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Fuel effects on the stability of turbulent flames with compositionally inhomogeneous inlets

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Abstract

This paper reports an analysis of the influence of fuels on the stabilization of turbulent piloted jet flames with inhomogeneous inlets. The burner is identical to that used earlier by the Sydney Group and employs two concentric tubes within the pilot stream. The inner tube, carrying fuel, can be recessed, leading to a varying degree of inhomogeneity in mixing with the outer air stream. Three fuels are tested: dimethyl ether (DME), liquefied petroleum gas (LPG), and compressed natural gas (CNG). It is found that improvement in flame stability at the optimal compositional inhomogeneity is highest for CNG and lowest for DME. Three possible reasons for this different enhancement in stability are investigated: mixing patterns, pilot effects, and fuel chemistry. Numerical simulations realized in the injection tube highlight similarities and differences in the mixing patterns for all three fuels and demonstrate that mixing cannot explain the different stability gains. Changing the heat release rates from the pilot affects the three fuels in similar ways and this also implies that the pilot stream is unlikely to be responsible for the observed differences. Fuel reactivity is identified as a key factor in enhancing stability at some optimal compositional inhomogeneity. This is confirmed by inference from joint images of PLIF-OH and PLIF-CH_2O, collected at a repetition rate of 10 kHz in turbulent flames of DME, and from one-dimensional calculations of laminar flames using detailed chemistry for DME, CNG, and LPG.

Keywords: Turbulent flames; Piloted flames; Inhomogeneous inlets; Flame stability

1. Introduction

Turbulent flames with compositionally inhomogeneous inlets are common in gas turbines due to imperfect mixing between fuel and air [1–4]. This is an issue in non-premixed, as well as premixed, systems where instabilities propagate upstream of the combustor to induce pulsations in the fuel supply

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[3,4]. Fuel stratification is also induced in modern direct injection reciprocating engines where overall lean operation is sought while rich mixtures are maintained near the spark plug to ensure ignition [5–8]. These issues have prompted extensive research into laminar and turbulent stratified flames to resolve the effects of concentration gradients on the structure and stability of these flames [9–11]. These references as well as others are further discussed in the thorough review of Masri [12]. This work has recently been extended to cover not just flammable mixtures but the entire mixture fraction space, using the Sydney piloted burner with compositionally inhomogeneous inlets [13–16].

A key feature of the burner is the ability to recess a fuel tube within an air annulus, providing a method of varying the inhomogeneity of the mixture at the jet exit plane. With methane or compressed natural gas (CNG), it was found that flame stability is enhanced significantly at some intermediate recess distance that produces optimal gradients in mixture fraction at the burner exit. Detailed measurements at locations near the pilot have revealed that this enhancement is largely due to the existence of premixed/stratified fuel samples augmenting the stabilizing effects of the pilot [13,16]. The question addressed in this paper is whether such enhancements may be carried across to other fuels.

In addition to CNG, two other fuels are studied here: dimethyl ether (DME) and liquefied petroleum gas (LPG). DME is one of the simplest oxygenated fuels available for possible use in compression ignition (CI) engines [17]. It has low sooting propensity and lends itself to advanced laser diagnostics [18–20], including laser-induced fluorescence. This is employed here at a high repetition rate of 10 kHz to make joint measurements of formaldehyde (CH_2O) and OH in selected flames of DME/N_2 (1/1 by vol.). Results from laminar flame calculations and non-reactive RANS simulations for mixtures of DME, CNG, and LPG are used to interpret experimental trends.

2. Stability limits

The burner is similar to that used in [13–16] for the investigation of piloted turbulent CH_4/air flames with inhomogeneous inlets. It includes two tubes surrounded by an annular pilot and an air co-flow, as shown in Fig. 1. The inner tube supplying the fuel can recess within the main tube which supplies air, hence varying the degree of mixing between fuel and air at the burner's exit plane. A recess distance L_r =300 mm results in an almost homogeneous fuel/air mixture, as evidenced by the uniform mixture fraction radial profile, measured for CNG by Rayleigh scattering in [15] and shown in Fig. 2. The other extreme of L_r =0 mm corresponds to the fully non-premixed limit. Intermediate recess distances yield non-uniform mixture fraction profiles with a broad range of equivalence ratios across the jet exit plane as for example case L_r =100 mm, also shown in Fig. 2. A stoichiometric C_2H_2/H_2/air mixture with the same C/H ratio as the main fuel powers the pilot flames stabilized on a perforated plate. The sensitivity of the flame to pilot conditions such as composition, temperature, and velocity has recently been thoroughly studied and is reported elsewhere [29]. The burner assembly is located in a 15×15 cm square wind tunnel, providing a uniform air co-flow at 15 ms^{-1}.

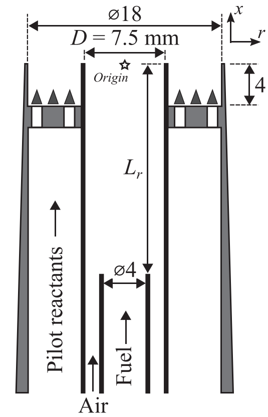

Fig. 1. Cross-section schematic of burner assembly showing pilot, annulus air, and central fuel streams.

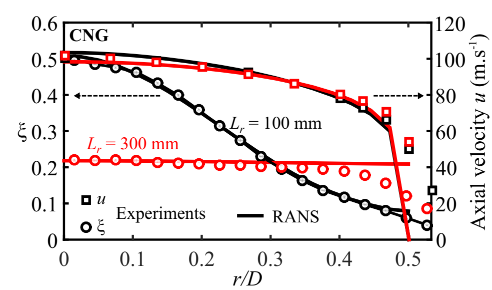

Fig. 2. Computed and measured [15] mixture fraction and axial velocity radial profiles at burner exit plane for CNG, V_A/V_F =2, U_j =82 ms^{-1}, and L_r =100 mm (black) and L_r =300 mm (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Three fuels are used: DME, LPG which contains 90% C_3H_8 by volume (the balance being 5% butane and 5% other hydrocarbons), and CNG which is 88% CH_4 by volume (the balance being 7.8% ethylene, 1.9% carbon dioxide, 1.2% nitrogen, and 1.1% hydrogen, water, and other hydrocarbons). The mass flow rates are regulated with mass flow controllers (Alicat MC and MCR series), with a relative accuracy better than 2%. Table 1 lists relevant properties for the cases studied here, including