FVTR's 1VDS18/15CR, was used for a comprehensive investigation of the fuel's impact on the fuel supply system, fuel injection system, engine performance, combustion, emissions, and optionally exhaust gas treatment. The layout and size of the engine are representative of a maritime medium-speed engine.

On the SCE, the compatibility of the injection equipment is tested under severe but realistic conditions. As the common rail injector uses uncooled nozzles, the relatively high surface temperatures result in comparatively strong stress on the fuel. Because of the constant fuel pressure of the common rail system, power loss through nozzle deterioration is more easily detected compared to a mechanical injection system.

The single-cylinder engine test bed is equipped with a state-of-the-art pressure-trace indication system to calculate the rate of heat release, as well as exhaust analysis using FTIR and particle analysis systems, e.g., for FSN or PN/PM. Engine tests are performed at steady-state operation points at rated engine speed and varying engine loads, rail pressures, and injection timing.

The engine test is conducted according to the E2 cycle of ISO 8178.[19] This testing cycle is designed for highly stressed propulsion engines operating at constant engine speed. Engine parameters and emissions are measured at 100%, 75%, 50%, and 25% load. Using the weighting factors, the corresponding emissions can be calculated and compared to standards such as the IMO Tier limits for NO_x emissions.[20]

At the different load points, testing began with the engine's IMO Tier II compliant operating parameters for injection timing and fuel pressure. Additionally, rail pressure variations were conducted to analyze the influence and potentially optimize combustion behavior for this specific fuel blend. The testing was first performed with the base fuel (VLSFO) and then repeated using the B20 blend.

3.3 Results of the SCE tests

Continuous monitoring of engine performance and emissions during the testing of the B20 blend did not show any abnormal behavior, such as cyclic fluctuations in NO_x or CO emissions. This indicates that no severe deposits are building up on the outside of the injection nozzle. Furthermore, since emissions remained stable throughout the individual test phases, no severe deterioration of the inner injector parts is expected.

The analysis of specific NO_x emissions while running on the B20 blend shows an increase at all engine loads compared to the results achieved with pure VLSFO (Figure 4). Although the increase in NO_x emissions can be up to almost 3 g/kWh, applying the weighting factors, the increase in cycle-averaged NO_x emissions is only 13% compared to the VLSFO baseline.

Except for the 25% load operating point, the CO emissions while running on the B20 blend are in line with those from pure VLSFO. The soot emissions, expressed as FSN, are lower for the B20 fuel compared to pure VLSFO.

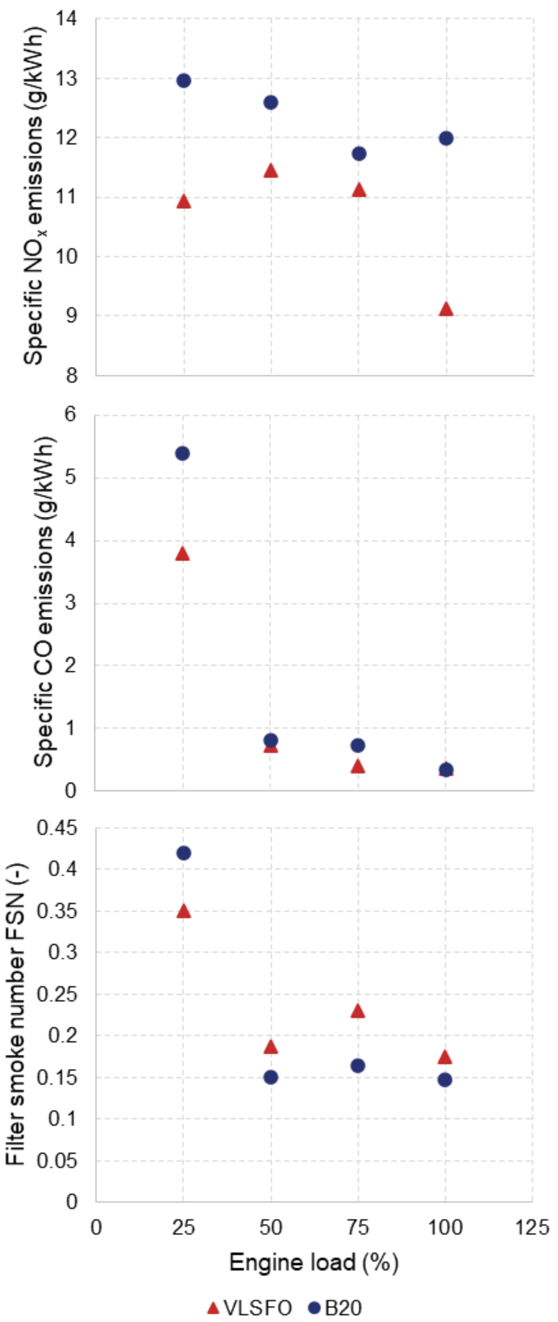

Figure 4. Emission results. Specific NOx emissions (top), specific CO emissions (center) and filter smoke number FSN (bottom).

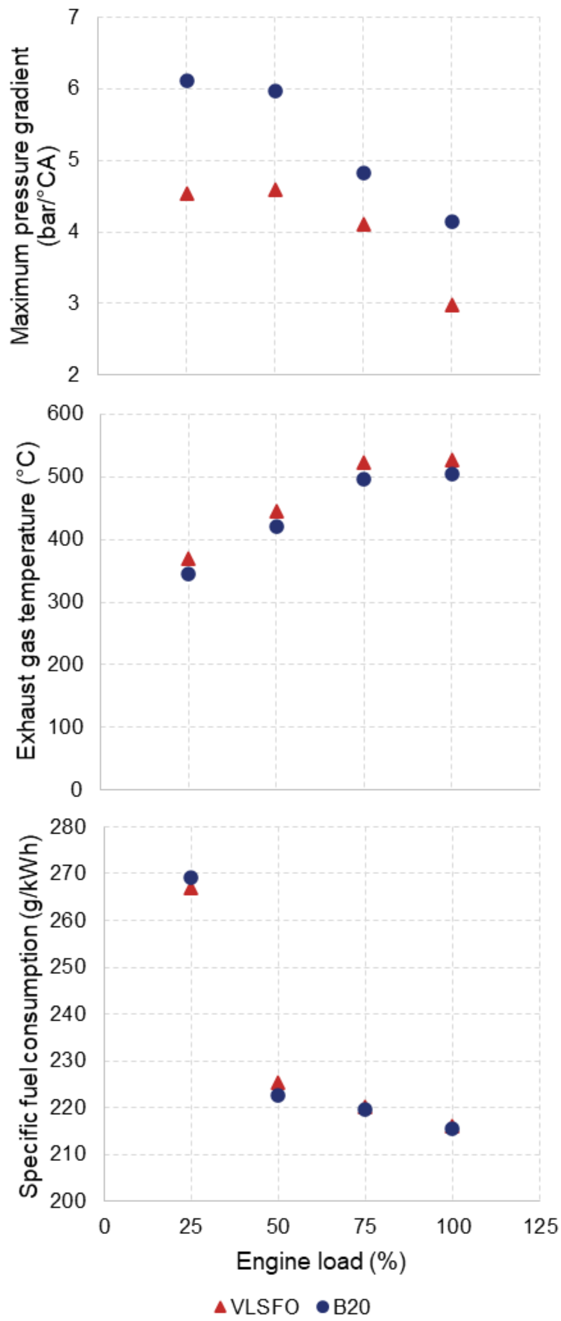

Figure 5. Maximum in-cylinder pressure gradient (top), exhaust gas temperature (center) and specific fuel consumption (bottom).

The specific fuel consumption of the engine running on the B20 blend shows no deviation compared to the measurements done on VLSFO. Furthermore, the exhaust gas temperature was lower with B20 than with VLSFO (see Figure 5). The maximum pressure gradient of the B20 measurements is higher compared to the measurements on pure VLSFO, suggesting a longer ignition delay and, consequently, more fuel premixed with air burning rapidly after the start of combustion.

The in-cylinder pressure traces are shown in Figure 6. It is clear that the use of the B20 blend results in slightly higher in-cylinder maximum pressure, even though the injection timing was kept constant. However, no abnormal combustion behavior was observed.

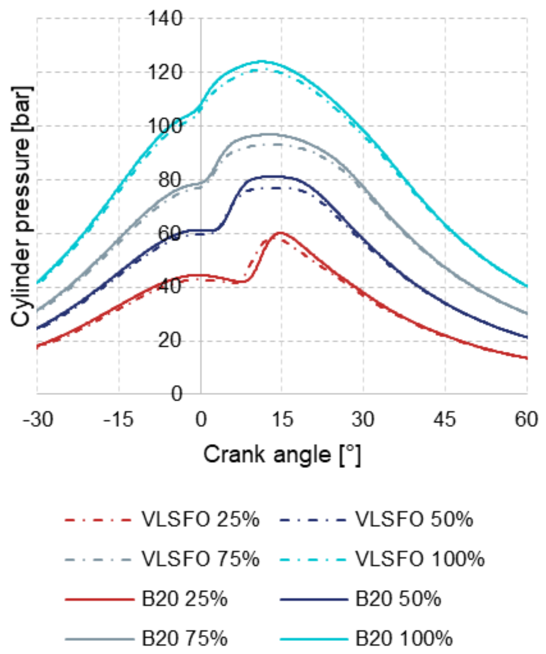

Figure 6. In-cylinder pressure trace at engine loads according to ISO 8178 E2 cycle. Dashed lines: reference fuel VLSFO 0.5%S. Solid lines: B20 POCC/VLSFO.

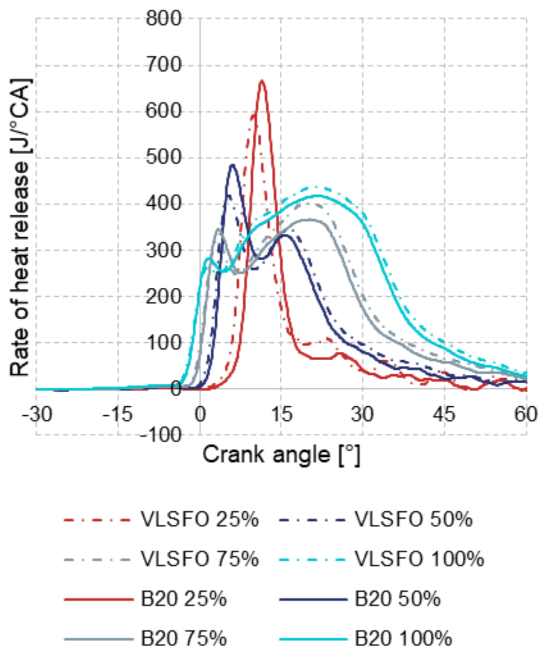

Figure 7. Rate of heat release for various engine loads according to ISO8178 E2 cycle. Dashed lines: Reference fuel VLSFO 0.5%S. Solid lines: B20 POCC/VLSFO.

Based on the in-cylinder pressure traces, the rate of heat release was determined for all operating points (cf. Figure 7). From this analysis, it is clear that blending POCC into VLSFO results in a longer ignition delay, followed by a higher degree of premixed combustion. These two phenomena are the root causes of the increased maximum pressure gradient and, consequently, the higher NOx emissions.

Furthermore, it is clear from the rate of heat release that the center of gravity of combustion is later for the B20 blend than for VLSFO operation. However, the burnout phase is completed earlier when running on the B20 blend compared to pure VLSFO.

After completing the engine operation on the B20 POCC/VLSFO blend, the injector was removed from the engine for inspection. It was found that there was no abnormally large build-up of deposits on the outside of the nozzle (Figure 8, top). The injector needle could be extracted from the nozzle with ease, and no deposits were detected on the guiding surface or the sealing surface of the needle. For comparison, Figure 8 (bottom) shows the injector nozzle after running the single-cylinder engine on a problematic biofuel blend. In this case, deposits on the nozzle tip obstructed the fuel spray, resulting in poor spray breakup and consequently late combustion with high CO emissions. However, the injector needle did not show any hard deposits on the surface.

Additionally, an imprint of the inside of the injector nozzle was made using high-resolution silicone. The imprint was inspected using a microscope after being extracted from the nozzle. Figure 9 shows the microscopic image of the imprint for the B20 case (image (c)), where almost no deposits can be found. For reference and comparison, Figure 9(a) and (b) show nozzle imprints of a brand-new nozzle and a nozzle run on diesel fuel, respectively. Figure 9(d) shows the result of running an engine on a problematic biofuel blend for only a few hours.

Figure 8. Deposit formation on fuel injection nozzle tip and on injector needle after running on B20 MASH POCC/VLSFO blend (top) and after running on problematic biofuel-blend (bottom). [13]

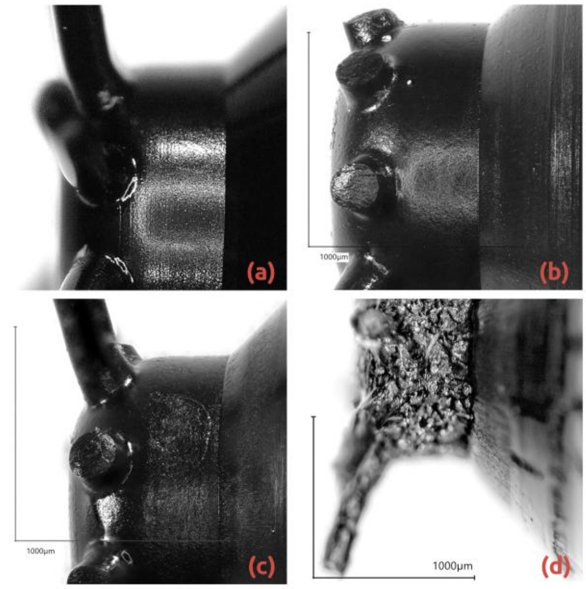

Figure 9. Microscopic imaging of fuel injector nozzle imprints. (a) new nozzle, (b) nozzle after running on diesel, (c) nozzle after running on B20 POCC/VLSFO blend, (d) nozzle after running on problematic biofuel blend. [13]

In conclusion of the land-based testing, it was decided to proceed with a first set of on-board vessel trials to evaluate the behavior of the fuel in a real-world operational environment. The setup of the vessel trial and the results will be discussed in the following section.

4 ON-BOARD VESSEL TRIAL

4.1 Vessel and machinery description

The vessel selected for the trial is the Capesize bulk carrier M.V. NORD POWER (IMO No. 9537848), chosen in part due to the better predictability of its voyages, which facilitates the bunker logistics for this new grade of fuel.

The vessel is equipped with an MAN 6G70-ME-C engine for propulsion and three Hyundai HiMSEN 5H21/32 diesel generators. The engine particulars can be found in Table 2.

Modifications have been made to the fuel supply system so that one individual auxiliary engine can be run in isolation on the B20 POCC/VLSFO blend while the remaining machinery operates on HSFO. Since the B20 blend requires heating to achieve the correct kinematic viscosity for injection at 12 cSt, the second set of settling/service tanks has been dedicated to this fuel. Additional piping has been installed to route the B20 blend via the diesel oil lines to the engine.

Table 2. Particulars of Hyundai HiMSEN H21/32 auxiliary engines used for the trial on NORD POWER.

Parameter	Value
No. of cylinders (-)	5
Bore (cm)	21
Stroke (cm)	32
Speed (rpm)	720
Rated mechanical power output (kW)	790
Rated electrical power output (kW)	740

Dedicated fuel flow meters have been installed at the engine inlet and outlet to determine the fuel consumption of this individual engine. Lastly, a pocket for measuring the exhaust gas emissions has been created in the exhaust pipe after the turbocharger, positioned with enough distance from the preceding and subsequent pipe bends to allow a uniform flow at the sampling point.

4.2 Fuel qualities

Table 3 shows the bulk properties of the fuels used during the trial on NORD POWER. To produce a B20 blend of POCC and VLSFO for the trial, a random VLSFO was procured. For reference, the table also includes the parameters of the pure, upgraded POCC and the pure VLSFO 0.5%S.

Table 3. Characteristics of the fuels compared during the trial on NORD POWER.

Parameter	Unit	B100 POCC	VLSFO 0.5%S	LSMGO 0.1%S	HSFO 3.5%S	B20 POCC/VLSFO
Density @ 15 °C	kg/L	0.9539	09603	0.8723	0.9661	0.9587
Kinematic Viscosity @ 50 °C (@40 °C)*	mm^2/s	14.02	47.60	3.524*	299.9	34.65
Sulfur Content	wt %	<0.03	0.489	<0.03	2.96	0.393
Pour Point	°C	-36	<-3	-3	<24	<-18
Flash Point	°C	67	>100	>70	>70	128
Micro Carbon Residue	%(m/m)	0.61	3.09	<0.1	11.68	2.34
Potential Total Sediment	%(m/m)	<0.01	0.01	-	0.02	0.01
Ash	%(m/m)	0.016	<0.01	<0.01	0.05	0.028
Sodium	mg/kg	<1	16	<1	21	23
Potassium	mg/kg	42	na	na	na	9
Vanadium	mg/kg	<1	<1	<1	117	3
Aluminium + Silicon	mg/kg	<15	<15	<2	5	19
Calcium	mg/kg	<3	<3	<1	6	24
Zinc	mg/kg	<1	<1	<1	<1	2
Phosphorus	mg/kg	<1	<1	<1	<1	<1
Total Acid Number	mg KOH/g	0.89	1.1	<0.1	0.2	1.3
Lower Calorific Value	MJ/kg	37.85	41	42.48	40.51	40.37

The VLSFO 0.5%S used to create the blend was compliant with ISO 8217-2017 Table 2, thus no FAME has been present in the fuel. Furthermore, no additives have been used in order to stabilize the blend or else alter its properties.

4.3 Test procedure

The trial of the B20 POCC/VLSFO involved continuous monitoring of engine behavior during standard service operation, as well as measuring engine performance and exhaust emissions.

During the monitoring, data such as cylinder-specific exhaust gas temperatures, temperatures at the turbocharger inlet and outlet, turbocharger speed, charge air pressure and temperature, and the corresponding electrical power output of the engine were recorded hourly. These data were sourced from the generator engines' monitoring system.

Exhaust gas emissions were measured at 25%, 50%, 75%, and 85% engine loads to determine the influence of the biofuel composition on NO_x and CO emissions, particularly to ensure compliance with the NO_x Technical Code.[20]

To establish the data for the emission evaluation, a Testo 350 Maritime emission test system [21] was used. This system determined the concentrations (on a dry basis) of CO_2, CO, SO_2, NO, NO_2, and O_2 with a 1 Hz resolution. The measurement procedure involved exposing the sample probe of the Testo 350 to the exhaust gas for 10 minutes at a time, interrupted by exposure to ambient air inside the engine room. Thus, the procedure for measuring emissions at a particular engine load took 70 minutes, following this sequence: *ambient air – exhaust gas – ambient air – exhaust gas – ambient air – exhaust gas – ambient air*.

Engine parameters such as exhaust gas temperatures, pressure levels, engine power, and fuel consumption were logged every ten minutes at the beginning of each phase. These parameters were then averaged over the entire measurement period, while the exhaust gas concentrations were averaged for the exhaust gas measurement periods and corrected for any zero-point offset.

Engine performance was measured at 50% engine load consistently in parallel with the emissions measurement, using a MarPrime [22] cylinder pressure testing device and the corresponding analysis software.

To establish a baseline for comparison of the B20 trial results, the engine was first operated on LSMGO 0.1%S and HSFO 3.5%S. A comparison with the pure VLSFO 0.5%S, used for creating the blend, would have been ideal. However, due to logistical constraints, this fuel was not available for the trial. After switching the engine to the B20 POCC/VLSFO blend, its operation was monitored for seven hours at approximately 30% engine load, with data logged at 30-minute intervals to identify any abnormal behavior early on. After 24 hours without any indication of abnormal engine behavior, emissions and performance measurements were started. These results will be described in the following section.

4.4 Results of the onboard emissions and performance assessment

The reference measurements on LSMGO were performed only at 25%, 50%, and 75% engine loads. As shown in Figure 10, the charge air pressure measured by the engine's monitoring system remained consistent regardless of the fuel used. However, higher deviations were found in the excess air ratio (EAR), calculated based on the exhaust gas composition. For the two lower engine loads, a significantly higher EAR was calculated for HSFO operation, while the difference between all tested fuels at 75% engine load was minor. The average turbine inlet temperature showed strong deviations for engine operation on LSMGO compared to operation on HSFO or B20. Combustion of HSFO and B20 resulted in approximately the same exhaust gas temperature level.

NO_x emissions were measured to be in the same range for all three tested fuel types, with only minor differences (see Figure 10). However, a clear increase in CO emissions was observed when running on the residual fuel grades HSFO and B20, compared to operation on LSMGO at 25% engine load. Operation on HSFO resulted in the highest CO emissions at this operating point. At higher engine loads, emissions of all tested fuel types were on par. To evaluate cycle-averaged specific NO_x emissions, the weights from the ISO 8178 D2 cycle were adjusted by distributing the weights of the missing engine loads equally to the remaining operating points resulting in the weights as shown in Table 4. As discussed before, the 100% load operating point had to be replaced with operation at 85% load.

Table 4. Weights for specific NO_x calculation modified from ISO 8178 D2 cycle.

	25% load	50% load	75% load	85% load
LSMGO	0.350	0.350	0.300	-
HSFO	0.325	0.325	0.275	0.075
B20	0.325	0.325	0.275	0.075

Applying the above stated weights, the cycle-averaged specific NO_x emissions were calculated to 8.3 g/kWh for operation on LSMGO, 8.5 g/kWh for operation on HSFO and 8.7 g/kWh for operation on B20, respectively. Thus, the emissions using the B20 fuel are less than 5% increased compared to the operation on LSMGO.

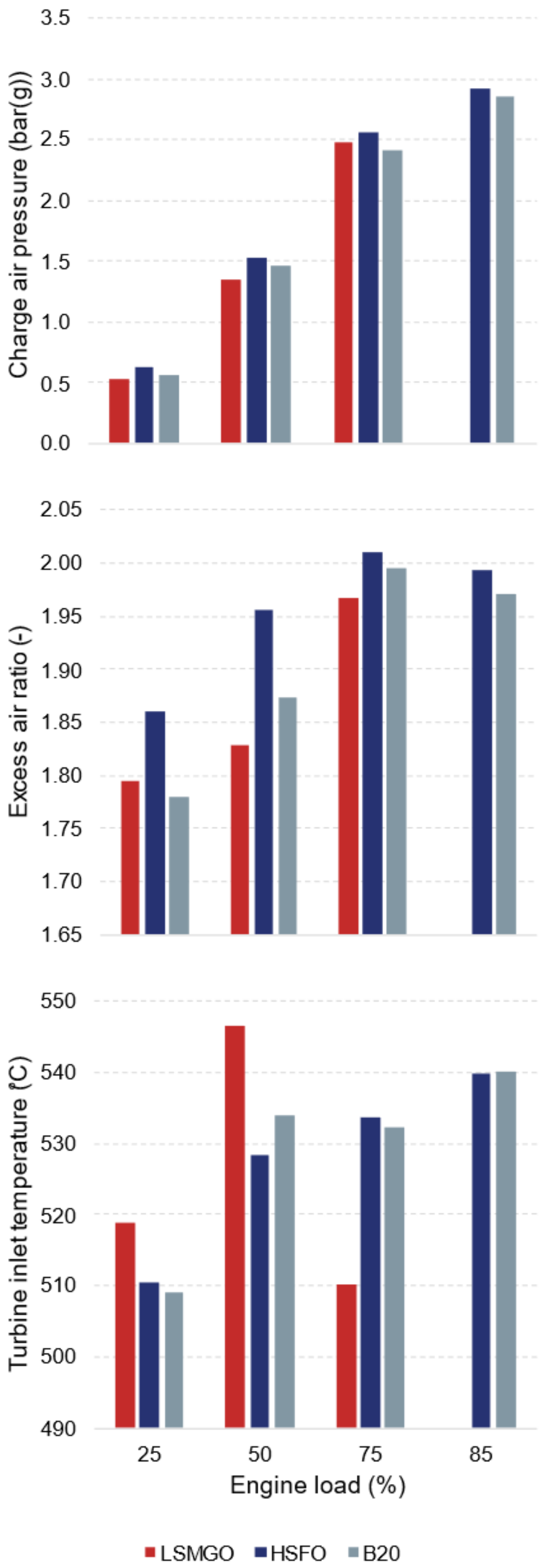

Figure 10. Charge air pressure (top), Excess air ratio (center) and turbine inlet temperature (bottom), comparing LSMGO, HSFO and B20.

Specific fuel consumption was adjusted to account for the different heating values of the tested fuels and is reported as MGO equivalent consumption in Figure 11. The adjusted specific fuel oil consumption was found to be in the same range for all tested fuels.

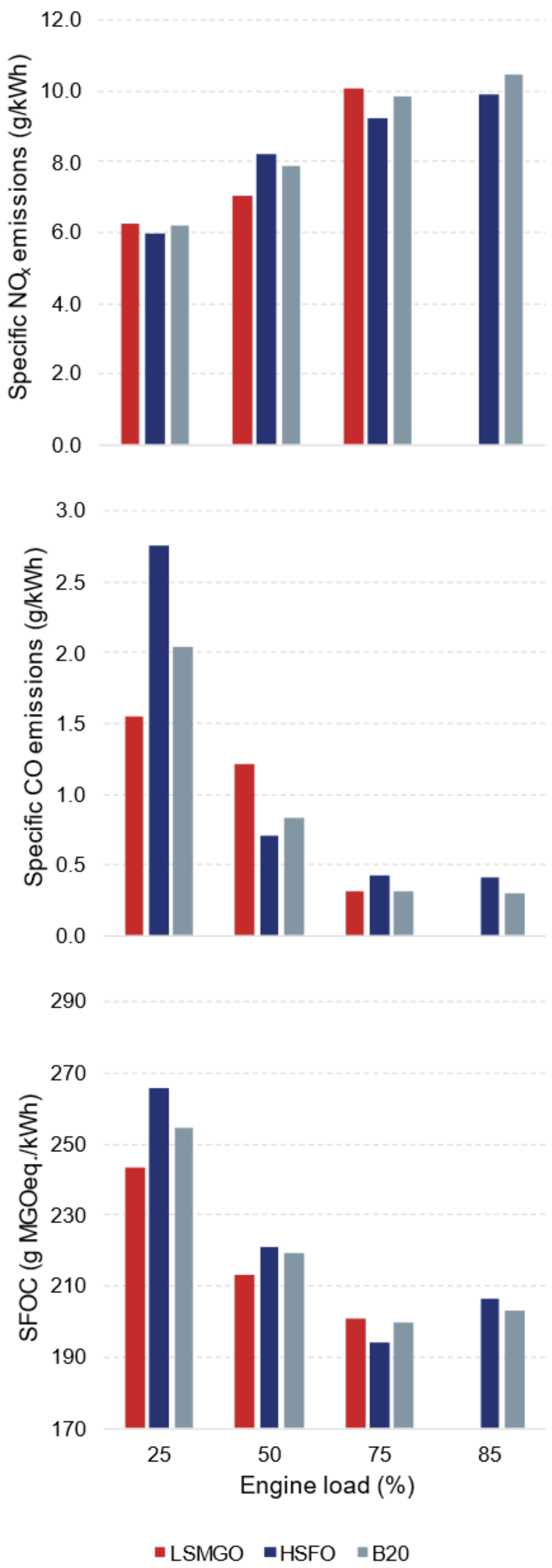

Figure 11. Specific NO_x emissions (top), specific CO emissions (center) and MGO-equivalent specific fuel consumption (bottom), comparing LSMGO, HSFO and B20.

In addition to measuring engine emissions and operating parameters, the in-cylinder pressure was recorded to further assess the direct impact of the fuel's properties on combustion. Figure 12 shows the pressure traces at 50% engine load for the two reference fuels, LSMGO 0.1%S and HSFO 3.5%S, in comparison to operation on B20. As engine load could not be controlled as precisely as on an engine testbed, deviations are clearly seen in the pressure level during the compression phase and, consequently, in the peak pressure after compression. Nevertheless, a clear difference between the fuels is visible in terms of combustion start. The earliest start of combustion was achieved with LSMGO, while the latest start was with HSFO. The B20 lies in between. Consequently, combustion was delayed for both B20 and HSFO relative to LSMGO, which is also evident in the falling flank of the in-cylinder pressure trace.

Comparing this analysis with the turbine inlet temperatures in Figure 10, a clear discrepancy is visible, as one would expect later combustion to result in higher temperature levels. However, it must be noted that the values given for the exhaust gas temperature have been averaged over the entire measurement period of 70 minutes, whereas the in-cylinder pressure measurement represents only a short duration during operation at this engine load.

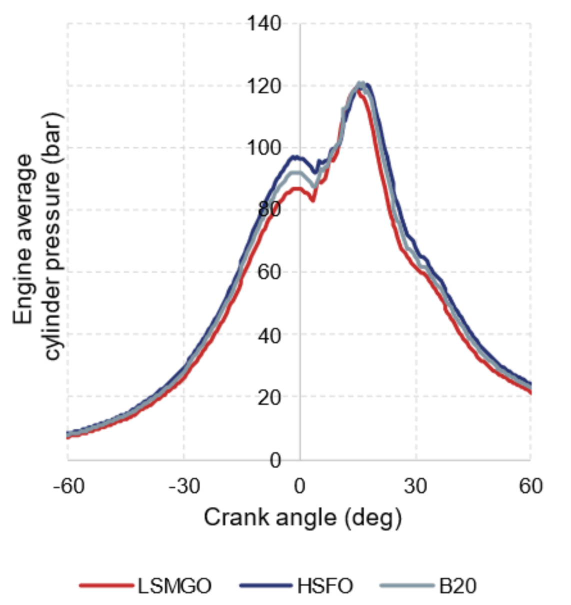

Figure 12. Engine average cylinder pressure traces at 50% engine load and operation on LSMGO, HSFO and B20.

Evaluating the engine's performance in terms of indicated mean effective pressure (IMEP) and maximum in-cylinder pressure (Pmax), no trend favoring or disadvantaging any of the tested fuels could be detected. Figure 13 compares the cylinder-specific results of the IMEP and peak firing pressure relative to the engine average results.

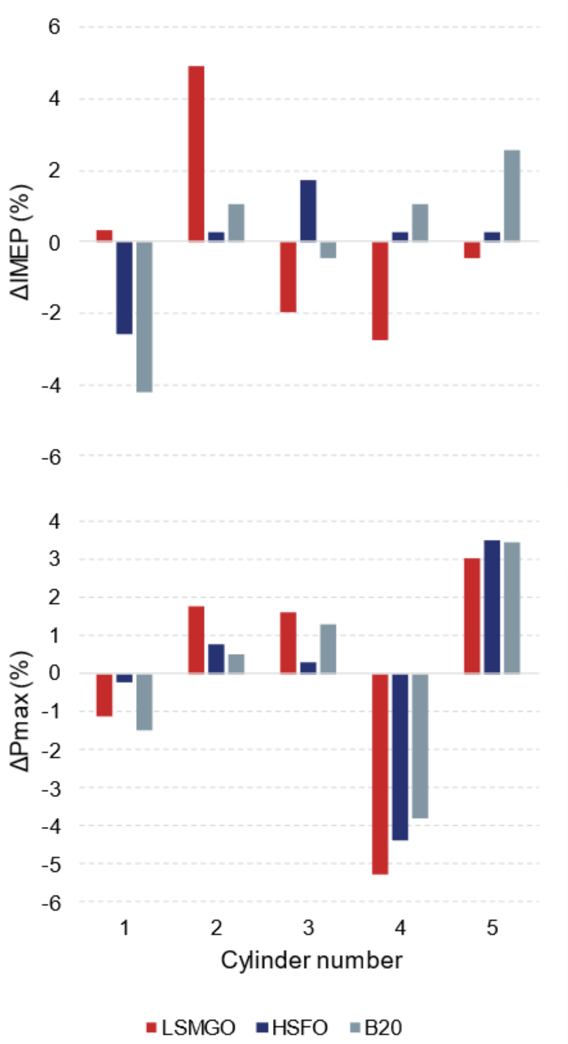

Figure 13. Deviation of cylinder individual performance results from engine average at 50% engine load. Top: indicated mean effective pressure IMEP, bottom: maximum pressure Pmax.

Based on the available dataset, the provided B20 blend of POCC and VLSFO showed satisfactory combustion performance and did not drastically increase NO_x emissions.

4.5 Assessment of the fuel's impact on engine components

The condition of the engine and its fuel-relevant components were assessed during and after completing the trial.

Inspections of the engine components confirm the land-based testing results, showing that deposits built up on the tip of the fuel injection nozzle had no impact on spray and mixture formation. As shown in Figure 14 (top), only a minor amount of deposits accumulated on the nozzle tip after approximately 60 operating hours. These deposits did not obstruct the spray holes, were soft in character, and could easily be removed with a fingernail. Figure 14 (bottom) shows that the amount of deposits on the nozzle-tip did not increase further after 360 operating hours. The deposits could easily be removed using brake cleaner and paper wipes.

Figure 14. Deposit build-up on the fuel injection nozzle after 60 operating hours (top) and after 360 operating hours (bottom).

After approximately 250 operating hours, the fuel injectors were inspected again, and an evaluation of the spray pattern and needle-opening pressure was performed. Both the spray pattern and needle-opening pressure were reported to be within normal parameters (Figure 15).

Figure 15. Spray pattern at 400 bar nominal opening pressure in an injector calibration rig after 250 operating hours.

A final assessment of deposits or wear inside the fuel injection nozzle was conducted using high-resolution silicone at the end of the trial. The nozzle, which had accumulated over 600 operating hours on the B20 blend, was found to have spray holes and the sac hole essentially free of deposits, as can be seen in Figure 16 and in comparison with the results shown in Figure 9.

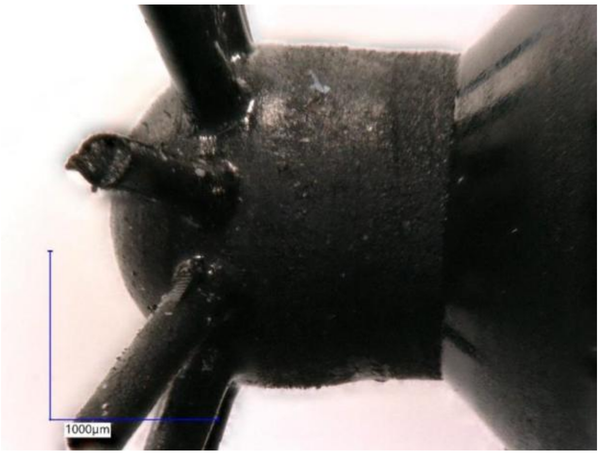

Figure 16. High-resolution silicone imprint of the fuel injection nozzle after a total of more than 600 accumulated operating hours.

The inspection of the fuel injection pump after 360 operating hours revealed only minor deposits on the plunger, that could be wiped off with a soft cloth and no signs of wear marks (Figure 17). The fuel pumps were found in good condition also at the end of the trial.

Figure 17. Plunger of a fuel injection pump after 360 operating hours.

Due to the relatively low presence of sodium and potassium in the B20 blend, only a minor build-up of deposits on the turbine nozzle ring was reported by the engine crew after 360 operating hours (Figure 18). The amount of deposits was assessed in the same order of magnitude as the crew would expect from running on HSFO for the same amount of time.

Figure 18. Deposit build-up on turbine nozzle ring after 360 operating hours.

5 SUMMARY AND CONCLUSIONS

The shipping industry’s drive to reduce GHG emissions requires the adoption of alternative fuels produced from sustainable feedstocks. Drop-in biofuels play an important role in this transition by enabling the reduction of GHG emissions on existing vessels without the need for expensive retrofits. Feedstocks for well-established biodiesel face cross-sectoral competition, making it necessary to establish new biofuel pathways. This publication provided insight into the initial aspects of developing a bio-oil, derived through pyrolysis of cashew nut shell presscake, into a drop-in blendstock for marine fuels.

Based on land-based testing on a single-cylinder research engine and an initial vessel trial, preliminary indications suggest that a solution to the problems associated with cashew-derived fuels could be found.

The first vessel-trial of this fuel has been successfully completed. Emissions and performance were found to be comparable to those of consuming pure fossil fuels, with no adverse effects on the fuel injection system observed after accumulating over 600 operating hours.

The next steps will involve scaling up the current upgrading facilities and producing a few hundred metric tonnes of fuel for a follow-up trial on a vessel's main engine. Furthermore, investigations will continue to increase the blend ratio of POCC in VLSFO.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

B20:	Biofuel blend with a share of 20% biofuel
CNSL:	Cashew nut shell liquid
CO:	Carbon monoxide
CO_2:	Carbon dioxide
CO_{2e}:	Carbon dioxide equivalent
EBC:	European Biochar Certificate
GHG:	Greenhouse gas
HSFO:	High sulfur fuel oil; > 0.5%m sulfur
IMEP:	Indicated mean effective pressure
ISCC:	International Sustainability & Carbon Certification
LSMGO:	Low sulfur marine gas oil; < 0.1%m sulfur
MGO:	Marine gas oil
NO_x:	Nitrogen oxides
Pmax:	Maximum in-cylinder pressure
POCC:	Pyrolysis oil from cashew shell presscake
RED:	Renewable Energy Directive
S:	Sulfur
SCE:	Single cylinder research engine
SFOC:	Specific fuel oil consumption
VLSFO:	Very low sulfur fuel oil; < 0.5%m sulfur
WtW:	Well to wake

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