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Investigation of combustion and spray of biowaste based fuel and diesel blends

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ABSTRACT

An alternative source of biofuels is through the use of biowaste, as an estimated 20 million dry tons of volatile organic compounds is deposited in U.S. municipal wastewaters every year. Most of the energy content is not recovered, though biowaste is theoretically a colossal source of renewable energy. Biocrude diesel can be converted from wet biowaste via a process called hydrothermal liquefaction (HTL), which can be created from various feedstocks such as algae, swine manure, and food processing waste. Previous experiments were conducted in a single-cylinder diesel engine used a diesel blend consisting of 10% and 20% HTL fuel. Preliminary results showed that the HTL blends had roughly similar power and emissions in comparison to pure diesel. In order to fully understand what the spray and combustion is like, it is necessary to study these mixtures in a constant volume chamber. The experiments were conducted at different temperatures and atmospheric conditions, revealing that the HTL blends has similar combustion and soot characteristics when compared to diesel. The HTL blends has roughly the same amount of apparent heat release rate and combustion pressure as diesel and performs better under low oxygen concentrations. The HTL fuel blends resulted in a shorter spray penetration length of HTL fuel than pure diesel, though showed more soot emissions.

1. Introduction

According to the Department of Energy's Vehicle Technology Office, approximately 69% of U.S. petroleum use in 2018 was from the transportation sector [1]. Improving the efficiency of vehicles is essential for minimizing pollution, as transportation accounts for more than 26% of the country's greenhouse gas emissions [2]. Furthermore, it is necessary to increase energy security and support domestic industries, as almost 10 million barrels of oil is imported each day [1]. Thus, interest has grown in renewable biofuels for the use in internal combustion (IC) engines [3]. These various biofuels, such as *n*-butanol and ethanol, have shown to reduce the amount of emissions from the engines without heavily compromising the power output of the engine. Typical biomasses from which biofuels can be sourced have mostly been agricultural sources, such as ethanol from corn or butanol from rice bran. Wet biowaste is an alternative source of biomass to produce bioenergy. Due to its ability to simultaneously reuse nutrients and improve the environment, this is potentially a valuable source, as it uses a waste stream instead of agricultural fields. Every year the United States produces 79 million dry tons of wet biowaste, including food processing waste and animal manure [3,4]. However, this energy content from these biowaste streams is not effectively harvested, even though the energy content is equivalent to all the existing U.S. renewable energy production processes, including wind, solar, geothermal, hydropower, and biomass [4]. This source is not without its difficulties, as one of the major hurdles for the current bioenergy conversion techniques is the high-water content of the biowaste. Nevertheless, the search from an effective means of repurposing biowaste is still important, as the created biowaste from industrialization, urbanization, and population growth is increasing rapidly [5,6].

Hydrothermal liquefaction (HTL) is a process that uses water as the reaction medium and converts non-lipid components into biocrude oil.

Abbreviations: EGR, exhaust gas recirculation; HRR, heat release rate; HTL, hydrothermal liquefaction; NOx, nitrogen oxide; SDP, salad production line; SINL, spatially integrated natural luminosity; SW, swine manure

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This process is well suited for the valorization of biowaste [7,8], as the hydrothermal liquefaction technique offers advantages over other biofuel production methods. Some advantages are its ability to use mixed feedstocks like wastes and lignocellulose, its high energy and separation efficiency, and the nonessential need to maintain specialized microbial cultures of enzymes. Additionally, by recovering energy from the downstream of the human food chain, this technique avoids competing with other bioenergy production requirements, like farmland and food supply. From this it is clear that the HTL process is valuable [9–11].

Even though the HTL technique is similar in processing various feedstocks, the resulting distillates and biocrude contents have differences. One of the experimental feedstocks available is sourced from swine manure (SW). The composition of swine manure is similar to other types of wet biowaste, such as human feces, allowing this feedstock to be considered as a representation of fecal matter [12,13]. Another feedstock is from the food processing waste from a salad production line (SDP). The composition of SDP resembles greasy biowaste such as rendered animal fat [14], slaughter house waste, and other food processing waste, such as from restaurants [12].

Earlier investigations of the validity of HTL (of the SDP variety) and diesel were conducted on a single-cylinder diesel engine [15]. The experiments involved 10% and 20% HTL-diesel fuel blends. The blends showed that they could achieve competitive power generation (96–100%) in comparison to diesel. While the CO emissions were reduced (89–91% CO), the blends demonstrated similar levels of nitrogen oxides (101% NO_x) and unburned hydrocarbons (92–125%). However, there was an increase in the soot emissions (109–115%) in comparison to regular diesel. Overall, the preliminary experiments have shown that HTL biocrude oil could potentially be a promising drop-in diesel blend stock. Other drop-in diesel blend stocks (such as butanol) misfire, while the HTL blends do not suffer under the same diesel engine test conditions [16].

In order to evaluate the potential of HTL blends as a possible diesel surrogate, the authors conducted a detailed experimental study in a constant volume chamber fueled with HTL and diesel blends. The HTL and diesel blends were tested in volumes of 10% and 20% HTL fuel with 90% and 80% diesel, respectively.

2. Experiment setup and method

2.1. Test fuels and conditions

The combustion process inside a real engine is controlled by multiple factors that are highly coupled together and the overall behavior is extraordinarily complex. In order to study the thermodynamic processes as a quasi-steady flow field, a constant volume chamber with a bore of 110 mm and a height of 65 mm and with a maximum operating pressure of 18 MPa is used. As seen in Fig. 1, the injector is mounted on the bottom of the chamber with a quartz-silica window situated at the top, allowing optical access. The chamber walls are heated to 380 K to mimic practical engine conditions as well as prevent water condensation and thermal shock to the window.

Acetylene (C_2H_2) is burned with oxygen and nitrogen in order to vary the temperature and pressure environment in the chamber. A plasma ignition system is used to ignite the premixed gases and the ignition event could be triggered at the chosen conditions. A quartz pressure transducer was used to record in-cylinder pressure. A high-speed camera (Phantom V7.1) is located above the chamber in order to record the combustion process through the optical access at the top. For the spray, a copper vapor laser is used as a light source and is synchronized with the high-speed camera. Using the refractive index between the liquid fuel and the ambient gas, the liquid spray could then be captured. The length from the injector tip to the furthest point where liquid can be observed is defined as the liquid penetration. Additional information about the experimental setups can be found in previous works with the same setup [17].

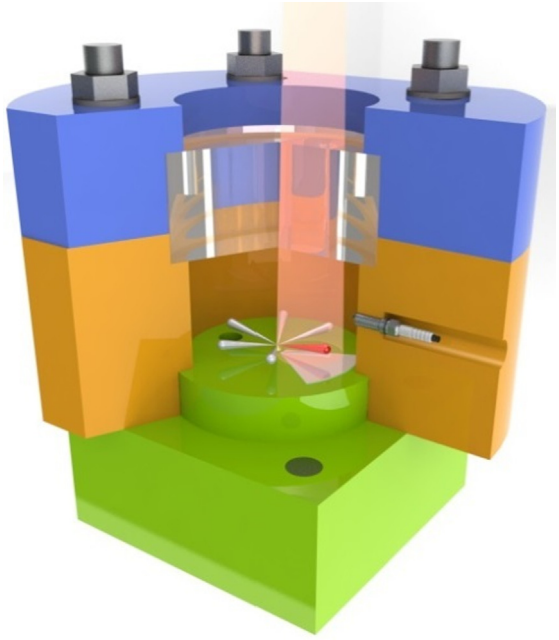


Fig. 1. Inner structure of a pre-burn type constant volume chamber.

The HTL products in this set of experiments were distillates from SDP. Three fuels were tested and denoted as HTL10 (representing a mixture of 10% HTL and 90% diesel), HTL20 (20% HTL and 80% diesel), and D100 (representing 100% diesel). Commercially available off-road diesel (with a 50 ppm or lower sulfur content) was selected as a baseline standard fuel in this study. The known HTL fuel properties are shown in Table 1, though the properties will change as the technology develops. It should be noted that the addition of HTL lowers the kinematic viscosity and the surface tensions, meaning the atomization of the overall fuel blend would increase unlike other biofuels [18,19]. The C/H/O ratios of the HTL fuel is around 4.5/8/2.3 by molar weight, which was previously obtained [12]. Additionally, pure other HTL fuel data is not available due to the limited quantity of the mixtures.

Three different oxygen concentrations of 21%, 17%, and 13% were used to study the combustion characteristics under different levels of exhaust gas recirculation (EGR). Each fuel blend was also tested at five different ambient temperatures of 1200 K, 1100 K, 1000 K, 900 K, and 800 K.

Table 1
Fuel specification analysis of different drop-in diesel blendstocks and regular diesel. Ref [15].

Fuel Spec Property	Upgraded-SDP		Diesel
Percentage of Diesel Blendstocks (Numbers shown after HTL or B)	HTL10	HTL20	N/A
Viscosity (at 20 °C, mm^2/s)	3.737 ± 0.01	3.050 ± 0.02	3.746 ± 0.02
Acidity (mg KOH/g)	0.10 ± 0.004	0.29 ± 0.05	N/A
Sulfur Content (ppm)	1000	N/A[h]	N/A
Existent Gum (wt%)	0.17 ± 0.01	0.21 ± 0.02	0.63 ± 0.06
Surface Tension (at 24 °C, mN/m)	27.2 ± 0.1	27.0 ± 0.0	27.3 ± 0.1
Cetane Number	44.2	43.6	41.4
Wear Scar Diameter for Lubricity (μm)	364	324	571 ± 5
Oxidation Stability/Oil Stability Index (h)	> 48	> 48	> 24

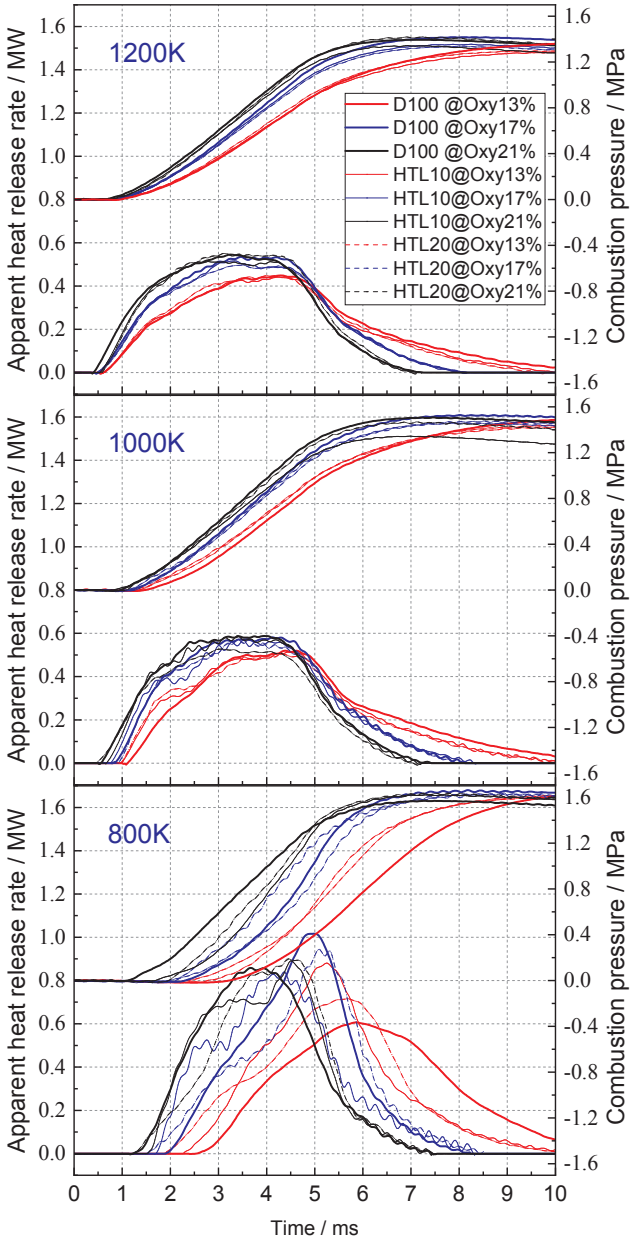


Fig. 2. Heat release rates and chamber pressures.

3. Results and discussion

3.1. Chamber pressure, heat release rate, and ignition delay

Fig. 2 compares the heat release rate and combustion chamber pressure of the fuels under different ambient temperatures and oxygen concentrations. Fig. 3 shows the corresponding comparison of the ignition delay periods. As the ambient temperature and the oxygen content decrease, the ignition delay period gradually increases. This is because that the lower ambient temperature causes the evaporation rate to of the fuel to slow down, and the lower oxygen content causes the fuel vapor to be further diffused to form a combustible mixture.

When the ambient oxygen concentration is high (21%), the ignition delay period of the HTL is longer than that of pure diesel. The higher the HTL blending ratio, the longer the ignition delay period. The HTL fuel has significantly higher surface tension, viscosity, and latent heat in comparison to diesel, which can cause the breakup of the spray and the evaporation of the droplets to slow down. As a result, the HTL spray takes a longer time to form a combustible mixture. Additionally, HTL contains a large number of macromolecular compounds, so its reaction activation energy is higher than that of diesel fuel. As a result, the mixture takes a longer time to be heated up by the ambient temperature to generate a flame.

When the ambient oxygen concentration is low (13%), HTL shows a shorter ignition delay period. The higher the HTL blending ratio, the shorter the ignition delay period. This is because when the ambient oxygen concentration is low, the proportion of fuel vapor and oxygen in the space near the spray is higher than the limit of combustion, and therefore the fuel vapor needs to be further diffused to reach a combustive mixture. The oxygen molecules contained in the HTL fuel can alleviate this anoxic phenomenon to some extent and accelerate the formation of the combustible mixture. In a low-oxygen environment, the shortening of the ignition delay is due to the oxygen-containing molecules in the HTL fuel.

Therefore, the influence of the HTL fuel on the ignition delay is a balanced between the promotion by the oxygen molecules and the suppression by the latent heat and activation energy. Under moderate ambient oxygen conditions (17%), 10% HTL fuel achieves the shortest period of the ignition delay period. At the same time, with the decrease of ambient temperature, the influence of the additional HTL becomes more apparent. As shown in Fig. 3, the difference in the ignition delay period of pure diesel at 21% and 13% ambient oxygen concentrations is 0.2 ms at the 1200 K ambient temperature, but when the ambient temperature drops to 800 K, this difference is extended to 1.2 ms. This is because as the ambient temperature decreases, the range of the flammability limits of the fuel vapor shrinks. The denser mixture that can be burned at higher temperature needs further diffusion to achieve combustible concentrations at low temperatures. In addition, the

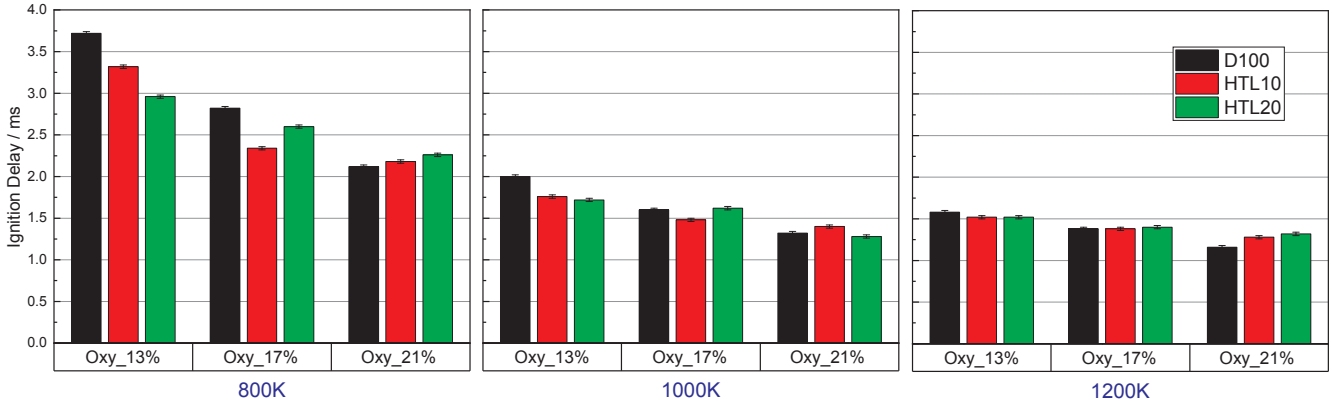


Fig. 3. Ignition delay under different ambient temperatures and oxygen concentrations.

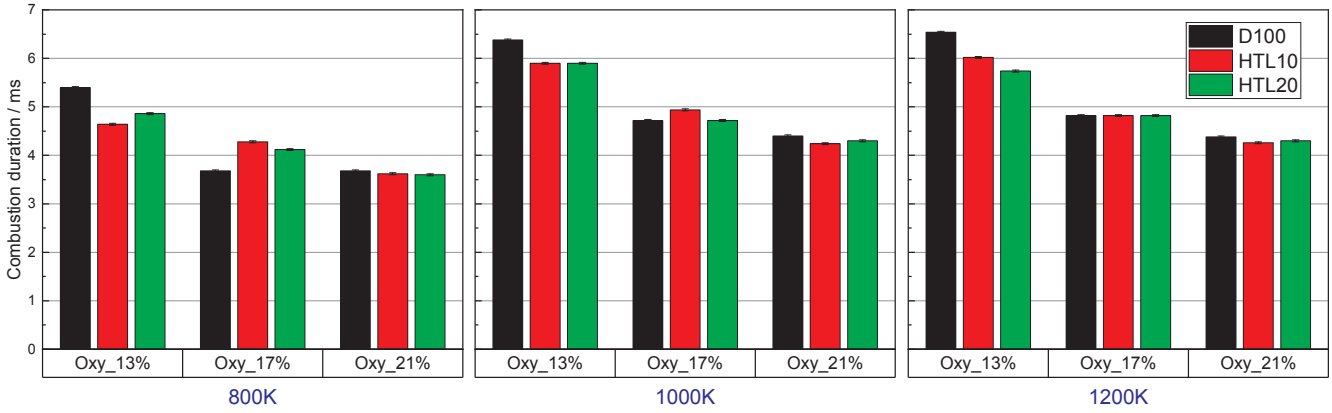


Fig. 4. Combustion duration under different ambient temperatures and oxygen concentrations.

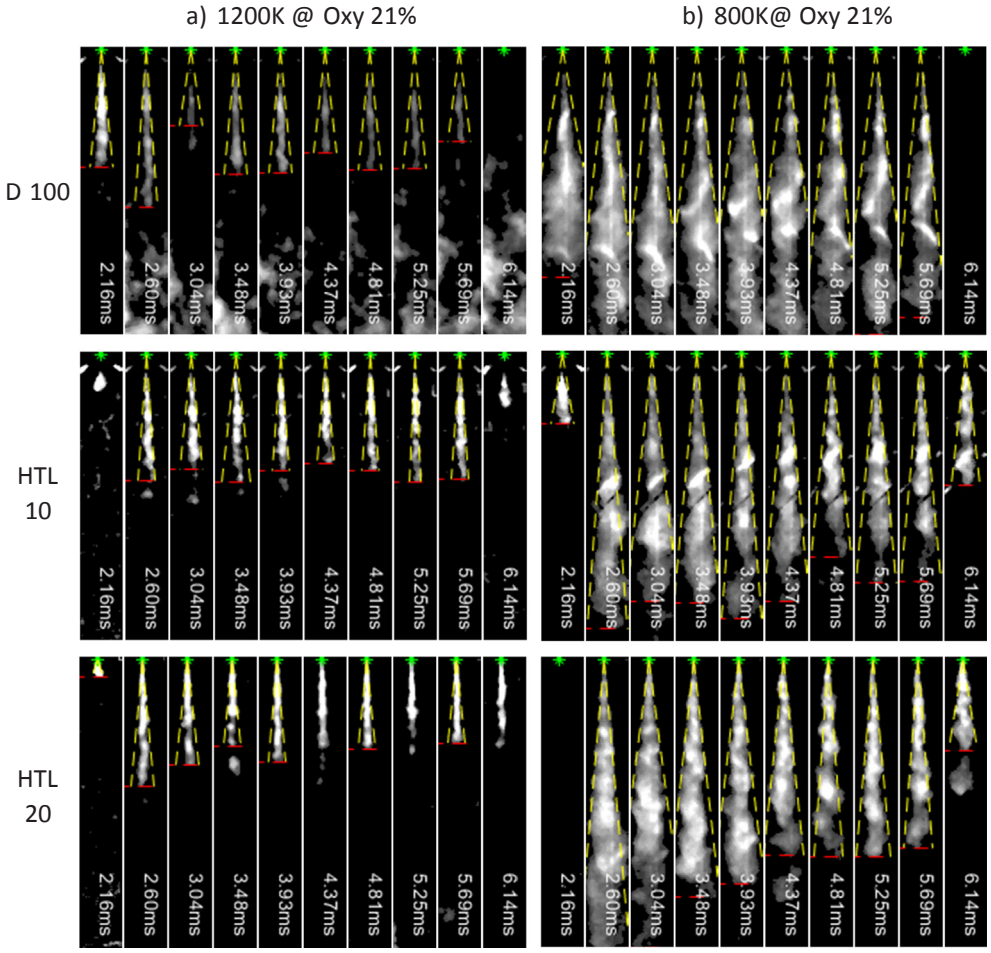


Fig. 5. Liquid penetration at various inputs.

generation of flames is more sensitive to the environmental oxygen concentration. Under these conditions, the promotion of oxygen molecules in the fuel will be more obvious. At the same time, under low ambient temperature, the lower thermal energy of the ambient air reduces, which causes the heating rate of the fuel and the mixture to slow down. The excessive heat of vaporization of the fuel will cause the local temperature to drop below the critical value of the flammability, extending the ignition delay period. Therefore, under low ambient temperature conditions, the promotion and suppression of the HTL fuel on the ignition period are both enhanced simultaneously. Even if the influences are the same, the degree of influence at low ambient temperatures is significantly higher than that at higher temperature. This shows that blending HTL fuel will weaken the robustness of the combustion system under cold start conditions, resulting in higher control difficulty.

Fig. 4 shows the comparison of the combustion duration of each fuel under different ambient temperature and oxygen concentrations. It can be seen that as the ambient temperature increases, the combustion duration becomes longer, which is due to the shorter ignition delay period and higher proportion of diffusion combustion.

At lower ambient oxygen concentrations (13%), the addition of HTL significantly shortens the combustion duration. Even the HTL fuels have

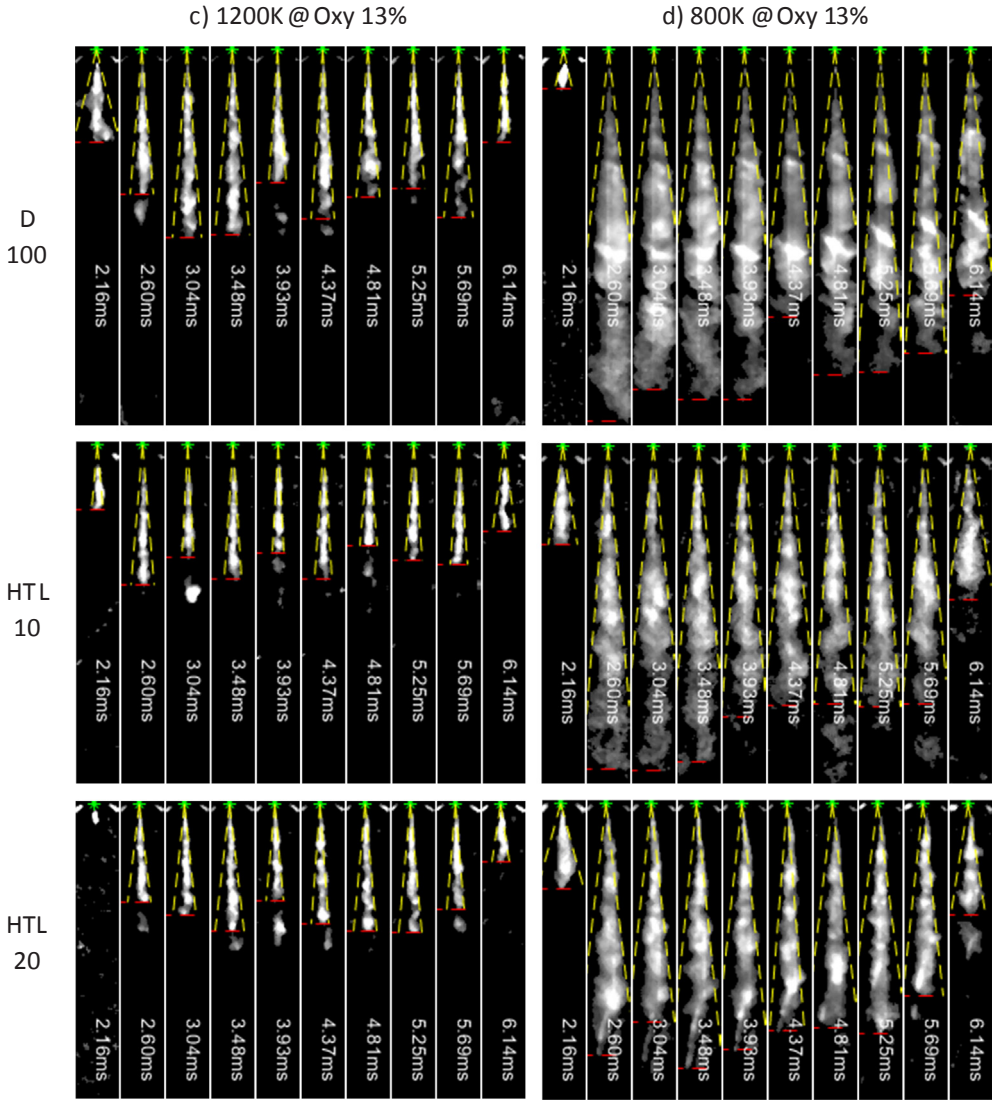


Fig. 5. (*continued*)

shorter ignition delay periods and higher diffusion combustion ratios. This is because of the oxygen-containing molecules in the HTL fuel accelerate the formation and combustion of the combustible mixtures. However, at low temperatures, the higher HTL blending ratio leads to an increase in the latent heat of vaporization of the fuel, which prolongs the combustion duration. This results in the shortest combustion duration of the HTL fuel with a 10% blending ratio under low ambient temperature and oxygen concentration conditions among the cases studied. When the ambient temperature is increased, the influence of the latent heat becomes weak, and the higher blending ratio of the HTL fuel achieved shorter combustion durations due to the increase of higher oxygen-containing molecules.

As the oxygen content increases to 17% and at the low ambient temperature conditions, the effect of the oxygen-containing molecules in the HTL fuel becomes weaker. The suppression of the latent heat of the HTL fuel is the dominant influence on the combustion duration, which leads to a longer combustion duration. When the ambient oxygen concentration reaches 21%, the flame generation and development both rapidly increase, and the difference between the different fuels is significantly reduced. The promotion of the oxygen-containing molecules and the inhibition of the latent heat of vaporization reach equilibrium, so that the combustion has little variation in duration.

Under low ambient temperature and oxygen content conditions, the addition of the HTL has a shorter ignition delay period and combustion duration, which leads to higher heat release rates and chamber pressure. Therefore, in actual use, the addition of HTL fuel can improve the working efficiency of the diesel engine, but on the other hand brings higher NO_x emissions.

3.2. Spray

The macroscopic characteristics of the fuel spray liquid phases were obtained by high-speed photography. Fig. 5 shows the spray evolution for the respective fuels under different ambient temperature and oxygen concentration conditions, covering 1200 K @Oxy 21%, 800 K @ Oxy 21%1200 K @Oxy 13%, and 800 K @Oxy13% corresponding to Fig. 5a, b, c, and d respectively. Only one of the six spray plumes is fully captured due to the limitations of the viewing field. Fig. 6 shows the penetration length for D100 and HTL20 for the 21% oxygen concentration.

Fig. 7 compares the spray area of all three fuels under different ambient conditions. The spray area is calculated by accumulating the pixels in the spray liquid phase image captured by the high-speed camera, with the gray value higher than the critical value. Sprays are generally considered to be approximately axisymmetric cones, so the spray area in a plane can be used to represent the spray volume. At the same time, a smaller volume of liquid phase means that more fuel has been evaporated into the gas phase.

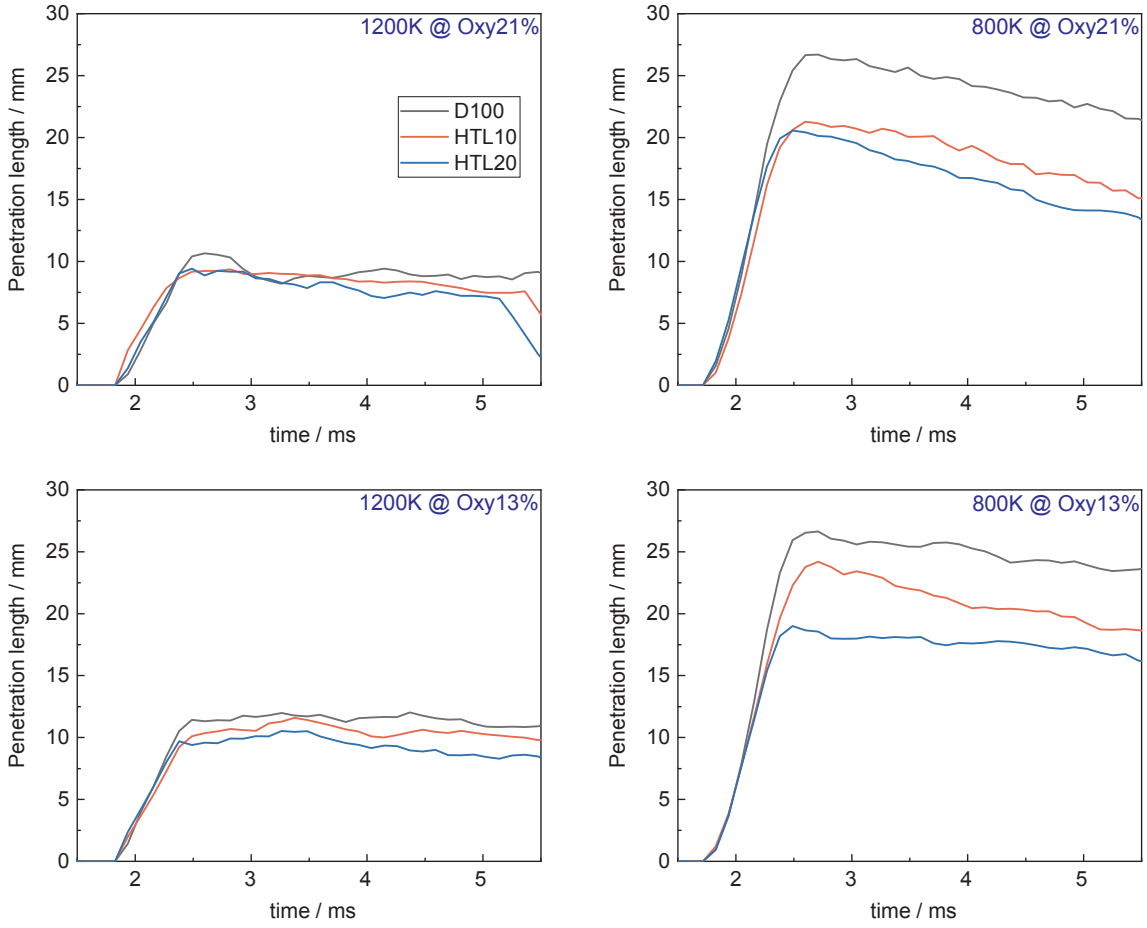


Fig. 6. Liquid penetration length under different ambient temperatures and oxygen concentrations.

At high ambient temperature and oxygen concentration conditions, the spray areas of all the fuels are almost the same during the entire injection process. This is due to the rapid generation and development of the flame, which causes the temperature in the cylinder to rise rapidly, and the upstream fuel is rapidly evaporated. Under high ambient oxygen content, the oxygen atoms in HTL fuel do not affect the flame obviously. And due to the high ambient temperature, the temperature loss due to the high vaporization latent of HTL fuel can be quickly compensated. Therefore, the addition of HTL fuel will not significantly affect the evaporation process of diesel spray. As the oxygen concentration drops to 13%, the spray volumes are still small, but the addition of HTL results in a smaller spray area than that of diesel. This is because the oxygen content in the HTL accelerates the combustion process and increases the in-cylinder temperature, which can evaporate the fuels more rapidly.

At low ambient temperatures, the spray volumes become much larger, and the volumes of HTL fuels are significantly smaller than that of diesel. This is because of the high latent heat of vaporization of the HTL fuels, which will result in longer ignition delay periods and larger premixed combustion. The premixed combustion results in higher in-cylinder temperature. From the Figs. 3 and 4, it can be found that under the 800 K and Oxy_21% condition, the ignition delay periods increase with the proportion of HTL, while the combustion duration does not change by much. The noticeable difference between the two HTL fuels appears under the low ambient temperature and oxygen concentration conditions. Under these conditions, the generation of flames is limited by the ambient oxygen content and ambient temperature. And the oxygen molecules in the HTL can make up for the lack of oxygen in the ambient to a certain extent, thereby accelerating the generation of flames. However, the large latent heat of vaporization of the HTL fuel will cause the local temperature of the spray to decrease, which will hinder the flame generation. From Fig. 3, it can be seen that as the proportion of HTL increases, the ignition delay decreases significantly. This means the oxygen concentration dominates the flame generation under such conditions. Therefore, the addition of HTL can accelerate the flame generation under low ambient temperature and oxygen concentration conditions and bring a higher initial in-cylinder temperature, which will accelerate the vaporization of upstream fuels.

When the ambient temperature is lowered, the difference between the HTL fuel and pure diesel is more noticeable; the volume of the HTL spray is smaller than that of pure diesel. This is because of the low temperature and rich oxygen conditions, as the ignition delay period of the HTL is longer than that of pure diesel. As the proportion of the premixed combustions increase, the initial cylinder temperature rises faster, accelerating the atomization and evaporation process. Under the low ambient temperature and oxygen concentration conditions, the oxygen molecules in the HTL fuel accelerate the generation and development of the flame. As shown in Fig. 2, the combustion peak is further than pure diesel, resulting in rapid evaporation of the fuel plume. Therefore, under low temperature and low oxygen conditions, the addition of HTL fuel has the most noticeable effect on the spray penetration length.

Fig. 8 compares the lift-off length of all three fuels under different ambient conditions. After 7 ms, the flame lift-off length first decreases and then increases rapidly. This is because the fuel injection ends at 7 ms. At the end of the fuel injection, the solenoid valve of the fuel injector opens, and the fuel pressure drops to close the needle valve. When the injection pressure is significantly reduced, the flame develops along the spray toward the nozzle. As the injection ends completely, there is no longer any fuel supplement in the space near the nozzle, and

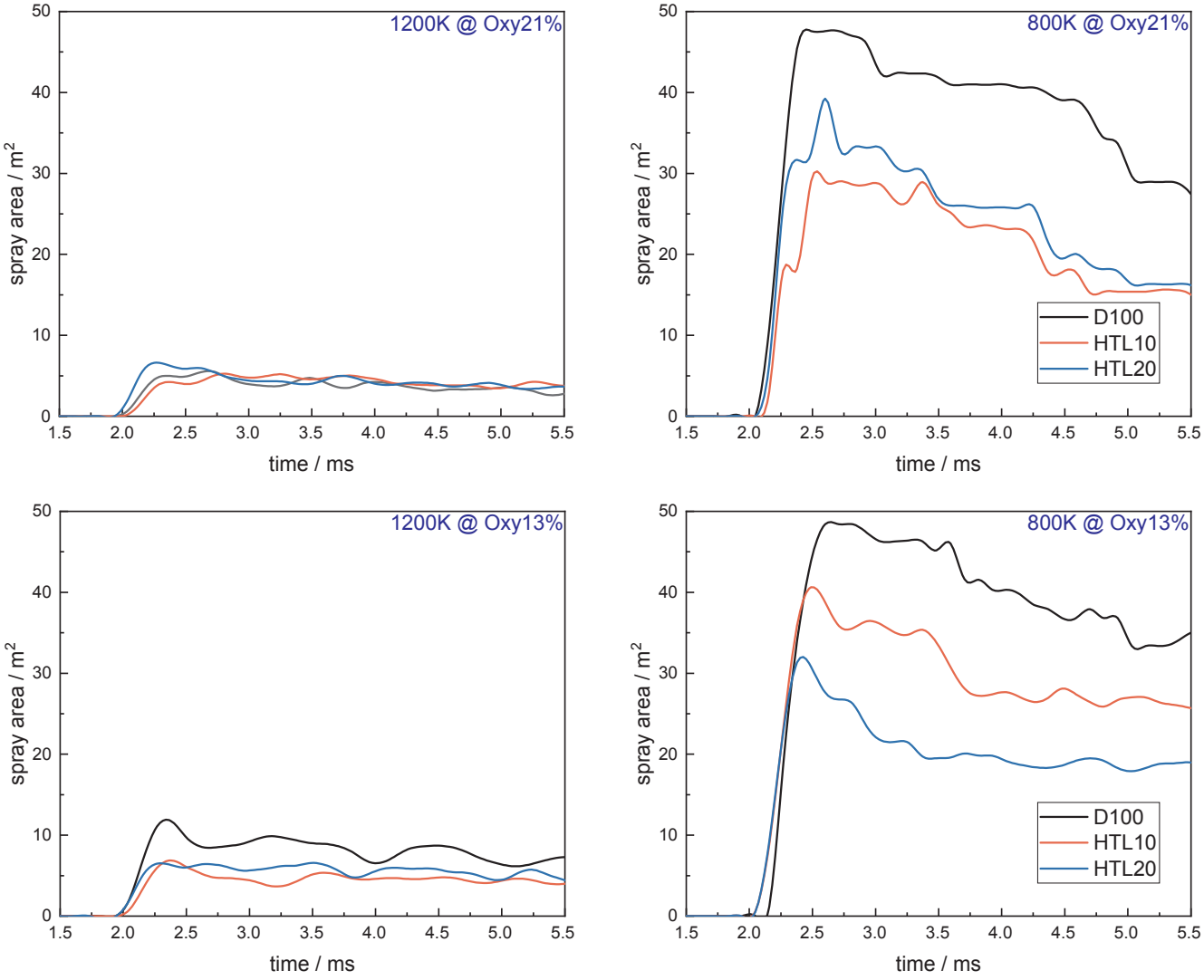


Fig. 7. Spray area of all three fuels under different ambient conditions.

the flame moves downstream with the movement of the spray and is concentrated near the wall of the combustion chamber.

At higher ambient temperatures, after the flame is generated, the lift-off length remains near a relatively stable value until the end of the injection. But at lower ambient temperatures, after the flame is generated, the lift-off length first reaches a larger value and then quickly decreases until the end of the injection. This is because at a lower ambient temperature, the ignition delay period is significantly extended. During this period, the downstream fuel molecules diffuse into a larger space to obtain sufficient energy to overcome the activation energy of the reaction to generate a flame. Therefore, the flame appears at the position far away from the nozzle. Once the flame is generated, the intense premixed combustion rapidly raises the temperature in the cylinder, so that the upstream fuel is ignited, resulting in a rapid shortening of the lift-off length. At higher ambient temperatures, due to the short ignition delay period, the flame is rapidly generated, and the propagation speed of the flame and the movement speed of the spray quickly reach a balance, thereby maintaining the lift-off length at a relatively stable value.

Under higher ambient oxygen content conditions, it can be seen that lift-off lengths are directly related to the natural flame luminosities. Under the condition of 1200 K and 21% oxygen content, the lift-off lengths of the three fuels are basically the same, and the natural flame luminosity curves are also identical. Under the 800 K and 21% oxygen content condition, the lift-off length of pure diesel and HTL10 are longer than that of HTL20 fuel, which means that the fuel molecules have a longer time to mix with the air and reduce the soot emissions.

This correlation no longer exists under low oxygen content conditions. Under the condition of 1200 K and 13%, the lift-off lengths of the three fuels are basically the same, and the lift-off length of diesel is slightly higher than that of the HTL fuels. At the same time, according to Fig. 3, the ignition delay period of the three fuels are identical. However, the combustion durations are significantly different. With the increase of the proportion of HTL fuel, the combustion duration is shortened. Although the oxygen-containing molecules in the HTL fuel reduced the local concentration to some extent, it still brought stronger flame luminosity. This further illustrates that the key factor affecting the soot generation of the HTL fuel at this time is the flame temperature, not the fuel air mixing quality. Under low ambient temperature and low ambient oxygen concentration condition, the shapes of the lift-off length curves are very similar, but the times of appearances are noticeably different.

The addition of HTL fuel shortens the ignition delay period under low oxygen concentration conditions, increases the proportion of diffusion combustion, and also shortens the combustion duration and increases the combustion temperature. Both of these works together to increase the flame luminosity and soot production. However, at this time, the ignition period has been significantly extended, and the

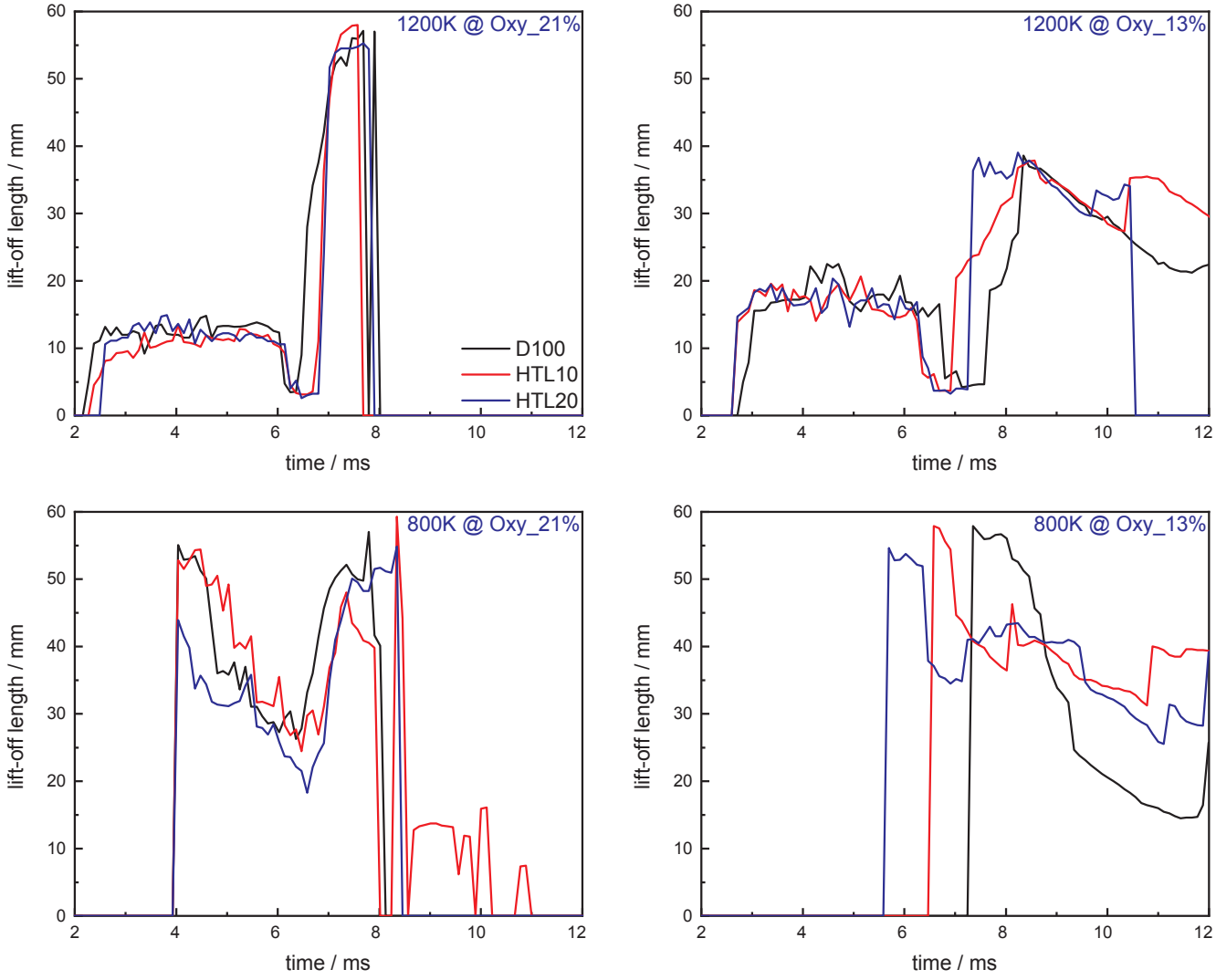


Fig. 8. Lift-off length of all three different fuels under ambient conditions.

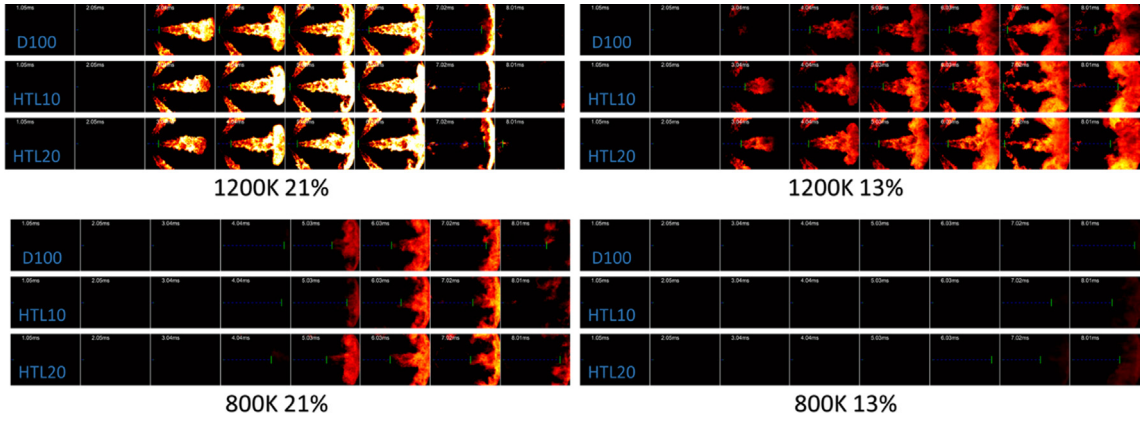


Fig. 9. Flame images under different ambient temperatures and oxygen concentrations.

proportion of diffusion combustion is very low. Therefore, the overall production of soot is lower than that under other operating conditions.

Therefore, the addition of the HTL fuel will accelerate the development of the downstream flames and accelerate the evaporation and combustion of the upstream fuel sprays, resulting in a shorter spray penetration length of HTL fuel than pure diesel. The higher the ratio of HTL and the closer the environment is to the low temperature and low oxygen concentration conditions, the difference is more obvious. In actual engine operations, the addition of the HTL fuel can alleviate the phenomenon of fuel wet wall under cold start conditions.

3.3. Flame luminosity

Fig. 9 displays the flame images and natural luminosity under

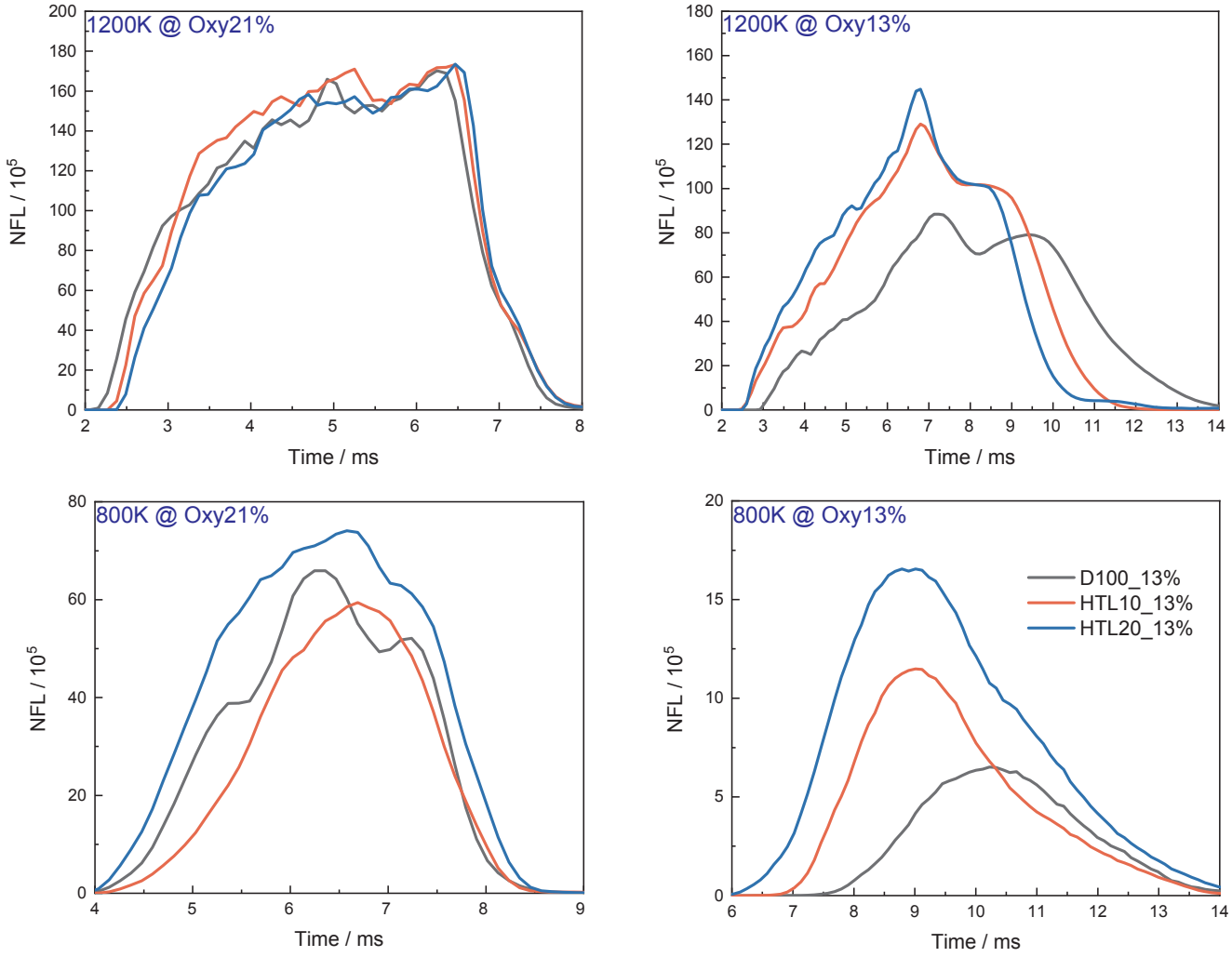


Fig. 10. Spatially-integrated natural flame luminosity.

different ambient temperatures and oxygen concentrations. Fig. 10 shows the spatially integrated natural flame luminosity (SINL), which represents the overall intensity of the flame luminosity. The SINL consists of all the signals captured by the high-speed camera from the combustion flame in a single exposure. This can represent the instantaneous soot level inside the chamber during the spray combustion process [14]. In all the operating conditions, the addition of the HTL fuel resulted in a significant increase in the self-illuminating brightness of the flame. However, in the high temperature and rich oxygen conditions, the difference of the brightness is miniscule, though these are not the real results. Under these conditions, a large number of pixels are saturated (where the maximum value of the pixels is reached) due to the camera setting parameters that are set in order to capture the difference between different fuels under other conditions. At lower oxygen levels, this phenomenon can be explained by the fact that the addition of the HTL fuel resulted in a significant shortening of the ignition delay period and the duration of the flame, resulting in an increase in the proportion of the diffusion flame and an increase in the combustion temperature, promoting soot generation. At higher oxygen concentrations, HTL fuel still produces stronger illumination characteristics, even though the ignition delay of the HTL fuel is prolonged and the proportion of the diffusion combustion is decreased. It can be seen from the composition of the HTL fuel that although the HTL fuel contains oxygen components, the ratio of macromolecular naphthene and aromatic compounds is significantly higher than that of ordinary diesel. These macromolecular hydrocarbons are more susceptible to cracking and dehydrogenation than the medium length chain alkanes in diesel to form soot particles.

4. Conclusions

In this work, the authors studied detailed experiments on products from hydrothermal liquefaction (HTL) and diesel blends to evaluate the potential of HTL as an alternative fuel on a constant volume chamber. The distillates from a salad production line (SDP) were used to create the HTL fuel. Three blends of fuel were tested and denoted as HTL10 (representing a mixture of 10% HTL and 90% diesel), HTL20 (20% HTL and 80% diesel), and pure diesel.

- The HTL blends have around the same amount of combustion pressure and apparent heat release rate as diesel. Due to the oxygenates within the HTL fuel blend, the blends with HTL performed better under low oxygen concentrations.
- The ignition delay for the HTL blends were shorter than that of diesel in the lower oxygen concentration cases, while in the higher oxygen concentration cases, it was longer.
- Due to the lower boiling points of the hydrocarbons within the HTL blends, the evaporation increases and HTL blends have a shorter penetration length than that of pure diesel.
- The HTL blends will produce as much soot as diesel. At low oxygen ratios, it will generate more soot than pure diesel.

Overall, the HTL blends roughly match diesel in terms of combustion. Although the addition of the HTL fuel has similar effects on diesel fuel on heat release rates and cylinder pressures as other alcohol additives, it contains a large amount of long-chain compound components, which leads to a noticeable increase in soot emissions under the various working conditions. In the actual use of diesel engines, other fuel additives might be needed for improvement on the soot tendency. Future experiments at higher concentrations of the HTL fuel are needed to demonstrate the effects of the HTL fuel blend on the combustion characteristics.

CRediT authorship contribution statement

Timothy H. Lee: Methodology, Investigation, Writing - original draft, Formal analysis. **Ziming Yang:** Methodology, Investigation, Writing - original draft, Formal analysis. **Yuanhui Zhang:** Conceptualization, Resources, Funding acquisition. **Wan-Ting Chen:** Conceptualization, Resources, 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.

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