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Fuel Flexible Injetion System - How to Handle a Fuel Spectrum from Diesel-Like Fuels to Alcohols

11 - Basic Research & Advanced Engineering - Technologies, Materials & Tools for Future Engines

Paper 404

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ABSTRACT

The marine industry faces interesting times as the desire for reduced Green House Gas emissions rises. In parallel the global sulphur cap will become active in 2020. The newest LNG-powered, low pressure gas engines are an interesting option for ship owners. Nevertheless, as not an LNG installation is available yet for, liquid fuels still play a major role in merchant shipping industry. Large marine two-stroke engines for the propulsion of merchant vessels are nowadays powered with classic fuels such as Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), Marine Gasoil (MGO) or a similar, convenient distillate waste stream. The “Global Sulphur Cap” in 2020 (GSC2020) or the ongoing discussions about Black Carbon have the potential to change this.

With the GSC2020 for example, the sulphur content of any sea-going fuel will be limited to 0.5% - worldwide. This will give room for alternative fuels. For todays’ shipping sector though alcohols are interesting only in very special cases, as their availability and price are not yet competitive enough. For WinGD however, they represent one end of a broad spectrum of fuel possibilities. An injection system capable of injecting both classic fuels like HFO or MDO as well as low viscosity fuels with drastically reduced energy densities like ethanol and methanol, should be able to cover a large portion of possible fuel candidates.

Work Package 1 of the European Union’s HERCULES-2 project had the objective “To develop engines able to switch between fuels, whilst operating in the most cost-effective way and complying with the regulations in all sailing regions”. Between 2015 and 2018 such a system has been developed and first results were shown at the ICLASS conference 2018 in Chicago.
To do so an injection concept was developed and evaluated with different tools: On an injection rig the hydraulic performance was captured. Spray morphology and combustion performance were assessed in WinGD’s Constant Volume Chamber “SCC“ in order to understand the processes and interrelationships within the engine’s combustion chamber. Finally, WinGD’s test engine RTX-6 was equipped with such an injection system and was used to burn ethanol and diesel fuel as two representatives of a broad fuel spectrum.

Among different other results, the engine tests will be discussed in this paper. Rate of heat release looks promising and for the fuel consumption and efficiency interesting results could be accomplished. The injector design proved a good repeatability and a stable spray pattern.

WinGD has now a prototype system with which to investigate new fuels and to offer the possibility to develop a fuel system which can be tailored to the needs of the customer for their specific fuels.

1 INTRODUCTION

The ideal choice of fuel for large two-stroke engine applications will become increasingly complicated. While these engines have been traditionally operated with distillate waste stream fuels such as Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO), the number of gas engine installations is increasing significantly. The increasingly stringent emission regulations and the need to reduce greenhouse gas emissions could make the use of alternative fuels a feasible option. With the “Global Sulfur Cap” in 2020 (GSC2020) for example, the sulphur content of any sea-going fuel will be limited to 0.5% - worldwide [1].

A wide range of alternative fuels and technologies could be used. However, as of now, no single fuel has been identified that could replace the diesel fuels [2]. Therefore, the objective of the work package 1 [3] of the European Union’s HERCULES-2 project was “To develop engines able to switch between fuels, whilst operating the most cost-effective way and complying with the regulations in all sailing regions”. The results of this project shall be described in the following.

So far, alcohols are not widely used in marine applications due to their limited availability, high prices and low energy density. For WinGD, however, they represent the one end of a broad spectrum of fuel possibilities. An injection system capable of injecting both classic fuels like HFO or MDO as well as low viscosity fuels with drastically reduced energy densities like ethanol and methanol, should be able to cover a large portion of possible fuel candidates.

The requirements for such a fuel flexible injection (FFI) system are wide-ranging. The energy density of alcohols is approximately half of traditional marine fuels. Using the same injection system as for traditional fuels would yield very long injection durations. Moreover, due to the very low lubricity of alcohols, the long-term reliability of moving parts is a challenge. Also, the span of kinematic viscosity is very wide with values of 1 cSt to over 700 cSt at 50 °C. [4] Consequently, a completely new injection system had to be developed.

To overcome the challenge regarding the difference in energy density, the idea of the new system is an injector with a variable flow area. The needle can be positioned at three different levels as shown in Figure 1.

1. Needle closed: All orifices are closed by the needle.
2. Medium lift: The needle opens the lower row of orifices. This level can be used to inject traditional fuels with a higher energy density.
3. Full lift: The second row of spray orifices is opened, thus increasing the injection rate and allowing the use of fuel with low energy density.

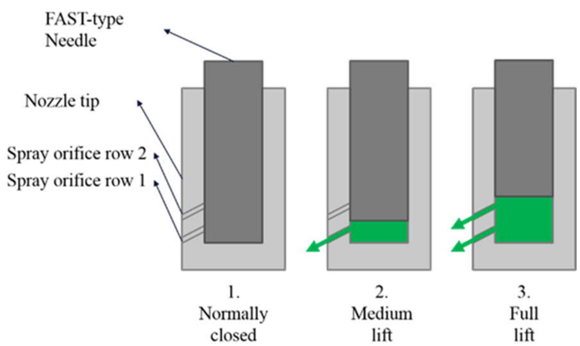


Figure 1. Needle Lift Concept [4]

Between 2015 and 2018 such a prototype system has been developed at WinGD and first results were shown at the ICLASS conference 2018 in Chicago [4]. To do so, an injection concept was evaluated with different tools and tested on an injection rig to capture its hydraulic performance. Spray morphology and combustion performance were assessed in WinGD’s Spray Combustion Chamber to understand the processes and interrelationships in the combustion chamber. Finally, the test engine RTX-6 was equipped with the new system and was used to burn ethanol and diesel fuel as two representatives of a broad fuel spectrum.

2 EXPERIMENTAL SETUP

2.1 Spray Combustion Chamber

Investigations regarding spray morphology have been performed in the Spray Combustion Chamber (SCC). In the SCC, engine like conditions can be set as initial conditions. By means of optical, pressure and temperature measurements, the spray and the combustion can be studied.

To investigate fuels like ethanol with very limited self-ignition qualities, an ignition source is necessary to stabilize combustion. Therefore, a second injector – pilot injector - was installed and used to inject a small amount of diesel that self-ignites. The diesel flame is carried by the swirl flow to the fuel flexible injector. The alternative fuel injected by the fuel flexible injector is then ignited by the diesel flame. The setup is shown in Figure 2.

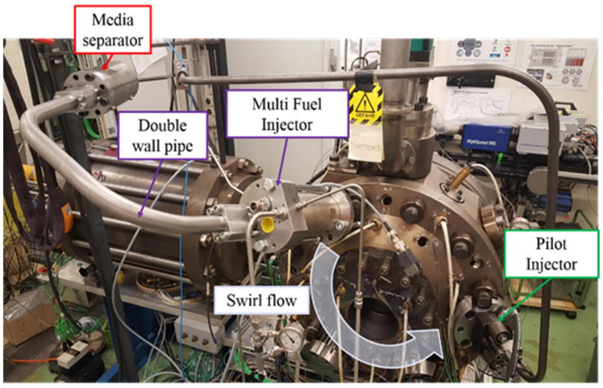
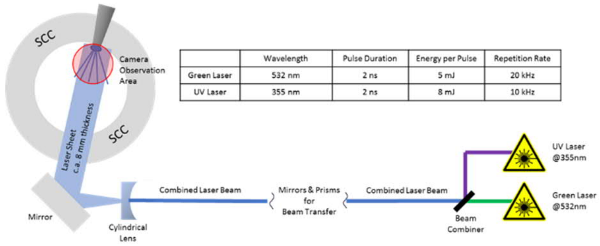


Figure 2. Setup of Spray Combustion Chamber [4]

2.1.1 Optical Setup

The optical setup has been described in detail in [4]. The goal was to gather information on the spray, the ignition as well as the combustion characteristics of the different fuels. Therefore, three different measurement techniques have been applied: Two laser based techniques and one passive technique.

The liquid phase was investigated with Mie scattering using a green laser (532 nm). The flame was detected with OH*-chemiluminescence while Laser Induced Fluorescence (LIF) was used to detect formaldehyde using a UV laser (355 nm). The two laser beams are combined to one beam and transferred via several mirrors to a cylindrical lens below the SCC main body. A mirror on the bottom of the SCC is used to direct the light sheets of green and UV light into the chamber and towards the spray tip as shown in Figure 3.



	Wavelength	Pulse Duration	Energy per Pulse	Repetition Rate
Green Laser	532 nm	2 ns	5 mJ	20 kHz
UV Laser	355 nm	2 ns	8 mJ	10 kHz

Figure 3. Laser Specification and Optical Alignment [4]

Three cameras were used to detect the light emitted from the combustion. One camera was used to record OH*-emissions and soot incandescence, another camera to detect formaldehyde while a third camera was used to record Mie scattering. The setup of the cameras and the according wavelengths are shown in Figure 4.

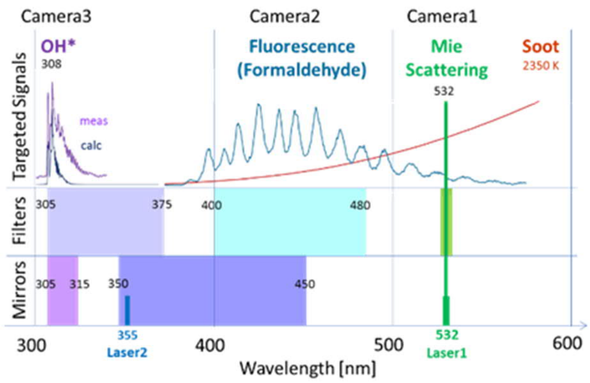


Figure 4. Targeted Optical Signals [4]

With this setup, it was possible to record and investigate the Start of Injection, Start of Combustion, ignition location and the spray penetration length. [4]

Additional changes were necessary for the fuel supply in order to operate the fuel flexible injector. To enable the injection of various alternative fuels, a media separator has been designed and installed onto the existing hydraulic system as shown in Figure 5. The common rail system provides the injection pressure which is then transferred onto the alternative fuel via the media separator.

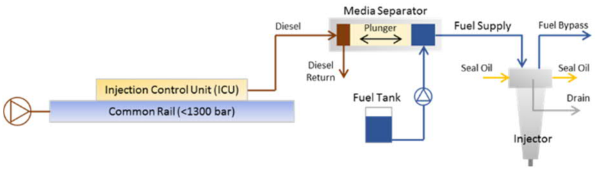


Figure 5. Fuel Supply Setup [4]

2.2 Injection Rig

The focus of the SCC was the investigation regarding the spray morphology and combustion. To test the hydraulic functionality of the injectors before the installation on the engine, a test rig for the injection system was built (Figure *6*).

The same hardware as on the test engine (see section 2.3) was used. The pump was used to feed the high-pressure fuel rail and the fuel flexible injectors. As fuels, ethanol as well as diesel were used.

Figure 6. Injection Rig

2.3 Test Engine

One objective of the HERCULES-2 project was to investigate the effect of an alternative fuel on the engine performance. Therefore, tests were carried out on the WinGD's research engine RTX-6.

Table 1. Specifications of RTX-6 Test Engine

Engine	RTX-6
Type	2-Stroke Diesel Engine
Number of cylinders	4
Bore	500 mm
Stroke	2250mm
Speed	105 rpm
Power	1624 kW/cyl.

The FFI-system was installed in addition to the conventional RT-flex diesel injection system as an independent second fuel system. Therefore, the engine could be operated with either one of the two injection systems alone or a combination of the two. This concept is not comparable to a commercial application. However, it enabled a wide range of investigations. On the one hand, it allowed for maximum flexibility regarding the sharing of diesel and alternative fuels. On the other hand, this created a safe environment to study the behaviour of the fuel flexible injection system as the engine could be switched to the RT-flex injection system during engine operation. The disadvantage of this approach was that the minimal fuel quantities for a pilot injection were much larger than for a dedicated pilot injection system.

The fuel system was made of stainless steel to be resistant against a variety of fuel candidates. A separate fuel pump housed outside the engine hall is used to feed the fuel from the tank to the engine. The design of the system is shown in Figure 7.

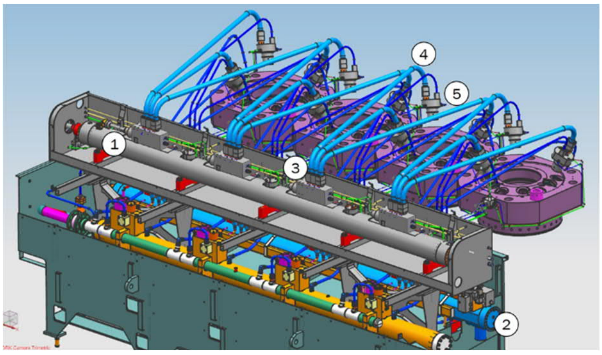


Figure 7. CAD Design of FFI on RTX-6 [5]

The high-pressure fuel rail for the alternative fuel (1) was situated on top of the gallery that houses the RT-flex rail for traditional fuels (2). From there the fuel was fed via the distribution block (3) through the double walled, high-pressure pipes (4) to the three fuel flexible injectors (5) per cylinder. [5]

The final setup on the engine is shown in Figure 8. For the FFI-system, the high-pressure fuel rail from the injection rig was used (red box). The setup does not represent a realistic solution for a commercial product. However, it allowed for a wide range of investigations which is necessary for a research application.

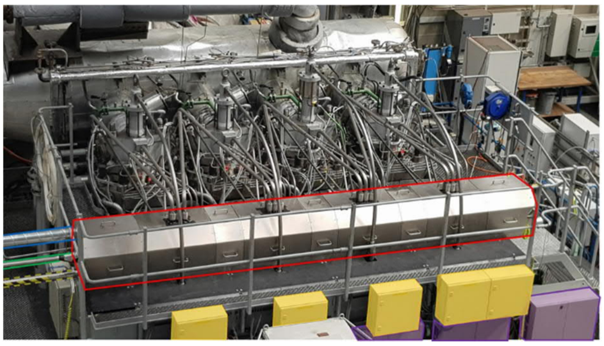


Figure 8. Overview of Installation on RTX-6 Test Engine [5]

In addition to the hardware changes on the engine, the engine control software needed to be adapted to allow operation with the FFI-system. The new control software allowed changing the timings of the three fuel flexible injectors as well as the RT-flex injectors which were used as pilot injectors. With this setup, a wide range of operating conditions could be investigated. The graphical user interface is shown in Figure 9.

Figure 9. Control Panel for Engine Operator [5]

2.4 Fuels

In the SCC, ethanol and methanol were used to investigate the spray morphology and ignition behaviour of the FFI-system. As a reference, Light Fuel Oil (LFO) was also used. On the engine, only LFO and ethanol were tested. Table 2 shows the properties of the tested fuels.

Table 2. Fuel Properties

Fuel	LFO	Ethanol	Methanol
Lower Heating Value [MJ/kg]	42.7	26.8	19.9
Auto-ignition temperature [°C]	210	365	470
Boiling Point [°C]	180-360	78.2	64.7
Heat of Vaporization at 1 bar [kJ/kg]	250	841	1089

The energy density of alcohols is much lower compared to traditional diesel fuels. This means that approximately twice the volume needs to be injected for the same energy as with diesel. To keep the injection duration constant regardless of the fuel used, the FFI-system uses a variable flow area.

The auto-ignition temperature of alcohols is higher than for diesel. This, in combination with the significantly higher heat of vaporization, will drastically affect the ignition delay. During the evaporation of the fuel, the charge is cooled significantly. Therefore, the time to reach the auto-ignition temperature increases. However, the lower boiling temperature of alcohols compared to diesel reduces the time to evaporate the fuel. [4]

3 RESULTS AND DISCUSSION

3.1 Spray Chamber

In order to gain first insight regarding the injection of ethanol and, thus, reduce engine testing time, the FFI-system was tested on the SCC. One target was to investigate the spray tip penetration to understand the interaction of the spray with either walls or spray from other injectors. Another target was to optimize the combustion. The results have been previously presented in [4].

3.1.1 Set Points

The initial conditions in the SCC were set to be representative of in-cylinder conditions of the RTX-6 at 25 % load. This way, the learnings could be directly applied to the engine test. At the start of injection, the pressure was set to 70 bar and the temperature to 900 K. The rail pressure was set to 950 bar.

3.1.2 Spray Tip Penetration

The spray tip penetration was measured by means of Mie scattering during the initial phase. After ignition, the flame was tracked by soot incandescence. A visualisation of the measurement process is shown in Figure 10.

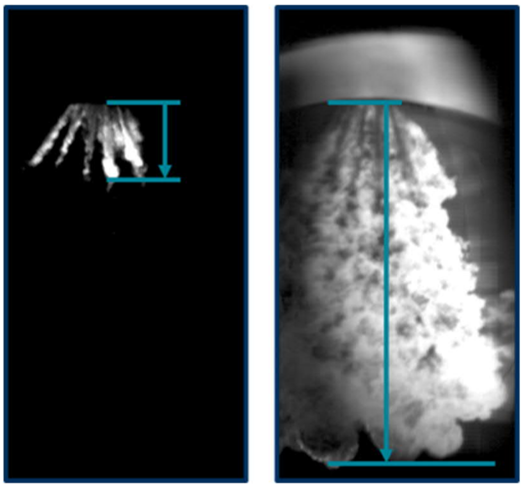


Figure 10. Visualisation of Spray Tip Measurement Before (Left) and After Combustion (Right) [4]

Shortly after the start of injection, the fuel is still liquid. The green laser illuminates the liquid phase. The result is shown in the left image. After ignition, the light visible is emitted from soot incandescence as shown in the right picture.

The penetration is measured and plotted over time as shown in Figure 11. The diesel fuel takes much longer to gain momentum compared to ethanol and methanol. While the reason for this behaviour is not fully understood, it is assumed that the in-nozzle flow is significantly influenced by the fuel properties, namely the compressibility. After the acceleration phase, the diesel spray reaches a similar propagating speed as the two other cases. By extrapolating the linear phase to zero, the secondary breakup and momentum of fuel can be estimated. [4]

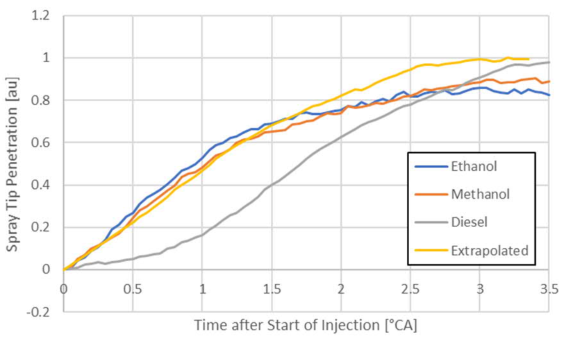


Figure 11. Spray Tip Penetration for Ethanol, Methanol and a Diesel Fuel Under Engine Relevant Conditions [4]

3.1.3 Thermodynamic Behaviour

One of the targets of the investigations on the SCC was to optimize the combustion. A diesel pilot injection was necessary to stabilize the combustion with ethanol. The ignition delay of ethanol for the investigated conditions was observed to reach values of up to 20 ms. However, the ignition delay is subject to strong cycle-to-cycle variations. Therefore, the injection timing of ethanol cannot be advanced on the engine to compensate for the ignition delay as cycles with very high pressure-peaks would be observed. These could potentially damage engine components. To stabilize the ethanol combustion, a diesel pilot injection was applied.

The diesel of the pilot injection self-ignites and, thus, creates a hot zone into which ethanol can be injected to ignite it. As shown in Figure 12, the pressure increase is faster with the alternative fuels compared to the diesel reference.

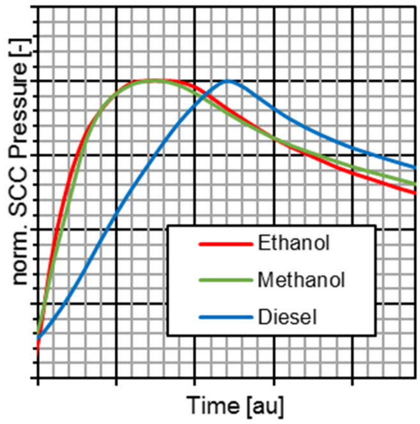


Figure 12. Pressure Trace for Three Different Fuels

The alternative fuel has been injected and evaporated. This fuel mixes with the air and combusts quickly when ignited by the diesel pilot. This can be seen in Figure 13. The alternative fuels have a high peak of the heat release in the initial phase due to the premixed combustion. Towards the end of the combustion, a long fade out region is observed for the alternative fuels. The diesel injection has a sharper end of the combustion. The influence of this is discussed in section 3.3.

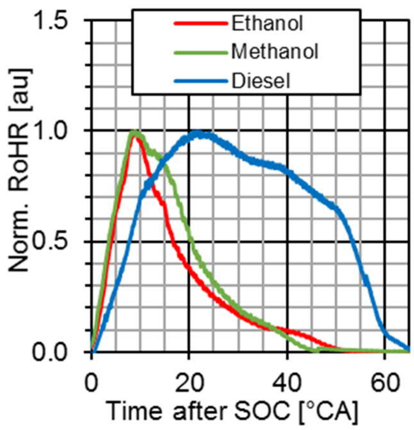


Figure 13. Rate of Heat Release for Three Different Fuels

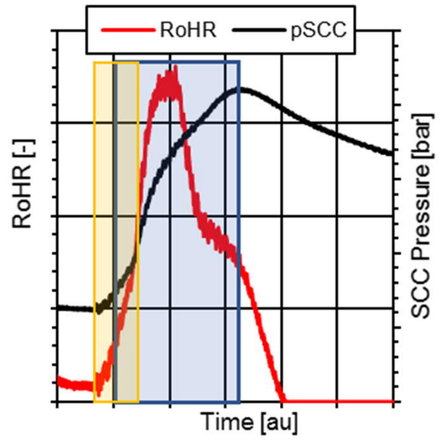


Figure 14. Pressure Traces and Rate of Heat Release for Early Pilot Timing Setting

As the combustion characteristics of alternative fuels are different to traditional diesel fuels, the operation settings will vary significantly. The SCC was used to perform an optimization of the timing settings, thus saving engine testing time.

Ethanol does not easily self-ignite. Therefore, the combustion is initiated by the diesel pilot injection. Consequently, the timing of the pilot injection was of special interest. The influence of the pilot timing is shown in the figures 14-16. The blue rectangle represents the injection begin and injection duration of ethanol. The orange rectangle indicates the injection timing of the diesel pilot. The pilot timing was varied from early to late.

Figure 14 shows an early pilot timing. The diesel injection starts earlier than the ethanol injection. Thus, the injected ethanol ignites quickly and only a small share is premixed. This leads to a high rate of heat release in the initial phase of the combustion. After the end of the diesel combustion, however, the heat release rate drops. The overall length of the combustion is longer than for the other cases and the pressure increase is lower, indicating a lower efficiency.

For the case shown in Figure 15, the ethanol injection is started before the diesel pilot. Consequently, ethanol vapour is present in the combustion chamber when the pilot is injected. This vapour burns in a premixed combustion and is followed by a diffusive combustion of the ethanol. Of the three cases presented, this leads to the highest pressure rise and shortest combustion.

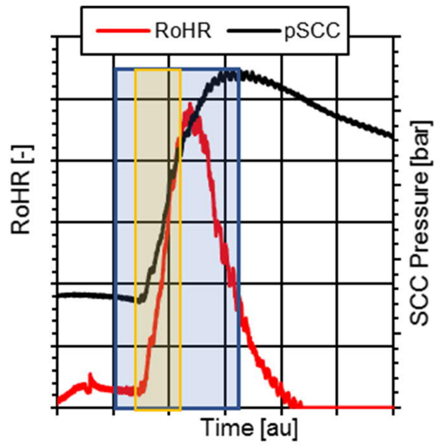


Figure 15. Pressure Trace and Rate of Heat Release for Optimal Pilot Timing Setting

In the last case (Figure *16*), the ethanol vapour share is increased by delaying the diesel injection further. This leads to a steep heat release and pressure rise due to the fast combustion of the premixed fuel. This behaviour is not desired for engine operation. Furthermore, the diesel and ethanol flames are interfering and locally reducing the oxygen content. This results in a lower heat release rate.

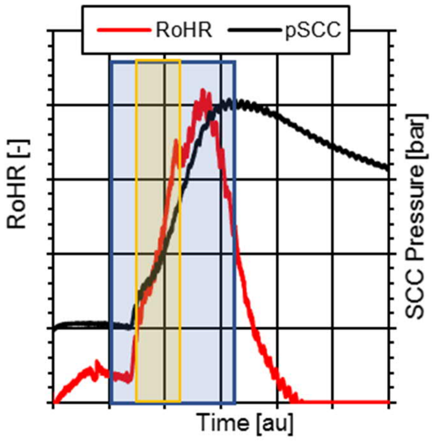


Figure 16. Pressure Trace and Rate of Heat Release for Late Pilot Timing Setting

The initial injection settings for the injection timing on the test engine have been derived from the findings described above. [5]

3.2 Injection Rig

The hydraulic functionality of the FFI-system was tested with the injection rig. Special attention was given to the functionality of the two needle lift steps. The two lift levels of the needle are supposed to control the mass flow through the injector. This in turn enables the operation with fuels of different energy densities as it is the case for diesel and ethanol.

To ensure that the mass flow can be controlled with the needle lift, a test with ethanol was performed. First, only the first step was actuated. Then, the second step was activated. A significant increase in mass flow was expected. The results are shown in Figure 17. The injection pressure is shown in green. Oscillations are observed when the needle is moved. The mass flow through the injector can be estimated based on the stroke of a quantity piston (QP) shown in black. It can be observed that due to the higher mass flow rate, the QP stroke increases much faster when both steps are actuated. Therefore, it can be assumed that the needle seals the second row sufficiently and no significant amount of fuel flows through the second row of holes when only the first level is activated.

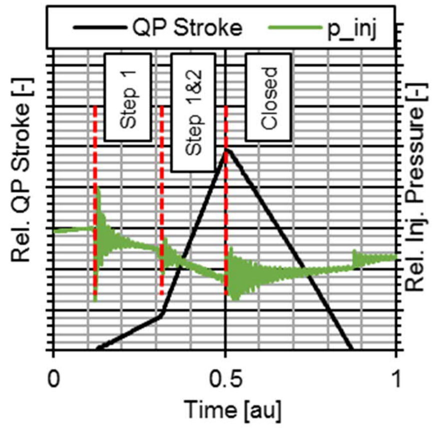


Figure 17. Quantity Piston Stroke of the Fuel Flexible Injector and Injection Pressure

The difference in energy density of diesel and ethanol requires a much larger injection of ethanol. Therefore, the quantity piston stroke is much larger when operating with ethanol as shown in Figure 18. With the FFI-system, the difference in energy density can be compensated. Therefore, the injection duration remains constant regardless of the fuel.

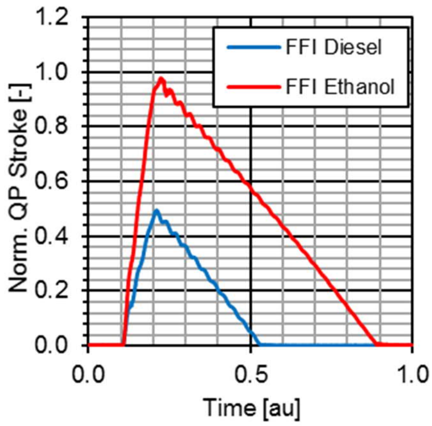


Figure 18. Quantity Piston Stroke for Ethanol Compared to Diesel

3.3 Engine Tests

In the SCC or the injection rig, neither the fuel consumption nor the emissions can be determined. Therefore, the FFI-system has been installed on the RTX-6 test engine. For safety purposes, one of the requirements for the FFI-system was the possibility to change back to diesel operation with the RT-flex system during engine operation. This scenario was tested, the results are shown in

Figure 19. The engine speed drops as the injection is stopped on the FFI-system. It recovers quickly after starting the injection with the RT-flex system. Therefore, the engine could be safely operated with the FFI-system.

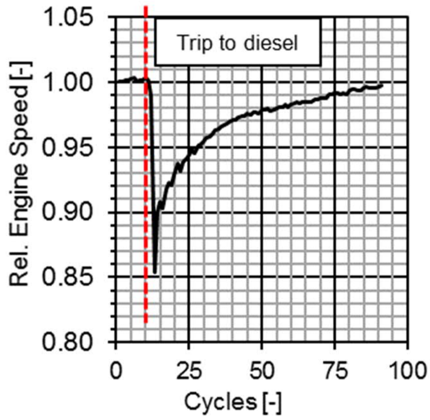


Figure 19. Change of Engine Speed after Trip from Ethanol to Diesel

A reference load curve with the FFI-system and diesel fuel was measured to enable the differentiation between influences on the engine performance of the injection system itself and the alternative fuel. The rate of heat release is shown in Figure 20. While the initial phase of the combustion is similar, the tail of the combustion is longer with the FFI-system. This behaviour was already observed in the SCC (see Figure *13*).

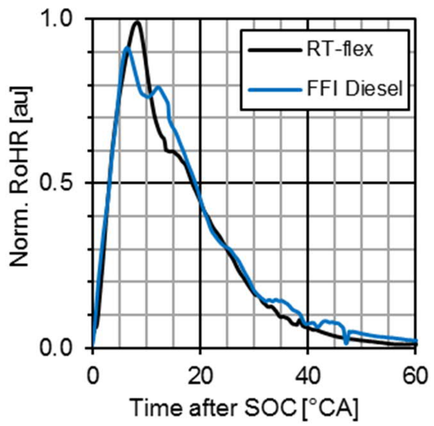


Figure 20. Rate of Heat Release with Diesel for RT-flex Compared to FFI-System

The initial settings for engine operation on ethanol were derived from the SCC findings. The RT-flex injectors were used to inject a small amount of diesel to ignite the ethanol injected by the FFI-system. The diesel amount was reduced to the minimal possible injection volume of the RT-flex injection system. Stable engine operation could be achieved over the entire load range.

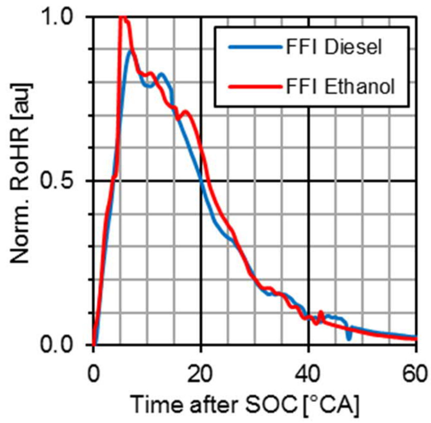


Figure 21. Rate of Heat Release for FFI-System with Ethanol Compared to Diesel

The rate of heat release is shown in Figure 21. The initial part of the combustion is dominated by the combustion of the diesel pilot. Later, the ethanol burns which leads to a higher peak in the rate of heat release. The difference between diesel and ethanol is small.

The efficiency of the engine operated on ethanol is similar to diesel operation. Therefore, the BSFC is similar when correcting for the difference in lower heating value as shown in Figure 22.

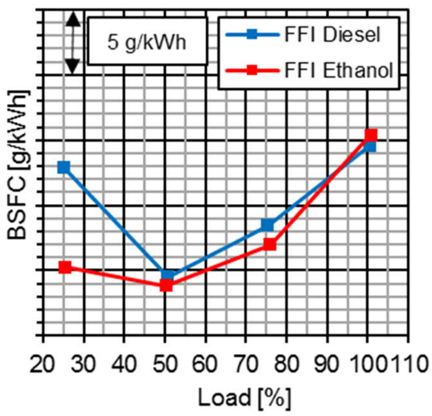


Figure 22. ISO-Corrected Brake Specific Fuel Consumption at same Lower Heating Value (42.7 MJ/kg)

At the same time, the nitrogen oxides emissions decreased slightly. As ethanol has a high heat of vaporization, the charge is cooled during the evaporation. Due to the lower temperatures, less NOx is formed.

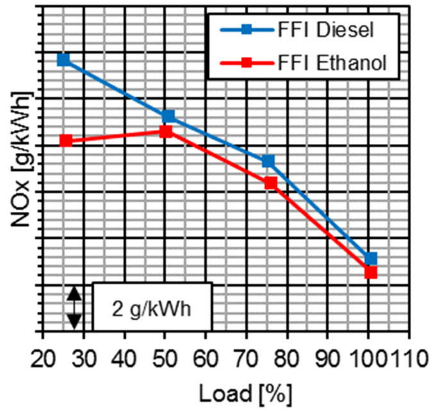


Figure 23. NOx Emissions with Ethanol Compared to Diesel

More importantly, the smoke emissions decreased significantly as shown in Figure 24. While the filter smoke number is low, even when operating on diesel fuel, the use of ethanol improves the emissions. On the one hand, this is due to the oxygen within the ethanol molecule which reduces the chance for rich zones and helps the combustion as well as the oxidation of particulates. On the other hand, the longer ignition delay of ethanol leads to more evaporated and ready for combustion fuel, thus further reducing the chances for fuel-rich zones.

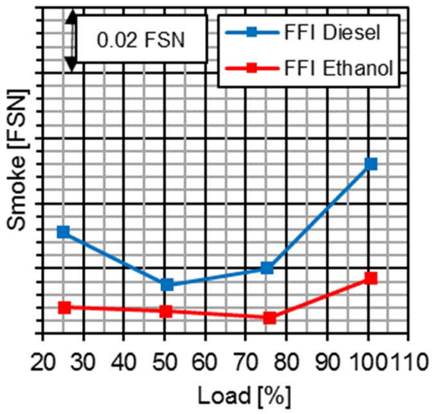


Figure 24. Smoke with Ethanol Compared to Diesel

The unburned hydrocarbon emissions are shown in Figure 25. With ethanol, the emissions are higher than with diesel. The charge is cooled during the evaporation of ethanol, which leads to a longer ignition delay. During the ignition delay, the fuel penetrates into the combustion chamber and mixes with air. At the time of ignition, a share of the charge will have become too fuel-lean to ignite, thus leading to higher HC emissions.

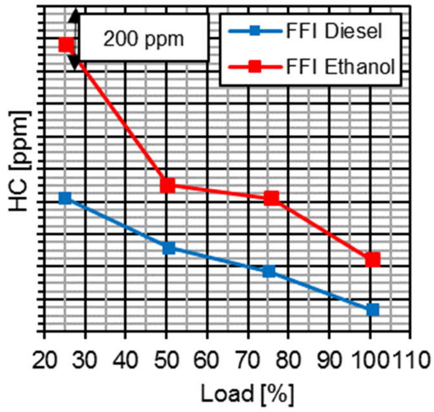


Figure 25. Unburned Hydrocarbons with Ethanol Compared to Diesel

The CO emissions are similar or lower with ethanol compared to diesel as shown in Figure 26. Therefore, it can be assumed that the combustion efficiency is similar to diesel operation.

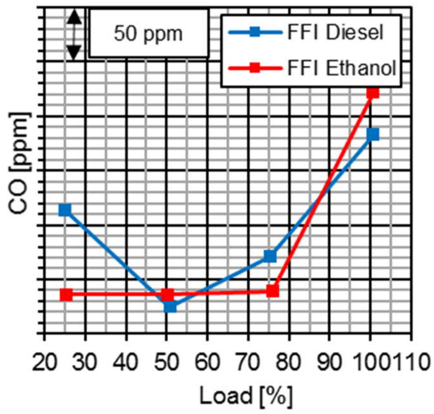


Figure 26. CO Emissions with Ethanol Compared to Diesel

4 SUMMARY & CONCLUSION

Between 2015 and 2018, a new injection system capable of using a wide range of fuels has been developed and tested at WinGD as part of Work Package 1 of the European Union's HERCULES-2 project. Tests have been performed on an injection rig, in a spray combustion chamber as well as on the research engine. As fuels, ethanol, methanol and diesel have been investigated.

The new injection system was proven to work reliably on the injection rig as well as the SCC. The spray tip penetration was measured and the interaction of diesel pilot injection and alternative fuel injection was studied.

Furthermore, the RTX-6 research engine was run successfully on ethanol as well as diesel over the entire load range. Switching from diesel to ethanol operation is possible at any point during engine running.

A potential regarding the reduction of emissions has been demonstrated. Smoke emission could be almost completely inhibited, while NOx emissions were slightly reduced at similar engine efficiency.

However, so far only one alternative fuel has been studied. Other possible fuel candidates need to be considered in order to further validate the FFI-system.

Furthermore, improvements regarding the injection system are possible. So far, a setup has been applied that is optimized for research purposes. Two independent full-scale injection systems were installed on the test engine. The RT-flex system used for pilot injections was not optimized for this purpose. With a dedicated pilot injector and, thus, reduced diesel amounts, even better results might be possible.

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