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Stabilization of piloted turbulent flames with inhomogeneous inlets

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Abstract

This paper investigates the stabilization mechanism of turbulent jet flames with highly inhomogeneous inlet conditions. A modification of the standard piloted burner is employed here with the addition of a central tube (inner) carrying fuel that can slide within the existing (outer) tube carrying air. Both tubes are located within the pilot annulus and inhomogeneity is varied by translating the inner tube upstream of the jet exit plane. Two flames with identical overall air/fuel ratios, bulk jet velocities, and pilot conditions but different levels of homogeneity in the fuel/air mixture are selected for detailed investigations. Measurements are performed using Sandia's Raman–Rayleigh–LIF line facility, and Large Eddy Simulation (LES) using the stochastic fields approach are also conducted for the same flames. Results reported here focus on the early stabilization region.

The flame with inhomogeneous inlet conditions is more stable being at 57% of blow-off compared to the homogeneous counterpart, which is at 78% of blow-off. It is found that, very close to the jet exit plane, premixed combustion dominates the flame with an inhomogeneous profile. This is in contrast to the homogeneous case, which behaves like a diffusion flame. Further downstream, but still within the pilot region, partial mixing starts to occur between richer samples and hot combustion products. A comparison of the relative conditional scalar dissipation rates, χ_r shows that in the upstream region, and within the reactive limits, the homogeneous case has higher values of χ_r. Premixed combustion with higher rates of heat release and lower scalar dissipation rates in the near field are therefore key reasons for the improved stability of the flames with inhomogeneous inlets. These findings are corroborated by results from LES.

Keywords: Turbulent combustion; Inhomogeneous boundary conditions; Flame stabilization

1. Introduction

Turbulent flames with inhomogeneous inlet conditions constitute an important class of problems that has received little attention despite their common use in practical applications [1–3]. Typical examples include lean premixed pre-vaporised gas turbines, augmenters and air-blast spray atomisers, which may be loosely referred to as "partially premixed". Stratified combustion, is a subset of this class where mixture inhomogeneity is generally restricted to within the flammable limits. Practical applications of stratified

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combustion are becoming more common with the advent of HCCI and DISC engines [4,5]. While such flows may feature improved stability and favourable levels of emissions, reasons for such behaviour are not fully understood.

Stabilization of turbulent flames can be achieved in many ways, the most common of which are with a pilot [6,7] or by inducing recirculation with a bluff-body or quarl [7–9] or through the generation of swirl [3,10,11]. The focus here is on pilot-stabilization that has been used extensively as a model problem for advancing the modeling of turbulent non-premixed and partially-premixed flames, albeit with homogeneous conditions at the inlet [6,12]. Combustors in lean premixed gas turbines tend to use rich pilots with overall lean conditions in the main burner, and one or both streams may be partially premixed with some inhomogeneity leading to improved flame stability [3]. The prevailing mechanisms of stabilization are only vaguely understood, particularly in the presence of inhomogeneous boundary conditions.

The current paper explores this issue by investigating turbulent flames where the homogeneity in the boundary conditions may be varied hence changing the stability limits [13]. This is achieved by a modification to the well-known piloted burner [6,12] which involves adding to the central jet which now carries air, an inner tube that carries the fuel. The inner tube can be recessed to introduce mixture fraction gradients and a varying degree of inhomogeneity such that mixtures at the exit plane may span the entire mixture fraction range. It has been demonstrated [13] that the stability of a flame with inhomogeneous inlet profile can be up to 50% higher than that of the corresponding flame with homogeneous inlet, both having an air/fuel ratio of two. This optimum occurs at intermediate recession distance with fuel flowing through the recessed inner tube and air flowing in the annulus surrounding the inner tube. Reasons for such behaviour are further explored in this paper. Two flames with different levels of inhomogeneity yet similar bulk jet velocities and air/fuel volume fractions are selected for detailed investigations. Extensive measurements are made using Sandia's Raman–Rayleigh–LIF line imaging facility. In addition, Large Eddy Simulations (LES) are performed for the same flames employing the Eulerian stochastic field method [14,15]. Details of the flame structure within the first few diameters of the jet are reported here revealing extensive information about the mechanism of stabilization.

2. Burner and selected conditions

Figure 1a shows an isometric cut-out view of the modified piloted burner featuring two tubes surrounded by an annular pilot. One of the tubes issues fuel, while the other issues air, such that a fixed air/fuel ratio can be maintained. The inner tube ($D_i = 4$ mm inner diameter and 0.25 mm wall thickness) can slide within the main tube ($D = 7.5$ mm inner diameter and 0.25 mm wall thickness) inducing variable fuel–air mixing at the burner exit. Homogeneous mixtures are obtained at sufficiently large recession distance, while the non-premixed condition prevails at zero recession. The outer diameter of the complete

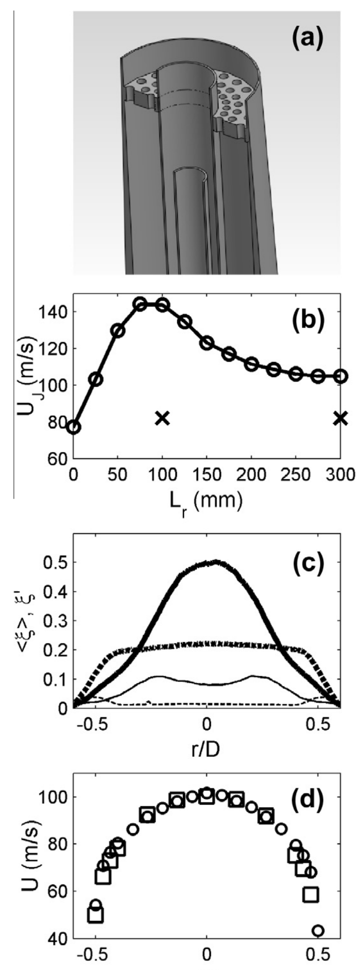

Fig. 1. (a) Schematic cutaway of the burner showing the pilot stream, outer jet and inner tube recessed upstream of the jet exit plane. (b) Bulk jet blow-off velocity as a function of recession distance, L_r for the case with air/fuel ratio of two. Crosses indicate the two flames selected for further study. (c) The mean mixture fraction profile $\langle\xi\rangle$ (thick lines), and its rms ξ' (thin lines), at $x/D = 0.5$ for FJ200-100-82 (solid lines) and FJ200-300-82 (dashed lines). (d) Mean axial velocity profiles for FJ200-100-82 (circles) and FJ200-300-82 (squares) measured at $x/D = 0.2$.