- IDEALFUEL -

Lignin as a feedstock for renewable marine fuels

GRANT AGREEMENT No. 883753

HORIZON 2020 PROGRAMME - TOPIC LC-SC3-RES-23-2019
"Development of next generation biofuel and alternative renewable fuel technologies for aviation and shipping"

Deliverable Report

D5.1 – Ignition & combustion behaviour of baseline fuels

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883753

Deliverable No.	IDEALFUEL D5.1	
Related WP	WP5	
Deliverable Title	Ignition & combustion behaviour of baseline fuels	
Deliverable Date	21-12-2023	
Deliverable Type	REPORT	
Dissemination level	Public (PU)	
Written By	Michel Cuijpers, Alexander Nijst	24-11-2021
Reviewed by	Roy Hermanns (TU/e)	21-12-2023
Approved by	Project Coordinator	21-12-2023
Status	Final	21-12-2023

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Publishable summary

This report addresses the growing need for sustainable energy sources, focusing on the combustion characteristics of Bio-HFO and CLO fuels in marine engines. Building on prior fuel screening efforts, the study emphasizes detailed analysis of spray, ignition, and combustion performance. The knowledge gap in essential combustion properties of these emerging drop-in fuels is addressed through the utilization of a specialized Combustion Research Unit (CRU) enhanced for a comprehensive evaluation of ignition quality under diverse marine engine scenarios.

The primary objective is to systematically explore the ignition and combustion behaviour of Baseline reference fuels, including MGO, HFO, and RMD. Findings are to be integrated into map-based approaches for system modelling, contributing to the benchmarking of Bio-HFO against conventional marine fuels at later stage of the project.

- MGO exhibits combustion properties comparable to diesel at high temperatures, with similar maximum rates of heat release (RORH) and ignition delay (ID). Notably, MGO displays multiple heat release peaks at lower temperatures, suggesting sequential ignition of components. Ideal injection temperatures for MGO are identified at around 510°C and 490°C, achieving maximum RORH and pressure with low ID.

- HFO low sulphur 3300 PPM Viscosity measurements indicate that HFO has high viscosity at temperatures below 120°C, decreasing significantly with higher temperatures. Lower RORH and chamber pressure are observed in HFO compared to Diesel and MGO, attributed to higher density affecting the injected volume. Further research will explore possibilities for matching the injected volume.

- RMD 80 Viscosity measurements of RMD reveal boiling off of components above 100°C, indicating potential impurities. Consequently, RMD 80 is excluded from CRU testing, requiring further investigation into these unexpected phenomena.

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Abbreviations

Symbol / short name	
HFO	Heavy Fuel Oil
MGO	Marine Gas Oil
RMD	Residual Marine Diesel
CRU	Combustion Research Unit
ROHR	Rate of heat Release
CVCC	Constant Volume Combustion Chamber

1 Introduction

The pursuit of sustainable and efficient energy sources has driven the exploration and utilization of alternative fuels in various industrial applications. This report focuses on advancing our understanding of the combustion characteristics of Bio-HFO (Biodiesel-Heavy Fuel Oil) and CLO (Customized Liquid Organic) fuels, particularly in the context of their application in marine engines. Building upon the preliminary screening of fuels in Workpackage 4, where emphasis was placed on combustion and ignition properties, this task seeks to delve into a higher level of detail, specifically concentrating on spray, ignition, and combustion performance.

At present, there exists a conspicuous knowledge gap pertaining to essential combustion properties of these emerging drop-in fuels. To address this gap on a global scale, a Combustion Research Unit (CRU), akin to an ignition quality tester, will be employed at the Eindhoven University of Technology (TUE). The CRU, already adept at assessing ignition quality, will undergo expansion to incorporate a high-temperature chamber and an HFO injection system. This enhancement enables a comprehensive evaluation of ignition quality across a diverse range of operating conditions representative of typical marine engine scenarios.

Utilizing the optical accessibility of the CRU to unravel the intricate behaviour of Bio-HFO and CLO fuels under these challenging conditions. The study will scrutinize ignition delay and heat release rate, offering valuable insights into their performance in conditions closely resembling those encountered in marine engines.

The primary focus of this deliverable lies in a systematic exploration of the ignition and combustion behaviour of Baseline reference fuels, namely MGO 1000 ppm (MGO), HFO 380 low sulphur 3300 ppm (HFO) and, RMD 80 (RMD). Through rigorous experimentation, the goal is to quantify the distinct characteristics of these fuels. The outcomes of this study will be encapsulated in map-based approaches, facilitating their integration into system models. Ultimately, these findings will contribute to the ongoing efforts to benchmark the newly developed Bio-HFO against conventionally used marine fuels such as Marine Gas Oil (MGO), Heavy Fuel Oil (HFO), and Diesel in a documented in Deliverable 5.2.

2 Fuel and combustion properties

2.1 Samples

This chapter describes the fuels used in this study. These different fuels contain properties that affect the fuel and combustion behavior. In this study, different commercially available samples were tested:
MGO 1000 ppm (MGO), HFO 380 low sulphur 3300 ppm (HFO) and, RMD 80 (RMD). These substances were supplied by the project partners Goodfuels and Varo energy.

2.1.1 Viscosity

The viscosity of the new received samples is measured with an Anton Paar MCR 302 rheometer, see Figure 2.1. When the viscosity is measured, the liquid will be placed between two parallel plates, whereby the upper plate (cone plate) rotates at a fixed speed. The viscosity is measured in a linear temperature sweep from 50-150°C, this is done to obtain the correct viscosity at injection temperatures.

Figure 2.1 Anton paar MCR 302 rheometer

Figure 2.2 shows the viscosity of HFO low sulfur 3300 ppm and RMD 80. The chart shows that HFO has a high viscosity at lower temperatures. Both fules are benchmarked against Diesel (EN590). As shown in the graph, the measurement of RMD did not go all the way to 150 degrees Celsius. The reason for this is that at temperatures above 100 degrees Celsius, RMD started to boil and excessive gas formation occurred. This led to an early termination of the measurement. The reason behind the boiling of light components is an unstable RMD 80. Further investigation into RMD 80 led to similar observations from projectpartners. In the rest of this research the RMD 80 will be excluded.

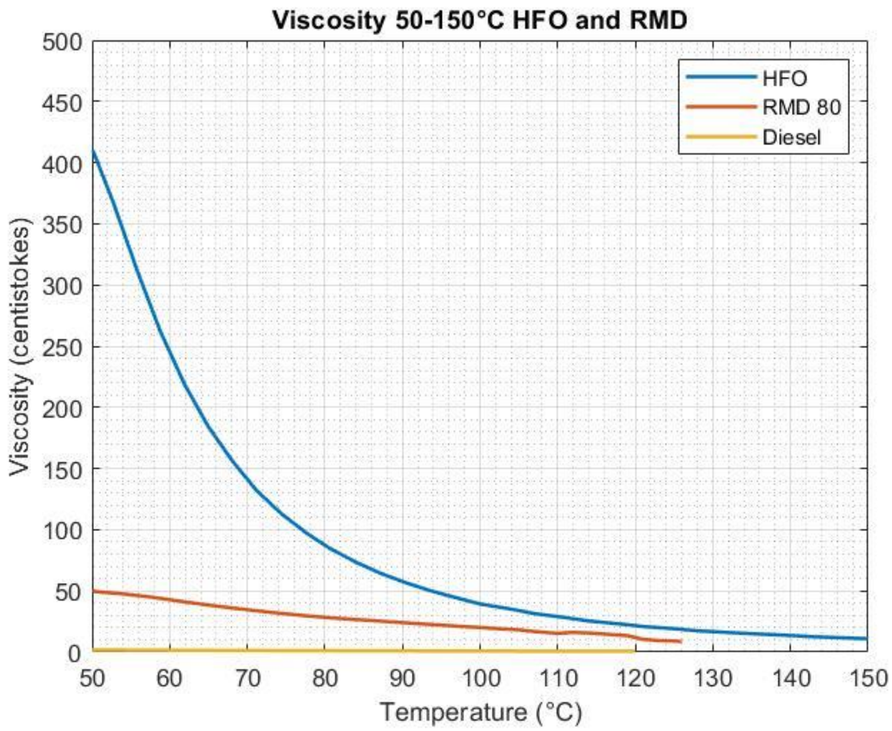

Figure 2.2 Viscosity of HFO low sulfur 380, RMD 80 and Diesel EN590

3 Methodology

3.1 CRU

The Fueltech-manufactured Combustion Research Unit (CRU) serves as a tool for evaluating the ignition and combustion characteristics of various fuels. This CRU incorporates a Constant Volume Combustion Chamber (CVCC) that undergoes pressurization and precise heating before fuel injection. An external high-pressure gas cylinder, containing compressed synthetic air, introduces ambient gas into the chamber. The chamber pressure is monitored by a static pressure sensor, while electric heaters bring the combustion chamber to the desired temperature. The CRU is configured with two distinct injection systems: a standard fuel injection system and a heavy-fuel oil (HFO) injection system. The standard fuel injection system is employed for testing fuels resembling diesel in viscosity, utilizing a pressure amplifier to achieve a ten-fold pressure increase, enabling injection pressures up to 1600 bar. Figure 3.1 provides a schematic representation of the CRU setup.

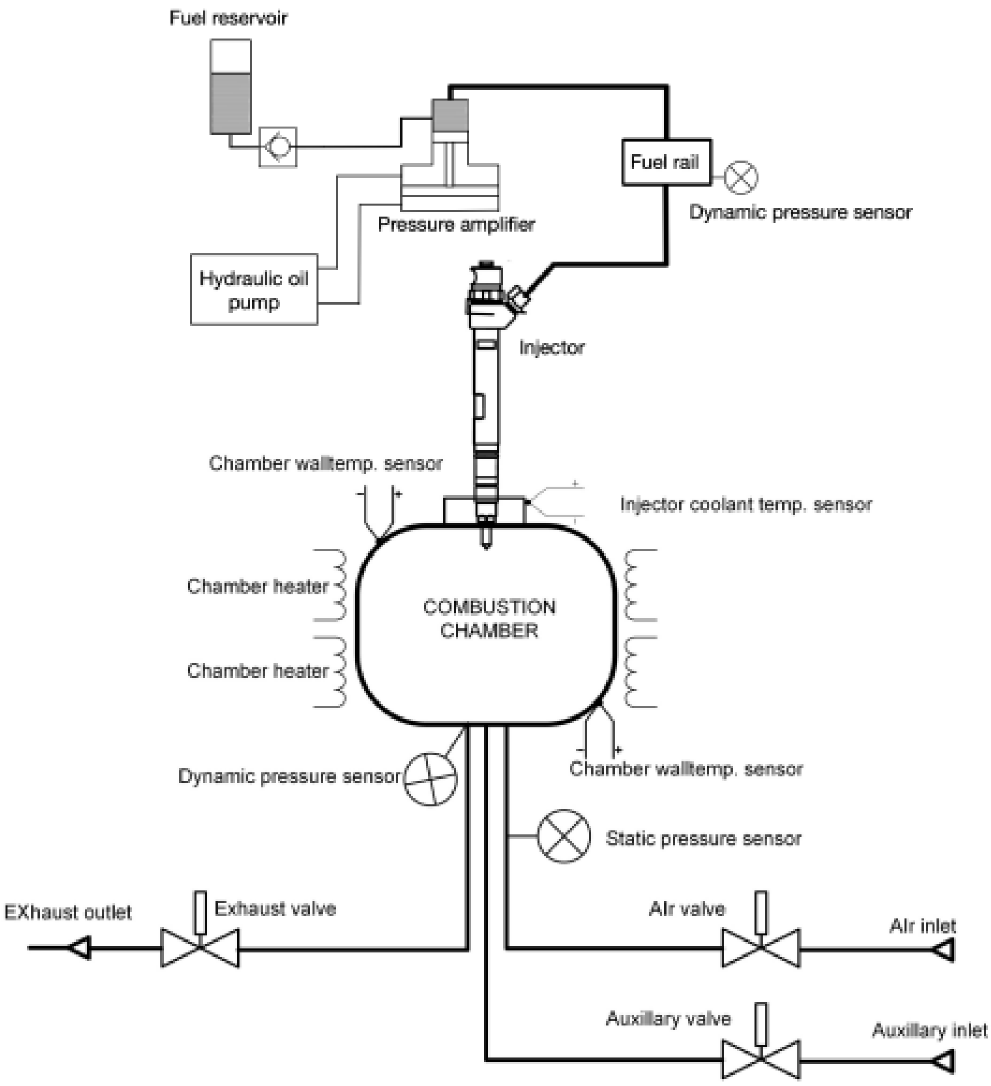

Figure 3.2 Schematic overview of the CVCC system in the CRU

The measurements were performed at different temperatures, starting at 590 degrees Celsius to 430 degrees Celsius (depending on the ignition of the fuel). From the pressure signal of the CVCC, the Rate of Heat Release (ROHR) can be calculated.

3.2 CRU Modification

Different from the diesel like fuels, we received also benchmark fuels with higher viscosities. In our case, the HFO 380. To test these HFO like fuels, some modification to the injection circuit of the CRU have to be made (which will be called the HFO injection system, figure 2.2). For the Heavy fuel oil (HFO) injection system, the fuel reservoir (1), fuel pressurizer (2) and injector (3) are modified. These parts can be preheated (30 – 140 °C). Fuel preheating can significantly decrease the viscosity of heavy-fuel oil (see figure 3.2). The HFO Injector consists of standard CR injector components, which allows us to change the parts easily. The injector body and nozzle are custom made. The test fuel circuit (blue) goes to the lower part of the body into the injector nozzle, here also a flush valve is installed. A separate control circuit (red) is directed to the top of the injector body. Here the control valve is installed. Equal pressures in these two circuits are maintained by a floating piston in the fuel pressurizer (2).

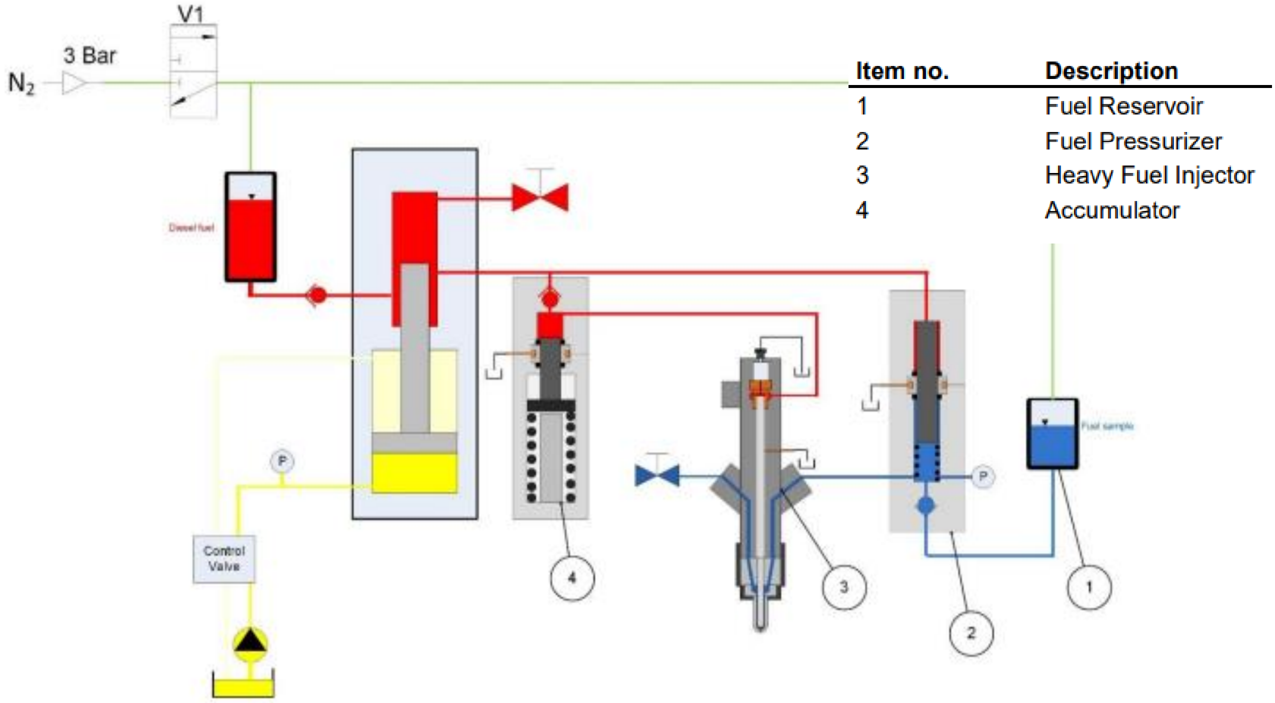

Figure 3.2 Schematic overview of the HFO injection system with its respective components

In addition, more modifications are implemented to facilitate the flushing and cleaning of the fuel supply system. The maximum fuel pressure in HFO injection system is limited to 1000 bar, and the 7-hole nozzle of HFO injector has the same parameters as the standard one (mentioned in table 3.1), only an additional flush channel is introduced in the nozzle.

Table 3.1 CRU Parameters

Parameter	Value
Chamber volume [L]	0.475
Chamber wall temperature [°C]	300 – 590
Initial chamber pressure [bar]	10 – 70
Injection pressure [bar]	300 – 1600 (200 – 1000 for HFO injector)
Injection duration [ms]	0 – 1.5

4 Results

4.1 MGO combustion results

In order to compare the combustion properties of Diesel and MGO, this report will focus on Ignition delay (ID) and rate of heat release (ROHR). Figure 4.1 shows the energy conversion of Diesel and MGO, which was measured by rate of heat release as a function of time. A maximum ROHR (35,11 bar/s) of MGO is attained at 530ºC with an mean (ID) of 1,99 ms. Whereas diesel attained a maximum ROHR (35,49 bar/s) at 510ºC at an ID of 2,00 ms. The results show that Diesel and MGO start off with a similar profile, but as the temperature decreases, some difference can be observed. It can be seen that the ID of MGO becomes relatively longer compared to diesel. The RORH peaks are similar to those of diesel at same ID. One may also notice that while the temperature decreases, MGO appears to have double peaks, which can lead to a non-simultaneous combustion of the fuel. Components in the MGO with a lower auto-ignition temperature will ignite first, the remaining components will combust due to the released heat of this first combustion.

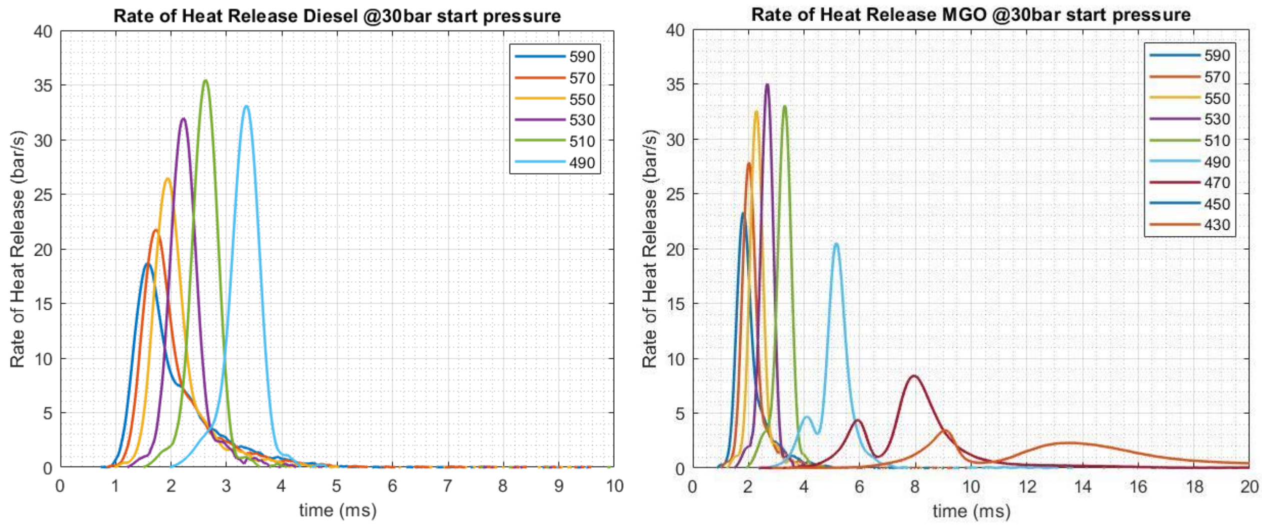

Figure 4.1 Rate of heat release of Diesel and MGO at 30 bar start pressure

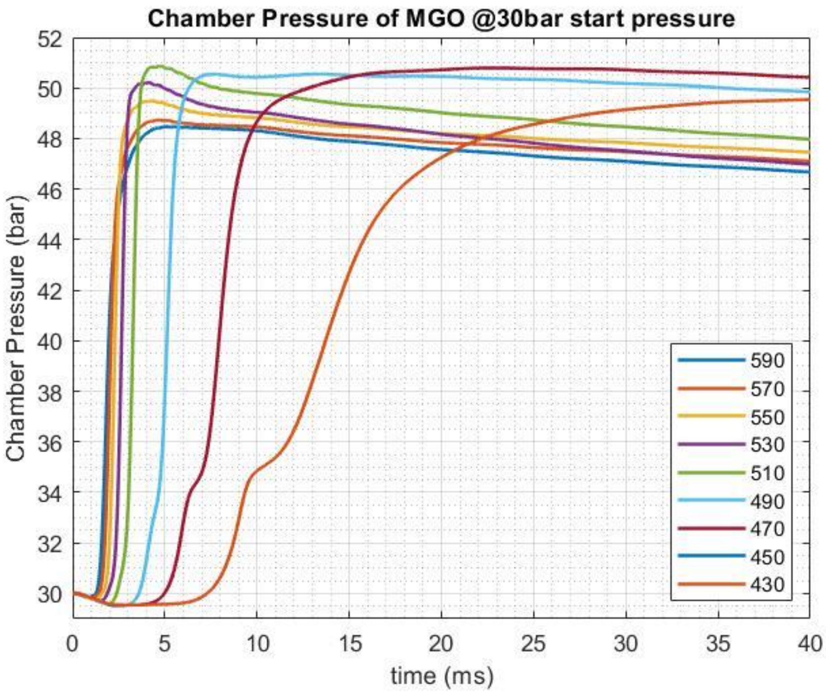

Figure 4.2 Chamber pressure of MGO at 30 bar starting pressure.

In order to fully investigate the combustion of MGO, the chamber pressure is plotted as function over time (figure 4.2). It can be seen that the pressure at temperatures from 590 °C up to 510 ° C are comparable with diesel. If we decrease the chamber temperature even further, we see some differences. From 490 °C we start to see the cause of the double peaks in the RoHR, which is clearly visible. The maximum pressure is reached at 510 °C at 51.2 bar. This is due to increase ID, which ensures a homogeous mixture, and thus a faster rection. At lower temperatures, there is no fast combustion, and the maximum pressure peak is reached at the end of the measurement. This suggests that not all the substances in the MGO fuel ignite at the same time, so the maximum pressure cannot be achieved at this temperature.

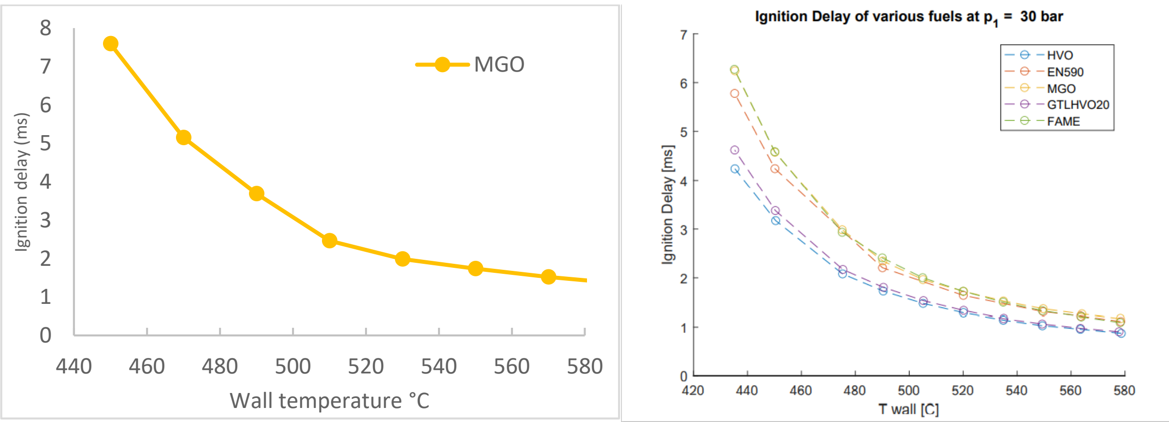

Figure 4.3 Ignition delay of MGO at 30 bar(left) in comparison the prior research of MGO ID (right).

In an earlier study, the ID of different fuels were compared, shown in figure 4.3. Based on the results from earlier tested samples of MGO (and other benchmark fuels), the results are consistent with each other. It can be seen that the ID at lower temperatures is somewhat higher, this becomes proportionally smaller at higher temperatures.

4.2 HFO combustion results

In addition to the combustion properties of MGO, we also tested HFO 380. From section 2.1.1 we observe the relative high viscosity for the HFO 380. For this reason the CRU is converted to the HFO injection circuit. Using this set-up, the fuel can be preheated and the correct injection temperature can be set. In figure 4.4 the chamber pressure and the ROHR of HFO low sulphur 3300 ppm are shown. This sample will be referred to as HFO and is measured with a starting pressure of 30 bar. The fuel injection pressure is 800 bar, which is different from the 1500 bar used for MGO and Diesel. Looking at the heat release, it can be seen that the maximum peak is obtained at 590 °C. The heat release decreases rapidly at lower temperatures. When lowering the temperature, a similar observation compared to MGO can be seen (double heat release peaks). This first peak possibly indicates a pre-mix combustion and the second peak the burning of the fuel. The ID also increases significantly as the temperature decreases, reaching a value of 8.49 ms at 450 °C, at which we stopped the experiment. These long ID are not desired and can cause problems to the set up (and also in real life).

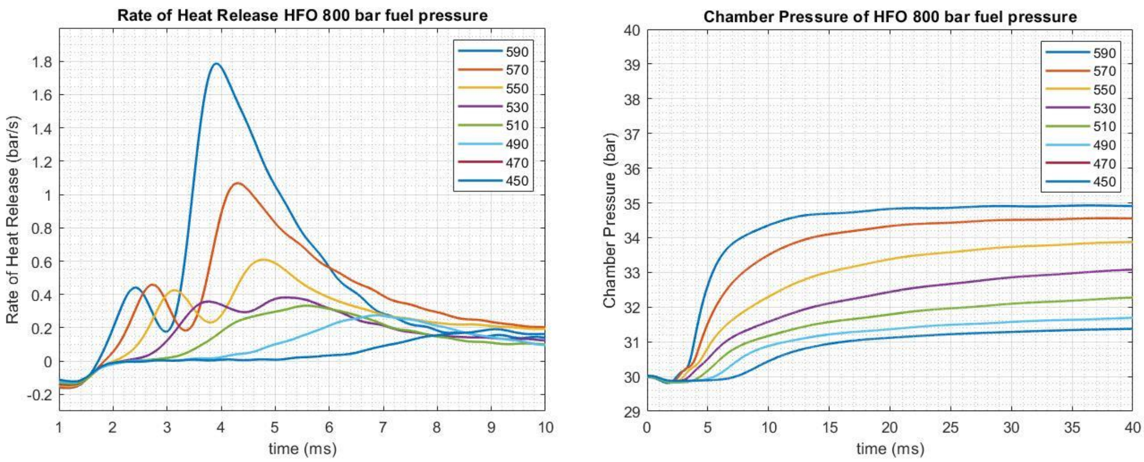

Figure 4.4 Rate of heat release and chamber pressure of HFO at 800 bar Fuel pressure.

In the graph of the chamber pressure in Figure 4.4 we see similar results as in the case with MGO. Here, the highest chamber pressure is reached at a temperature of 590 degrees Celsius. Then, as the temperature decreases, the pressure also decreases. In comparison with, for example, diesel and MGO, the pressure released during the combustion of HFO is significantly lower.

5 Discussion and Conclusions

In this chapter, the results will be discussed and a conclusion will be given.

5.1 MGO

From the results of the combustion properties, MGO was injected into a constant volume chamber at various temperatures. Compared to diesel, the properties of MGO do not differ much at high temperatures. Both achieve the same maximum rate of heat release and ignition delay respectively. What is remarkable is that MGO shows several heat release peaks at lower temperatures. A possible reason for this could be that not all components ignite simultaneously. This means that components with a lower auto-ignition temperature will ignite earlier and those with a higher auto-ignition temperature will only ignite with the heat released from the first ignition.
The results show that the ideal injection temperatures for MGO are around 510 degrees Celsius and 490 degrees Celsius. At these temperatures, maximum RORH and pressure are achieved while the ID remains low enough.

5.2 HFO low sulphur 3300 PPM

A viscosity measurement was carried out to determine at the right injection temperature for the CRU. This shows that HFO has a high viscosity at temperatures below 120 °C. The viscosity decreases significantly as the temperature increases, which is why we recommend preheating the injector of the CRU to 120 °C. From the results obtained, a significantly lower RORH and chamber pressure were observed in HFO compared to Diesel and MGO. A possible explanation is a higher density of HFO, which may result in a lower injected volume due to the lower injection pressure and the lower density. If less is injected, the total heat and pressure released will be lower. The maximum RORH 1.79 bar/s and chamber pressure 34.9 bar have been reached at 590 °C in the CRU at 800 bar fuel pressure. In further research, we will investigate the possibilities to match the injected volume.

5.3 RMD 80

Viscosity measurements of RMD have shown that at temperatures above 100 °C, different components in the RMD 80 starts to boil off. This could possibly lead to impurities in the batch of RMD 80, as RMD should not yet show these phenomena at this temperature range. This has led to RMD 80 not being tested on the CRU.

6 Risk Register

Risk No.	What is the risk	Probability of risk occurrence[1]	Effect of risk[1]	Solutions to overcome the risk
WP5	CRU Injector blocks or fuel (Bio-HFO) cannot be injected in a proper way	2	1	Other injectors can be used that are on the market
	Bio-HFO is not mixable with RMG or HFO	2	3	Specialised mixing methods need to be explored

[1)] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner short name	Partner Full Name
1	TUE	Technische Universiteit Eindhoven
2	VERT	Vertoro BV
3	T4F	Tec4Fuels
4	BLOOM	Bloom Biorenewables Ltd
5	UNR	Uniresearch B.V.
6	WinGD	Winterthur Gas & Diesel AG
7		(Formerly SeaNRG, is now GOODFUELS #12)
8	TKMS	Thyssenkrupp Marine Systems GMBH
9	OWI	OWI – Science for Fuels gGmbH
10	CSIC	Agencia Estatal Consejo Superior De Investigaciones Cientificas
11	VARO	Varo Energy Netherlands BV
12	GOOD	GoodFuels B.V.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883753