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Author(s): Hissa, M.; Niemi, S.; Sirviö, K.

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Combustion property analyses with variable liquid marine fuels in combustion research unit

M. Hissa*, S. Niemi and K. Sirviö

University of Vaasa, School of Technology and Innovations, Department of Energy Technology, P.O. Box 700, FI-65101 Vaasa, Finland
*Correspondence: Michaela.Hissa@uva.fi

Abstract. The quality of ignition and combustion of four marine and power plant fuels were studied in a Combustion Research Unit, CRU. The fuels were low-sulphur Light Fuel Oil (LFO, baseline), Marine Gas Oil (MGO), kerosene and renewable wood-based naphtha. To meet climate change requirements and sustainability goals, combustion systems needs to be able to operate with a variety of renewable and 'net-zero-carbon' fuels. Due to the variations in the chemical and physical properties of the fuels, they generally cannot simply be dropped into existing systems. The aim of this research project was to understand how changes in fuel composition affect engine operation. The focus was on how various properties of the fuels impact on the combustion process – especially ignition delay and in-cylinder combustion. The goal of the research project was to allow broad fuel flexibility without any or only minor changes to engine hardware. Before the engine tests, the CRU forms an easy and cost-effective device to find out the engine suitability of the fuel. The results showed that the ignition delay decreased expectedly with all fuels when the in-cylinder pressure and temperature increased. The differences in the maximum heat release rates between fuels decreased in high-pressure conditions. MGO had the shortest ignition delay under both pressure and temperature conditions. Based on the CRU results MGO and kerosene are suitable to use in compression-ignited engines like the reference fuel LFO. In contrast renewable naphtha had a long ignition delay. If naphtha is used in a CI engine, the engine must be started and stopped with, e.g. LFO or MGO.

Key words: Diesel engines, alternative fuels, ignition delay, heat release rate.

INTRODUCTION

In compression ignition (CI) engines the combustion process starts when liquid fuel is injected as one or more jets into the cylinder fulfilled with hot high-pressured air near the top dead centre (TDC) position of the piston. The ignition delay (ID) is a period when injected fuel entrains to cylinder, atomizes and mixes with existing air. Chemical reactions start slowly and ignition occurs after the ID. Good atomization provides rapid air-fuel mixing decreasing the ID. The ignition of air-fuel mixture prepared during the ID causes a rapid pressure rise that is called as rapid uncontrolled or premixed combustion. Controlled combustion follows and is the part where preparation of fresh air-fuel mixture determines the rate of combustion. Combustion continues until all the fuel or air is utilized. This last phase is called as final combustion.

Due to variations in the chemical and physical properties of the fuels, they generally can not simply be dropped into existing systems. The aim of this research project was to understand how changes in fuel composition affect engine operation. The fuel properties have a significant effect on the ignition and combustion as well as pressure, temperature and mechanical issues (e.g. nozzles and their hole diameters). The viscosity, density, heating value and cetane number have a major effect on good atomization and ignition delay especially under low pressure conditions (Heywood, 1988; Bae & Kim, 2016). Too rapid a chamber pressure increase may cause engine damage and also increase NO_x emissions (Steenberg & Forget, 2007). Buchholz (2013) and Chang et al. (2013) even states that current diesel fuel ignites too easily causing poor mixing with oxygen, which leads to increasing levels of soot and NOx emissions. As a solution they suggest that one way to cut down number of aftertreatment devices and high injection pressure, is to use less processed fuel.

Currently most of the energy sources rely on fossil fuels which have limited resources. That is why alternative energies are necessary. Based on Bae & Kim (2016) significance of using alternative fuels can be defined as followes:

'(1) pursuing energy sustainability through the extended usage of those alternative fuels derived from renewable energy sources and mitigating the concerns of limited fossil fuel energy

(2) improving engine efficiency and engine-out emissions with the aid of superior physical or chemical properties of alternative fuels compared to those of conventional fuels

(3) relieving the unbalanced usage of conventional petroleum-based fossil fuels'.

In this study, the ignition characteristics of four marine and power plant fuels were studied in a Combustion Research Unit, CRU. The fuels were low-sulphur Light Fuel Oil (LFO, baseline), Marine Gas Oil (MGO), kerosene and renewable wood-based naphtha. MGO represents recycled fuels cause it is produced from used lubricant oils. LFO and kerosene may be called as heavier fuels and naphtha represents lighter fractions, which is generally the product of the initial distillation of crude oil. In this study, used naphtha was renewable wood-based naphtha.

Studies (Chang et al., 2013; Wang et al., 2013; Bae & Kim, 2016) have shown that crude oil-based naphtha, run in compression ignition engines, had a high efficiency with good transient operation and acceptable noise levels, while achieving NOx emissions below the EURO6 levels, lower particulate matter (PM) emissions and lower smoke levels than with diesel fuel. However, the low CN and viscosity of naphtha may cause increased NOx emissions due to the retarded start of combustion and prolonged ignition delay (Subramanian et al., 2018).

Kerosene is primarily used in the aviator sector particularly in gas turbine engines. Behind the kerosene usage in diesel engines is North Atlantic Treaty Organization (NATO) military's intending to use JP-8 fuel for all their automobiles and equipments, based on their Single Fuel Concept (SFC), due to logistical benefits. Another reason to study kerosene in diesel engine is adulteration of diesel by mixing it with kerosene, which is big problem in some parts of world. JP-8 has very similar chemical composition compared to the present Jet-A fuel despite some additives (Yadav et al., 2005; Lee et al., 2012). Based on the research of Vasu et al. (2007), JP-8 and Jet-A have very similar ignition delay times. Although, low lubrication may cause problems in the fuel pump system (Anastopoulos et al., 2002; Bae & Kim, 2016).

MGO is commonly known as shipping fuel. The ship owners have been driven to examine how to comply the forthcoming sulphur emission regulations (IMO, 2008), and MGO is promising alternative besides sulphur scrubbers and alternative fuels. MGO is required in a vessel by existing and upcoming regulations depending on time and location. For example a vessel uses MGO when it is inside Emission Controlled Area (ECA) or within EU ports. Outside the ECA, HFO is used. However, by 2020 low-sulphur heavy fuel oil (LSFO) is required outside of the ECA (Germanischer Lloyd and MAN, 2012). Jiang et al. (2014) calculated that it is more beneficial to use MGO in a old ships compared to use scrubber retrofits.

However, MGO has a higher viscosity and density compared to diesel fuel which may lead to poor atomization resulting in incomplete combustion with higher soot emissions (Nabi et al., 2012). However, the studied MGO had a significantly higher CN (68), compared to other studied fuels, which may count as a compensatory property to higher viscosity and density. In literature (i.e. Karavalakis et al., 2008; Nabi et al., 2012; Ushakov et al., 2013) the CN of MGO is generally around 47−55.

Due to the variations in the chemical and physical properties of the fuels, they generally cannot simply be dropped into existing systems. Proper fuel analysis is necessary before engine use to observe suitability of the fuel. Ensured fuel flexibility of IC engine is needed to manage with fuel availability and fuel price fluctuation, and to meet emission regulations set for industrial engines and end-users. The goal of the research project was to allow broad fuel flexibility without any or only minor changes to engine hardware. Before the engine tests, the CRU forms an easy and cost-effective device to find out engine suitability of the fuel.

MATERIALS AND METHODS

Fuels

The studied fuels were selected to enlarge the choice of fuel alternatives of marine engines. The fuels were Light Fuel Oil (LFO), Jet A-1 -type aviation fuel (100% kerosene), Marine Gas Oil (MGO) produced from used lubricant oils and wood-based naphtha that was a side-product of wood-based biodiesel production. Chemically, all the fuels contained several hydrocarbon compounds; that is why no simple chemical formulas could not be given.

The research started by analysing the basic fuel properties (Table 1). The kinematic viscosity has an important role in fuel injection and droplet formation. Too high or too low viscosity causes poor fuel injection and increases fuel consumption. Too high viscosity leads to poor atomization resulting in incomplete combustion. However, too low fuel viscosity may cause mechanical problems in engine use as leaking from the nozzle sealing and the fuel pump system. All selected fuels had a relatively low viscosity. At a temperature of 40 °C wood based-naphtha had the lowest viscosity (0.50 $mm^2 s^{-1}$) and MGO (8 $mm^2 s^{-1}$) the highest. Kerosene (0.94 $mm^2 s^{-1}$) and the reference fuel LFO (3.0 $mm^2 s^{-1}$) were between the values of naphtha and MGO. The lower viscosity of naphtha and kerosene, compared to diesel, could improve the fuel atomization, evaporation and air/fuel mixing process (Subramanian et al., 2018).

A high fuel density may indicate higher energy content and minimize fuel losses. Too high a density correlates with higher viscosity and it has a negative effect on the formation of the fuel spray incurring poor burning process and high emissions. Among the studied fuels, the correlation between kinematic viscosity and fuel density was correct. Wood-based naphtha had the lowest viscosity and the lowest density (722 kg m^{-3} at 15 °C). MGO had the highest viscosity and the highest density (843 kg m^{-3}). Kerosene (787 kg m^{-3}) and LFO (836 kg m^{-3}) were between the values of naphtha and MGO.

The cetane number (CN) indicates how quickly fuel auto-ignites under compression. A low CN increases ignition delay causing problems for engine starting and running, e.g. unstable engine running leads to noise and smoke. MGO had a relatively high CN, 68, probably caused by used lubricants that formed the feedstock. The calculated cetane index of LFO (EN ISO 4264) was 54. The CN of kerosene (41) and wood-based naphtha (34) were lower, most likely resulting in a longer ignition delay.

A high lower heating value (LHV) implicates good heat release rate during the burning process improving the engine performance. The level of LHV of alternative fuels must meet the level of that of conventional fuels, other way there will be problems in volumetric fuel consumption (Bae & Kim, 2016). Unexpectedly the highest LHV was with wood-based naphtha (44 MJ kg^{-1}). However, the LHV of wood-based naphtha equated to earlier studied values of crude oil-based naphtha (Chang et al., 2013; Bae & Kim, 2016). All the other studied fuels had the same LHV, 43 MJ kg^{-1}.

Table 1. Studied fuel properties

		LFO	MGO	naphtha	kerosene
C	wt.%	87	83	81	89
H	wt.%	14	14	15	15
N	wt.%	< 0.1	0	0	0
S	wt.%	0	0	0	0
Pour point	°C	-42	Max. -6	< -50	
Flash point	°C	64	110	10	Min. 38
Boiling point	°C			20−220	170−300
Density at 15 °C	kg m^3	836	843	722	787
Kinematic viscosity at 40 °C	mm^2 s^{-1}	3.0	8.0	0.5	0.94
Surface tension at 20 °C	mN m^{-1}		29	20	25
HHV	MJ kg^{-1}		46	47	46
LHV	MJ kg^{-1}	43	43	44	43
Cetane number		54*	68	34	41
Sulphur	wt.%	< 0.01	Max. 0.1		0.1
Ash cotent	wt.%	< 0.01	< 0.001	0.005	0.001
Water content	mg kg^{-1}	< 100	22		35
Lubricity	μm	345	491		

*calculated cetane index (EN ISO 4264).

Combustion Research Unit

The Combustion Research Unit, CRU, is a constant volume combustion chamber based instrument designed to resemble engine conditions. In the CRU there are no moving parts and the starting conditions of the fuel injections are controlled more precisely than in a real compression ignition (CI) engine. Fuel is injected in a fixed injection period (250–3000 µs) through a twin nozzle injection system into a chamber with fixed dimensions (500 cm^3 ± 2%). In the injection system the first nozzle is the main injector and the second is a pilot injector, which can be activated or de-activated. In this study the pilot injector was de-activated. The used injector was a BOSCH CR injector which has electronic control of timing, opening period and pressure. The combustion and fuel pressures were observed with piezoelectric pressure sensors. Air was heated by heating the chamber wall. Fig. 1 illustrates the CRU used in this study.

To meet broad fuel flexibility without any or only minor changes to engine hardware, the fuel injection duration was assigned to be 1,000 µs with all fuels despite the differences in kinematic viscosity between the fuels. The pilot injector was de-activated and research was conducted under two different pressure and temperature conditions, 50 bar; 550°C and 70 bar; 590 °C. The results showed, however, that with MGO the injection duration had been 1,025 µs instead of 1,000 µs. Due to this slight difference, MGO is not completely comparable with other studied fuels. Based on Heywood (1988), under normal operation conditions, increasing the quantity of injected fuel has no significant effect on delay period. However, under engine starting conditions, the delay increases due to the larger drop sizes which are associated with evaporating and heating the increased amount of fuel.

All fuels were first centrifuged and then hot filtrated through a 10 µm filter before the CRU measurements. The fuels were at room temperature when injected into the fuel injection system. Measurements were performed two to three times under the both measurement conditions. Information about the set-up configurations of the CRU can be found in Table 2.

Table 2. Research set-up configurations of the CRU

		High pressure	Low pressure
Temperature at fuel injection (theoretical)	°C	590	550
Pressure at fuel injection	bar	70	55
Max. chamber pressure	bar	70	55
Max, pressure	bar	81.2	65.9
Injector period, main (LFO, naphtha, kerosene)	µs	1,000	1,000
Injector period, main (MGO)	µs	1,025	1,025

It should be noted that the actual engine conditions differ from conditions in the CRU. The major difference is the cylinder pressure that in 4-stroke engines reaches even more than 200 bar while the pressure in the CRU was max. 81 bar. Other differences are the fuel injection process and injection timing. In the CRU fuel is injected in a fixed period (1,000 µs), in this study, all fuel was injected before ignition, since all fuels had

an ignition delay of longer than 1 ms. In engines, especially at high loads, the fuel injection overlaps ignition and combustion (Steernberg & Forget, 2007). This means that in an engine large amount of the fuel (max. 80%) is injected into a space with a flame. Despite the differences between the CRU and actual engine conditions, the CRU is fast, easy and cost-effective device to find out the engine suitability of the fuel.
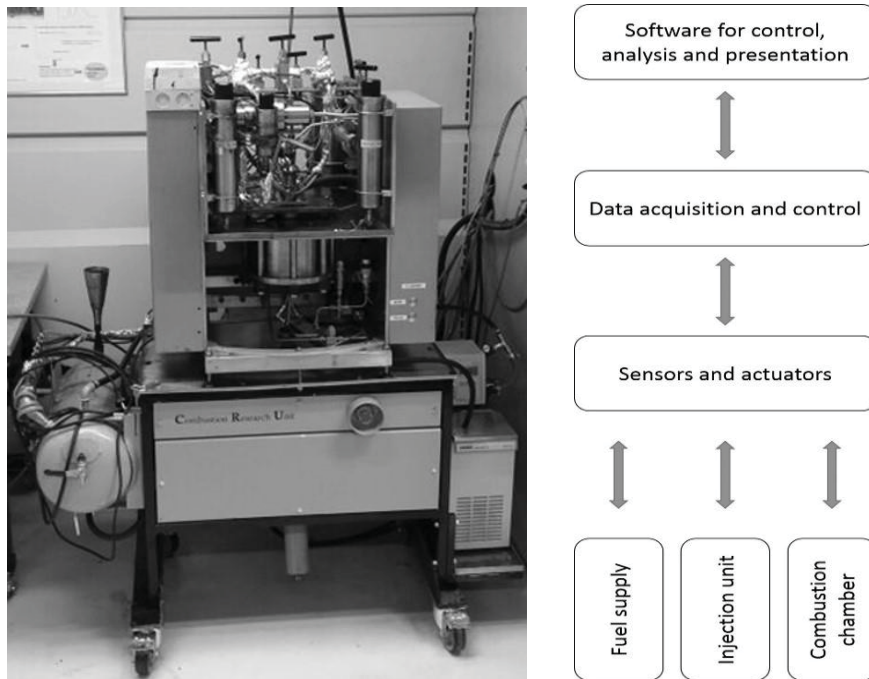

Figure 1. Combustion Research Unit and its modules. (Modules based on Fueltech AS, 2005).

CRU measures the Ignition Delay (ID) from the start of injection (t = 0) until the pressure in the chamber increases 0.1 bar. The following phases are determined:

- Pre Combustion Period (PCP) starts at the point where pressure is increased by 0.1 bar and ends when pressure is 1 % of maximum pressure increase.

- Main Reaction Delay (MRD) is considered when pressure is increased 10 % of the maximum pressure increase.

- The time between fuel ignition until 10% of the maximum pressure increase is achieved is called as Pre Combustion Period (PRP).

- Main Combustion Period (MCP) is measured from the MRD until 85% of the maximum pressure increase is reached.

- After the main combustion period, After Burning Period (ABP) starts, which continues until 95% of the maximum pressure increase is reached. At the end point of ABP, the combustion is considered end (EC).

In the next chapter, Fig. 2 shows these above-mentioned parameters in a pressure diagram with LFO.

RESULTS AND DISCUSSION

Based on the obtained results in the CRU, the ignition delays, complete combustion periods, maximum chamber pressure increases, and maximum rate of heat release rates of the fuels are examined in this chapter. The CRU chamber pressure results are presented as a function of time at high and low initial chamber pressures. The heat release curves are converted to pressure rises versus time in the combustion chamber. The effects of the measured fuel properties on the above-mentioned combustion parameters are considered.

High pressure

Fig. 2 presents the CRU chamber pressure results as a function of time for the studied fuels at high initial chamber pressure. All the variables were calculated from the raw data of one measurement and the results of LFO are marked in Fig. 2. The injection duration of the fuels was identical, despite the MGO (+2.5%), but the amount of the fuel during injection varied due to the different densities of the fuels. The results of MGO are only directional due to the slightly longer main injector period. The results determined from Fig. 2 are listed in Table 3.
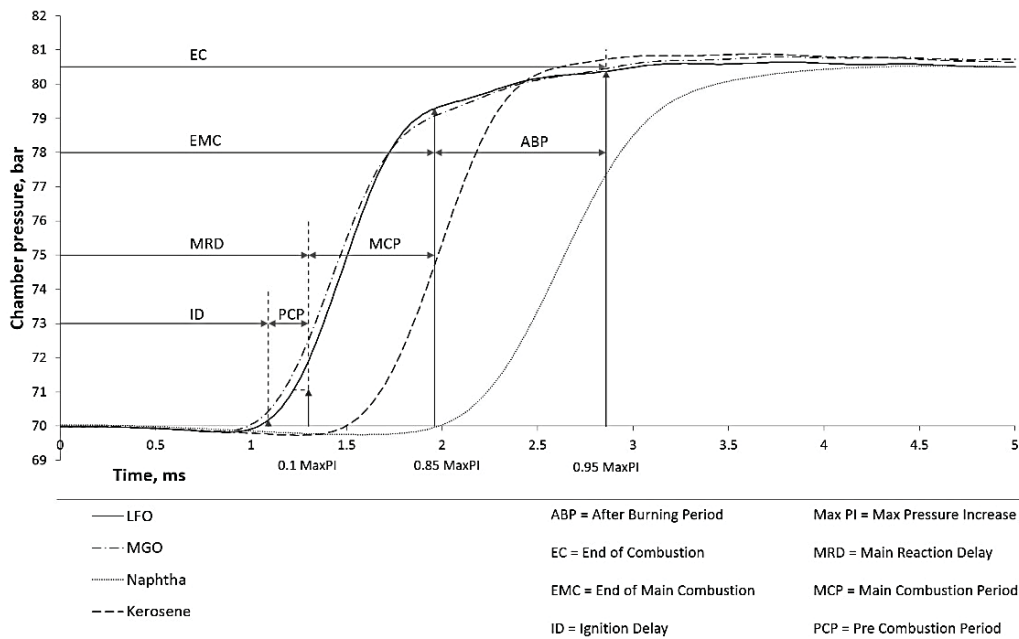

Figure 2. Chamber pressure diagram of LFO, MGO, naphtha and kerosene at high pressure.

Fig. 2 and Table 3 show that MGO had the shortest ignition delay (1.04 ms), perhaps partly due to slightly longer main injector period (MGO 1.025 ms versus other fuels' 1 ms) and significantly higher CN, as Grab-Rogalinski & Szwaja (2016) also noticed. Among other studied fuels, LFO had the shortest ID (1.08 ms), kerosene was the second (1.54 ms) and the longest ID was detected with naphtha (2.04 ms). The difference between ID of MGO and naphtha was 1.0 ms. In engine use the longer ignition

delay allows more fuel to be injected which once ignited gives a stronger pressure peak. Steenberg & Forget (2007) suggests that too strong a pressure peak may lead not only to engine damage but also to increased NOx emissions. The ignition delay period can be shortened by increasing the fuel injection pressure (Chen et al., 2013). On the other hand, Agrawal et al. (2013) noticed that too high a fuel injection pressure may lead even into too short an ignition delay. In that case, homogenous mixing may decrease and combustion efficiency reduce. Gnanasekaran et al. (2016) even noticed that the prolonged ignition delay may also be exhibited as lower smoke levels because the better mixture formation.

Table 3. CRU measurement results at high pressure

High pressure conditions		LFO	MGO	naphtha	kerosene
Ignition Delay (ID)	ms	1.08	1.04	2.04	1.54
Pre Combustion Period (PCP)	ms	0.16	0.14	0.22	0.16
Main Reaction Delay (MRD)	ms	1.24	1.18	2.26	1.7
Main Combustion Period (MCP)	ms	0.74	0.98	0.78	0.6
End of Main Combustion (EMC)	ms	1.98	2.16	3.04	2.3
After Burning Period (ABP)	ms	0.9	0.86	0.26	0.26
End of Combustion (EC)	ms	2.88	3.02	3.3	2.56
Max. Pressure Increase	bar	80.9 at 10.5 ms	81.2 at 10.3 ms	80.2 at 47.7 ms	80.9 at 10.9 ms
Max. Rate of Heat Release (MaxROHR)	bar/ms	16.3	15.2	11.7	16.2
Position of MaxROHR (PMR)	ms	1.5	1.44	2.62	2

Naphtha had a slightly higher LHV but it required more time to ignite than other fuels. Kerosene, MGO and LFO had a very similar LHV, but MGO had the shortest ID.

Despite the longer ID of kerosene, the complete combustion period (EC) of kerosene (2.56 ms) was shorter than that of LFO (2.88 ms), MGO (3.02 ms) or naphtha (3.3 ms). This can be assumed to relate to light components of kerosene that burns more rapidly than the heavier compounds of other fuels. Kerosene's lower viscosity and surface tension, compared to LFO and MGO, leads to a more rapid EC due to better fuel-air-mixing caused by smaller droplet sizes and faster vaporization characteristics (Lee et al., 2012; Agarwal et al., 2013; Chen et al., 2013). Based on Steenberg & Forget (2007) the EC may give information on the formation of combustion products and unburned or burned fuel components that affect emission, and may also relate to the formation of engine deposits and wear. The studies of Gnanasekaran et al. (2016) and Nabi et al. (2012) concerning a DI diesel engine showed that a shorter ignition delay and combustion duration results in lower heat release rate, peak pressure and rate of pressure rise.

The maximum pressure increase (Max.PI) of MGO (81.2 bar at 10.3 ms) was a slightly higher than Max.PI of kerosene (80.9 bar at 10.7 ms) and LFO (80.9 bar at 10.5 ms) but the peaks were almost equal. Naphtha had a long ID and that caused delay in the position of the peak of Max.PI (80.2 bar at 47.7 ms). Naphtha also included more heavier compounds that take time to burn and evaporate. Grab-Rogalinski & Szwaja (2016) also noticed a correlation between an ID and pressure increase.

Fig. 3 shows the heat release curves as converted to pressure rises versus time in the combustion chamber. The heat release (bar msec^{-1}) was the fastest with LFO (16.3 bar msec^{-1}) and kerosene (16.2 bar msec^{-1}). The placement of the curve against time depends on the fuel ID. The MaxROHR of naphtha was the lowest (11.7 bar msec^{-1}) and the position was delayed due to its long ID. The shape of MaxROHR curve shows that naphtha burned more slowly and the curve was not as spiky as with other fuels.
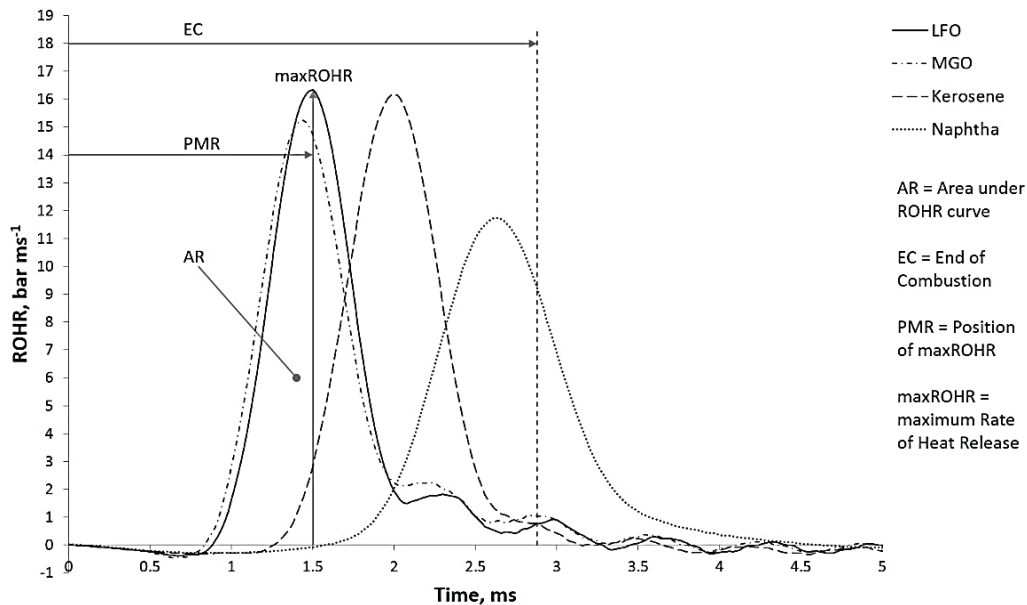

Figure 3. Rate of heat release curve of LFO, MGO, naphtha and kerosene at high pressure.

Low pressure

Fig. 4 presents the CRU chamber pressure results as a function of time for the studied fuels at low chamber pressure that was adjust at 55 bar. All the variables were calculated from the raw data of one measurement, and the results of LFO are marked in Fig. 4. The injection duration of the fuels were identical, despite the MGO (+2.5%), but the amount of the fuel during injection varied due to the different densities of the fuels.

The lower pressure conditions set higher demands for the used fuels and the differences between the research fuels were clearer. The injection temperature of the fuels was also dropped from 590 °C to 550 °C. Based on the CRU results, the fuels can roughly be divided into two groups; LFO and MGO, kerosene and naphtha.

Wood-based naphtha had almost twice as long an ID (3.20 ms) as LFO (1.76 ms) and MGO (1.74 ms). Figs 4−5 and Table 4 show that a long ID also reflected to the position of MaxROHR and the position of Max.PI. The Max.PI of naphtha (64.6 bar) was near the values of other studied fuels (LFO 65.9 bar, MGO 66.0 bar and kerosene 65.0 bar), but the slow ignition is shown in the position of Max.PI of naphtha (35.8 ms). The position of Max.PI of naphtha occurred 9.1 times later than that of LFO (3.92 ms) or MGO (3.94 ms). The study of Grab-Rogalinski & Szwaja (2016) also showed that a lower initial chamber temperature and pressure lead to worse atomization and evaporation and delayed ignition. With constant volume vessel, Bae & Kim (2016)

observed that the ID of the kerosene type JP-8 fuel (CN 38) was 25% to 50% higher compared to diesel fuel (CN 48). It was also noticed that when the CNs of the fuels meet, the difference in the ID's is no longer detected.
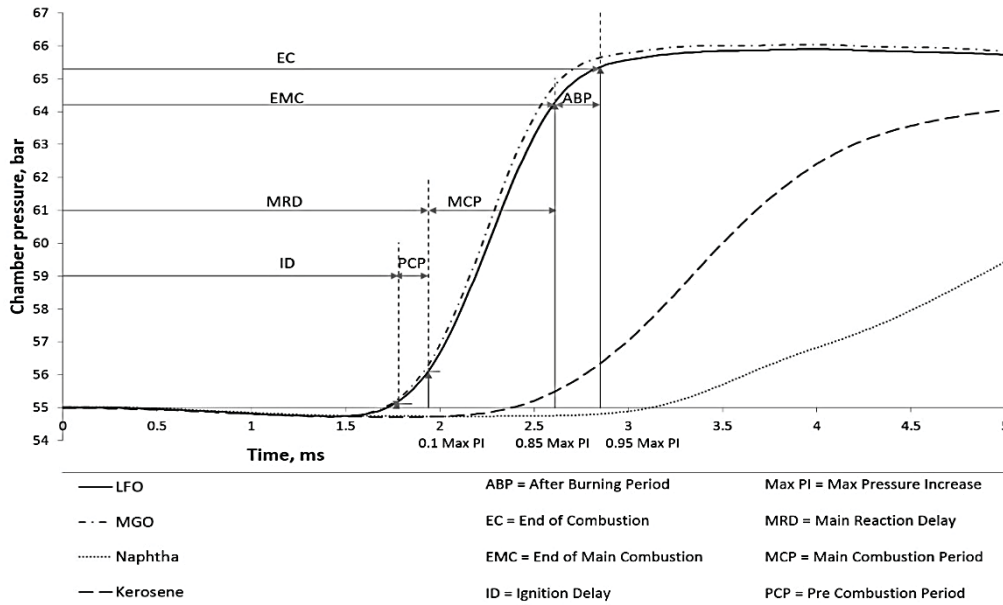

Figure 4. Chamber pressure diagram of LFO, MGO, naphtha and kerosene at low pressure.
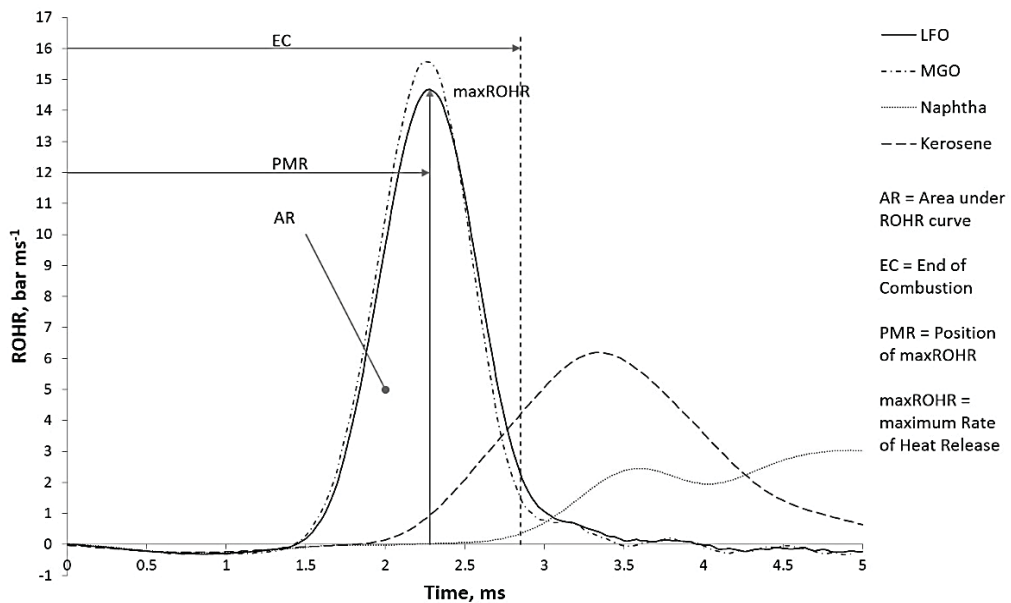

Figure 5. Rate of heat release curve of LFO, MGO, naphtha and kerosene at low pressure.

The whole combustion period (EC) was the fastest with MGO. The fast ignition and good combustion of MGO under low pressure conditions may be related to the high CN (68). In high pressure conditions, kerosene had the fastest combustion (EC), maybe due to the major amount of the light compounds in the fuel. Now, it can be assumed that the chamber pressure and the injection temperature were too low to burn the light compounds of kerosene well enough.

The MaxROHR varied more under the low than the high pressure conditions, Fig. 5. LFO and MGO burned almost similarly in both pressure conditions. MGO released heat even faster at the low (15.6 bar ms^{-1}) than high pressure (15.2 bar ms^{-1}). The MaxROHR curves of kerosene and naphtha differed considerably. The combustion was slow and the peak of the MaxROHR curve was low. The MaxROHR curve of naphtha also had a little drop at time of 4 ms. The reason might be that the light components of naphtha burned first and heavier compounds needed more time to ignite. Once the heavier compounds were also ignited, the MaxROHR reached its highest peak at 4.92 ms (3.03 bar ms^{-1}). According to Bergeron & Hallett (1989) higher mass components of a fuel have also higher ignition delay times.

Table 4. CRU measurement results at low pressure.

Low pressure conditions		LFO	MGO	naphtha	kerosene
Ignition Delay (ID)	ms	1.76	1.74	3.20	2.46
Pre Combustion Period (PCP)	ms	0.18	0.18	0.42	0.32
Main Reaction Delay (MRD)	ms	1.94	1.92	3.62	2.78
Main Combustion Period (MCP)	ms	0.68	0.64	4.26	1.72
End of Main Combustion (EMC)	ms	2.62	2.56	7.88	4.50
After Burning Period (ABP)	ms	0.24	0.22	3.92	3.84
End of Combustion (EC)	ms	2.86	2.78	11.8	8.34
Max. Pressure	bar	65.9 at 3.92 ms	66.0 at 3.94 ms	64.6 at 35.8 ms	65.0 at 12.5 ms
Max. Rate of Heat Release (MaxROHR)	bar/ms	14.7	15.6	3.03	6.19
Position of MaxROHR (PMR)	ms	2.28	2.26	4.92	3.34

Based on the received results of the CRU measurements, kerosene can be used in CI engines without or with only minor changes. The possible modifications could be starting and stopping an engine with other fuel (e.g. LFO) or the change of the nozzles to have smaller diameter holes. Based on Heywood (1988) the nozzles with smaller diameter holes improves droplet formation and may promote better combustion with a shorter ID. The low lubricity of kerosene may result in malfunction of the injection system. Lubricity improvers and additives may be required in engine use (Bae & Kim, 2016).

Naphtha in CI engine use needs other fuel for starting and stopping engine. The lower CN and lower viscosity may limit the use of naphtha as a drop-in fuel to a diesel in CI engines because the retarded start of combustion and prolonged ignition delay may cause increased NOx emissions. Fuel additives may be needed to improve the ignition i characteristics and decrease NOx emissions. (Subramanian et al., 2018).

Due to the very similar results of MGO and LFO, MGO can be used in a CI engine like LFO without any modifications to engine or injection system.

Continue of the research

The research continues with engine measurements to validate the engine operation with each fuel. At the same time, the correlation between combustion parameters from the CRU (e.g. EC, EMC, ID) and engine parameters are studied. Only few similar studies have been performed. One is the study of Steenberg & Forget (2007) where the correspondence of the Fuel Ignition Analyzer (FIA) parameters and engine parameters was examined. Good results of the correlation between the FIA and the engine combustion parameters were achieved at high loads. At low loads, poor correlation between the FIA and the engine combustion parameters was detected. It might be partly due to the differences in the test conditions between the FIA and the engine. The fuel injection in the engine was also very different and strongly affected the combustion process.

CONCLUSIONS

The quality of ignition and combustion of four marine and power plant fuels were studied in a Combustion Research Unit, CRU. The fuels were low-sulphur Light Fuel Oil (LFO, baseline), Marine Gas Oil (MGO), kerosene and renewable wood-based naphtha. The research fuels were selected to broaden the choice of alternatives of marine and power plant engine fuels.

Based on the results obtained in the study, the following conclusions could be drawn:

Under the high pressure conditions:

- MGO had the shortest ID that indicated good atomization and high CN. A good atomization provides rapid fuel-air mixing decreasing ID.

- Naphtha had the longest ID, maybe due to the high amount of heavy components of naphtha. Heavy components also affects atomization and the whole combustion process.

- Kerosene burned quickly due to its light components, lower viscosity and surface tension, and showed a short EC period. Naphtha had the longest EC which may in engine use lead to higher emissions and engine damages.

- Under the higher pressure conditions, the combustion parameters of the fuels were closer to each other than under the lower pressure conditions

Under the low pressure conditions:

- The lower chamber pressure and the lower fuel injection temperature affected clearly the combustion performance of the fuels

- Fuels could be roughly divided into two groups:

1) Straightly usable in engine without any modifications: LFO & MGO

2) Fuels that require some minor modifications (e.g. starting and stopping the engine with another fuel): kerosene and naphtha

- The long ID of naphtha and kerosene affected the positions of Max.PI curve and MaxROHR curve

- Kerosene was competitive under high pressure conditions but fell behind when the chamber pressure and injection temperature were lowered.

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