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Reaction zone characteristics of iso-pentanol swirl spray flames using OH-PLIF and 2C-LII

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Abstract

This paper focuses on the reaction zone and soot emission characteristics of swirl spray flames of iso-pentanol and blends. OH planar laser induced fluorescence (PLIF) measurements were used to study the lift-off and local extinction features. Soot emission was investigated using the planar time-resolved two-colour laser induced incandescence (2C-LII) diagnostic technique. Fuels used in this study were n-heptane, iso-pentanol, ethanol and blends of n-heptane/iso-pentanol and n-heptane/ethanol. Different operating conditions were tested and categorized into three flame types including stable, near blow-off, and far away from blow-off. A clear double flame sheet structure appeared in most flames, referred to as the inner and outer regions in this study. Also, all flames other than pure iso-pentanol displayed an open-up spray in a cone-like "V" shape. Results of stable and near blow-off conditions showed that the addition of iso-pentanol to an n-heptane flame caused the flame to become more attached to the bluff-body. In stable flames, the addition of iso-pentanol to n-heptane increased the occurrence of local extinctions. Whereas the addition of ethanol to n-heptane decreased occurrences of local extinction. Across near blow-off conditions, the impact on lift-off height caused by the addition of ethanol to n-heptane was less than that of the addition of iso-pentanol to n-heptane. In the far from blow-off conditions, less local extinction in pure iso-pentanol was found compared to the n-heptane/iso-pentanol mixture. Soot volume fraction of the iso-pentanol flame was less than the n-heptane flame, and the addition of iso-pentanol to the n-heptane flame reduced the soot volume fractions to a lower level than in the pure n-heptane flame.

Keywords: Iso-pentanol; OH-PLIF; Lift-off; Local extinction; 2C-LII

1. Introduction

Climate change is one of the big problems that many countries are trying to find solutions through transition to net-zero of carbon emissions in transport. Iso-pentanol is an oxygenated alcoholic fuel, which could potentially reduce the level of emissions, especially NOx and soot. Iso-pentanol/kerosene blends have been found to increase thermal efficiency and decrease CO and unburned hydrocarbon emissions at high loads in an aircraft compression ignition (CI) engine [1]. Therefore, iso-pentanol (if bio-derived) can be used

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as a carbon neutral fuel to decarbonize the transport sector, such as in aviation or marine sectors. This paper focusses on iso-pentanol fuel as a sustainable aviation fuel and carbon-neutral candidate for gas turbine combustion applications.

The physico-chemical properties of iso-pentanol are quite similar to ethanol, indicating the feasibility of mixing it with hydrocarbon fuels. Recently, it has been suggested [2,3] that long-chain alcohols have some advantages over ethanol, for example greater energy content and lower hygroscopicity [2,4], that can make them a better alternative to conventional fuels. Iso-pentanol has good potential in reducing soot formation because it increases the amount of oxygen atoms [5–7] and also improves air entrainment due to its long ignition delay [8]. Ying et al. [9] investigated the soot emission of iso-pentanol/ethylene blend in a reverse diffusion flame. They observed that the addition of iso-pentanol made the soot agglomerates more compact and improved the oxidation reactivity of soot particles [9]. There are a few studies on CI engine applications and chemical kinetics of iso-pentanol blends carried out to understand its role in low-temperature chemistry and soot reduction. Jin et al. [3] studied the impact of long-chain alcohols (C3-C5) on solubility when mixed with diesel fuel. They found that iso-pentanol (C5) has less solubility on water than C4 alcohols such as iso-butanol. A study carried out on HCCI engines [10] observed that iso-pentanol has more advantages as a fuel for future HCCI engines than currently used ethanol.

Flame lift-off and local extinction are important features to investigate and study as they help in understanding the flame stabilization and dynamics of liquid fuels combustion. There are a few studies that have investigated the lift-off and local extinction characteristics of liquid fuels in swirl spray burners. Recent work conducted by Gimeno et al. [11] studied the flame lift-off height of n-heptane, n-decane, and n-dodecane spray flames in a non-swirled co-flow configuration. According to their findings, the fuel with the greatest droplet size and the lowest volatility has the maximum lift-off height. Additionally, when the lift-off height increases as a result of increasing the co-flow velocity, a less rich reaction zone occurs downstream of the lift-off height leading to less soot formation [11]. Local extinction and lift-off heights of non-swirled n-heptane spray flames were studied through large-eddy simulation by Benajes et al. [12]. The occurrence of local extinction in the inner reaction zone was associated to the high turbulence level. Previous studies [13,14] investigated the flame lift-off height and local extinction of different liquid fuels using a spray burner. Their OH-PLIF measurements showed that with increasing airflow velocity the average lift-off height decreases, and less local extinction occurs in the inner reaction zone, notably for the heavier fuels [13]. However, there is a lack of studies on the flame lift-off and local extinction of iso-pentanol fuel in a bluff-body swirl spray flame. Therefore, this work will also focus on how iso-pentanol (the low carbon alternative) would affect the flame structure including lift-off and local extinction.

Laser induced incandescence (LII) is a well-known diagnostic technique for measuring soot emissions. There are few studies that have reported soot measurements using LII in spray flames. Abu Saleh et al. [15] measured soot emission concentrations of iso-pentanol/n-heptane blend using planar time-resolved 2C-LII in a swirl spray burner. Their results concluded that the addition of iso-pentanol to n-heptane fuel reduced the overall soot volume fraction. Wang et al. [16] carried out auto-compensating LII (AC-LII) to measure soot emission of a Jet A-1 swirl spray flame. However, there is no study yet reported the soot emission of pure iso-pentanol swirl spray flames. Therefore, this work will measure the soot volume fraction of pure iso-pentanol and its mixture with n-heptane fuel using planar time-resolved 2C-LII.

2. Methodology

2.1. Burner and experimental setup

A bluff-body swirl spray burner with a confined chamber was used for different flames conditions. The air stream was sourced from an air compressor (SXC 4) and controlled using a calibrated air mass flow controller (Alicat). Inside the burner, an annular air stream travelled through a six-vane (60° vane angle) swirler prior to its entrance to the confined chamber. Nitrogen gas was utilized to pressurize the liquid fuels. A calibrated Coriolis flow meter (CODA) was used to monitor the liquid density and flow rate. The confined combustion chamber (100 mm W × 100 mm L × 150 mm H) is surrounded by 4 polished quartz plates, giving access for the camera and laser. A pressurized atomizer (Delavan) with 0.21 mm orifice diameter was used for all flame conditions, providing a solid cone spray pattern with a cone-angle of 60°. A similar experimental setup of the current study is described in the study of Abu Saleh et al. [15]. The schematic of the burner is shown in Fig. 1.

2.2. Flow Conditions

Liquid fuels including pure iso-pentanol, n-heptane, ethanol, a 50:50 volume ratio mixture of iso-pentanol/ n-heptane, and a 50:50 volume ratio mixture of ethanol/n-heptane were used in this study. Fuel mass flow rates were in the range of 0.50 - 0.54 g/s. The investigations were mostly carried out on those conditions with fuel mass flow rate of 0.52 g/s for stable and near blow-off

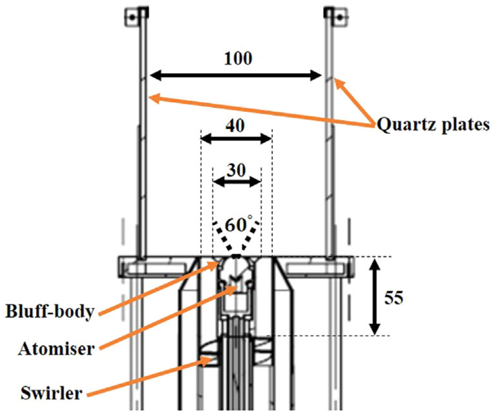

Fig. 1. Schematic of the swirl spray burner.

events. Moving from stable to near blow-off condition was achieved by increasing the air flow rate. Lower fuel mass flow rate of 0.506 g/s was applied for studying the soot signal in iso-pentanol, n-heptane and blended flames. The flow conditions and fuel properties are shown in Table 1. The non-dimensional parameters are calculated using equations described in previous work [13]. S denotes to the stable conditions, NB as conditions nearer to blow-off.

2.3. PLIF

The OH-PLIF diagnostic technique was implemented to investigate the impact of fuels on flame sheet structure including lift-off and local extinction. Yuan et al. [13] employed this diagnostic technique previously for swirl spray flame of different fuels featuring a hollow-cone spray. The diagnostic system in this work comprised of a dye laser (Sirah Cobra-Stretch) pumped by a pulsed Nd:YAG laser (Quantel Q-smart 850), providing laser beam around 283 nm wavelength for OH measurements, allowing the excitement of the Q1(6) (282.940 nm) line in the $A^2\sum - X^2\prod(1,0)$ band.

The laser was coupled with a set of expansion optics to form a laser light sheet. An intensified CCD LaVision camera coupled with a narrow band wavelength filter at 308 nm comprised the detection system.

A further off resonance frequency signal denoted as B(Q) at 282.923 nm near the Q1(6) transition was recorded for all cases to investigate the fuel fluorescence signal of each fuel type. This provides an indication on fuel atomization, and locations of remaining fuels, both liquid and vapour.

The background noise in all images have been reduced by background subtraction and the use of a median filter. The local extinction was then calculated via Matlab by manually selecting the places where the flame cut off, for all the instantaneous images.

2.4. Time-Resolved 2C-LII

Self-calibrated planar time-resolved two-colour laser induced incandescence (2C-LII) technique was implemented to measure soot emissions. The methodology of 2C-LII measurements used in this study has been addressed in detail in a recent publication by Abu Saleh et al. [15]. This part of the study was applied only on the cases far away from blow-off, including n-heptane, iso-pentanol, and their blend. The light source used was the Nd:YAG laser second harmonic passing through expansion optics, forming a laser sheet to heat up the soot particles. Soot emission was filtered through two bandpass filters with wavelengths of 550 nm and 650 nm, each of 10 nm FWHM, before being projected into the intensified CCD LaVision camera, capturing two images simultaneously. Mirrors were used to split and project two images into one camera. The transmission coefficients at the 550 nm and 650 nm wavelengths were obtained by calibrating the imaging system using a standard spectral irradiance lamp. Soot signals were detected at a fixed delay time (0 ns off the laser pulse), and an acquisition duration of 100 ns. The 2C -LII signals were captured after the end of the laser pulse thus avoiding Mie scattering, additionally with a narrow bandpass filter (550 ± 10 nm) to minimise interference from PAH-LIF.

The two-color soot pyrometry technique was used to estimate the soot temperature (T), which was calculated through an equation derived from Planck's law as described by Abu Saleh et al. [15]. Soot temperature was then used to calculate the soot volume fraction [15].

3. Results and discussion

3.1. Flame appearance

Fig. 2 shows examples of direct images of swirl spray flames from left to right of iso-pentanol, ethanol, and n-heptane/ethanol blend. These flames had identical flow conditions in terms of air and fuel mass flow rates. Most of the flames showed an open-up spray in a cone-like "V" shape. In addition, most of flames presented a clear double flame branched structure, formed along the outer shear layer above the edge of the bluff-body (outer region) and inside the V shape spray cone (inner region). The ethanol flame and its mixture with n-heptane are both blue, whereas the others are yellow-blue flames. The yellow color in the iso-pentanol flame could indicate soot. Nevertheless, more results and discussions on soot will be discussed further in the soot volume fraction section. It can be observed in Fig. 2 that the iso-pentanol

Table 1
Fuel properties.

Fuel	n-heptane (H)			iso-pentanol (P)		
Name	HS0	HS1	HNB	PS0	PS1	PNB
Air velocity, U_a(m/s)	10.6	18.2	28.8	10.6	18.2	28.8
Fuel velocity, U_f(m/s)	20.6	22.8		18.8	23.3	
Global equivalence ratio, ϕ	1.0	0.7	0.4	1.0	0.6	0.4
Fuel density, ρ_f(kg/m^3)	663			777		
Surface tension, σ (N/m)	2.21×10^{-2}			2.47×10^{-2}		
Mixture viscosity, ν (m^2/s)	6.10×10^{-7}			4.67×10^{-6}		
Power, P (kW)	22.8	25.8	24.8	19.1	22.7	24.9
Fuel Reynold number, Re_f	7.11×10^{3}	7.88×10^{3}		8.46×10^{3}	1.05×10^{3}	
Air Reynold number, Re_a	6.96×10^{3}	1.19×10^{4}	1.89×10^{4}	6.96×10^{3}	1.19×10^{4}	1.89×10^{4}
Fuel Weber number, We_f	2.68×10^{3}	3.30×10^{3}		2.34×10^{3}	3.61×10^{3}	
Air Weber number, We_g	1.14	2.48×10^{-1}	3.96×10^{-1}	6.80×10^{-1}	2.71×10^{-1}	2.98×10^{-1}

Fuel	50:50 iso-pentanol/n-heptane (HP)			ethanol (E)		50:50 n-heptane/ethanol (HE)	
Name	HPS0	HPS1	HPNB	ES1	ENB	HES1	HENB
U_a(m/s)	10.6	18.2	28.8	18.2	24.3	18.2	25.2
U_f(m/s)	18.6	20.9		21.4	21.4	20.9	
ϕ	1.0	0.6	0.4	0.43	0.32	0.59	0.39
ρ_f(kg/m^3)	722			759		699	
σ (N/m)	2.34×10^{-2}			2.01×10^{-2}		2.11×10^{-2}	
ν (m^2/s)	1.68×10^{-6}			1.42×10^{-6}		9.45×10^{-7}	
P (kW)	20.2	22.5	22.9	16.9	16.6	22.3	20.8
Re_f	2.33×10^{3}	2.62×10^{3}		3.17×10^{3}		4.66×10^{3}	
Re_a	6.96×10^{3}	1.19×10^{4}	1.89×10^{4}	1.19×10^{4}	1.59×10^{4}	1.19×10^{4}	1.65×10^{4}
We_f	2.24×10^{3}	2.85×10^{3}		3.64×10^{3}		3.06×10^{3}	
We_g	6.82×10^{-1}	8.24×10^{-2}	6.54×10^{-1}	1.29×10^{-1}	1.00×10^{-1}	9.14×10^{-2}	2.08×10^{-1}

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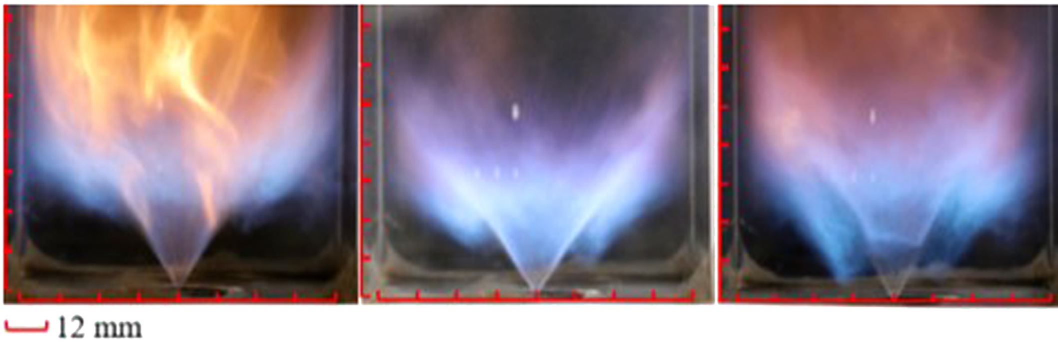

Fig. 2. Flame images of solid-cone swirl spray flames of (left to right) iso-pentanol, ethanol, and n-heptane/ethanol blend.

flame did not present a clear inner region of the flame structure. This is because the fuel is not as well atomized as the others.

The lift-off feature could be observed in the outer region of all flames, such as shown in n-heptane/ ethanol blend (Fig. 2). The lift-off height from the bluff-body surface is different for each fuel. Hence, lift-off of all flames was analyzed using OH-PLIF measurements, which will be shown later in this paper.

3.2. PLIF signal at Q1(6) and its background B(Q)

This section will discuss the fuel-PLIF and OH-PLIF results in Sections 3.2.1 and 3.2.2, respectively.

3.2.1. Fuel-PLIF

The background signal, B(Q), provided the opportunity to measure the fuel-PLIF of all cases. The measurement of fuels fluorescence signal is important as it gives indications of the fuel spray distribution and trajectory. During the experiment, 200 images of Q1(6) and B(Q) were recorded for each of the cases. Fig. 3 shows examples of instantaneous images of fuel-PLIF of the stable conditions of HS1, PS1, HPS1, ES1, and HES1. The red line shown along the x-axis is an indication of the bluff-body surface, and the area between the red and blue lines is where the annular air enters the chamber. The pure n-heptane and ethanol cases showed a clear V-shape (opened-up) atomization, where no apparent fuel (liquid or vapor) was observed in the inner recirculation zone (IRZ), similar to fuel distributions observed in the hollow-cone spray flames [12]. Whereas the trajectory of pure iso-pentanol spray fuel has a narrower angle, distributing in a jet-like shape, where abundant fuel was seen in the downstream of the spray cone inside the IRZ. This caused complexity in analyzing the OH signal in the inner region of pure iso-pentanol flames (PS1, PNB). Nevertheless, the addition of iso-pentanol to n-heptane provided a similar distribution of fuel trajectory as the pure n-heptane case.

3.2.2. OH-PLIF

Fig. 4 displays the OH-PLIF images of the stable and near blow-off cases of n-heptane, iso-pentanol, and n-heptane/iso-pentanol mixture. The OH-PLIF images shown provide visualization of the flame sheet and its location in different flames. The double structures of flame sheets are shown in the mean images OH-PLIF images of all cases, in which the fuel spray is located in between them. The outer flame sheet of all conditions is observed to be wider near the blow-off event. Although the inner flame sheet of the iso-pentanol is absent in the cases studied due to the poor atomization compared with other fuels, but the outer region is similar in terms of size and location, as the other cases. OH-PLIF mean images of n-heptane flame show that the inner flame sheet between the “V” shape is lifted in both stable and near blow-off conditions. The start of flame sheets in the outer region are closer to bluff-body at near blow-off conditions, as observed by the mean images in Fig. 4. OH-PLIF instantaneous images are used to study lift-off and local extinction features of all flames. It has been noticed that local extinction occurs more at near blow-off events in all cases, especially in the HPNB case.

Fig. 5 shows the instantaneous and mean OH-PLIF images of ethanol and ethanol/heptane cases: ES1, ENB, HES1, and HENB. The observations here are very similar to the ones shown in Fig. 4 in terms of flame sheet locations. The addition of ethanol to the n-heptane flame resulted in a narrower fuel spray angle as can be seen in the mean images in Fig 5. Whereas the addition of iso-pentanol to the n-heptane flame showed a slightly wider angle of fuel spray. Overall, all flames have almost identical flame structure. Although utilizing a solid-cone spray atomizer, no apparent signal from the fuel spray were observed in the inner recirculation zone in most of the cases, except for iso-pentanol flames (PS1, PNB), for which under the same flow conditions, abundant fuel was observed

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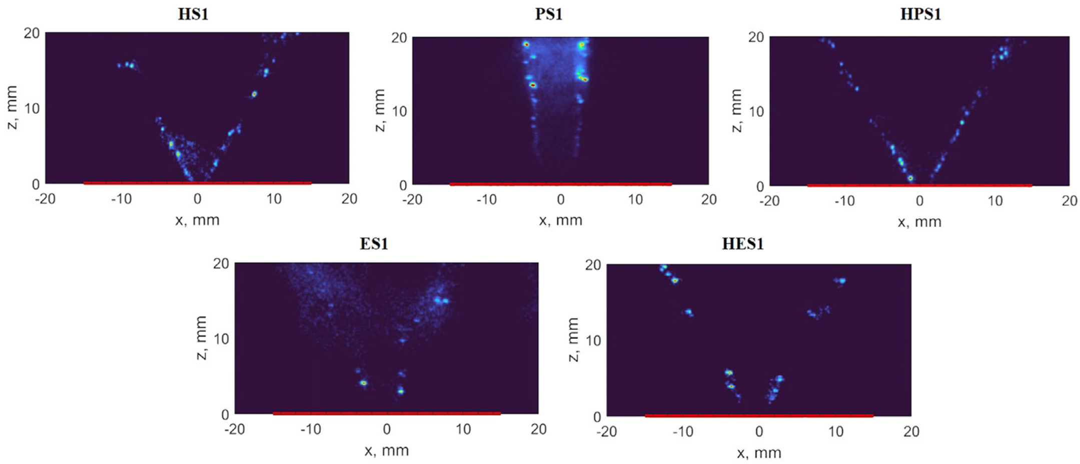

Fig. 3. Instantaneous images of fuel-PLIF signal for HS1, PS1, HPS1, ES1, and HES1. Red line indicates the bluff-body. surface

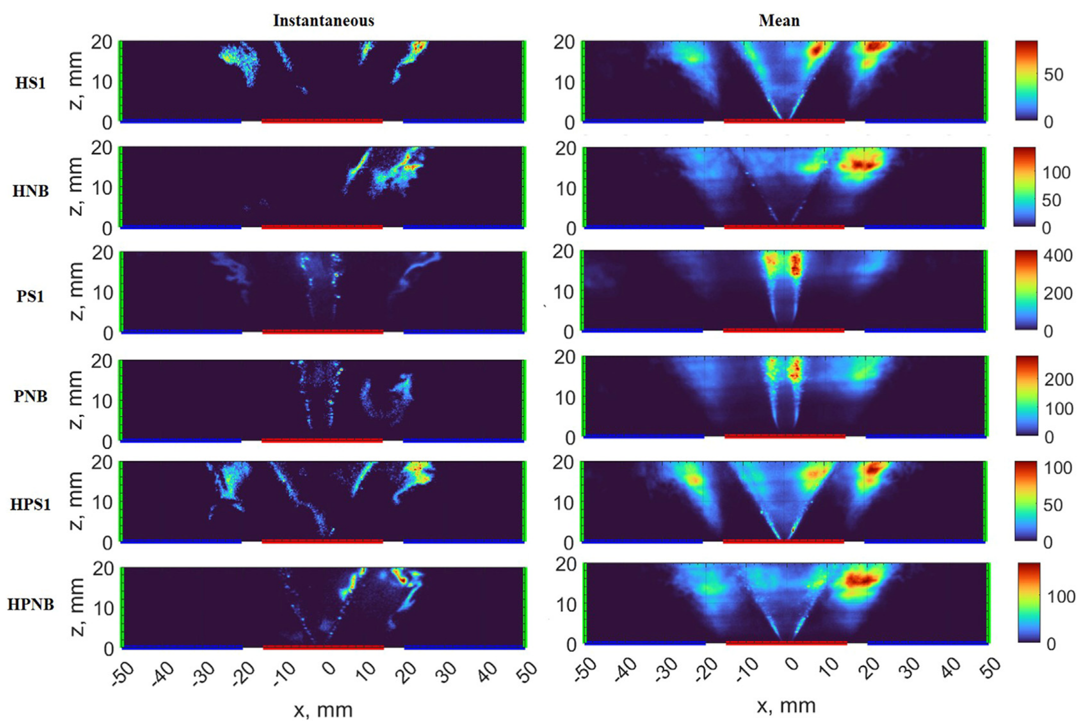

Fig. 4. Instantaneous and mean images of OH-PLIF for HS1, HNB, PS1, PNB, HPS1, and HPNB cases. Red line indicates the bluff-body surface, blue line indicates the bottom surface of the combustion chamber, and green line indicate the location of the laser beam.

in the inner recirculation zone. The reaction zone locations and appearance are similar to the ones utilizing a hollow-cone nozzle in the previous study [13], except for the pure iso-pentanol flames, where the inner flame branches were absent at the lower distance (0-20 mm) to the nozzle, dominated by fluorescence signals from the fuel.

3.3. *Lift-off and local extinction*

Flame stabilisation in terms of the local extinction and lift-off was investigated in both stable condition pairs (S1, NB, with varying air flow rates) and the far from blow-off (S0) condition (a richer flame with lower fuel and air flow rates).

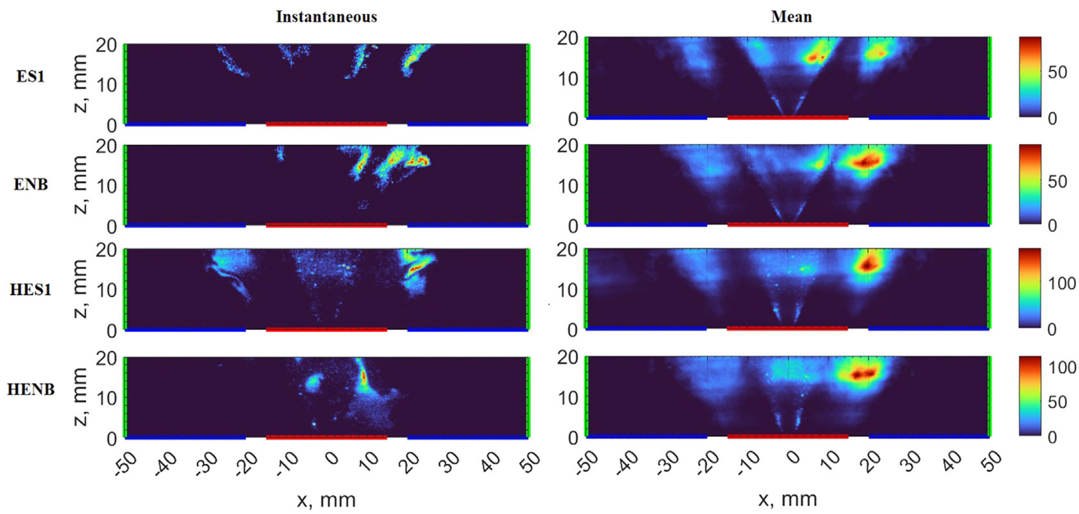

Fig 5. Instantaneous and mean images of OH-PLIF for ES1, ENB, HES1, and HENB cases. Red line indicates the bluff-body surface, blue line indicates the bottom surface of the combustion chamber, and green line indicate the location of the laser beam.

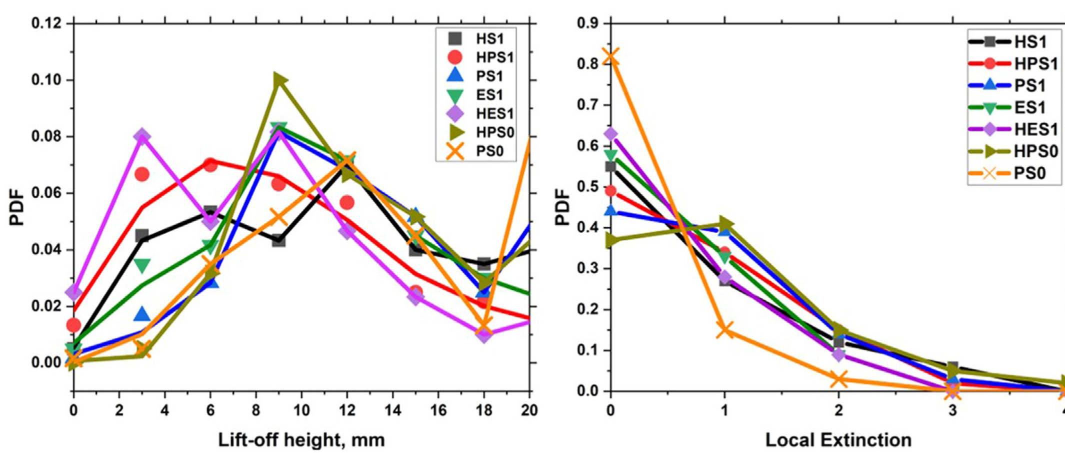

Fig 6. PDF of lift-off and local extinction of stable condition and far away from blow-off conditions.

3.3.1. Stable condition

In this sub-section, the lift-off and local extinction features of all stable flames are discussed. Fig. 6 presents the probability density function (PDF) of all cases of stable flames. The peak of HS1, HPS1, PS1, ES1, and HES1 occurred at lift-off heights of 12 mm, 6 mm, 12 mm, 9 mm, and 9 mm, respectively. The addition of iso-pentanol to the n-heptane flame caused the flame to become more attached to the bluff-body. Ethanol also had the same impact on the n-heptane flame, but less than iso-pentanol. In regard to the local extinction in stable flames, pure iso-pentanol had the highest occurrence (55% showing local extinctions) compared to other flames, and lowest in the n-heptane/ethanol mixture. The addition of iso-pentanol to n-heptane increased the number of local extinction events. Whereas the addition of ethanol to n-heptane showed less occurrences of local extinction.

3.3.2. Near blow-off condition

In general, it was found that as the air flow rate increases and approaches blow-off, lift-off height decreases. Fig. 7 shows the mean lift-off heights normalized by the bluff-body diameter for the stable and near blow-off conditions. Pure iso-pentanol showed the highest average lift-off amongst the stable and near blow-off cases. However, the iso-pentanol /n-heptane blend (HPNB) showed the lowest mean lift-off height of 4.8 mm amongst all near blow-off cases. The stable condition of n-heptane/ ethanol mixture had almost same mean lift-off height as near blow-off condi-

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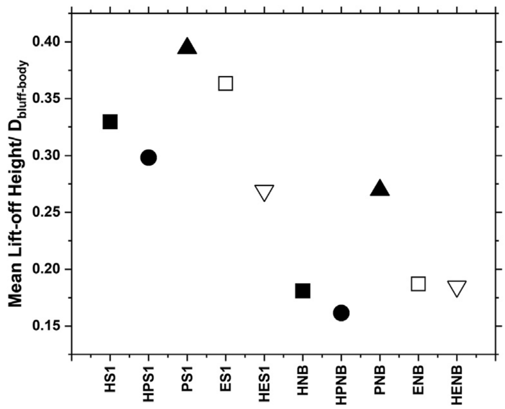

Fig. 7. The mean lift-off heights normalized by the diameter of bluff-body (30 mm) for the stable and near blow-off cases.

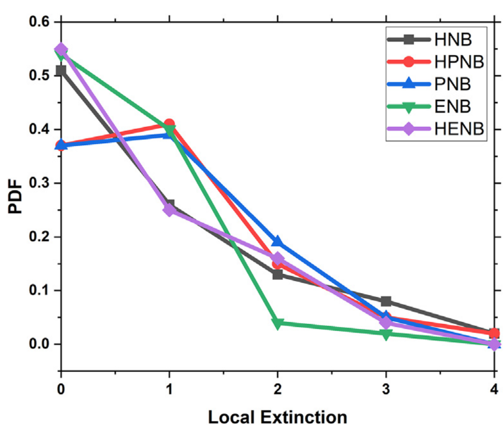

Fig. 8. PDF of local extinction for all near blow-off cases including HNB, HPNB, PNB, ENB, and HENB.

tion of pure iso-pentanol. The near blow-off case of pure ethanol had an average lift-off height of 5.6 mm, lower than iso-pentanol (PNB, 8 mm). Nevertheless, the impact on lift-off height caused by ethanol when was added to n-heptane is less than iso-pentanol.

Fig. 8 displays the PDF of local extinction for near blow-off cases. Overall, more of local extinctions were found to happen near the bow-off event than the stable case. Iso-pentanol (PNB) was found to have the highest number of local extinction events, and ethanol the lowest. The addition of iso-pentanol to n-heptane resulted in increasing the local extinctions.

3.3.3. *Far away from blow-off condition*

Far away from blow-off cases of iso-pentanol and its mixture with n-heptane were investigated to study the soot emission concentrations. This subsection will discuss their lift-off heights and local extinctions before presenting their soot volume fraction. Fig. 6 shows the PDF of lift-off for HPS0 and PS0. Both profiles have similar trends, but the HPS0 have overall lower lift-off heights than the PS0 case. Regarding local extinctions, pure iso-pentanol was found to have fewer local extinctions than n-heptane/iso-pentanol.

The pure iso-pentanol flame was found to reach to a higher blow-off air bulk velocity condition than the heptane counterpart, giving expectation of a lower degree of local extinctions (further from blow-off). The laminar flame speed of iso-pentanol *vs* heptane were reported at almost similar level (i.e. similar chemical time scales) [17,18]; however, the atomisation of iso-pentanol (of a lower *We* and *Re* number, and a narrower cone angle) is not as efficient *vs* heptane under the same flow conditions studied. The effect from the insufficient atomisation may have led to increased local extinction occurrence in the outer flame branch of the iso-pentanol cases.

3.4. *Soot volume fraction*

Measurements for soot emission were investigated in n-heptane, n-heptane/iso-pentanol blend, and iso-pentanol flames and discussed in this subsection. Fig. 9 shows the 2D soot volume fraction measurements from instantaneous images of n-heptane, n-heptane/iso-pentanol, and iso-pentanol flames at far away from blow-off conditions, where a reduced area was captured (projecting 2 images into 1 camera) and positioned to include the centre jet and one side of the annular air path. These measurements were recorded at 30-50 mm height above the bluff-body, where the soot signal is strongest. The color maps in Fig. 9 indicate that the addition of iso-pentanol to n-heptane flame reduces the soot volume fraction. Pure iso-pentanol was found to have the lowest soot volume fraction amongst the other cases shown in Fig. 9. Therefore, this gives a positive sign in achieving both carbon neutral combustion (if bio-derived) and soot emissions reductions with iso-pentanol addition. Chemical kinetic simulations will be conducted in the next step to analyse the reaction pathway of iso-pentanol and its soot emissions.

The averaged soot volume fraction results are shown in Fig. 10 along with the contour plot of the mean OH-PLIF data of each case. The trend in soot levels in averaged results is similar to the one from the instantaneous images. Reduced soot level was found with the addition of iso-pentanol to n-heptane.

The same laser fluence was used for the measurement in the three flames. The mean (spatial) soot temperature of instantaneous cases in Fig. 9 was 2495.5 K, 3188.4 K and 3793.9 K for HS0, HPS0 and PS0 respectively, indicating possible differences in the soot compositions (such as any coating with

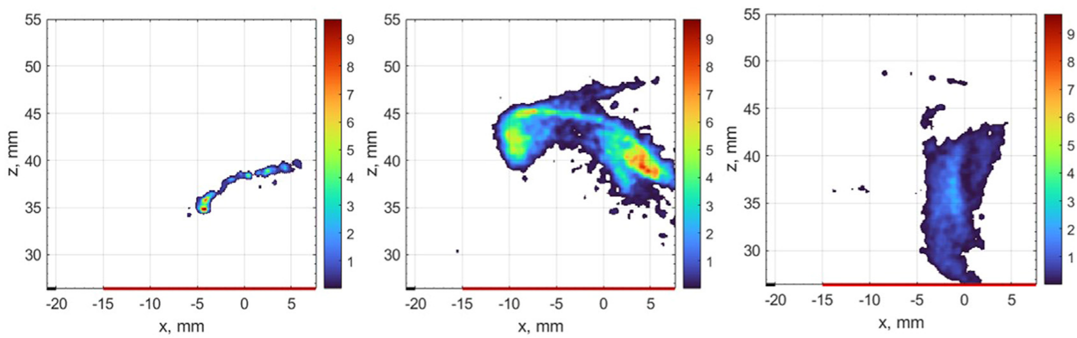

Fig. 9. Soot volume fraction measurements from instantaneous images of (from left) n-heptane (HS0), n-heptane/iso-pentanol (HPS0), and pure iso-pentanol (PS0) flames from 2C-LII. Colour maps are shown in parts per million (ppm).

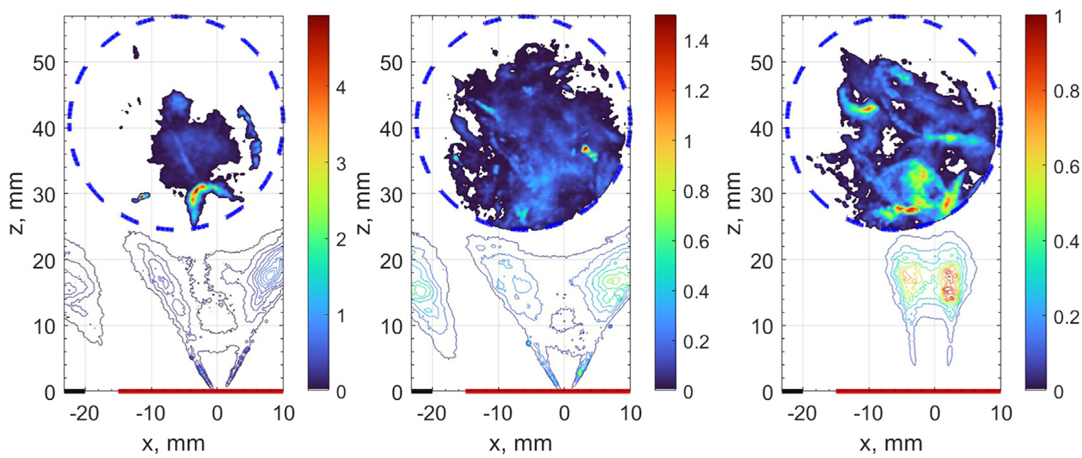

Fig. 10. Mean soot volume fraction measurements of (from left) n-heptane (HS0), n-heptane/iso-pentanol (HPS0), and pure iso-pentanol (PS0) flames from 2C-LII. Colour maps are shown in parts per million (ppm). Blue dashed circle indicates the field of view of the 2C-LII measurements. Superimposed on each case the contour plot of mean OH-PLIF data, showing the main reaction zone, the spray trajectories, and inner recirculation zone for information.

volatile organic compounds) generated in these flames.

4. Conclusion

This work mainly focused on the swirl spray flame reaction zone characteristics of iso-pentanol and blended flames, including flame stabilization and soot distributions. Iso-pentanol fuel and its mixture with n-heptane were also compared at the same operating conditions to ethanol flames. OH-PLIF measurements were used to investigate the flame sheet characteristics, whereas the 2C-LII diagnostic technique was used to study the soot emissions.

The results showed that all flames presented a clear double flame sheet structure, described as inner and outer regions in this study. In addition, most of the flames showed, with the exception of pure iso-pentanol, an open-up spray in a cone-like "V" shape. The outer flame sheet of all conditions is observed to be wider (of a broader area) near the blow-off event. The start of flame sheets in the outer region are more attached to the bluff-body surface at near blow-off conditions.

Lift-off and local extinction features of all stable flames were investigated and discussed. In stable flame conditions, the addition of iso-pentanol to n-heptane flame caused the flame to become more attached to the bluff-body. The largest number of local extinction events happened in the pure iso-pentanol flame, and lowest in the n-heptane/ethanol mixture. In addition, the addition of iso-pentanol to n-heptane increased the number of local extinctions. Whereas the addition of ethanol to n-heptane decreased the occurrence of local extinction. In near blow-off flame conditions, iso-pentanol showed the highest average lift-off height amongst all near blow-off cases. Addition of iso-pentanol to n-heptane decreased the lift-off height to the lowest amongst all near blow-off

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cases. Additionally, the impact on lift-off height that is caused by ethanol when added to n-heptane was less than that of iso-pentanol.

In far away from bow-off conditions, n-heptane/iso-pentanol flame had an overall lower lift-off height than the iso-pentanol flame case. Less local extinction in pure iso-pentanol was found compared to the n-heptane/iso-pentanol mixture. Regarding soot emissions, the addition of iso-pentanol to the n-heptane flame was found to reduce the soot volume fractions.

Iso-pentanol flame showed the lowest soot volume fractions compared with the pure heptane and heptane/iso-pentanol blend flame, promising in soot emission reductions.

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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