Stabilisation of swirling dual-fuel flames

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Abstract

C_7H_{16}-CH_4-air flames stabilised in a bluff body swirl burner have been examined with flame photographs, OH* chemiluminescence, and simultaneous 5 kHz OH-PLIF and Mie scattering with a focus on local an global extinction characteristics. The aim of this study is to investigate flame structure when more than one fuel is present and provide both insight and data for dual-fuel modellers. Flame imaging shows that the presence of an additional fuel affects the stabilisation characteristics of one fuel, whether it be liquid or premixed gaseous. With the addition of more CH_4 in the oxidiser channel, dual-fuel flames with C_7H_{16} spray became more premixed in appearance, evidenced by flame photographs, mean OH* chemiluminescence images, and instantaneous and mean OH-PLIF images. Addition of CH_4 to such systems also forces the flame to stabilise on the outside of the swirled channel, similar to premixed CH_4-air flames far from blow-off. However, the flame branch in the region of the shear layer directly above the bluff body edge moves further from the base of the burner with the addition of CH_4, suggesting that typical spray flame behaviour is lost even with a small addition of CH_4 to the system. This observation is supported by global extinction curves, which show that C_7H_{16}-CH_4-air flames appear to behave more similarly to premixed flames than spray flames, but remain of fundamental interest due to their unique stabilisation behaviour and relative insensitivity to bulk velocity changes compared to spray-only flames at similar equivalence ratios.

Keywords: dual fuel, turbulent combustion, sprays, heptane, methane, gas turbine

1. Introduction

Knowledge of the stabilisation characteristics of systems with multiple fuels is limited considering most dual-fuel experimental and numerical studies have

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Abbreviations: IRZ - inner recirculation zone; ORZ outer recirculation zone; PDF probability density function focused on reciprocating engines. These studies have conventionally emphasised pollutant emissions and ignition mechanisms, particularly in natural gas-air systems with a pilot spray [1, 2, 3, 4, 5]. However, dual-systems are of fundamental interest outside of their importance of natural gas systems. Staged fuel injection systems involve one fuel combusting in the hot products of a richer flame or, depending on the system timescales and mixing characteristics, a partially-unreacted mixture of fuel and air. Further still, if combustion devices have the capability to operate in various fuel modes, the switching period between these modes must be well understood to avoid inadequate mixing, flame destabilisation, or even global extinction. The ability switch fuels through continuous operation and understand the flame physics of a system with both a primary and secondary fuel is important for such systems, particularly power generation gas turbines. This was the primary motivation behind work presented by Sidey and Mastorakos [6], in which C_2H_5OH-CH_4-air dual-fuel flames were examined with flame visualisation techniques. In this work, an augmentation of the attachment characteristics of spray-only flames with the addition of CH_4 in the oxidiser channel was observed. However, only local extinction characteristics above the bluff-body were explored and an oxygenated fuel was used, which may not be representative of systems of interest. In this work, C_7H_{16} will be used in the same configuration and both local and global extinction behaviour will be investigated.

Beyond its usefulness in staged and fuel-flexible combustion systems, the understanding of combustion systems with multiple fuels is important considering the challenging nature of turbulent dual-fuel systems numerical modelling. The development of models which can handle mutliple fuels is also important for systems with multiple injections, such as diesel engines where such injections are treated as independent fuel streams. [7]. To aid in the development of such methods, work provides data for the validation from a continuous combustion rather than transient perspective. Furthermore, the use of C_7H_{16} rather than C_2H_5OH provides modellers with an opportunity to examine more realistic chemistry with a non-oxygenated fuel and the inclusion of global extinction behaviour provides a challenging metric for numerical simulations. In this work, a burner previously studied with C_7H_{16} [8] and C_2H_5OH spray [9, 6], is used to study an C_7H_{16} spray burning in air premixed with increasing amounts of CH_4. Apart from providing information on flame shape, OH-PLIF signal is used as a metric of local extinction at the anchoring point, providing a challenging target for numerical models. Global extinction behaviour is also investigated and compared to data presented in previous work investigating both C_7H_{16}-air and CH_4-air extinction characteristics.

2. Method

Globally lean C_7H_{16}-CH_4-air flames were stabilised in an enclosed bluff body burner [10, 6] shown in Fig. 1, left. Air or premixed CH_4-air were supplied through a $D = 37$ mm pipe with a 60 swirler 47.6 mm upstream of the burner base. This configuration is described in detail in Refs. [11]. A pressure atomiser

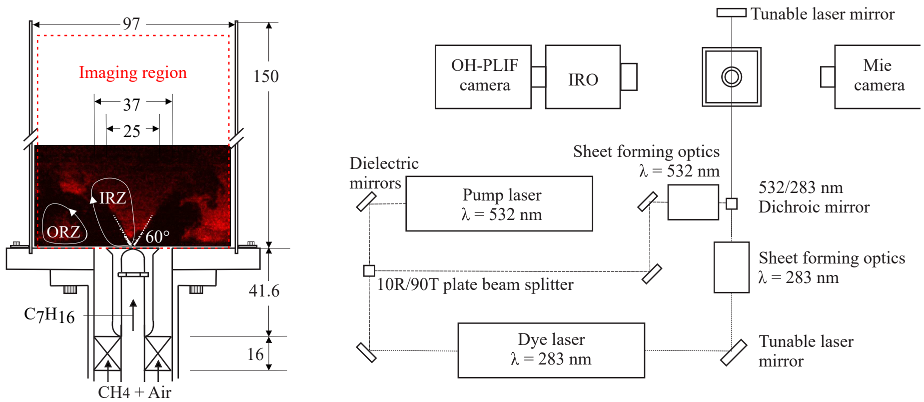

Figure 1: A schematic of the experimental set-up (left) and simultaneous OH-PLIF and Mie scattering imaging system (right).

Table 1: Steady flame conditions

Case	ϕ	ϕ_{pmx}	U_{pmx} [m/s]
H1	0.31	0.00	18.5
HP1	0.45	0.14	18.8
HP2	0.59	0.28	19.1
HP3	0.73	0.43	19.4
HP4	0.87	0.56	19.7
P1	0.56	0.56	19.7
P2	0.66	0.66	19.9

(Lechler 212.054) was used to supply a flow rate of C_7H_{16} with a 60° hollow cone angle housed inside a d = 25 mm conical bluff body centred in the pipe. For the stable flames presented in this work and summarised in Table 1, this flow rate was held constant at 0.27 g/s. This geometry encourages the formation of an outer recirculation zone (ORZ) outside of the swirled channel and an inner recirculation zone (IRZ) above the bluff body [11]. A $\phi = 0.31$ C_7H_{16}-air flame (referred to as H1) and two CH_4-air premixed flames, $\phi = 0.56$ and 0.66 (referred to as P1 and P2, respectively) were compared with a series of stable C_7H_{16}-CH_4-air flames with incrementally increasing CH_4 flow rates in the swirled annular stream, referred to as HP1, HP2, HP3, and HP4, with ϕ = 0.45 - 0.87. These flames correspond to a CH_4 flow rate, Q_{CH4}, of 10, 20, 30, and 40 L/min in the swirled channel, respectively.

The overall equivalence ratio, ϕ, accounts for both C_7H_{16} and CH_4, while the premixed equivalence ratio, ϕ_{pmx}, describes the CH_4-air mixture entering the burner through the annulus at a bulk velocity U_{pmx}. Gaseous flow rates were controlled with Alicat mass flow controllers, with flows of 100 L/min and 1000 L/min full scale for CH_4 and air, respectively. A Bronkhorst LIQUI-flow controller (0 - 2 g/s) was used to supply C_7H_{16} from a tank pressurised with N_2 at 4 bar.

Flame photographs were taken with a Nikon D3100 DSLR camera and a 1/13 s exposure time and OH chemiluminescence images were recorded at 5 kHz with a Photron SA1.1 CMOS camera, LaVision highspeed IRO intensifier, Cerco 2178 UV f2.8 lens, and 270 - 370 nm bandpass filter. OH chemiluminescence images were averaged over 1 s and are presented after an inverse Abel transform. The optical set up for the simultaneous OH-PLIF and Mie Scattering diagnostic is shown in Fig. 1, right. This arrangement is described in detail in Ref. [12]. OH-PLIF and Mie images were filtered with a 2-D 4x4 median filter and OH-PLIF images were corrected for laser sheet non-uniformities with a Gaussian laser-sheet profile.

In each OH-PLIF image, the flame edge distance from the bluff body edge was calculated by identifying the first axial location where the OH exceeded a threshold indicative of a flame. This was taken as the lift-off height in the inner recirculation zone (IRZ). Similarly, the lowest axial location with a flame edge, defined by the same threshold, over the burner base outside the swirled channel was taken to be the lift-off height in the outer recirculation zone (ORZ). Probability density functions (PDFs) of such-determined lift-off heights, h_{LO}, were calculated by analysing one side of the bluff body.

To investigate the stability of spray flames with additional gaseous fuel in the oxidiser channel, global flame extinction characteristics were also investigated. These extinction, or blow-off, curves were obtained by holding both C_7H_{16} and CH_4 fuel flow rates constant and increasing the bulk air flow rate in steps of approximately 5% of the total, hence lowering both the overall equivalence ratio and ϕ_{pmx}. The air velocity at which extinction occurred was recorded as the air velocity at blow-off, U_{BO}. For each condition considered, six test cases were recorded. The mean is presented in this work, although differences in U_{BO} are less than 5% of the mean for all the presented conditions. The burner temperature was measured with three k-type miniature thermocouples to ensure that extinction data was collected at a constant burner temperature. Results are presented in terms of C_7H_{16} fuel flow rate with an added CH_4 flow rate, Q_{CH4}, or in terms of global equivalence ratio including both fuels, ϕ.

3. Results and Discussion

Flame photographs of stable flames investigated in this work are shown in Fig. 2. The steady C_7H_{16}-air flame H1 is shown in Fig. 2a, C_7H_{16}-CH_4-air flames HP1-4 in Figs. 2b-2e, and premixed CH_4-air flames P1 and P2 are shown in Figs. 2f and 2g. Figures 2b - 2e show flames with increasing CH_4 content from left to right. Note that, for the premixed flames, flame P1 matches the CH_4 flow (i.e. ϕ_{pmx}) of HP4, and that P2 matches the overall ϕ of HP3. The spray flame H1 stabilises on the bluff-body edge with a short, symmetric reaction zone, as observed in previous work [8, 11]. In flames with C_7H_{16} spray (H1, HP1-4), a high intensity region along the inside of the spray cone is visible. The addition of CH_4 to the oxidiser flow broadens and extends the reaction

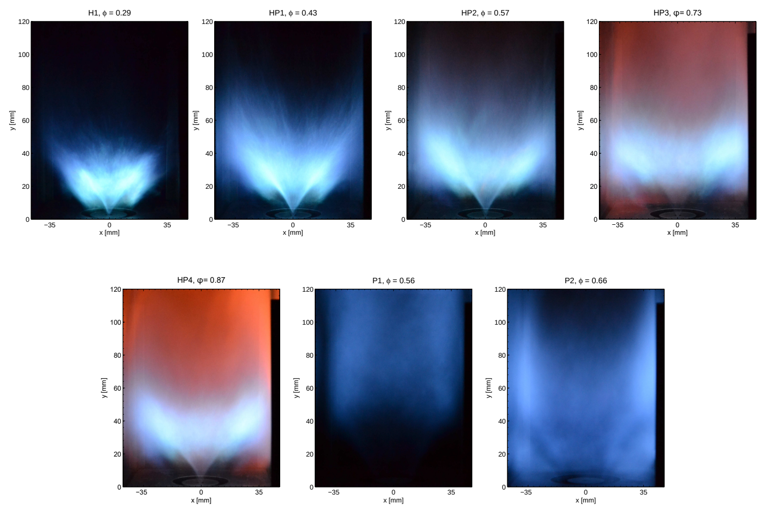

Figure 2: Photographs of stable flames investigated in this paper. Conditions correspond to those in Table 1.

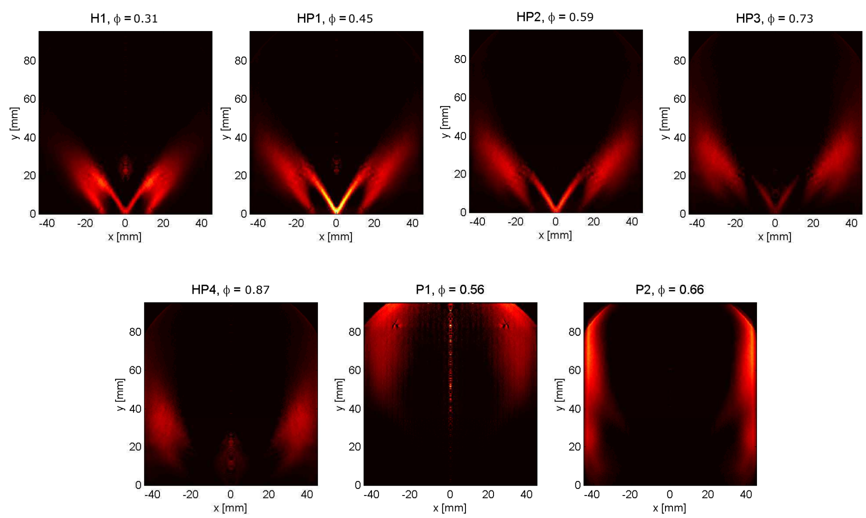

Figure 3: Mean OH* chemiluminescence images of stable flames.

zone towards the top of the burner. Differences in attachment of the flame with the addition of CH_4 are immediately visible, especially in comparison with the premixed flames P1 and P2. These differences will be discussed in detail with local and global extinction results.

Figure 3 shows mean inverse Abel transformed OH* chemiluminescence im-

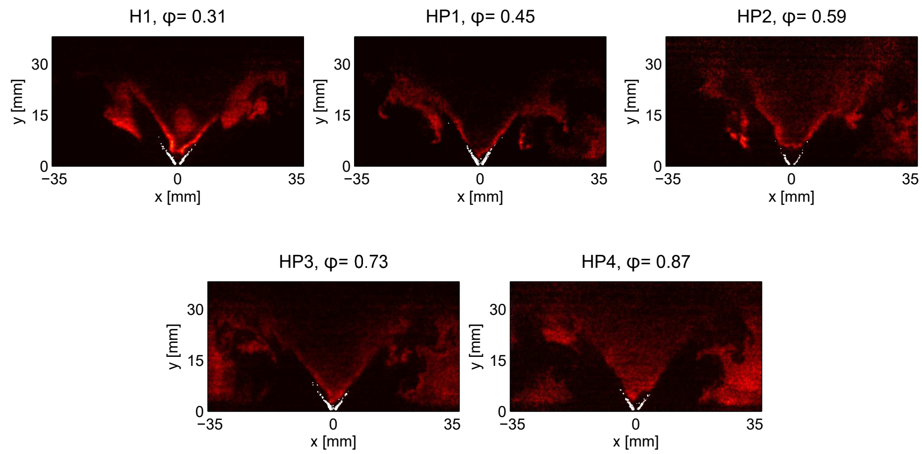

Figure 4: Instantaneous OH-PLIF and simultaneous Mie scattering images of stable flames.

ages of a C_7H_{16}-air flame (H1, Fig. 3a), C_7H_{16}-CH_4-air flames (HP1-4, Figs. 3b - 3e), and premixed CH_4-air flames (P1 and P2, Figs. 3f - 3g). With the addition and incremental increase of CH_4 to the swirled channel, the dominant reaction region, as indicated by OH* chemiluminescent signal, appears to shift from the inner recirculation zone (IRZ) and the edge of the spray to the outer recirculation zone (ORZ), causing the flame to lose a well-defined spray structure around the C_7H_{16} spray in the centre of the bluff-body. These images suggest that the spray only flame is attached solely to the bluff body, while dual-fuel flames show less evidence of bluff body attachment, instead stabilising downstream or in the sudden expansion on the outer side of the annular inlet. This behaviour is similar to that observed in dual-fuel flames with an oxygenated liquid fuel, C_2H_5OH, presented in Ref. [6]. Considering the stabilisation behaviour of the premixed-only flames (P1 and P2), it is seems that the presence of CH_4 in the premixed channel forces the stabilisation of flames in this configuration further downstream. Conversely, these results suggest that the addition of spray to a premixed system may be useful to encourage stabilisation and attachment at the point of injection: P1, a flame with the same CH_4 flow as HP4, shows only weak attachment to the burner base indicating it is near blow-off [11] while flame HP4 appears well-anchored. The piloting action of the spray fuel, C_7H_{16}, to promote the combustion of very lean secondary fuel, CH_4, is evident here, although the spray itself is affected and destabilised by the secondary fuel.

Figure 4 shows instantaneous OH-PLIF images with instantaneous Mie scattering signal overlaid in white for the stable conditions investigated here. Regions of OH in the H1 flame, in Fig. 4a, appear thin and trace the region of the spray cone with branches above the edges of the bluff body, typical of spray flames in this geometry [8, 11, 12]. As CH_4 is introduced in the oxidiser stream, the OH signal weakens and the flame branches on the outside of the spray cone

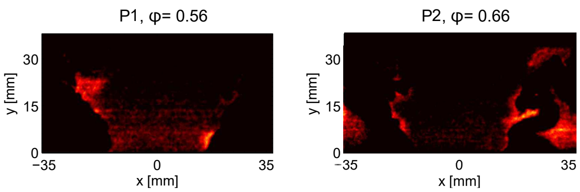

Figure 5: Instantaneous OH-PLIF images of premixed flames P1 and P2.

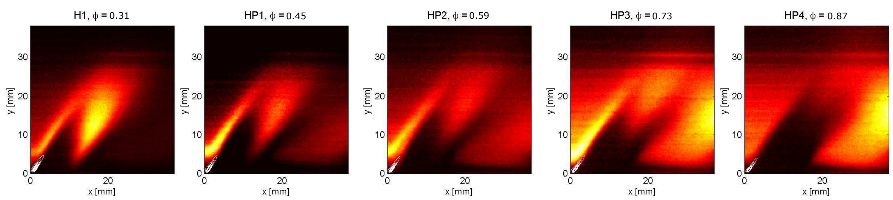

Figure 6: Mean OH-PLIF images with mean Mie scattering contours. Each image shows an average of both halves of the burner overlaid.

move further from the burner base. In flames HP14 (Fig. 4b to 4e) OH is visible inside the spray cone and, in flames HP2, HP3 and HP4, in the ORZ. To allow for comparison with premixed flames P1 and P2 at similar conditions, instantaneous OH-PLIF images of flames P1 and P2 are given in Figs. 5a and 5b. The leaner premixed flame, P1, appears close to blow-off with attachment only on the bluff-body edge in the IRZ, while the stabilisation occurs in the ORZ at richer conditions (P2). The transition of the presence of OH from the IRZ to the ORZ with the addition of CH_4 in C_7H_{16}-CH_4-air flames is indicative of a transition from a non-premixed spray flame structure to a premixed structure far from blow-off with large post-flame OH regions in both the IRZ and ORZ [10, 13, 14]. In particular, flame HP4, with a relatively high ϕ_{pmx}, has large regions of OH in the recirculation zones in comparison with spray flame H1 and dual-fuel flames with less CH_4 (HP1-2), suggesting that OH thickness widens significantly when the flame becomes dominated by premixed CH_4 behaviour, as expected. The high intensity OH signal on the inner edge of the Mie signal in flame H1 is not visible in flame HP4, but instead the entire region inside the spray cone contains OH.

Time averaged OH-PLIF images and mean Mie scattering iso-contours are shown in Fig. 6. Note that images presented in Fig. 6 show only half of the symmetrical burner, with $x = 0$ mm corresponding to the centre of the bluff body. Flames H1 and HP1, Figs. 6a and 6b have typical spray flame structures, with mean OH-PLIF images showing a dark region along the spray cone and a high intensity region of OH surrounding it where C_7H_{16} droplets evaporate

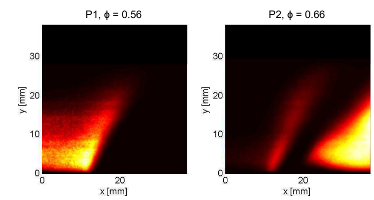

Figure 7: Mean OH-PLIF images premixed flames P1 and P2. Each image shows an average of both halves of the burner overlaid.

and burn. This high intensity OH region appears to be closely attached to the outer edge of the bluff body at x = 12.5 mm. With the addition of CH_4 to the swirled flow, the flame shows further increased detachment from the edge of the bluff body, seemingly stabilising in the ORZ. The centre region of the IRZ shows more OH signal in flames with a higher ϕ_{pmx} (HP2, HP3, and HP4) than those with little or no CH_4 in the swirled channel, which is likely long-lived post-flame OH as in purely premixed configurations (see premixed flames P1 and P2, presented in Fig. 7). The attachment on the bluff body edge, although consistent in both the C_7H_{16}-air and CH_4-air flames, is weaker in dual-fuel conditions HP1 - 4, suggesting that stabilisation characteristics of each fuel are disrupted by the presence of the other fuel. This may be attributed to either the interruption of the IRZ by the C_7H_{16} spray cone, leading to the absence of hot gases crucial for the anchoring of the flammable mixture from the annular stream [11], or to the lower O_2 content of the oxidiser available for the C_7H_{16} vapour diffusion flame.

By detecting the lowest flame branch above either the bluff body or burner base outside the swirled channel, the flame lift-off height, h_{LO}, in either the IRZ or ORZ, respectively, was calculated. Histograms of the lift-off height in the IRZ (above the bluff body) for C_7H_{16}-air and C_7H_{16}-CH_4-air flames are given in Fig. 8. As indicated by the OH-PLIF images shown in Fig. 6, C_7H_{16}-air spray flame H1 often attached closely to the edge of the bluff body with a mean lift-off height h_{LO} of 5.11 mm in the IRZ, shown in Fig. 8a. With the addition of CH_4 in the swirled channel, the mean lift-off height in the IRZ increased. With a ϕ_{pmx} of 0.56, flame HP4 has a mean lift-off height of h_{LO} nearly 24.34 mm (Fig. 8e) indicating that it is almost always detached from the edge of the bluff body. This suggests that the likelihood of local extinction in the shear layer at the edge of the bluff body increases as the swirled channel ϕ_{pmx} becomes richer. With more CH_4 in the oxidiser channel, the flame is less likely to attach and stabilise on the edge of the bluff body.

A converse trend is noticeable if the lift-off height in the ORZ is examined. Figure 9 shows histograms of the lift-off height in the ORZ (above the burner base outside of the swirled channel). Typical of spray flames in this configuration, Fig. 9a shows that the C_7H_{16}-air flame H1 is seldom attached in the ORZ. This is because of the tendency of bluff body spray flames to stabilise on the

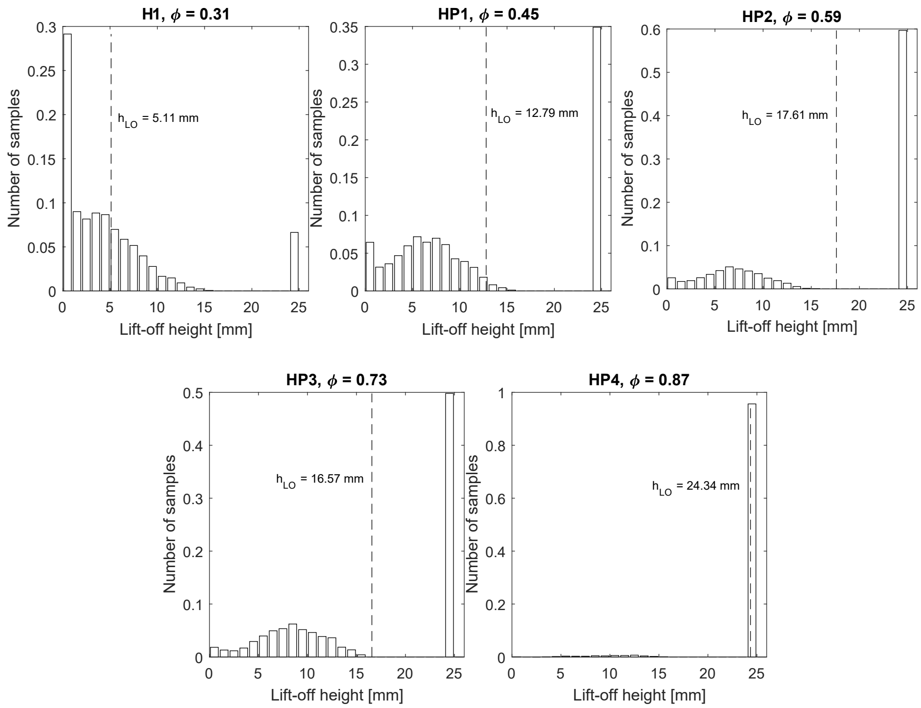

Figure 8: Histograms of lift-off height from above the bluff body edge (inner recirculation zone, IRZ) of flames with increasing CH_4 content in the swirled channel (left to right). Mean lift-off height, h_{LO}, is marked with a dashed line on each plot.

edge of the bluff body with regions of OH along the inner edge of the spray cone [8, 11, 12]. With the addition of CH_4 in the swirled channel, OH is frequently detectable in the ORZ, with mean lift-off height under 5 mm for flames HP3 and HP4 (Figs. 9d and 9e). This is likely not only because of the likelihood of stabilisation in the ORZ, but because of the post-flame OH in premixed systems.

Mean lift-off characteristics in the IRZ and ORZ are summarised in Fig. 10. Trends presented here clearly show the shift in attachment of C_7H_{16}-air and C_7H_{16}-CH_4-air flames with the addition of CH_4 in the swirled channel, marked by an increase in ϕ_{pmx}, given on the x-axis of Fig. 10. The IRZ mean lift-off heights, h_{LO}, of premixed flames P1 and P2 are also presented in Fig. 10. Both premixed flames stabilise on the bluff body edge, and appear closely attached with a h_LO of 4.5 mm and 5 mm for P1 and P2, respectively. This suggests that the spray fuel in C_7H_{16}-CH_4-air flames de-stabilises the IRZ attachment of the premixed flame.

In addition to local extinction and lift-off behaviour, global flame extinction characteristics were also investigated. These results are presented in comparison with blow-off behaviour reported for C_7H_{16}-air investigated by Yuan [9] and CH_4-air premixed flames presented by Cavaliere et al. [11] in the same

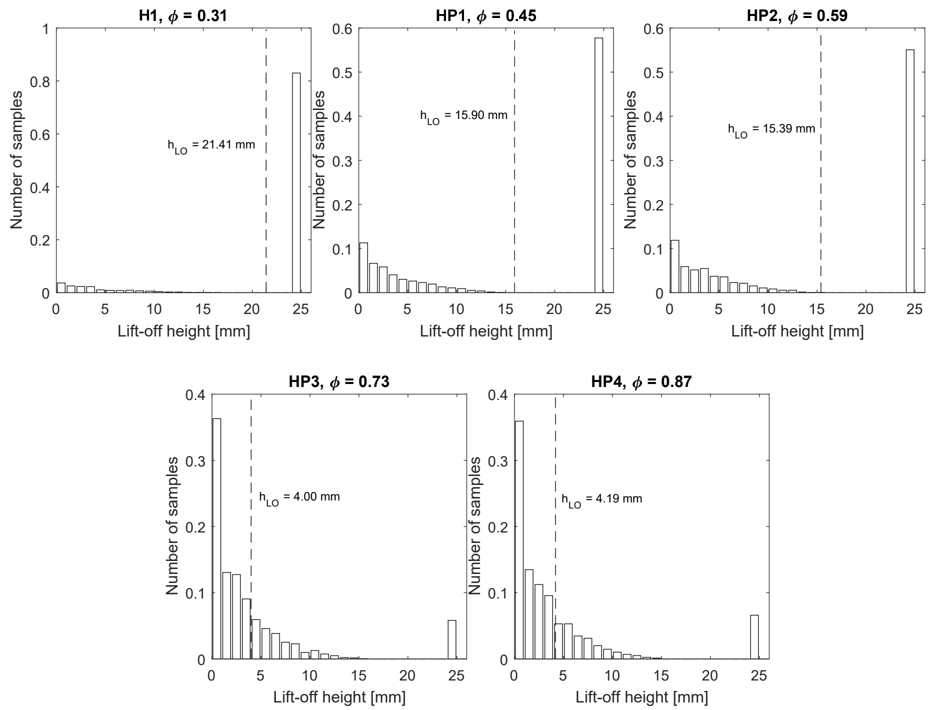

Figure 9: Histograms of lift-off height from above the burner base outside of the swirled channel (outer recirculation zone, ORZ) of flames with increasing CH_4 content in the swirled channel (left to right). Mean lift-off height, h_{LO}, is marked with a dashed line on each plot.

experimental configuration. A range of C_7H_{16} flow rates around 0.27 g/s, the stable C_7H_{16} flow rate, were examined. Each blow-off curve presented is associated with a fixed amount of CH_4 in the swirled channel (Q_{CH4} = 0, 10, 20, 30, or 40 L/min). Global extinction characteristics are presented as a function of C_7H_{16} flow rate in Fig. 11a. These results show that the addition of a gaseous fuel in the oxidiser channel increase the stability of spray flames, as would be expected with an increased overall equivalence ratio. Understood with the results presented in Fig. 10, this suggests that the lack of attachment on the bluff body edge (in the IRZ) with the addition of CH_4 in the swirled channel is not important for global flame stability. Further, attachment in the ORZ must be the primary mechanism for flame stabilisation in C_7H_{16}-CH_4-air flames.

Figure 11b shows global extinction characteristics of C_7H_{16}-CH_4-air flames as a function of liquid fuel flow rate (left) and global equivalence ratio, ϕ, on the x-axis (right). Blow-off behaviour of C_7H_{16}-air flames from Yuan [9] are shown with filled black square markers and that of CH_4-air premixed flames from Cavaliere et al. [11] are shown with hollow square markers. Stable flames discussed earlier in this work are marked in red. It is worthwhile to note that premixed flame P1 is very close to extinction. This is reasonable considering its

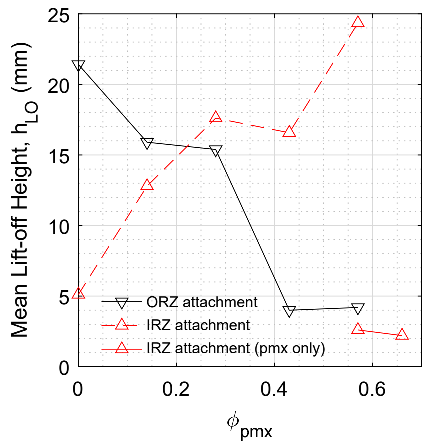

Figure 10: Mean lift-off heights (h_{LO}) for spray and dual-fuel flames on the bluff body edge (IRZ, red dashed line) and burner base outside the swirled channel (ORZ, black line). Mean lift-off heights of premixed flames on the bluff-body edge are also given (IRZ pmx only, solid red line).

lean equivalence ratio and lack of attachment in the ORZ, notable from Fig. 5a.

The trend that C_7H_{16}-air and CH_4-air flames have an increasing overall equivalence ratio with increasing air velocity at blow-off is expected and a correlation has been discussed in Ref. [11]. Examination of Fig. 11b (left) shows that an increasing amount of CH_4 in the air stream results in a U_{BO} higher than for the liquid-fuel-only flame, for the same liquid fuel flow rate. However, U_{BO} is not a unique function of the global equivalence ratio. Expressed in terms of the global equivalence ratio (Fig. 11b, right), the presence of CH_4 allows a U_{BO} that is unreachable with the C_7H_{16}-only operation. Hence, from a global stability perspective, the presence of methane has a stabilising effect. This is in contrast to the lift-off height statistics presented previously in this paper, where the CH_4 was found to have a destabilising effect in the sense of causing more pronounced lift-off and hence less secure flame anchoring. The data suggests that global extinction is not simply a progressive deterioration of stability at the nominal anchoring point, but that the whole combustor volume needs to be examined. This is consistent with the finding of Kariuki et al. [13], where the local extinction of an unswirled premixed flame was observed at downstream locations, and not at the anchoring point, suggesting that the overall extinction is because an increased likelihood of such local extinctions causes the recirculation zone to contain pockets of partially-quenched or fully-unreacted reactants that then fail to stabilise the flame [10]. Further understanding of the present blow-off data needs laminar flame numerical simulations such as those of Ref. [6] and intermediate species measurements such as CH_2O.

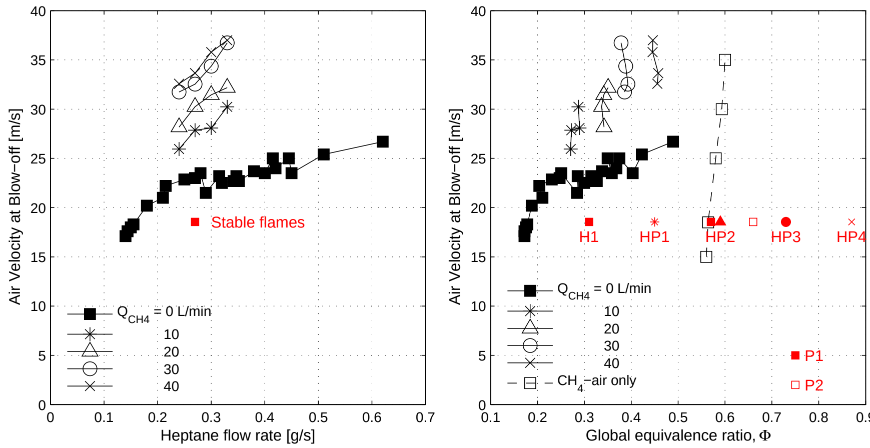

Figure 11: Air velocity at blow-off, U_{BO}, as a function of heptane flow rate (left) and global equivalence ratio ϕ (right). Stable flames discussed in this work are marked in red. Spray flame data (black filled squares, $\phi_{pmx} = 0.00$) from Ref. [9] and premixed flame data (black open squares, CH_4-air only) from Ref. [11].

4. Conclusions

In this work, the flame structure, local stabilisation, and global extinction characteristics of dual-fuel C_7H_{16}-CH_4-air flames is investigated and compared to C_7H_{16}-air spray and CH_4-air premixed flames in a bluff body swirl-stabilised burner. The reaction zone of C_7H_{16}-CH_4-air flames is modified from that resembling a C_7H_{16}-air spray flame to a CH_4-air premixed flames with the incremental increase of CH_4 in the oxidiser channel. This is observable both in flame photographs and mean OH* chemiluminescence images. The analysis of mean OH-PLIF images shows that the main point of attachment, indicated by the lowest point of OH signal above the bluff body or burner base by some threshold, shifts from the IRZ above the bluff body to the ORZ above the burner base outside of the swirled channel as more CH_4 is added to the system. Compared with single fuel spray and premixed gaseous OH-PLIF images, this suggests that the presence of second fuel may de-stabilise the typical attachment points characteristic of the first fuel. However, dual-fuel flames show a clear trend toward attachment in the ORZ rather than the IRZ, which is characteristic of premixed gaseous flames far from blow-off. Dual-fuel flames also show large regions of OH signal within the spray cone region in the IRZ and in the ORZ itself, which may be post-flame OH similar to that of premixed systems.

Observed attachment characteristics are summarised by an investigation into mean lift-off height in both the IRZ and ORZ for the stable spray and dual-fuel flames presented here. The addition of CH_4 to spray systems causes a stabilisation outside of the swirled channel, indicating that the attachment point near the edge of the bluff-body edge is a point of local extinction or a region of the system which is too rich to host a flame attachment point. This behaviour is similar to premixed flames far from blow-off. Despite this, global extinction characteristics suggest that dual-fuel flames are more resistant to blow-off than single-fuel spray flames at the same global equivalence ratio. This is likely due to the attachment in the ORZ, which is less sensitive to velocity fluctuations in the swirled channel than attachment in the IRZ along the shear layer. The global extinction, or blow-off, curve for C_7H_{16}-CH_4-air flames tends to resemble that of premixed CH_4-air flames. This result suggests that such flames are of fundamental interest due to their unique stabilisation behaviour and relative insensitivity to bulk velocity changes in comparison with spray-only flames at similar equivalence ratios.

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