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Visualisation of turbulent swirling dual-fuel flames

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Abstract

Swirl C_2H_5OH-air flames with increasing amounts of CH_4 premixed with the oxidiser flow have been examined with OH* chemiluminescence, OH-PLIF, and Mie scattering, supplemented by laminar counterflow calculations. The aim of this study is to investigate dual-fuel flame structure and stability and provide experimental data for model validation. Imaging results show an inner flame branch along the hollow-cone spray and an outer flame branch at the shear layer between the annular oxidiser and an inner recirculation zone over the bluff body. As the CH_4 equivalence ratio in the annular channel increases, ϕ_{pmx}, the probability of flame lift-off at the outer branch increases. A premixed flame at the same flow conditions is stably attached, implying a detrimental competition of the two fuels for the locally-available O_2 leading to extinction. If the oxidiser contains CH_4 such that ϕ_{pmx} is above the lean flammability limit (LFL), OH in the inner recirculation zone appears in wide fronts, contrasting the thin regions visible in the spray flame. If CH_4 is mixed with air at a ϕ_{pmx} below the LFL, laminar flame simulations show the consumption of CH_4 due to the high temperature of the C_2H_5OH reaction zone and an extinction strain rate that decreases initially with increasing the ϕ_{pmx}, but increases again as ϕ_{pmx} approaches the LFL. The results offer a database for turbulent dual-fuel model validation.

Keywords: Dual-fuel; Spray; Stabilisation; Swirl

1. Introduction

Studies involving dual-fuel combustion systems are limited, having primarily focused on reciprocating engines with emphasis on pollutant emission and the ignition mechanism of a natural gas-air flammable mixture by a pilot spray [1–5]. Dual-fuel systems also have relevance for staged gas turbine combustors, in which different fuels may be injected in sequential chambers [6]. Staged fuel injection involves the addition of fuel to the hot products of a richer flame, while the piloting and ignition of low-calorific value fuels may be achieved through a second fuel. With the exception of Refs. [7–9], which reported on the behaviour of C_2H_5OH or CH_3OH spray in natural gas hot combustion product coflow and crossflow, respectively, within the context of a preheated and diluted combustion regime, few investigations have attempted to fundamentally understand dual-fuel systems in contexts other than reciprocating engines.

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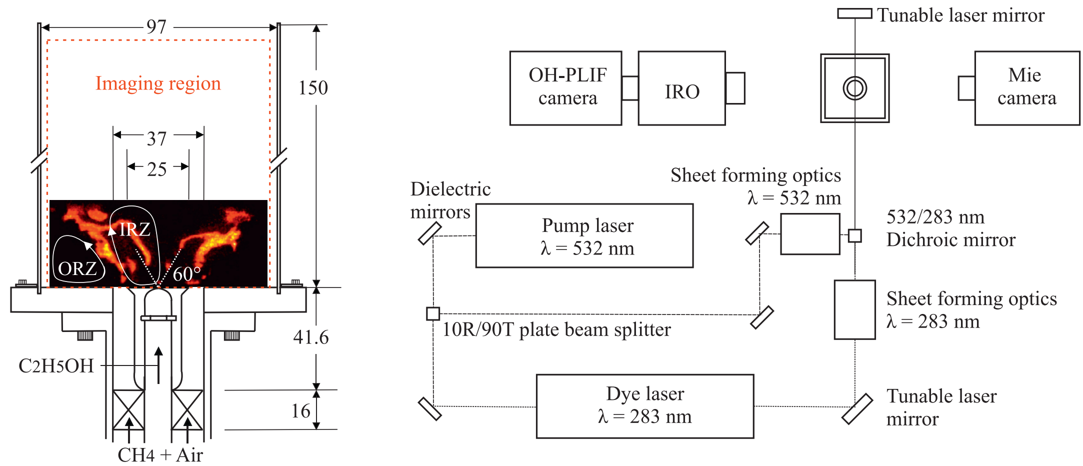

Fig. 1. Schematics of the bluff body burner (left) and experimental set up (right).

The numerical modelling of turbulent dual-fuel systems is challenging. Apart from methods based on the transported PDF equation [10,11] that seem to be natural candidates for such problems, mixture-fraction based approaches such as flamelet and Conditional Moment Closure methods need development to allow for the characterisation of two fuels through multiple mixture fractions [12] and the underlying sub-models need further validation. The development of such methods are important not only for dual-fuel combustion, but also for multiple-injection diesel engines where individual injections have been modelled as separate fuel streams [13–15].

In this work, a novel experimental configuration is studied with the aim to provide information on dual fuel reaction zones, flame shape, and local extinction. A burner previously studied with n-heptane [16] and C_2H_5OH spray [17], is used to study an C_2H_5OH spray burning in air premixed with increasing amounts of CH_4. Flame conditions involve CH_4levels corresponding to mixtures both leaner and richer than the nominal lean flammability limit ($\phi_{LFL} = 0.5$; [18]). 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. In order to predict this behaviour accurately, models must successfully predict dual-fuel combustion extinction behaviour. Finally, simulations of laminar, gaseous, steady counterflow flames between $C_2H_5OH$and CH_4-air streams are presented to provide insight into both local extinction and flame structure.

2. Method

Lean C_2H_5OH-CH_4-air flames were stabilised in an enclosed bluff body burner [16,19] shown in Fig. 1. Air or premixed CH_4-air were supplied through a $D = 37$ mm pipe with a nominally 60° swirler 47.6 mm upstream of the burner base. The swirled flow, described in detail in Ref. [19,20], had a swirl number of 1.23, calculated according to the method presented in Ref. [21], and a Reynolds number, calculated with the bulk velocity U_{pmx} and the annulus hydraulic diameter, ranging from 13900 to 14300. A pressure atomiser (Lechler 212.054) was used to supply 0.38 g/s C_2H_5OH with a 60° hollow cone angle housed inside a $d = 25$ mm conical bluff body centred in the pipe. This geometry encourages the formation of an outer recirculation zone (ORZ) outside of the premixed channel and an inner recirculation zone (IRZ) above the bluff body [20]. A $\phi = 0.24$ C_2H_5OH-air flame (referred to as S1) and two CH_4-air premixed flames, $\phi = 0.57$ and 0.66 (referred to as P1 and P2, respectively) were compared with a series of C_2H_5OH-CH_4-air flames with incrementally increasing CH_4 flow rates in the oxidiser (annular) stream, referred to as SP1–4, with $\phi = 0.38–0.80$. Note that, by increasing CH_4 in the oxidiser stream, the velocity of the annulus flow increases. These conditions are summarised in Table 1. C_2H_5OH-air spray flame measurements are presented in Ref. [17,20] and

Table 1
Experimental conditions.

Case	ϕ	ϕ_{pmx}	R	U_{pmx} (m/s)
S1	0.24	0.00	1.00	18.5
SP1	0.38	0.14	0.04	18.8
SP2	0.52	0.28	0.02	19.1
SP3	0.66	0.43	0.01	19.4
SP4	0.80	0.57	0.01	19.7
P1	0.57	0.57	0.00	19.7
P2	0.66	0.66	0.00	19.9