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Cashew Nutshell Liquid Compatibility Testing – Methodology and Case Reports

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Abstract

Renewable fuels will have a large share in the future marine fuel mix. In addition to potential electricity-based fuels such as methanol and ammonia, which are not yet produced on an industrial scale, bio-based fuels and oils are already available today. HVO (hydrogenated vegetable oil) and FAME (fatty acid methyl ester) are the best-known representatives. While their properties in terms of engine compatibility are sufficiently well known, those of a new generation of bio-oils based on as yet unused feedstocks are still unknown. Currently, different types of pyrolysis oils and fluids derived from HTL (hydrothermal liquification) are in the focus of research. The so-called "cashew nutshell liquid" (CNSL) in particular is one of the candidates for an attractive alternative. It can be used in different stages of refinement as a blend with conventional fuels like a DMA or even VLSFO. However, every blend matrix from a bio-oil and a fossil base component is its own challenge in terms of compatibility and operability. Therefore, special test methods need to be developed to assess compatibility for marine engines and components.

In recent years, FVTR GmbH has established a test procedure to analyze the properties and effects of future bio-oils and blends, such as CNSL fuels, on engine components and combustion behavior based on laboratory tests, component tests, single-cylinder and full-engine tests. In this article, CNSL-based fuel blends of different quality and production processes are compared with regard to various chemical properties. Furthermore, their behavior in the engine fuel path and their combustion characteristics are presented. The article focuses in particular on the possible sludge formation of the fuels in fuel separators during processing the fuel blends, the impact on the deposition behavior in the fuel injection systems, e.g. the injector nozzle, and therefore the influence on fuel evaporation and finally combustion and emission behavior.

As a result, we found that possible issues in the fuel processing due to massive sludge formation can simply be avoided by adjusting the operation scheme of the separator. But knowledge of that fact as well as sensitizing the vessel crew is mandatory. The overall performance of the different bio-blends ranges from good operable and inconspicuous to clear difficulties in stable engine operation already after shortest operating time. Regarding exhaust emissions there is only minor impact for blends up to B30, containing 30% of the used bio-oil. However, this is only valid as long as there is no deposit formation in the nozzle. So, emissions are one precursor monitoring the engine state.

1. The feedstock

1.1. Usage of bio-oils

The rate of change in the maritime industry is at an all-time high. Engine and component manufacturers need to develop new products tailored to fuels that have completely different properties compared to conventional distillate and residual fuels. Ship builders face the challenge to incorporate this technology into a package while at the same time increasing their ships' efficiency through novel designs, new materials and other technological innovations. Ship operators have plenty of options at their disposal to lower their CO_2 emissions through smart monitoring, maintenance, antifouling, and CO_2 neutral fuels. The latter has gained even more importance through the Fuel EU laws demanding the usage of 2% carbon neutral fuels in the period from 2025 to 2029 and 6% from 2030 to 2034. The percentages continue to rise from there on. Until this goal can be economically achieved using carbon capture technologies, the importance of drop-in capable carbon neutral fuels - at least as a bridge technology - is drastically high.

Until recently, the usage of biofuels was mainly governed by the quotas imposed by legislation on the fuel suppliers for on-road traffic. This highly regulated usage of biofuel resulted in the addition of 7% FAME to diesel fuel, called B7. The goal here was to allow all-encompassing or at least very broad compatibility of the fuel with engines and fuel systems. With the new Fuel EU law, the responsibility for reducing the fossil fuel usage is passed on to ship owners without clear specification of the fuels and technologies to be used. As there are currently quite limited options for fuel substitution, biofuel is the easiest measure for fulfilling the quotas. Therefore, in preparation for 2025, the biofuel demand is currently rising.

The individual responsibility for fuel usage pared with the sturdiness of marine fuel system results in a significantly more flexible use of biofuels including a fast-growing range of qualities and feedstocks. So, this new generation of biofuels for shipping has a focus on the fuel price rather than broad compatibility. Many fuel producers, vendors and ship operators have turned to FVTR to help in assessing the opportunities and limits of fuels from new feedstocks, new fuel qualities and new blending recipes. One of the feedstocks that is hoped to be exploited is the cashew nut, rather the waste products from cashew nut production.

1.2. Cashew nut and CNSL

The cashew nut, as known to the end consumer, is only a small part of the whole fruit (Figure 1). The larger part of the cashew fruit is the cashew apple, which is edible, has a high nutritional value and an acquired taste. It can be hard to digest and may require special preparation, which may be the reason for its scarce usage in western countries [1]. Attached to the outside of the cashew apple is the cashew nut. It consists of a hard shell and the kernel. The kernel again is surrounded by a thin skin called testa. The shell contains within its honeycomb structure a brown viscous liquid known as cashew nutshell liquid, CNSL. The edible kernel is widely known and marketed all over the world. The testa has little use so far but is also gaining more attention as it contains bioactive compounds with functional and health-promoting benefits which may be valorized in the future. [2]

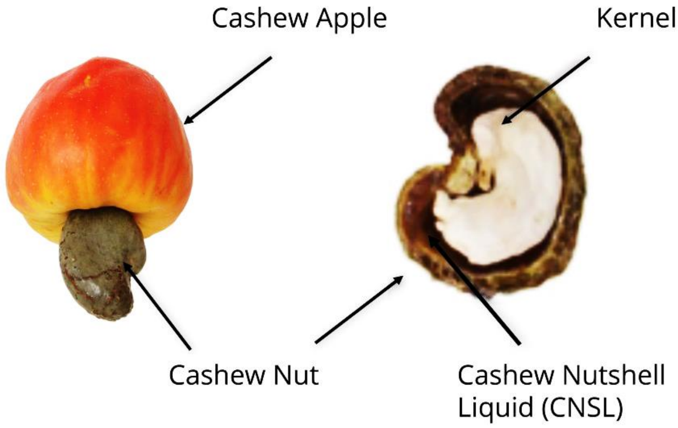


Figure 1: Cashew nut [3]

Cashew trees are grown in plantations in tropical regions like South America, Africa and Asia within the region between 23°N and 23°S of the equator. The tree can reach up to 12 m height. It is draught resistant and its sturdy root system can be used to control soil erosion and desertification. It is thus a valuable plant that can at the same time provide food and a feedstock for biofuel. The greatest perils probably lie in the creation of monocultures and in the working conditions on the farms, both of which can and should be addressed by traders and end users. Comparing the annual cashew nut production shown in Figure 2 to the country size, it becomes clear that especially Côte d'Ivoire will suffer from excessive monoculture.

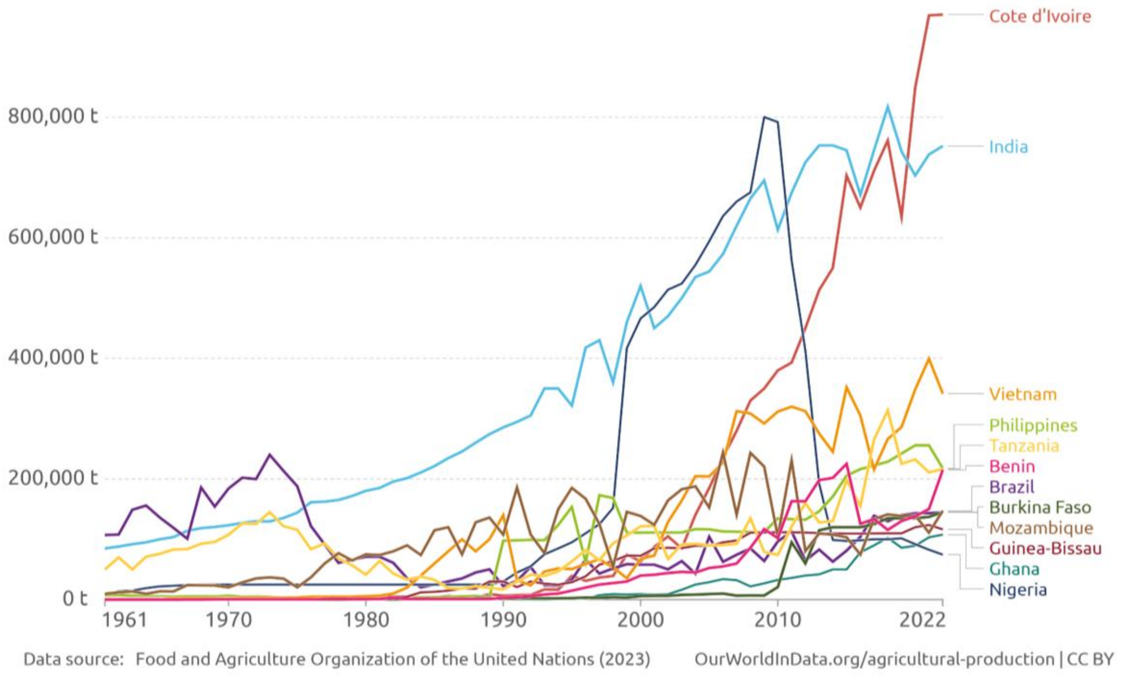


Figure 2: Cashew nut production volumes [11]

Apart from the usage of the kernel as food, the other parts of the cashew fruits have also been used in the past. Cardanol, one of the main components of the liquid, has been used for curing agents, foams, coatings and elastomers. The entire shells have also been used for their high heating value in pressed pellets. Employing this feedstock as liquid fuel for internal combustion engines will significantly increase its value. This increased value can hopefully make an impact on wages and working conditions of the producers, which is an important issue for all biofuels that has been addressed in various reports [4].

1.3. Composition and properties of CNSL

CNSL consists of four main phenolic components, depending on the production path: Anacardic acid, cardanol, cardol and 2-methylcardanol. The C_{15} side chain of these molecules can be completely unsaturated as well as mono-, di- and tri-unsaturated. The basic chemical structures of the CNSL components are shown in Figure 3 [5][6][7][8].

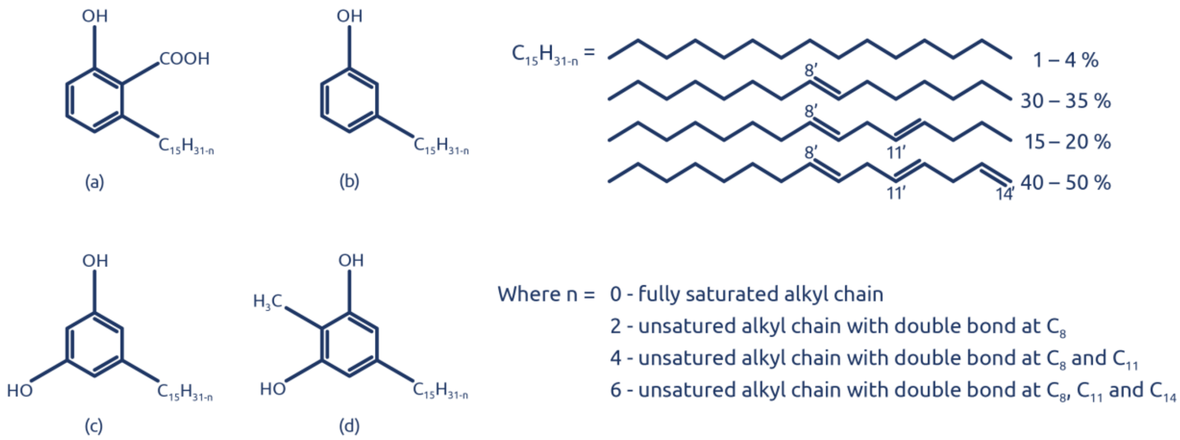


Figure 3: Chemical structures of CNSL – (a) Anacardic acid, (b) Cardanol, (c) Cardol, (d) 2-methylcardanol [5]

Technically interesting properties of CNSL include its heating value, viscosity, acidity and potassium content. The acidity of phenolic compounds varies due to the substitutions present in the phenyl ring. However, when a substantial concentration of phenolic compounds is present in the fuel, it may lead to corrosion, sludge formation and fuel injection issues. The components of CNSL typically show an elevated Acid Number ranging from 1.0 to >2.0 mg KOH/g.

All the components have polymeric properties due to their structure. The phenolic compounds in CNSL are quite reactive, due to the presence of the hydroxyl group and the unsaturated alkyl side chain with different degrees of unsaturation. This makes the reaction centers susceptible to polymerization.

Many CNSL samples have been found to contain high potassium levels. These are not native to the feedstock but might instead derive from wanted or unwanted contamination with potassium hydroxide and other alkalis used to inhibit polymerization. High levels of potassium can lead to increased post-combustion deposits. Potassium is also known to have a harmful effect on SCR (Selective Catalytic Reduction) units.

2. How to determine suitability of biofuels

FVTR and LKV have a long history and broad experience base in testing fuels. The scope here ranges from different distillate fuel qualities and determination of impurities, marine residual fuel qualities, normed biofuels and completely novel biofuels from a variety of feedstocks, blends of all the above and most recently different alternative fuels like for example methanol, ammonia and hydrogen.

The testing of these fuels depends on the application. While for on-road fuels the influence of a certain blend on the engine running characteristics at fixed engine controller settings might be of interest, other fuels might require tuning of the combustion method in various degrees using free controllers. In the case of testing biofuels for marine applications, an adaptation of the fuel system and engine control to the biofuel is not possible as the fuels are supposed to be drop-in capable. The combustion is analysed against a standard marine fuel. A big challenge arises from the high flexibility of the marine fuel system. These systems allow the usage of very low refined fuels with vastly varying properties, and the challenge is to make sure that the systems do indeed not suffer any deterioration. Generally, problems of compatibility of fuels with fuel systems can be related as shown in Figure 4.

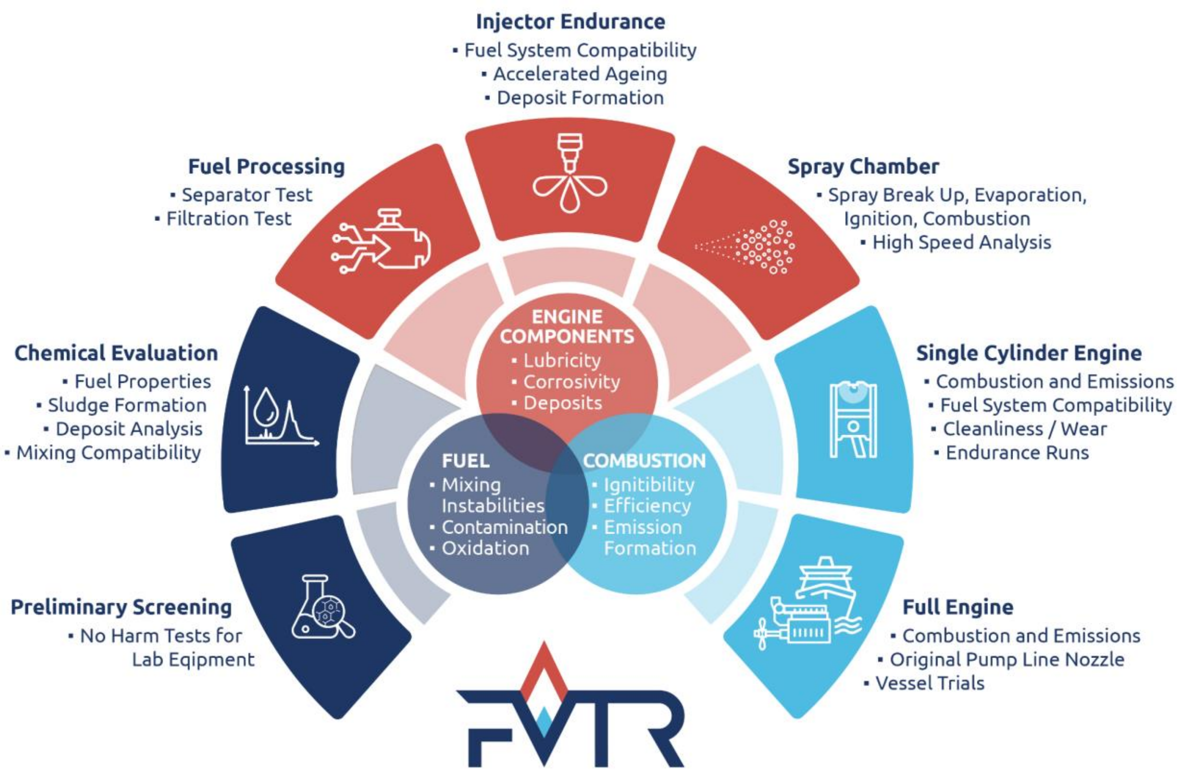


Figure 4: Compatibility issues and testing methodology for bio-oils and blends

These areas of compatibility are analyzed in a testing methodology that incorporates laboratory tests, component tests and engine tests and vary in its scope from straight forward practical orientation to a more academic focus.

2.1. Laboratory testing

ISO 8217 is meant to give minimum guarantee to ship owners that the fuel is suitable for engine use. In the case of new bio feedstocks and biofuels, the basic values of the ISO 8217 are not sufficient since the possible problems are of different nature. Therefore, additional testing or even developing new test methods seem necessary to overcome the challenges. Additional important parameters for the evaluation of biofuels are oxidative, thermal and mixing stability. In the case of oxidation and thermal stability, the aim is to examine how the fuels may change in the presence of oxygen or at higher temperatures. Oxygenated species could be formed when oxygen is incorporated. These oxygenated species can increase the acid number, i.e. the corrosiveness of the fuel, or polymerize. Biofuels are to be used primarily as drop-in fuels, so the mixing compatibility with conventional and alternative fuels must also be tested. These tests provide information on which fuels and in which ratios may exhibit mixing instabilities or whether reactions can occur between the fuels. The influence that water can have on the fuel being tested is also important here. In addition, tests and methods are also being developed to investigate the interactions of new fuels with lubricating oils.

2.2. Purifier and injection test rig

In this stage the fuel is tested for its compatibility during the fuel handling process. Significant amounts of fuel can be lost in the separator and effort is spend on the separator operation, sludge disposal and maintenance and repair in case of a clogging of separator and subsequent filters due to excessive sludge. Especially biofuels exhibit reactions with water from the separator. This happens in purifier mode due to the liquid interface but also in clarifier mode as water is often used for automatic flushing of the bowl, which can lead to deterioration and alteration of the fuel.

The separator test bench was originally created to answer a customer's request for reproducible and realistic determination of a fuel's sludge formation tendency. The test bench is a good representation of an onboard fuel handling system and features the following main components:

- Tilted barrel representing a settling tank
- Elwa electric fuel heater
- Krohne Coriolis for exact measurement of separator flowrate
- Alpha Laval MIB 503 manual separator
- Boll Filter with different mesh sizes

The testing procedure is chosen to represent the stressing and ageing of a fuel on a vessel by including phases of heating, settling and stirring. Boundary conditions of the procedure can be set very accurately by the use of an electric heater and the Coriolis flow rate measurement.

The manual separator used in the setup has a lower rotational speed compared to large automatic separators, which is compensated by a lower feed rate and therefore a longer retention time in the centrifuge. This is outweighed however, by the small size allowing small fuel quantities and the manual emptying of the bowl allowing very accurate determination of the sludge content.

The fuel handling test bench is accompanied by a common rail injection system test rig, consisting of high-pressure pumps, rails and injectors of different sizes depending on the system to be tested. On this test bench the injector can be operated at increased injection rates, simulating an engine endurance run. Fuels that are suspected to cause deposits and wear to the injection equipment at long operation durations are ideally tested on this rig instead of the engine to reduce testing costs.

2.3. Research engine test rigs

After passing all prior tests, a final proof of usability is the engine test. Here, different options from single cylinder research engine (SCE) to full engine are possible, see Table 1.

A single-cylinder research engine (1VDS18/15CR) is used for comprehensive investigation of fuel 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 is representative for a maritime medium speed engine. The SCE offers many degrees of freedom regarding all aspects of engine operation:

- Fuel handling
- High pressure generation
- Injection settings (Common Rail)
- Charge air and engine back pressure

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 deterioration of the nozzles is more easily detected compared to a mechanical injection system.

The engine also allows limited duration endurance runs for testing the impact of the fuel and its additives on different engine parts (auxiliary, FIE and power unit) regarding wear and cleanliness. For this purpose, new parts can be installed prior to the test, run in and stressed. Afterwards all parts of interest are rated qualitatively using charts and quantitatively using laser scanning microscopy.

The test bed is equipped with a state-of-the-art pressure-trace indication system to calculate the rate of heat release and 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 engines loads, rail pressures and injection timing.

The final step of the fuel evaluation is a test on our full engine, a medium-speed marine research diesel engine. It's based on a Caterpillar MaK 6M20 engine block and power unit and coupled to an electric load unit, which can be tuned to allow engine operation in generator as well as in propeller mode. Apart from the injection system, which can be converted to a common rail system developed in house with support by L'Orange, all other components such as valve timing or turbocharger setup, for example, are identical to the serial production engine. Table 1 gives an overview of the engine's technical data. Combustion in all cylinders is evaluated using high speed pressure indication. Exhaust gas measuring equipment is installed to acquire the exhaust gas component concentrations and the filter smoke number (O_2, CO_2, CO, NO_X (NO + NO_2), SO_2, HC, FSN).

While the common rail system is quite useful for some test scenarios, in our case of biofuel testing, the pump-line-nozzle system is an insightful extension of the single cylinder engine with its common rail system. While the common rail system is better at detecting small changes of wear, the PLN system is more robust and the mostly used system in the field. So, this test will most closely resemble an actual field trial.

Table 1: Specification of test engines

Unit	Single Cylinder Engine	Full Engine
Engine ID	1 VDS 18/15 CR	Caterpillar MaK 6M20
Charging system	Externally charged	Turbo charger
Engine type	4-stroke	Straight six cylinder 4-stroke
Stroke / mm	180	300
Bore / mm	150	200
Compression ratio	13 (15, 16)	14.8
Rated power / kW	80	1020
Rated speed / min^{-1}	1500	1000
Fuel injection system	Common Rail, HFO capable	Pump-Line-Nozzle, HFO capable (Common Rail, distillate fuel only)

3. Results and discussion

3.1. Fuel overview and lab tests

Different candidates of CNSL and cashew-based derivates were already tested with our methodology. These bio-oils are technical, hydrotreated, distilled and refined CNSL as well as oils derived by pyrolysis processes from the cashew material. For this study five different cashew-based fuels and blends thereof are used:

CNSL base-fuels

- Technical CNSL
- Refined CNSL
- Distilled CNSL
- Hydrotreated CNSL
- Pyrolysis oil from a Cashew feedstock

The initial testing of new fuels is carried out in accordance with ISO 8217, whereby the standard parameters are determined and tested for conformity to standards. Selected results of the tests are shown in Table 2.

Table 2: Basic characterization of various cashew-based bio-oils

CNSL type	Viscosity at 50°C [mm²/s]	TAN [mgKOH/g]	K [ppm]	S [ppm]
Technical CNSL	38.21	8.3	200	120
Low-refined CNSL	35.86	8.1	33	250
Distilled CNSL	6.584	2.2	14	6
Hydrotreated CNSL	13.14	0.4	11	18
Pyrolysis oil	8.795	0.3	12	88

The viscosity of the technical and low-refined CNSL is high compared to the other three grades. The viscosity can be significantly reduced by any additional processing step. The same effect can be observed with the acid values. The technical and low-refined CNSL have very high acid numbers (limit value < 2.5 mgKOH/g) and thus limit the highest possible blend rate to < 30%. If the acid values of the fuels are too high, this can lead to corrosion of metallic components in the system. However, if the CNSL is further processed, whether by distillation, hydrotreatment or gained by alternative processes, such as pyrolysis, the limit value of the acid number parameter can be adhered to and the blend rate is therefore not limited.

It is also noticeable that the potassium content of the technical CNSL is very high. The high potassium content can, for example, lead to increased post-combustion deposits. The remaining CNSL grades have significantly lower potassium values. Therefore, a further processing step of the technical CNSL is mandatory for reducing the potassium content. The lower sulphur content of all CNSL samples should be positively highlighted here. The technical and low-refined CNSL have a rather high sulphur content compared to the other three candidates. However, this value is well below the sulphur limits. This means that blending bio-oils with conventional heavy fuel oil alone could reduce the sulphur content.

GC-MS measurements have also been carried out (data not shown). This technique allows the determination of organic chemical composition of CNSL fuels to a certain extent. The main components have been identified for technical, refined and distilled CNSL. For the hydrotreated CNSL and the pyrolysis oil, significantly more signals or compounds were detected. For the hydrotreated CNSL partially and fully hydrogenated main compounds are identified as well. For the pyrolysis oil the main components (see figure 3) are not present at all, mainly smaller molecules are identified.

Of course, the goal in fuel testing is to be able to stop using engine and component tests and replace them with cheaper and faster laboratory test methods. For newly developed fuels, however, it might be insufficient to test strictly according to the normed procedures. Failure scenarios of these fuels, as experienced in the field or on our test engines, might be specific to the fuel and therefore require specialized methods for detection and quantification. In these cases, our experts have developed new or modified test methods in many customers and public projects to help analyze test fuels. Examples of this are outlined in the following paragraphs.

Water emulsification test – simulation of purifier system

Heavy oils are pre-cleaned in a purifier system where they are exposed to water and higher temperatures. Some biofuels are not stable in the presence of water or high temperatures (acid or sludge formation). A laboratory test for the behavior of the fuels in the purifier system was developed to make it easy to understand these processes. This involves adding water to the fuel, mixing the fuel and water phases sufficiently and then centrifuging them. The results of these tests are shown in Figure 5.

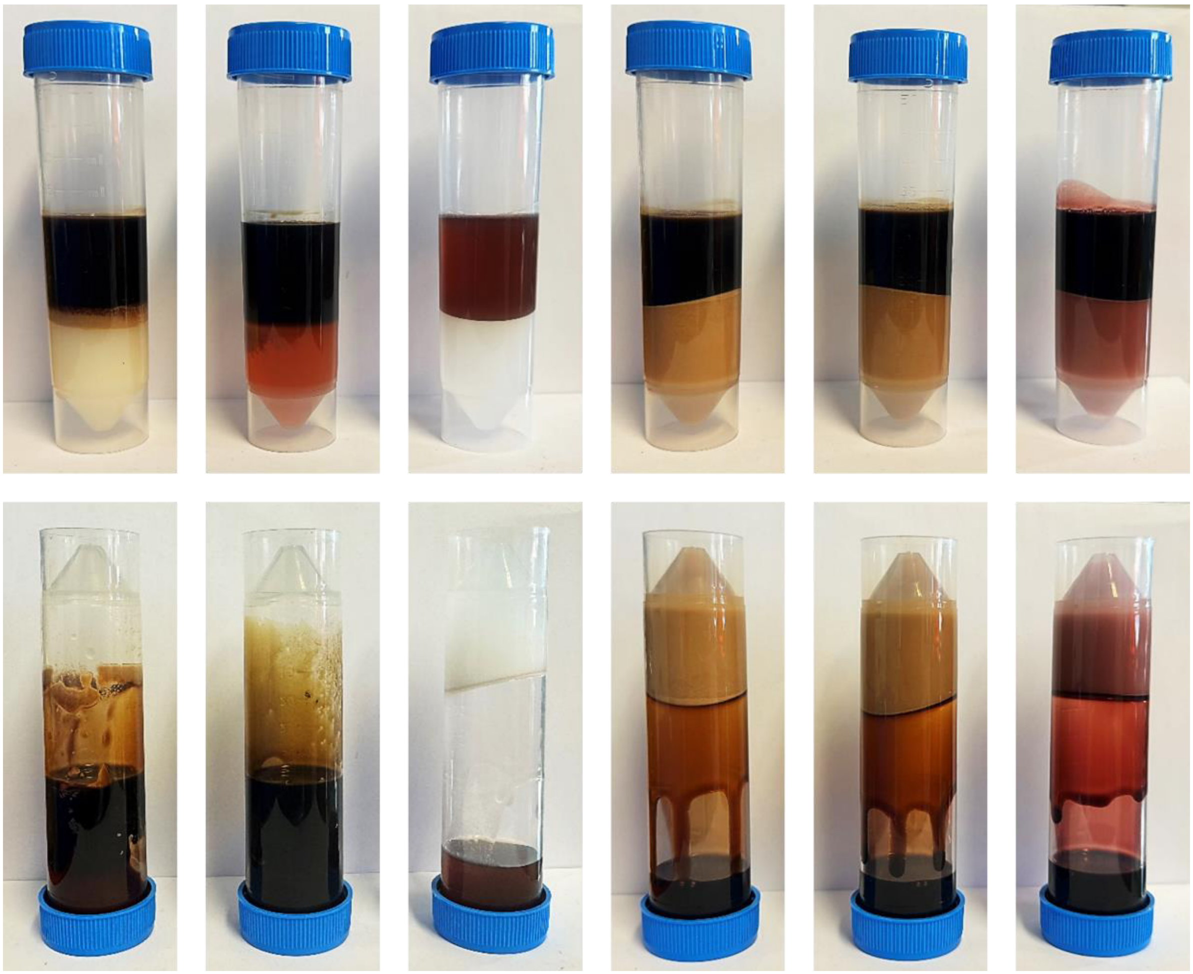


Figure 5: Water emulsification tests (left to right: technical, pyrolysis, distilled, refined, low-refined, hydrotreated CNSL)

By centrifuging the samples, the aqueous (bottom) and fuel phases (top) are separated. To check the extent of sludge or gel formation, the sample containers can be turned upside down. The figure shows that five of the CNSL fuels tested exhibit sludge formation. Only the pyrolysis oil shows no sludge formation. It has not yet been possible to clearly determine which compounds are responsible for this behavior. If these results are compared with the GC-MS measurements, it is noticeable that the pyrolysis oil is the only one that does not contain any of the basic structures of the technical CNSL already described. This suggests that the CNSL basic components could cause this behavior.

Thermal stability test – “Hot slope”

In an effort to evaluate the injector coking potential in a laboratory scale, the “hot slope” test was designed. The test addresses the processes in the injection nozzle: After an injection, fuel remains in the sac hole until the next cycle. Draining of the sac hole through the injection orifices depends on the fuel's viscosity and surface tension. The remaining fuel has a long time to heat up to the nozzle temperature especially during the combustion phase. A part of the fuel proceeds to evaporate through the injection orifices, leaving behind heavier, longer chained fuel compounds. Thermal stress can then lead to cracking and polymerization of the fuel. Depending on the fuel, this process can leave residues which have different tendencies to be washed away and solved during the next injection or adhere to the nozzle steel and start building up firm deposits.

This process chain of heating, evaporation and resolving was combined in a test by periodically dripping fuel on a heated, sloped metal surface. This slope is heated by an underlying copper block fitted with heating cartridges. In the current CNSL tests the temperatures were varied between 230 and 310°C. Aluminium sheets were used for the slope material. A total of 10 drops of fuel were dripped onto the slope periodically every 15 seconds forming a runnel on the slope. After another 15 seconds the remaining liquid film was removed using a paper swipe. Depending on the slope temperature and the fluid characteristics a deposit was formed on the sheet metal which was rated based on its appearance. In further tests a subsequent lab analysis is intended with the aim to determine the chemical composition of the deposits.

The results for the cashew-based fuels at two slope temperatures are presented in Figure 6. The temperatures of 270 °C and 290 °C were chosen for the comparison. At 270 °C the technical and refined CNSL start to develop a discoloration on the slope. On the sides of the runnel some fuel components can be observed during the test to concentrate and start solidifying. However, these accumulating components are almost completely washed away with the subsequent drop of fuel. At 290 °C the time between the droplets is enough to allow the formation of solid deposits. In the middle of the runnel the mentioned washing effect is still active and has a visible impact on the shape of the deposits.

For the distilled CNSL the main fuel components responsible for the deposits have clearly been removed or at least reduced. Thus, almost no discoloration is seen at 270 °C. At 290 °C an accumulation on the sides of the runnel, similar to the previously described, is starting to form. Even at 310 °C the washing effect still reduces the amount of deposits in the middle of the runnel.

The hydrotreated CNSL does not form any deposits up to a temperature of 310 °C where a slight discoloration remains on the aluminium.

The pyrolysis oil starts forming discolorations at 270 °C. But unlike technical and refined CNSL the washing effect in the middle of the runnel limits the amount of deposits at 290 °C. Similar to the distilled CNSL, at 310 °C there is still a washing effect noticeable.

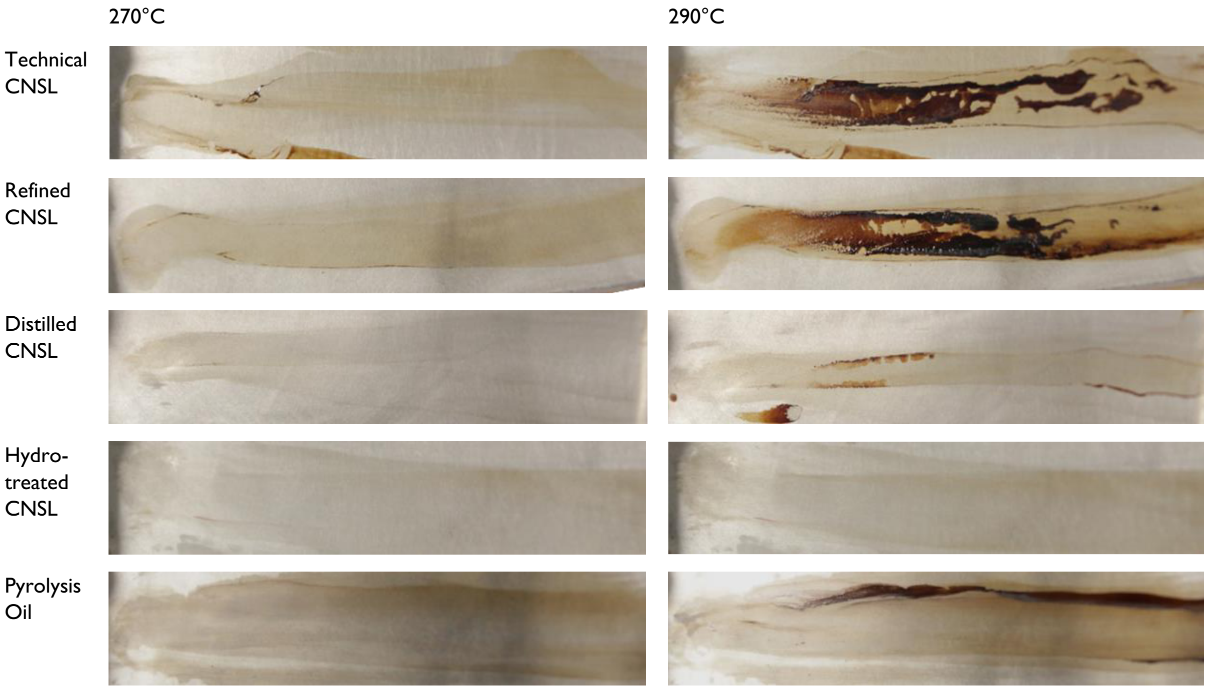


Figure 6: Resulting deposits from the hot slope test for two test temperatures

3.2. CNSL in the fuel system

For different cashew nut derived bio-oils so far, no issues regarding mixing compatibility were encountered. Heating the different blends up to typical temperatures of residual oil showed no problems, either. Therefore, the next critical step is the fuel treatment system on the vessel in term of purification.

Operating a purifier with raw or refined CNSL may cause a “gelification” of the fuel, which leads to massive sludge production on a vessel. This effect is reproduceable in the lab and was found to be caused by the interaction of the fuel with the purifier’s water seal, thereby fusing all fuel components and water into a sludge-like gel. As one measure, the purifier might be operated in clarifier mode – if technically possible. This minimizes possible contact of the CNSL and water. However, even in clarifier mode some water might be present in the bowl as leftover from the automatic flushing procedure, leading to the same effect as the water seal.

Another aspect is painting and coating. Compatibility with the desired blend might be tested prior to operating. During our testing, the coating was partly damaged first and came off completely in a follow-up test. According to the manufacturer, this should not have any influence on the purifier performance.

Nonetheless, when operated with the correct conditions, particles from the production process of the cashew nut-based bio-blends and impurities are removed securely, thus facilitating further operation.

3.3. Combustion of CNSL

Single Cylinder Research Engine

Compared to a full engine, the single cylinder engine (SCE) offers much more flexibility in terms of boundary conditions. Using the Common Rail system, injection pressure as well as injection timing can be modified to optimize combustion behavior and enable operability of a vast variety of fuels.

With respect to bio-oils that would likely enter the market as drop-in fuels for fuel blends, engine operating parameters need to stay the same since an adaptation of the combustion strategy is far beyond engine operation on a vessel.

Therefore, engine operation of the SCE is started with the standard set of injection and engine operation parameters to comply with IMO Tier II limits. Regarding operability and engine safety, injection pressure and injection timing might be modified – but that is a test rig measure only.

Using the different blends at the test engines, several metrics were identified for indicating a "good" or a "poor" blend in terms of operability. Mostly, these metrics react to the quality of combustion which depends on fuel evaporation and spray quality. A bad combustion therefore shows increased CO emissions as well as an increased filter smoke number (FSN) due to incomplete combustion. This also reduces the NOx emissions due to decreasing efficiency (or increased SFOC). In case of CNSL operation, the cause for these symptoms are deposits on the inside or outside of the injector nozzle, either blocking the spray holes or interfering with the spray and thereby causing its low quality. In case of a CR system as on the SCE, the partial blocking leads to increased injection duration and therefore a shift of the center of combustion (CoC) in direction "late".

Figure 7 and Figure 8 show one bio-blend with good and one with poor operability. The engine was run consecutively at four load point. For some load points the rail pressure is also varied. The order of the load point is not of importance. The most striking marker for the degradation of the nozzle and the spray quality is the highly fluctuating CO emission in Figure 8. This can be observed to spike periodically. It is believed that these spikes correspond to the buildup and recovery of nozzle deposits which directly affect the spray quality. The center of combustion and the injection duration fluctuate roughly in accordance with the CO emissions; however, the changes are less obvious.

Comparing different blends from different bio-oils including different base fuels, the picture becomes even more complicated. Figure 9 shows test results including a reference VLSFO, marking the state-of-the-art fuel nowadays. There are combinations that seem to work well. So, technical CNSL seems to work in a larger range of admixture with distillate fuels. Since temperature is the critical point here, residual oil-based blends that need intensive pre-heating for proper injection viscosity, a direct use for engine operation leads to deposit formation.

The most interesting parameters evaluating the suitability of the different bio-oil blends in the engine test are presented in Figure 9. The pressure gradient is an indicator for the ignition delay. The worse the blend is in terms of this parameter, the harder is the combustion and may affect lifetime of the engine components. With a lower energy content of the blend an increasing injection duration occurs. But injection duration also increases with deposits in the nozzle since the narrowing causes lower flowrates at a set fuel pressure. This lower injection rate also causes a shift in the center of combustion.

The worsened spray quality is responsible for the worsened combustion which is visible in the CO signal as well as in the Filter Smoke Number. If corrected for the energy content of the blends, the injection duration is a good indicator for operability in a CR based injection system. For a poor blend which already created deposits and therefore a bad spray with a bad combustion, the maximum pressure gradient also increases. The larger droplets need more time for evaporation which adds to the physical ignition delay and results in larger premixed shares of the combustion. At low loads, the complete combustion might take place as premixed combustion due to this effect.

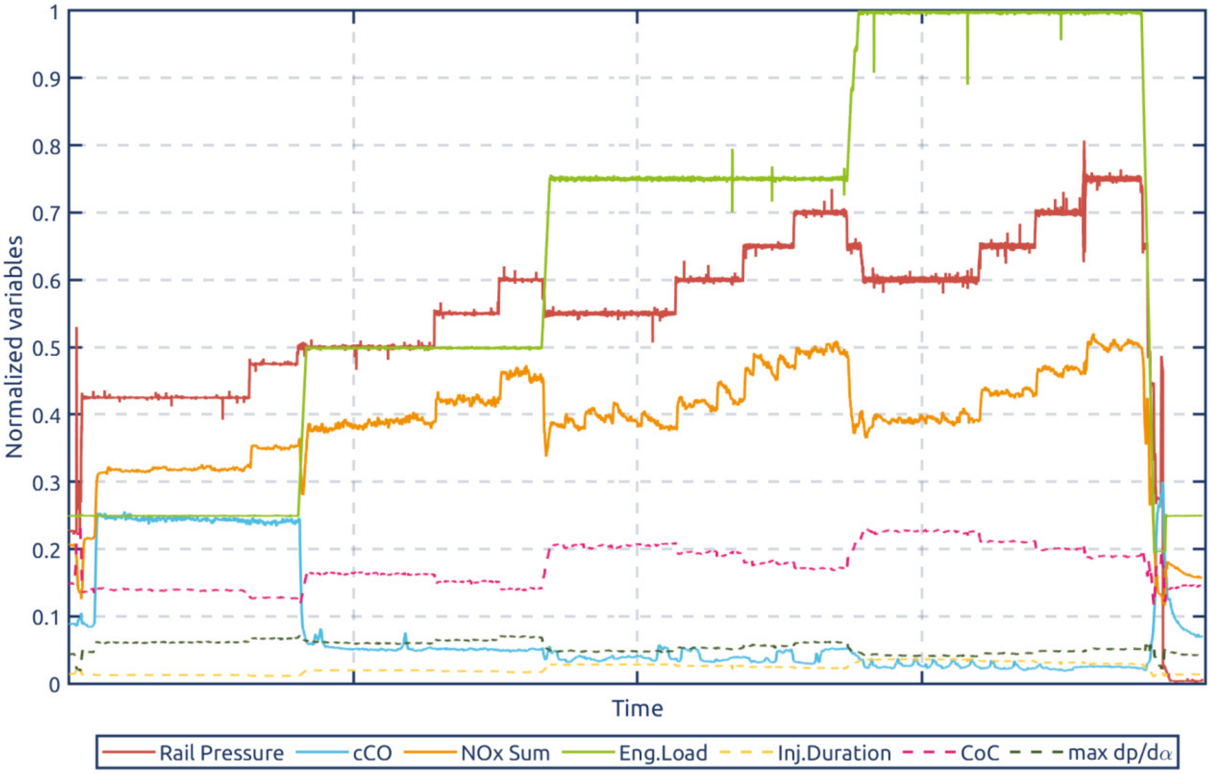


Figure 7: Test run with a promising bio-oil blend

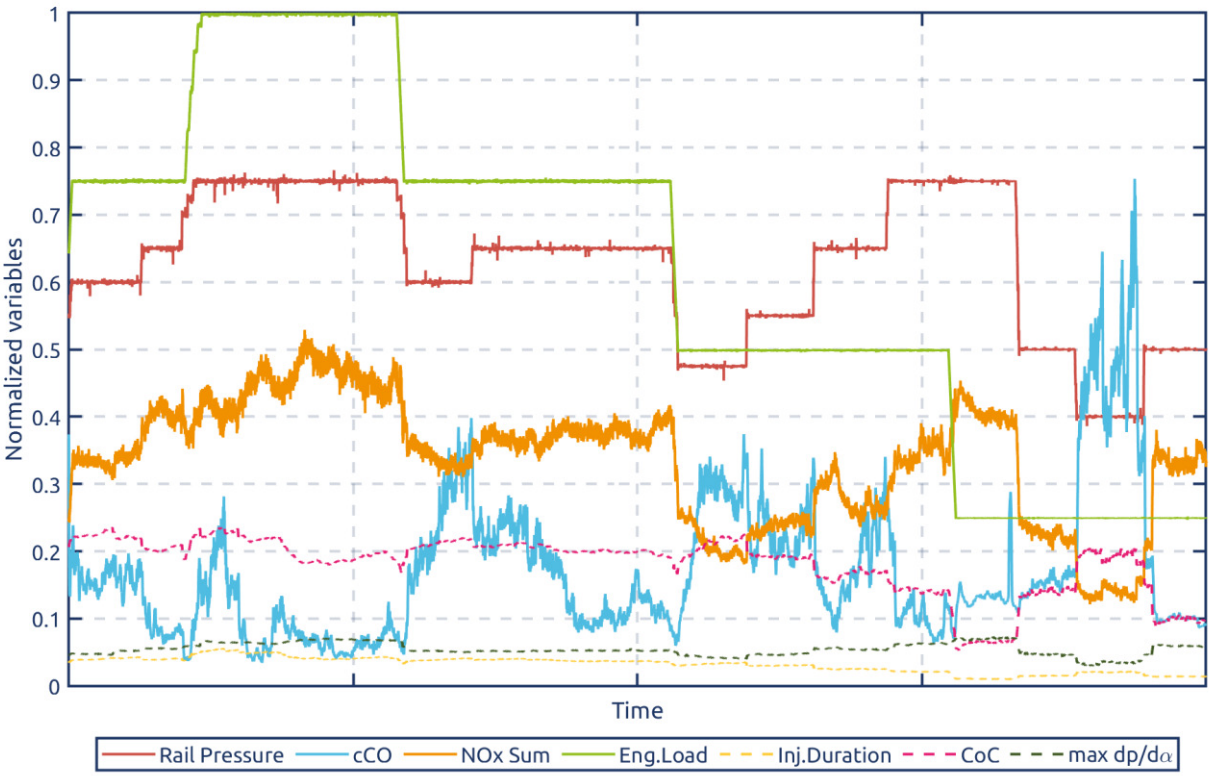


Figure 8: Test run with a problematic bio-oil blend

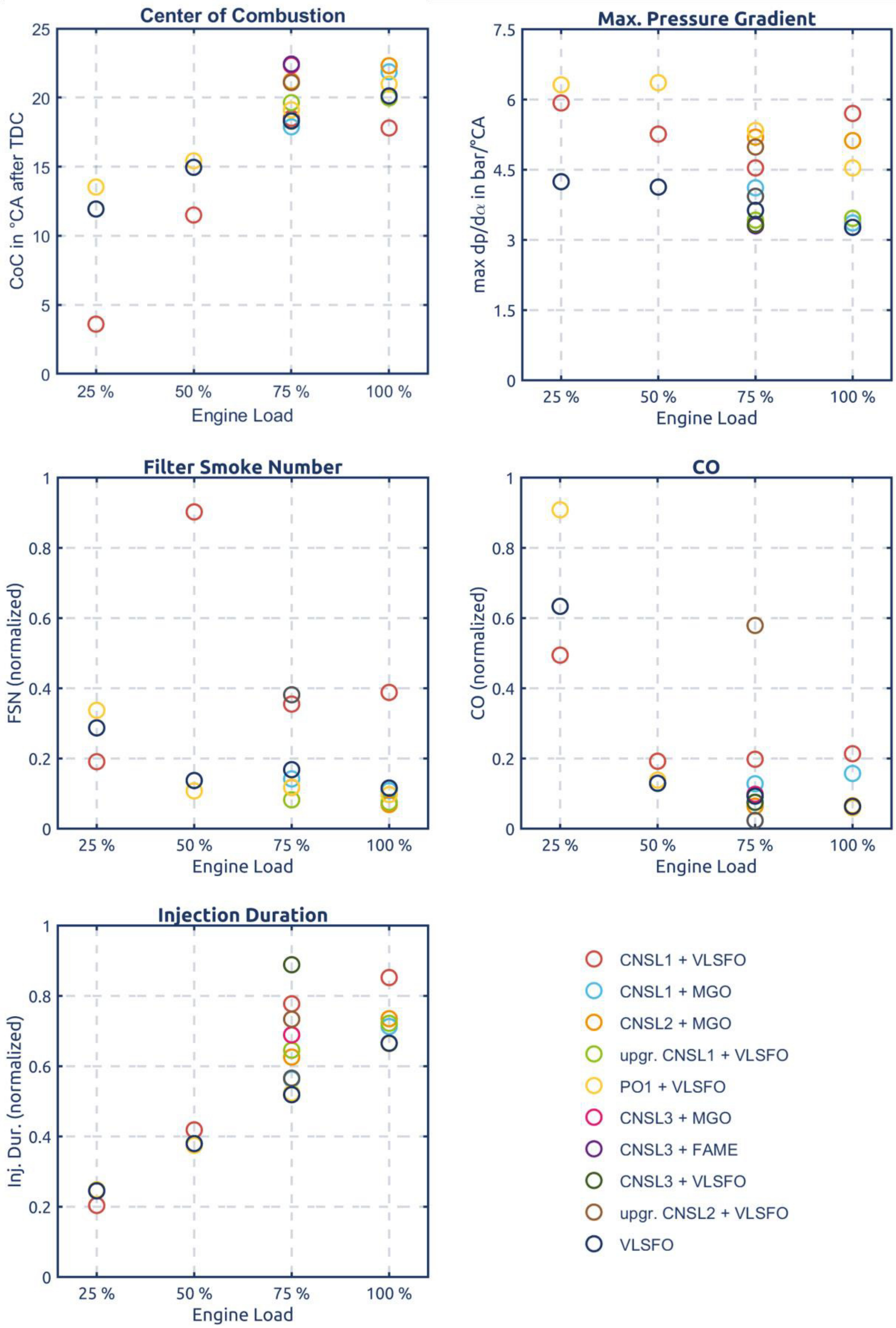


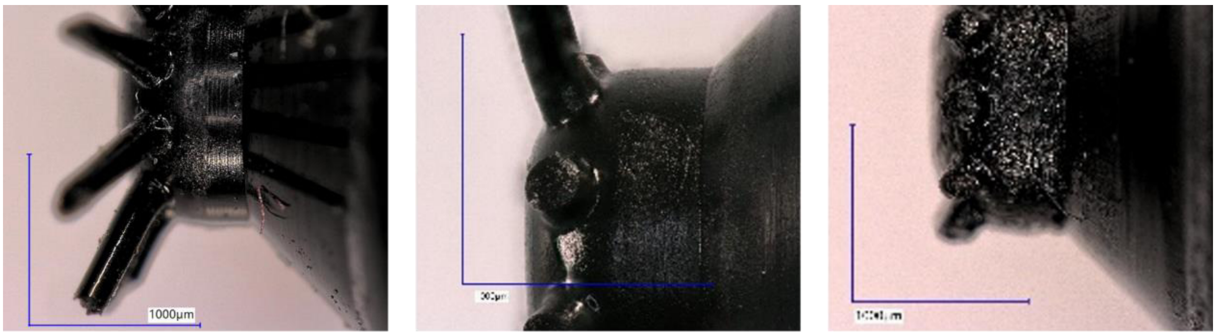
Figure 9: Comparison of engine parameters for different bio blends

In some tests with VLSFO-blends, external deposits are formed which are much firmer than typical nozzle coking from residual fuels (sometimes called “trumpets”). These external deposits can quickly deteriorate the fuel spray quality by causing larger droplet size and smaller spray angle. The external deposits however, vary in density and hardness. Figure 10 shows clearly visible deposits on the outer nozzle tip. In this case wide-opened “trumpets” are formed as the impulse of the fuel spray breaks its way through the deposits. Despite the impressive deposit formation, the corresponding test run was successful.

(a) (b)

Figure 10: (a) Nozzle tip after testing; (b) Nozzle, needle, inner parts: all clean using a proper working blend

Figure 11 shows imprints of the injector nozzle. The reference VLSFO as well as “good” blends in terms of operability show no marks of deposits in the sac hole nor the spray holes. Steady operation is the result, whilst for unsuitable blends the deposit marks inside the nozzle are clearly visible.



(a) (b) (c)

Figure 11: Nozzle imprints after test run with (a) Reference VLSFO, (b) a suitable bio blend and (c) a bio blend hard to operate

Full engine MaK 6M20

In case of the full engine MaK 6M20, the pump-line-nozzle injection system shows a different behavior. The injection pump is working mechanically and partial blocking or a higher resistance in the injector simply leads to pressure upbuild. Consequently, this allows better spray evaporation due to the better (smaller) droplet size of the fuel. In combination with oil-cooled nozzles, the risk of inner deposits is minimized as can be seen in Figure 12 (b) although the injector already shows deposits on the outside.

Figure 12 (c) shows a view via the injector port into the cylinder. There are deposits on the lower side of the cylinder head visible. If growing further, they might also influence the fuel spray and therefore the combustion quality. Despite these deposits one week of operation on a distillate based CNSL blend was possible.

(a) (b) (c)

Figure 12: (a) Massive coking on nozzle tip; (b) Still good state of nozzle interior; (c) Large deposits on the underside of the cylinder head in all cylinders

As a pre-cursor, again CO concentration as well as FSN can be used. Since injection duration stays constant with the mechanical injection pump, the maximum injection pressure (which increases in case of blocking in the injector) is an indicator for the onset of deposit formation.

Contrary to the SCE's CR injection system the PLN injection systems in combination with oil-cooled nozzles show a more robust behavior. The effect of deposits on the combustion was much less noticeable compared to the more sensible SCE testing. One reason for this might be the brute force injection pump pressing the fuel through the hp fuel line and the injection valve. With narrowing spray holes, the back pressure of the nozzle increases and leads to an increasing injection peak pressure. The additional stress that is caused by this for the fuel itself but also for the material of the injection system components must be considered.

4. Conclusion

The integration of renewable energy sources in marine fuels is approaching fast. As many alternative fuels require extensive infrastructural changes, currently the best option is the usage of drop-in capable biofuels. Driven by legislative pressure, previously unconsidered bio-feedstocks are entering the market. However, switching to a fuel with bio content is not straightforward. Current standards fail to guarantee operability with such fluids, as many potential issues are not covered by the required test methods.

The ultimate proof of usability of a fuel candidate is achieved through long-term engine tests that assess both performance and the condition of the engine components and peripheral systems. To minimize the risk for these long-term tests, preliminary laboratory and engine testing provides valuable support in introducing new fuel components. FVTR's methodology addresses most critical aspects of a marine fuel system, from the bunkering process to engine operation and combustion. This way, issues and potential solutions are identified early, avoiding critical situations at sea.

For cashew nut-derived biofuels, several critical scenarios have been identified in our labs. These are caused by the high temperature of fuel-contacting components as well as processing procedures like the fuel purification. In our tests, various bio-blends from the CNSL candidates and conventional base fuels could be identified that are fit for long term sea trials. Particularly promising is the use of distillate bases, which seem to work well with most CNSL products over a wide blending range. The promising hydrotreated CNSL failed in a VLSFO blend in the engine test, a result that does not correlate with preliminary test methods. It was not tested with distillates as base fuels yet. The distilled CNSL and the pyrolysis oil are the only candidates that could be used in blends with residual fuels. This result correlates well with the deposit tendencies indicated by the hot slope test. In general, although care must be taken regarding feed stock quality and blend partners, our results encourage the further development of cashew nut related feedstocks as drop-in fuels.

In the future, our insights into bio-oils and their specific challenges for safe use in marine engines will help us develop rapid, standardizable testing methods that align and extend existing protocols. By serving the maritime industry with these advanced tools, we aim to support the successful transition to sustainable energy solutions.

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