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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.

1. Introduction

Knowledge of the stabilisation characteristics of systems with multiple fuels is limited considering most dual-fuel experimental and numerical studies have focused on reciprocating engines. These studies have conventionally emphasised pollutant emissions and ignition mechanisms, particularly in natural gas-air systems with a pilot spray [1–5]. 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 multiple 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

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Abbreviations: IRZ, inner recirculation zone; ORZ, outer recirculation zone; PDF, probability density function

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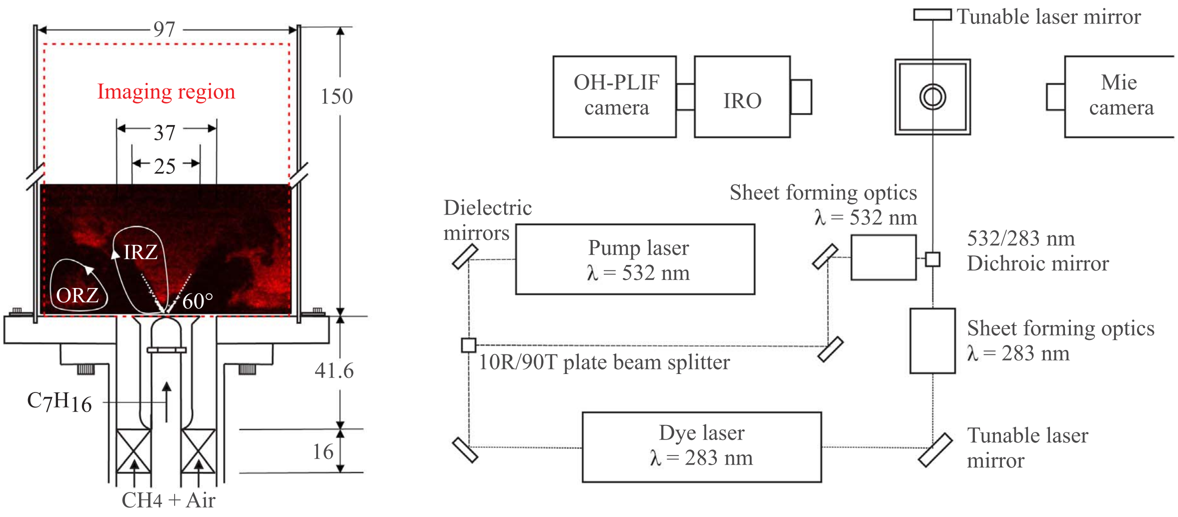

Fig. 1. A schematic of the experimental set-up (left) and simultaneous OH-PLIF and Mie scattering imaging system (right).

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 (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 $\phi = 0.45$–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.

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

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 4 × 4 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 Fig. 2b–e, and premixed CH_4-air flames P1 and P2 are shown in Fig. 2f and g. Fig. 2b–e 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