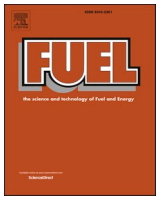
Fuel 351 (2023) 128888

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel



Full Length Article

Combustion and emission characteristics of hydrotreated pyrolysis oil on a heavy-duty engine

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ARTICLE INFO

Keywords:
Biofuel
Combustion
Engine
NOx
PM

ABSTRACT

Second-generation biofuel is promising to be applied in the field of long-haul transportation, aviation, and marine shipping. This work focuses on the ignition behavior, combustion process, and emission characteristics of hydrotreated pyrolysis oil. This biomass-derived oil was blended with marine gas oil from 10 to 30 wt% without a co-solvent or emulsifier. Tests were performed both on a combustion research unit and a commercial heavy-duty diesel engine setup. The results from the combustion research unit reveal that ignition delay increase as hydrotreated pyrolysis oil blend ratio increases at tested ambient conditions. Engine tests were first performed under factory settings at representative load/speed points based on the European stationary test cycle for benchmarking. Then start of injection and fuel pressure are varied to check the controllability and engine sensitivity of hydrotreated pyrolysis oil blends. It is shown that under engine conditions, the combustion characteristics and heat release are quite identical among hydrotreated pyrolysis oil blends and diesel. Though all cases present ultra-low particulate matter emissions, hydrotreated pyrolysis oil blends yield higher particulate matter emissions, which increase as the blend ratio increases. The particulate matter/NOx tradeoff is observed both for benchmarking tests and parameter study. The results indicate that the engine can run with HPO blends smoothly and safely without major modification.

1. Introduction

Consensus has been reached regarding the importance of reducing CO_2 emissions to relieve the greenhouse gas (GHG) effects globally. For the transportation sector, various technical routine has been investigated as potential powertrain solutions and energy carriers, such as lithium batteries, carbon-free fuels (i.e. hydrogen, ammonia), e-fuels, as well as biofuels. Biofuels are recognized to be carbon neutral and one of the most widely investigated technical solutions for their existing infrastructures and life cycle carbon-free from well to wheel. To deal with the goal of carbon neutrality and sustainable future mobility most countries and organizations have launched specific mandates for the usage of biofuels. The European Commission has launched the directive to target a minimum of 14% renewable energy percentage in the transport sector, containing at least 3.5% advanced biofuels by 2030 [1]. China also declared to generalize the compulsive usage of E10 fuel (10% ethanol in gasoline) to be a nationwide implementation by 2020 (NEA 2017) [2]. The US government announced at least 36 billion gallons of renewable fuels should be available in the market of transportation fuel by 2022 [3].

Therefore, scientific research and industrial development put significant efforts into investigating potential biofuels and their specific applications. Three generations of biofuels have been iterated based on the origins of biofuel: agricultural crop-based, non-edible biomass-

Abbreviations: **BD**, Burn duration; **COV**, Coefficient of variance; **CRU**, Combustion research unit; **CVCC**, Constant volume combustion chamber; **CR**, Compression ratio; **DFPO**, Distilled fast pyrolysis oil; **E10**, Gasoline contains 10% ethanol; **EEPS**, Engine exhaust particulate sizer; **EGR**, Exhaust gas recirculation; **EOC**, End of combustion; **EOI**, End of injection; **EU**, European union; **FPBO**, Fast pyrolysis bio-oil; **FSN**, Filtered smoke number; **GHG**, Greenhouse gases; **gIMEP**, Gross indicated mean effective pressure; **HPO**, Hydrotreated pyrolysis bio-oil; **HVO**, Hydrotreated vegetable oil; **HTHR**, High temperature heat release; **ID**, Ignition delay; **ITE**, Indicated thermal efficiency; **LTHR**, Low temperature heat release; **MGO**, Marine gas oil; **NO_x**, Nitrogen oxides; **PM**, Particulate matters; **PSFPO**, Phase separated fast pyrolysis oil; **RPM**, Rotation per minute; **RCCI**, Reactivity controlled compression ignition; **SOA**, Start of actuation timing; **SOC**, Start of combustion.

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https://doi.org/10.1016/j.fuel.2023.128888
Received 21 February 2023; Received in revised form 14 May 2023; Accepted 1 June 2023
Available online 10 June 2023

based, and micro-organism-based (non-terrestrial feedstocks) [4]. The ideal biofuels have some desired properties, such as tolerance to be able to be derived from multiple non-edible feedstocks without influencing the major physical and chemical properties significantly. The yield of biofuel should be high enough at a relatively low cost to satisfy the specific field of application. Last but not least, there should be a self-sufficient and complete industry chain for this specific biofuel.

Fast pyrolysis is an emerging technology to convert lignin-cellulosic biomass to liquid biofuel and is likely to conform the objective of carbon neutrality. At moderate temperature, the thermolysis process generally happens with a high heat transfer rate to the biomass particles and a transient hot vapor dwell in the reaction zone [5]. And the end product, fast pyrolysis bio-oil (FPBO), consists of various size molecules, which are mainly yielded via the fragmentation and depolymerization reactions of lignin, cellulose, and hemicellulose. Therefore, this method is a cost-effective and technically-feasible routine to facilitate the transition of fossil-based resources to renewable resources. The physical and chemical properties of FPBO vary slightly based on the type of recovery systems, feedstock source, and reactor configurations. Yet, the high water content (15–30%), oxygen content (35–40 wt%), viscosity (35–1000 cP at 40 °C), and corrosiveness (pH 2–3) are the shared common characteristics, which influence the combustion behavior and makes energy production and power generation on standard equipment and large-scale applications difficult [6]. To be more specific, the high corrosivity of FPBO can lead to 2.5%-6% mass loss for engine injectors when immersed in FPBO for 84 h [7].

To solve the issue of high water content in the wood-derived FPBO, Khan et al. reduced 60% water content via distillation and above 85% water content by phase separation [7]. And the storage stability, corrosivity, and energy density of FPBO were greatly improved after water removal. However, the issue of high viscosity deteriorates after water removal, leading to a viscosity 27 times larger than diesel. Moreover, shear thin was also displayed. It is therefore stated that usage of dewatered FPBO in diesel engines is limited due to the requirement of preheating and aforementioned characteristics. When emulsified with diesel, the maximum viscosity of which was determined as trinary of diesel. The authors further found surfactants like Atlox 4916 and Hyper 1599 can produce stable emulsions for FPBO. And the thermal gravimetric analysis showed that PSFBO showed 30% high carbon residue leftover, indicating a high possibility of coking. It was consequently concluded that moderate water removal should be more beneficial for the sake of application in diesel engines for electricity production. Yang et al. [8] mixed FPBO (produced from coffee bean residue) with diesel through emulsification in various ratios (0/5/10 vol%). The experiment was performed on a single-cylinder diesel engine connected to a 12 kW power generation system. The results show that the addition of 5/10 vol % FPBO increased fuel consumption at the same power output compared to pure diesel. The water content in FPBO causes increased ignition delay and decreased energy content. Yet, the NOx emissions were effectively reduced at the cost of more smoke emissions. The authors further concluded the micro explosions of FPBO droplets can enhance the combustion characteristics.

A small-scale non-generated micro gas turbine setup was utilized in [9] to investigate the FPBO/ethanol blends. Tests with 20 vol% and 50 vol% FPBO fuel blends showed successful engine operation. It was reported that CO emissions increase as the FPBO blend ratio increases, as the more viscous fuel leads to larger droplets. The increased NOx was assumed because of fuel-bounded nitrogen. The FPBO/ethanol blends achieved higher electrical efficiency than diesel as a result of more water steam in combustion and better mixing of air/fuel. The authors further performed the 100% FPBO run and claimed that the combustion was unstable with the carbonous deposit (at high temperature area) observed. The 100% FPBO fueled diesel engine (CR: 17) was also investigated in [10] at the inlet temperature of 100–120 °C. The authors reported that the inlet temperature can be reduced to 40 °C if CR increases to 22.4. It is further pointed out that increased CO and decreased NOx emissions were because of low LHV and high water content. Yet fuel economy and flue gas emissions were not heavily influenced during the 40 h of the consecutive test. Recently, a 500 h test was completed using wood-derived FPBO with 10 wt% ethanol added [11].

Fully understanding the atomization of the spray and mixing process is vital in optimizing the application of pyrolysis oil in the combustion system. Compared to CI engines and gas turbines, constant volume combustion chamber (CVCC) or burners benefit in decoupling pressure and temperature to study the ignition characteristics of a specific fuel and isolated effects of the operating parameter [28]. Researchers found that co-firing FPBO with a fossil fuel facilitates the warming-up process of combustor during the start-up to tackle the poor ignition quality of FPBO. Specifically, co-firing keeps the flame of FPBO stable and anchors FPBO flames by promoting combustion. The combined effects improve combustion efficiency, minimize carbon deposits and emissions, and prevent local extinguishment [12]. For example, Oasmaa et al.[13] reported that the combustion/flame stability of FPBO (containing 35 wt% water) improves remarkably when one-quarter of the burner's energy throughput is supplied with 25% heavy fuel oil. There were no combustor fouling or combustion issues noticed. Furthermore, the supporting heavy fuel oil also benefits in reducing PM and CO with a penalty of NOx emissions. FPBO generally shows high viscosity, high surface tension, and high density [14]. Consequently, FPBO suffers from poor atomization, carbon residues, and deposition. And fuel preheating (85–140 °C) is commonly applied with high atomization pressure. Nevertheless, this could also possibly lead to nozzle clogging, fuel polymerization, and severe fuel quality degradation [15].

FPBO benefits from adding extra solvent to maintain the viscosity in the acceptable scope (4–25cSt) [16,17]. For example, adding alcohol stabilize combustion because of prompt vaporization and heat release under the nozzle. The PM emissions decrease with a compromise of higher NOx emissions [18]. The ignition delay and combustion process of n-butanol/FPBO have been experimentally investigated in a CVCC facility [19]. 2-ethylhexyl nitrate (EHN) was also added as a cetane improver. It was observed that increasing FPBO content in the cetane-improved n-butanol/FPBO blends barely has any effects on the low temperature heat release, yet the high temperature heat release is delayed. Chamber wall temperature significantly shortens the ignition delay of the cetane-improved n-butanol/FPBO blends. With these blends, negative temperature coefficient behavior was observed in a chamber wall temperature range of 535–565 °C.

Medium and low-speed engines seem to be an ideal application scenario for FPBO for their flexibility in running on low-grade fuels. Especially in the field of marine shipping and combined heat and power process. Nevertheless, FPBO couldn't be blended with diesel or heavy fuel oil directly to serve as a drop-in fuel. Therefore, FPBO needs to be further upgraded and one option is catalytic hydrotreatment to produce a Hydrotreated Pyrolysis Oil, termed HPO. The hydrotreating of HPO typically consists of two steps: i) initial stabilization of FPBO by converting the most reactive components in the oil like carbohydrates, ketones, aldehydes, and ii) further deoxygenation of the product from the first step to obtain the drop-in fuel [20]. Both steps are carried out in a hydrogen atmosphere at high pressure and in the presence of a catalyst. Depending on the specific requirements of the application scenario, the method and process of upgrading varies. During the hydro-treatment process, conditions like residence time, H_2 pressure, temperature, and type of catalyst can be adjusted to control the fuel properties and qualities.

The pyrolysis oil feedstock is tolerant to multiple biomass resources such as roadside grass, wood residues, and so on. The initially produced small batch of HPO was investigated in [21], including viscosity and combustion properties. Five different HVO/HPO fuels are tested and benchmarked with diesel, MGO, FAME, and HVO. Under the CVCC ambient conditions, the ignition delay time is characterized by the ordering HPO > diesel-like fuels > HVO. When blended with a 75 vol% HPO ratio, the HVO/HPO blends present identical combustion

characteristics and heat release processes to diesel. The viscosity of HVO/HPO and diesel are quite similar, indicating potential usage as a drop-in fuel in modern engines.

The above-mentioned literature has shown HPO's potential as a carbon–neutral alternative fuel to enable high CO_2 reduction in challenging application fields. Yet, the research gap remains in the implementation of blended HPO fuels with commercial fuels in a heavy-duty engine without a co-solvent or emulsifier. This work further explores the utilization of HPO derived from softwood as drop-in fuels in the field of marine powertrain application. The major objective of this work is to evaluate the ignition behavior, combustion process, and engine-out emission characteristics of HPO as a drop-in fuel. The blends (up to 30 wt%) are extensively tested in a CVCC facility and a commercially available heavy-duty diesel engine in various operating loads/speeds and ambient conditions. With an intention to investigate retrofitting the engine without any modification, the engine operating condition remains at the factory setting without EGR. Then, the injecting-related parameters such as injection timing and pressure are varied to investigate the responsiveness of HPO and controllability.

2. Methodology

In this work, HPO is blended with MGO from 10 to 30 wt% and tested on the combustion research unit (CRU) and a heavy-duty diesel engine. They are named 10HPO, 20HPO, and 30HPO specifically. The HPO was produced by BTG using wood-derived FPBO as raw material. Subsequently, the FPBO was stabilized at 200 bar in the presence of a BTG proprietary catalyst (Picula™) and further hydrotreated using a sulphided CoMo catalyst. To increase the flashpoint, a light fraction was removed from the product by evaporation (~20 wt%). The remaining HPO product was used in the combustion and engine testing. The experimental investigation starts with the combustion properties tests on CRU, intending to reproduce the cylinder ambient condition of an HD diesel engine after compression stroke as closely as possible. Therefore, the chamber temperature is set from 575 °C up to 750 °C (maximum) in step of 25 °C, and the chamber pressure is fixed at 50 bar without EGR. A single injection is applied with an injection pressure of 1500 bar (quite identical to the engine settings at 30% load at A speed) and a duration of 1.0 ms. The aforementioned CRU test settings are identical for all measurements (10HPO, 20HPO, 30HPO, Diesel).

The investigation continues with engine tests at various load/speed combinations. To begin with, HPO fuel blends are benchmarked with B7 diesel in accordance with the European stationary test cycle at default OEM calibration. To explore the load/speed range of HPO fuels, three regular truck cruise speeds (A, B, C) are selected from low to high load (30%, 50%, 70% of max load), leading to 8 measure points in total displayed in Table 1. These selected loads are the most interesting and representative points in the mapping. Due to limited fuel production, 10HPO only covers A30, A50, and A70. While 20HPO and 30HPO cover all 8 measure points. Then, injection-related parameters such as the start of actuation timing (SOA) and fuel pressure are adjusted at A30 for all four fuels to investigate the controllability and response of these HPO drop-in fuels.

2.1. Combustion research unit

The combustion research unit (CRU) is a combustion system based on well-established CVCC technology to investigate the effects of chamber pressure (10–50 bar), temperature (300–750 °C), injection pressure (200–1600 bar), and injection strategy on ignition separately. The aforementioned ambient conditions are statically maintainable and realized by supplying the chamber with pressurized external synthetic air and nitrogen. It can be noticed from the schematic design in Fig. 1 that, both nitrogen and air pipes are connected to the bottom and controlled by the operating system to achieve specific oxygen concentration and chamber pressure (accuracy: within ± 3 bar). Two chamber heaters are located both at the upper and lower area of CRU chamber for a precise and uniform temperature distribution (accuracy: within ± 1 °C). The fuel of interest is injected directly from the top center of the chamber via Bosch CRIP2 DI injector (sac volume: 0.23 mm^3, 7 nozzle holes diameter: 0.139, spray angle: 159 °C), with the flexibility of tuning injection strategy. Multiple injections, injection pressure, and duration (100–1500 μs) can be customized based on study requirements. The detailed information and operating specifications of CRU can be found in [22].

A representative of the chamber pressure profile as a function of time is demonstrated in Fig. 2. After the injection signal, the pressure trace is sampled and recorded by CRU software in a period of 47 ms. According to the ASTM D7668-17 standard, the timing of 0.2 bar pressure increase is referred to as the start of combustion (SOC). And combustion is ended (EOC) when 95% maximum chamber pressure is reached. Therefore, the CRU ignition delay time (ID) can be referred to the period between injection timing to SOC, while CRU burn duration (BD) is defined as the time interval from SOC to EOC. More details about CRU definition can be found in [23].

2.2. Engine test rig

The engine experiments were carried out in an HD diesel engine test rig, named Goliath. It is a single cylinder research test bench, modified from a HD 6-cylinder engine. As is shown in Fig. 3, the remaining 5 cylinders are disabled. Therefore, brake power or efficiency is not relevant to this engine layout. The detailed engine specifications are listed in Table 2. The crankshaft is connected to and driven by an electric motor. Inlet air is supplied by external compressed air up to 8 bar. A pressure regulator is mounted so that desired pressure can be achieved. Exhaust gas can be redirected and cooled, then mixed with fresh air. The definition of exhaust gas recirculation (EGR) in this work is the CO_2 concentration ratio between the inlet and exhaust. The temperature of inlet air can be regulated by an external heater so that a stable ambient temperature is maintained. The pressurized fuel is delivered by common rail and directly injected by a Delphi DFI2 injector. PM emissions are detected by AVL 415s smoke meter as filtered smoke number (FSN) and converted to PM_{mass} by Equation (1). Gaseous emissions such as NOx, HC, and CO are detected by Horiba Mexa-7100DEGR. In addition, engine exhaust particle size distribution (EEPS) is also equipped for particle size concentration distribution detection. In each measurement, 200 cycles are sampled and recorded by TU/e in-house code, during

Table 1
Operating parameters.

	Unit	A30	A50	A70	B30	B50	B70	C30	C50
Load	[%]	30	50	70	30	50	70	30	50
Speed	rpm	1200	1200	1200	1425	1425	1425	1700	1700
EGR	[%]	0	0	0	0	0	0	0	0
Inlet pressure	[bar]	1.61	2.3	2.83	1.63	2.42	2.87	1.54	2.57
Back pressure	[bar]	1.77	2.67	3.16	1.92	2.75	3.16	1.83	2.96
Inlet Temp	[°C]	43	43	47	49	54	54	46	50
Injection	[°CA aTDC]	−5.8	−4.5	−4.3	−8.8	−11.2	−8.4	−5.8	−5
Fuel Pressure	[bar]	1557	1904	1931	1644	1735	1793	1754	1784

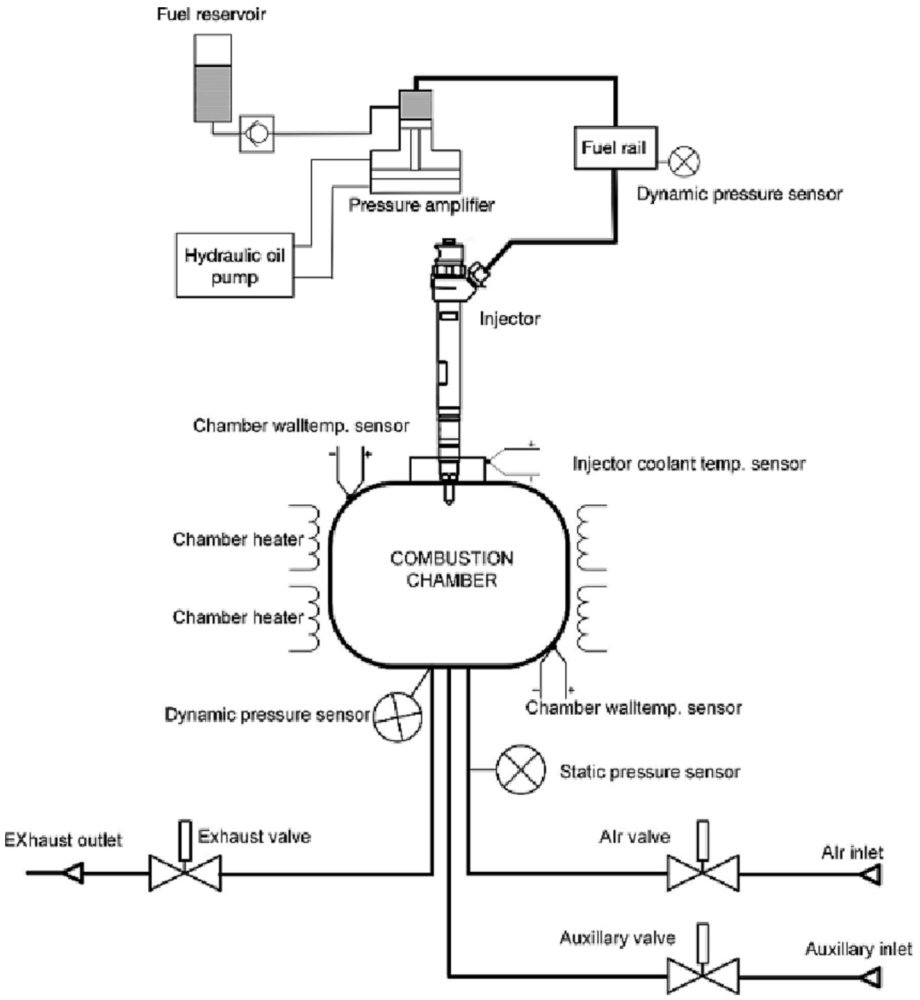

Fig. 1. Schematics of the combustion research unit.

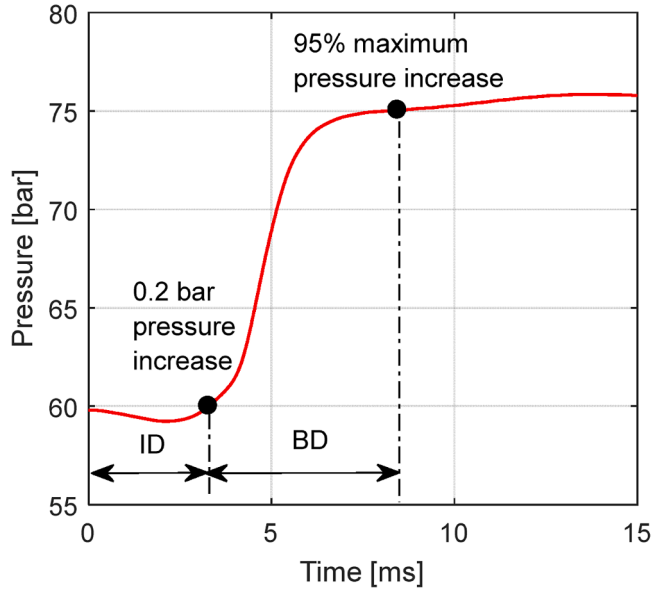

Fig. 2. Pressure trace after injection as a function of time. The definition of ID and BD is displayed.

which slow-data such as inlet-related parameters of the engine-out exhaust are also recorded.

$$PM_{mass} = 4.95/0.405 \times FSN \times e^{0.38 \times FSN} \quad (1)$$

$$gIMEP = \frac{\int_{-180}^{180} P \times dV}{V_d} \quad (2)$$

$$ROHR = \frac{\gamma}{\gamma - 1} P \frac{\partial V}{\partial \theta} + \frac{1}{\gamma - 1} V \frac{\partial p}{\partial \theta} \quad (3)$$

The engine load represented by gross indicated mean effective pressure (gIMEP) can be calculated by Equation (2), where P stands for the in-cylinder pressure and V stands for cylinder volume. Each measurement records a consecutive 200 cycles of cylinder pressure, the mean value is further filtered for post-process. To retain the authentic information, the cylinder pressure signal is filtered by a 4-point moving average as well as a 10th-order low-pass filter (cutoff frequency: 2500 Hz). The rate of heat release (ROHR) Equation (3), where θ is crank angle and γ is specific heat ratio. γ is determined by using the NASA polynomials.

2.3. Investigated fuels

The investigated hydrotreated pyrolysis oil (HPO) was provided by BTG [20], and its properties are given in Table 3. Since the ambition of the work is to have biofuel added in the commercial fuel up to at least 30% for marine application, the HPO is blended with marine gas oil

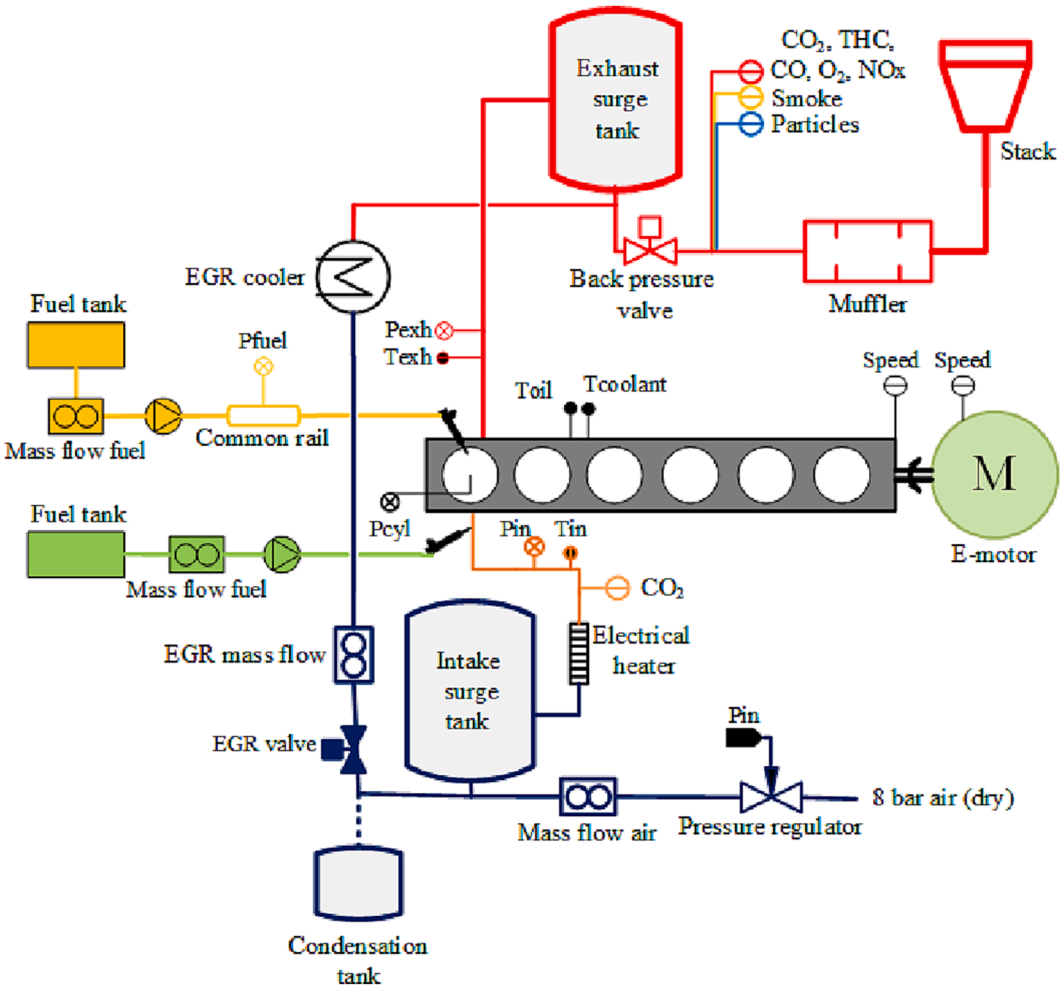

Fig. 3. Schematics of engine setup (Goliath).

Table 2
Engine specifications.

Base engine	
Stroke	158 mm
Bore	130 mm
Displacement	2.15L
Connecting Rod	266.7 mm
Compression ratio	17.2:1
Number of Valves	4
Cylinder head	Low swirl
Piston shape	Double step
Exhaust valve close (EVC)	−359°CA
Intake valve close (IVC)	−174°CA
Exhaust valve open (EVO)	146°CA
Intake valve open (IVO)	357°CA

Table 3
Fuel properties.

Property	HPO	MGO	Diesel
C [wt%]	86.2	NA	NA
H [wt%]	11.9	NA	NA
N [wt%]	0	NA	NA
O (balance) [wt%]	1.9	NA	NA
Density [kg/L]	0.906	0.85	0.83
Kinematic Viscosity [cSt]	2.6	2.6	2.56
Carbon Residue (MCRT) [wt%]	<0.1	NA	NA
Water content [wt%]	0.2	NA	NA
Acidity [mg KOH/g]	<0.1	NA	NA
Flashpoint [°C]	63	60	59
Lower Heating Value [MJ/kg]	42.2	42.7	43
Oxidation Stability [min]	190	NA	NA
Ash content [wt%]	<0.01	NA	NA

(MGO) from 10% to 30% by weight and named 10HPO, 20HPO, 30HPO, and commercial B7 diesel (which contains 7% bio-component) is also tested for benchmarking and reference.

3. Results and discussions

3.1. Combustion properties from CRU

Fig. 4 illustrates the combustion characteristics of HPO/MGO at various wall temperatures. Though the ID differences among the tested fuel are quite small under CRU conditions, the addition of HPO does increase the ID. It can be seen that the ID becomes longer at a higher blend ratio. Yet, keep in mind that this is the wall temperature and the ambient air temperature in the center of CRU is expected to be around 50 °C lower than the set wall temperature [24]. Since the real bulk gas temperature in an engine condition would be much higher than that of CRU, the ID differences are also expected to be even smaller. Although the ID of diesel also decreases from 0.92 to 0.38 ms as the wall temperature increases from 575 to 750 °C, it overlaps with the ID of HPO blends. This is possibly caused by ID differences between diesel and MGO. The burn duration of tested fuels is listed in Fig. 4b. It is seen that the BD decreases as the blend ratio increases for all fuels in general. While BD increases at high wall temperatures. For example, the BD of

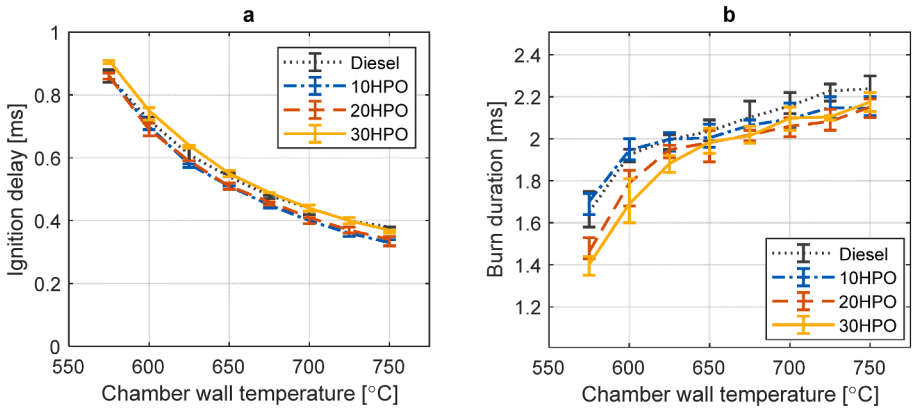

Fig. 4. ID (a) and BD (b) of HPO/MGO blends from CRU as a function of chamber wall temperature.

30HPO increases from 1.4 to 2.18 ms. This is related to the premixed combustion phasing due to different ID times, which will be elaborated on later in the section.

Fig. 5 compares the pressure and pressure rise rate (PRR) of HPO/MGO in CRU at high temperature cases. The pressure peak of HPO/MGO after combustion is lower than that of diesel, which is due to the energy density of base fuel MGO (42.7 MJ/kg) lower than diesel (43 MJ/kg). Furthermore, the pressure rise rate curves show a typical diffusive combustion, consisting of a premixed heat release and a mixing-controlled peak. The first premixed peak increases while the second mixing-controlled peak decreases at a higher HPO blend ratio due to a longer mixing time. Similarly, the same trend is noticed in Fig. 6 for the PRR of HPO/MGO when chamber wall temperature varies. As the chamber temperature decreases, the first premixed peak increases, and the dual-peak merges into unimodal because of elongated mixing time. Given that heat release profiles show strong dependency on ignition delay, any of the aforementioned parameters alone or in combination that strongly influents ID can have a significant effect on the combustion rate and heat release process. Interestingly, the chamber pressure peak increases at a lower chamber temperature. This is assumed due to the result of increased air density since the chamber pressure was kept constant at 50 bar for all cases. Therefore, the combustion process is expected to be more complete, and more heat is released.

3.2. Engine combustion and emission benchmarking

This session discusses the benchmarking tests of HPO/MGO fuels. Three typical cruise engine speeds (A, B, and C) and three (30%, 50%, and 70%) load cases are selected based on ESC. The default OEM engine calibration is applied throughout these aforementioned 8 test points for the sake of investigating possibilities of retrofitting commercial diesel engines without any modification both on engine hardware and calibration. It is noteworthy that EGR is not applied for all engine tests. For one thing, it is the intention to keep both CRU and engine settings alike. For another, the EGR valve of the current engine test rig is not fully functional. Fig. 7 compares the cylinder pressure and ROHR plots among diesel and HPO fuel blends at various load combinations. HPO/MGO blends show an identical combustion process as diesel at the same operating conditions. Specifically, both cylinder pressure and ROHR profiles of different blend ratios show similar shape as well as peak values. Comparing the cases of B50 and A30, the peak cylinder of cylinder pressure and ROHR increase at higher load as a result of more fuel

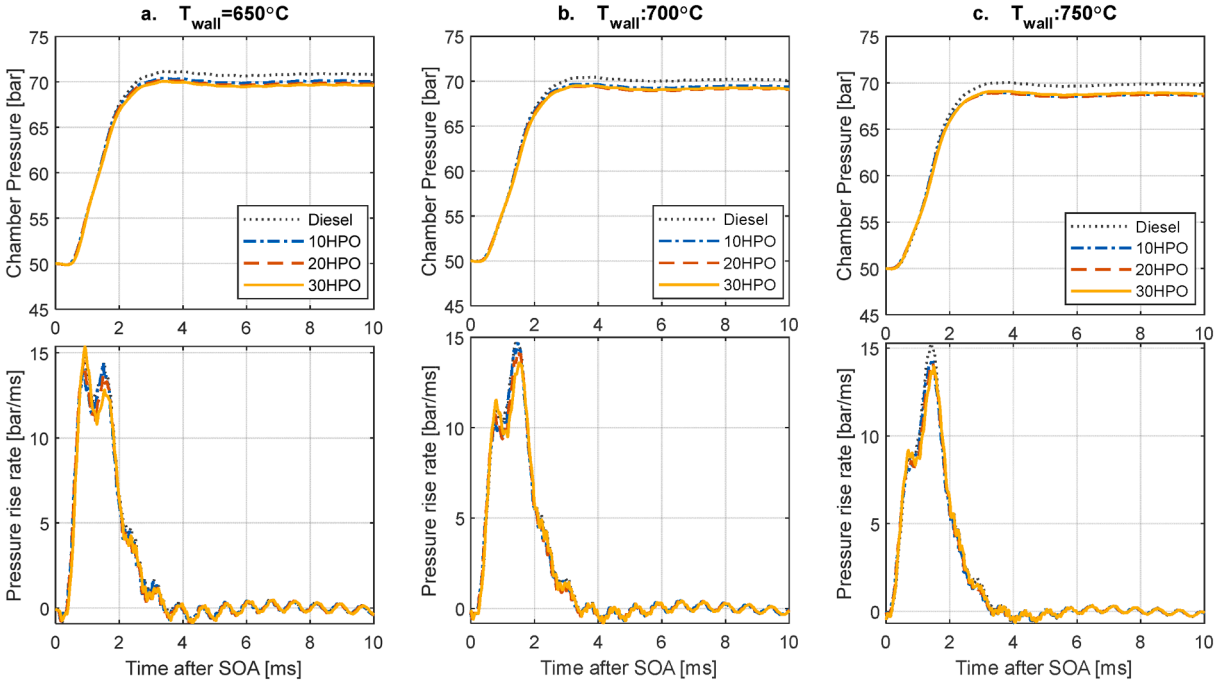

Fig. 5. Chamber pressure and PRR of HPO/MGO from CRU at various blend ratios (50 bar chamber pressure).

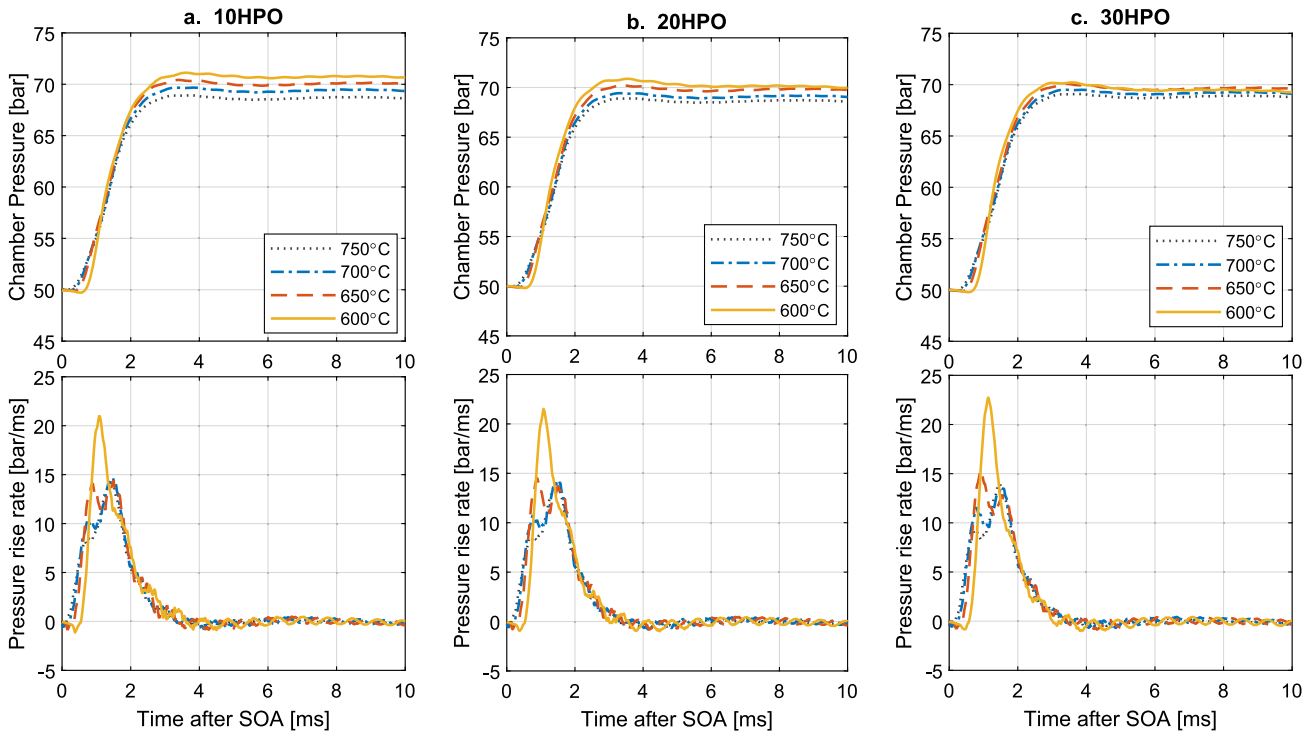

Fig. 6. Pressure and PRR of HPO/MGO at various wall temperatures (50 bar chamber pressure).

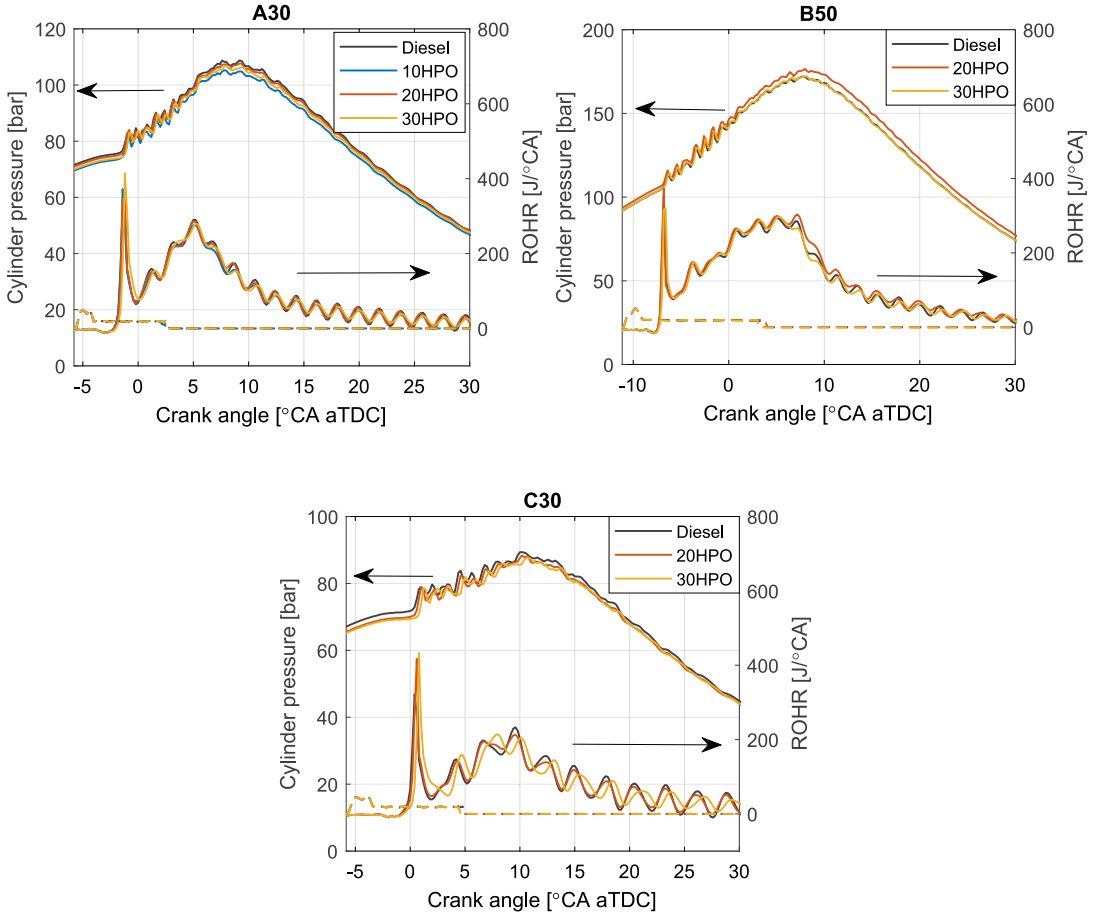

Fig. 7. Cylinder pressure and ROHR at different load/speed combinations.

being injected and more advanced injection timing. The minor differences in the cylinder pressure curves before the combustion at the same load are due to the variances of inlet boosting pressures. This is a result of control issues which leads to drift on the inlet air pressure settings. Therefore, after the compression stroke, the cylinder pressure differs marginally even before the combustion starts. Typical diesel heat release patterns are noticed for all tested fuels, both premixed peak and mixing-controlled combustion peak are observed. The HPO/MGO fuel blends yield a slightly higher premixed peak than diesel. All these observations actually indicate that the application of HPO as the drop-in fuel is viable since no further recalibration is necessary to achieve comparable engine performance and combustion process.

Fig. 8 further illustrates the important combustion characteristics of HPO/MGO fuel blends. The ID generally increases at high loads due to the more advanced injection timing, at which the ambient pressure and temperature are lower. The ID differences among the different HPO blend ratios and pure diesel are negligible. Similarly, the HPO blend ratio barely has any visible effects on CA50 (the centroid of combustion referred to combustion phasing, 50% heat released), as shown in Fig. 8 (middle). The burn duration, defined as the time interval between the CA10 (10% heat released) and CA90 (90% heat released), however, is load specific. And multiple parameters such as injection duration, ambient conditions, injection timing/pressures, etc. can exert significant influence. As is shown in the right of Fig. 8, the results indicate no consistent trend can be seen between the blends and diesel at different loads and speeds. This is due to both injection and intake-related parameters being different as specific load and speed combination change, which influences the ignition and combustion process. Interestingly, it also shows that the BD increases in higher HPO blend ratio cases. Since the ID and CA50 are identical for all tested fuels, it is presumed that the addition of HPO extends the burn-out (i.e. late) stage of heat release.

The PRRmax and COV of gIMEP are shown in Fig. 9. These two parameters are important parameters of engine robustness, operating smoothness, and noise level. The threshold of PRRmax should be 15 bar/^{o}CA while that of COV_{gIMEP} should be 5% [29]. And it is clearly shown in Fig. 9 that both PRR and COV_{gIMEP} are well below the thresholds, indicating that a smooth engine operating on HPO is feasible.

Carbon monoxide and unburnt hydrocarbon emissions are negligible for all tested fuels and not discussed in this work. This is expected as these fuels are diesel-like and the engine is running in a typical mixing-controlled combustion regime. Fig. 10 compares the engine-out ISPM and ISNOx emissions at various loads and speeds for diesel and HPO/MGO blends. It can be seen that the HPO addition yields more PM emissions than diesel. And PM emissions increase as the HPO blend ratio increases. This is possibly due to the aromatic component that existed in HPO, which contributes to the formation of the so-called soot precursors, polycyclic aromatic hydrocarbons (PAH). This is reported in many studies that though aromatic hydrocarbon presents low reactivity and extends the ignition, they tend to form more soot emissions and larger particulate matter in size [25–27]. Furthermore, though sufficient carbon burnout is expected under engine conditions, the self-contained ash particle content (due to the repolymerization of organic compounds) from HPO is still likely to form particulate [12]. Nevertheless, the overall engine-out PM emissions are quite low and close to the detecting limits of the AVL smoke meter. Except for the 30HPO case at the C30 test point, which yields a PM emission of 0.013 g/kWh. It exceeds the EURO VI standard (0.01 g/kWh), while all other measurements are well below the EURO VI standard. The overall low PM emissions are mostly due to the high injection pressure which benefits the atomization and fuel/air mixing. The ISNOx emissions on the other hand are quite high, and it generally decreases at a high HPO blend ratio. Specifically, the ISNOx emissions are above 10 g/kWh at A/B speed and above 6 g/kWh at C speed. It is worth noting that these are engine-out emissions and no EGR was applied during the test. The ISNOx emissions are expected to decrease remarkably with the EGR rate at the cost of more PM emissions [30]. Nevertheless, considering the negligible engine-out ISPM level, the application of EGR is assumed not to be a great concern. In general, the presented results indicate the HPO addition leads to a tradeoff effect on the PM and NOx emissions similar to that of diesel.

3.3. *Effects of injection timing and fuel pressures*

This section discusses how HPO/MGO fuel blends behave when injection-related parameters change. And the controllability and responsiveness of the engine fueled with HPO/MGO blends will be further illustrated. It is illustrated in Fig. 11a that 30HPO responds quite well to the start of injection timing (SOA). The cylinder pressure profile shifts right, and peak pressure decreases at a retarded SOA. Similarly, the premixed peak of ROHR decreases at late SOA. This is due to the enhanced pressure and temperature at a late SOA (the piston moves closer to the TDC), therefore less time for fuel/air mixing. Fig. 11b shows the effects of fuel pressure on the combustion process of 20HPO. It has to be noted that SOA and load were kept the same during the injection pressure sweep tests. Therefore, injection duration has to be shortened to keep gIMEP identical, as is shown in the injector current (dashed

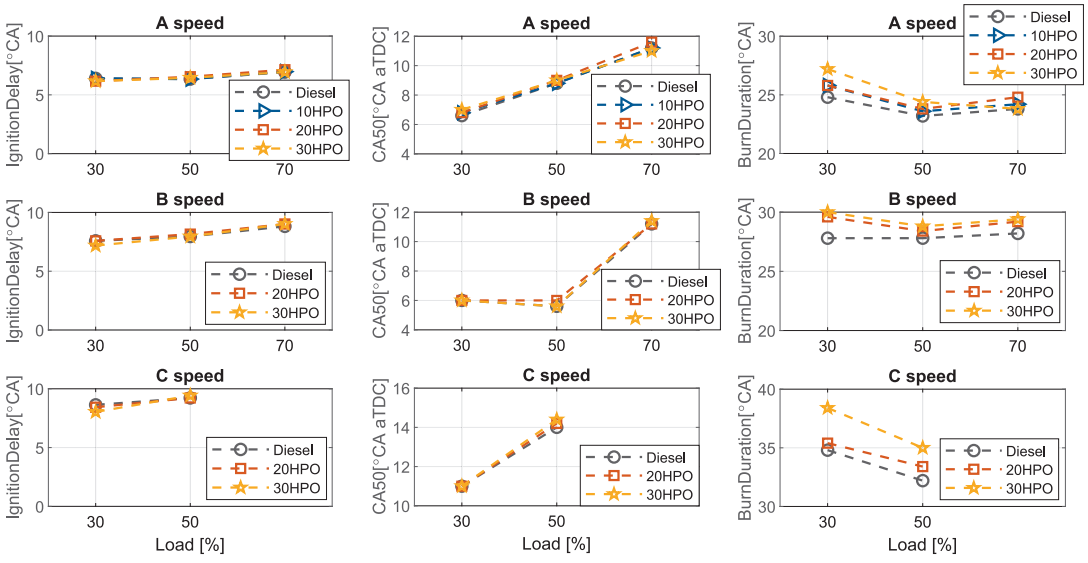

Fig. 8. ID (left), CA50 (middle), and BD (right) of HPO blends at various conditions.

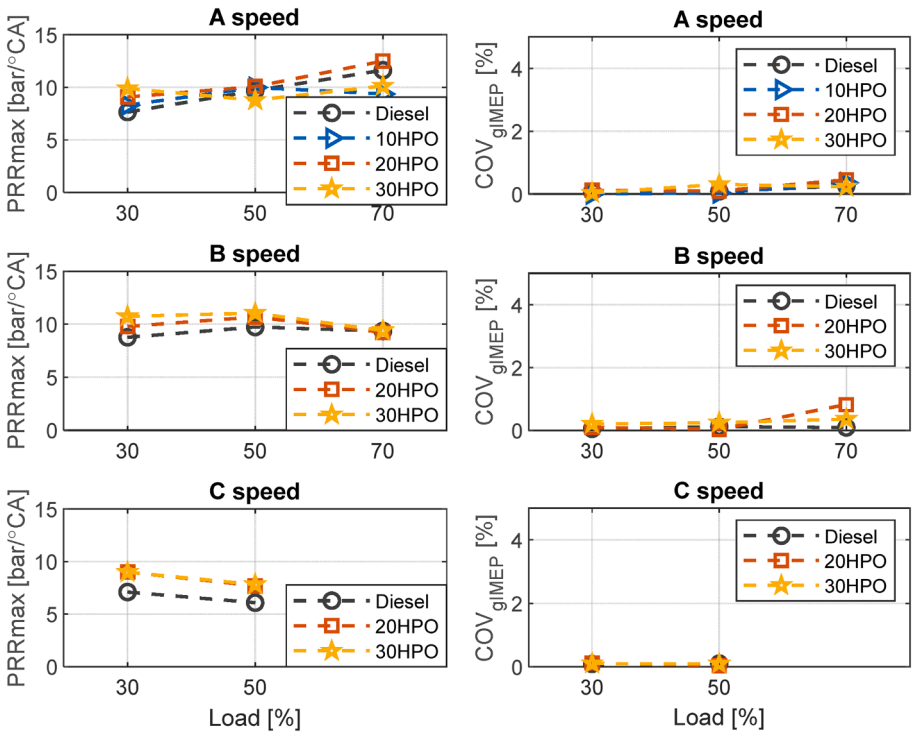

Fig. 9. PRRmax (left) and COV_{gIMEP} (right) of HPO fuel blends.

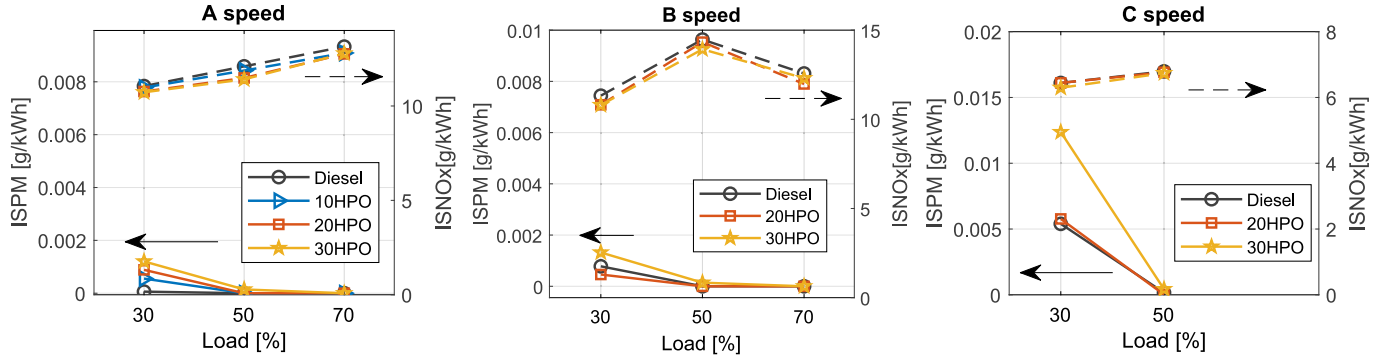

Fig. 10. ISPM and ISNOx as a function of load.

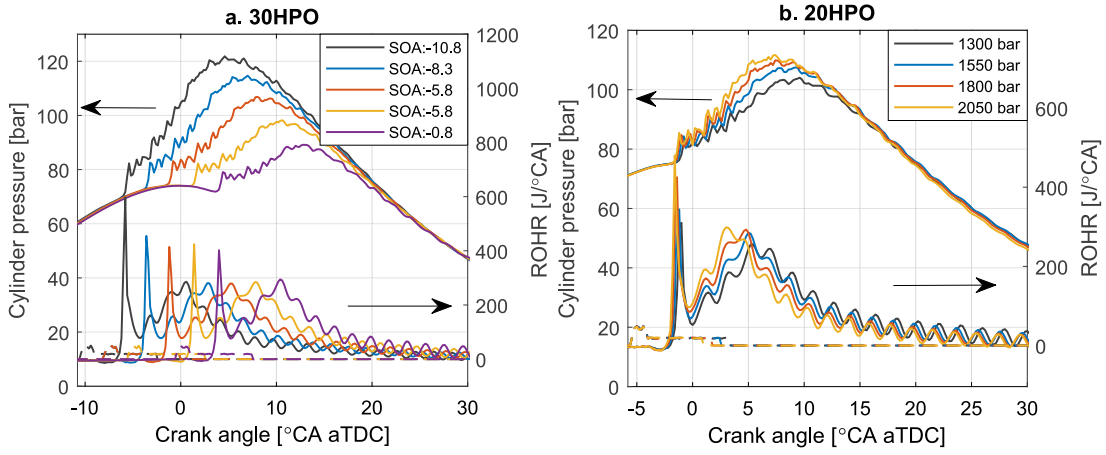

Fig. 11. Cylinder pressure and ROHR at various injection timing and fuel pressure at A30.

lines) in Fig. 11b. Apparently, the premixed peak decreases as fuel pressure decreases. This is a result of the decreased amount of fuel mixed with air, therefore, less premixed combustion is observed. The right shift of cylinder pressure indicates the whole heat release profile delays at lower fuel pressure. And this is fully validated by the variation of CA50 in Fig. 12. Linear correlations can be seen for both SOA and injection pressure. The different slopes just indicate that CA50 is far more responsive to the variation of SOA than to the variation of injection pressure, and this is again identical for diesel and HPO/MGO fuel blends.

Fig. 13 presents the effects of SOA and fuel pressure on emissions: ISPM and ISNOx. Though PM emissions are quite low in both of these cases, it can be seen that ISPM increases with later injection and decreases with higher fuel pressure regardless of the fuel type. As mentioned earlier, the combustion phasing becomes more retarded at a late SOA, which decreases the local combustion temperature. Therefore, PM oxidation deteriorates and thus PM emissions increase while NOx formation decreases. On the contrary, the increased fuel pressure advances the whole combustion phasing closer to TDC, leading to higher local temperatures. Moreover, the fuel atomization improves at higher injection pressure, which enables more air entrainment [25]. Hence, the combined effects of less PM formation and improved PM oxidation result in less engine-out PM emissions. Yet, the advanced combustion phasing at a high fuel pressure leads to higher NOx emissions (because of higher combustion temperature). The presented results indicate both the SOA and injection pressure variations lead to the known PM/NOx tradeoff, regardless of fuel type. The HPO addition only shows some minor effects on the PM and NOx emissions and does not break or offset the tradeoff. Similar to the emission in the previous benchmarking session, the PM emission increases at high HPO blend ratios while NOx shows the opposite trend.

4. Conclusions

In this work, a combustion research unit and a heavy-duty diesel engine setup are applied to evaluate the combustion and emission characteristics of hydrotreated pyrolysis oil in great detail. In order to investigate the implementation in marine powertrains, hydrotreated pyrolysis oil is blended with marine gas oil from 10 to 30 wt% and benchmarked against diesel in the aforementioned two facilities. The study starts with ignition delay tests at different chamber wall temperatures at the combustion research unit and is followed by the engine benchmarking tests at various load/speed combinations as defined in the European Stationary Test Cycle. The major findings from this study can be formulated as following conclusions:

1. With the combustion research unit, the ignition delay of hydrotreated pyrolysis oil blends shows similar values as diesel. The ignition delay elongates at a high blend ratio and low chamber wall temperature. Burn duration generally increases as chamber wall temperature decreases for all tested fuels due to increased mixing-controlled combustion phasing.
2. From 575 to 750 °C, the combustion is mainly mixing-controlled, and a typical diesel combustion mode is observed, namely a premixed peak and mixing-controlled peak. The premixed peak generally becomes more significant at a high blend ratio and low chamber temperature.
3. At default engine calibration settings, the hydrotreated pyrolysis oil blends show identical ignition delay, combustion phasing, and burn duration as diesel. Both heat release rate and cylinder pressure profiles of hydrotreated pyrolysis oil blends are quite similar to those of diesel as well. Increasing the hydrotreated pyrolysis oil blend ratio does not show significant effects on combustion characteristics and processes from low to high speed/load combinations.
4. Both PRRmax and COV_{gIMEP} are well below the safety threshold when the engine is running with hydrotreated pyrolysis oil blends. When running without exhaust gas recirculation, both diesel and hydrotreated pyrolysis oil blends yield ultra-low engine-out particulate matter emissions. Yet, particulate matter emissions increase while the NOx emissions decrease as the hydrotreated pyrolysis oil blend ratio increases.
5. When fueled with hydrotreated pyrolysis oil blends, good controllability and response of the combustion process are noticed when injection timing and fuel pressure are varied. Tradeoff among particulate matter/NOx emissions is shown for both hydrotreated pyrolysis oil blends and diesel. The engine-out NOx emissions are expected to decrease substantially when exhaust gas recirculation is applied.

In the foreseeable future, medium and slow-speed engines will serve as powertrains for marine powertrains for their proven merits and especially tolerance for fuel flexibility with minor or even no change on the engine itself. The presented results and discussion will be of interest to decrease life-cycle CO_2 emissions in the shipping industry. It also provides a deeper insight into fueling the engine with second-generation biofuels to contribute to a sustainable energy-carrier transition. The engine can be operated safely and smoothly with up to 30 wt% hydrotreated pyrolysis oil addition without a major influence on combustion and emission characteristics. This work also demonstrates that no major engine recalibration or engine hardware modification is required when a low and medium percentage of hydrotreated pyrolysis oil is blended with commercial fuel. Future work will focus on the even higher

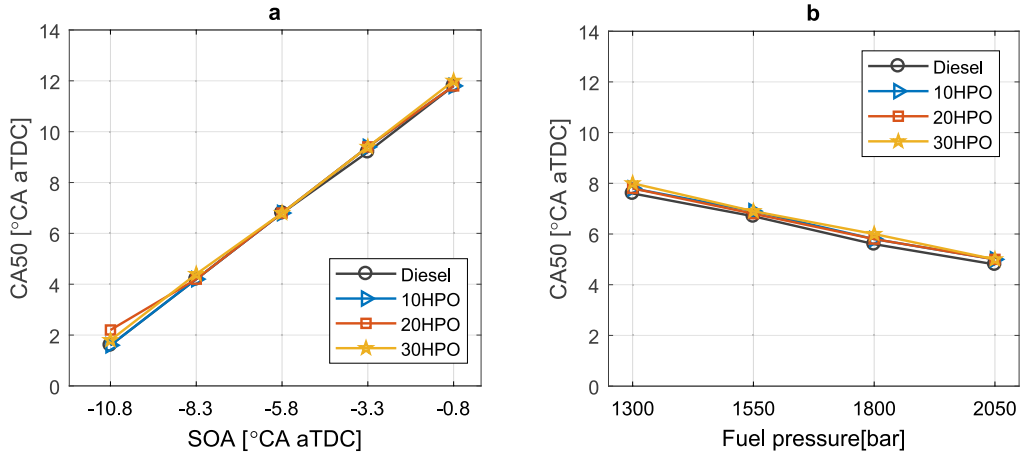

Fig. 12. CA50 as a function of injection timing and fuel pressure.

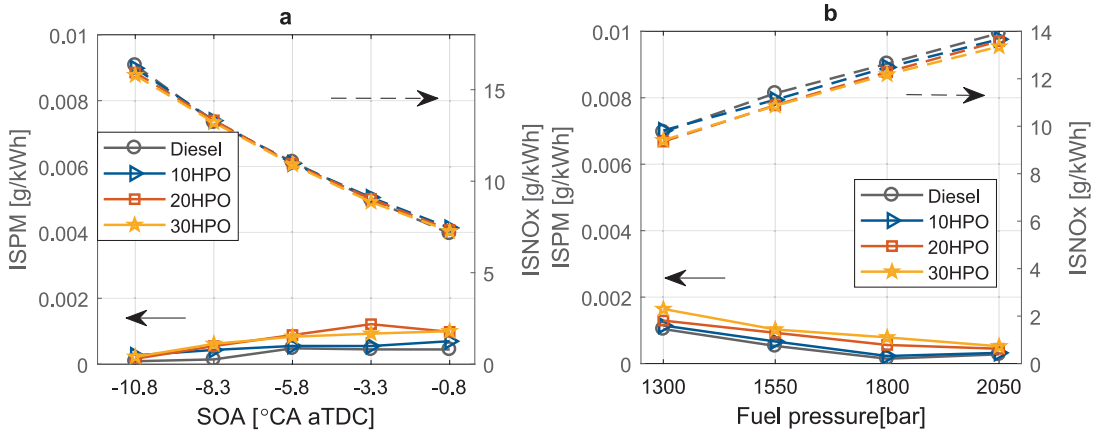

Fig. 13. ISPM and ISNOx as a function of injection timing and fuel pressure.

hydrotreated pyrolysis oil blend ratios (i.e. 50 wt%) and engine tests with moderate exhaust gas recirculation rate and particle size concentration analysis are required as well for a comprehensive evaluation. The combustion properties of the hydrotreated pyrolysis oil can be further improved by reducing the aromatic content. It will result in a reduction of the ignition delay and the particle emissions. Moreover, the density will be well below 0.9 kg/L and an increase in heating value is expected. The resulting hydrotreated pyrolysis oil will likely qualify as a drop-in, distillate marine fuel.

CRediT authorship contribution statement

Jinlin Han: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **L.M.T. Somers:** Supervision, Methodology, Software, Writing – review & editing. **Bert van de Beld:** Funding acquisition, Project administration, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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