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Statistics of scalar dissipation and reaction progress in turbulent flames with compositional inhomogeneities

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This paper presents detailed measurements of three-dimensional (3D) scalar dissipation rates collected in turbulent, piloted flames with varying degree of compositional inhomogeneity. Joints statistics of mixture fraction and reaction progress variable are also shown for a range of conditions. These measurements complement the already existing substantial data set for mixed-mode flames stabilized on the Sydney piloted burner with compositionally inhomogeneous inlets. It is found that the difference between 2D (χ_r) and 3D (χ) scalar dissipation increases with axial distance along the flame such that the ratio χ/χ_r may be as high as 2.6. The effects of spatial resolution become more significant as compositional inhomogeneity increases. Mixture fraction, ξ is well-correlated with reaction progress variable, c, in turbulent homogenous flames but the correlations deteriorates significantly as the compositional inhomogeneity increases. This transition should clearly be accounted for in modeling mixed-mode combustion. A new mode of conditioning the scalar dissipation data with respect to burnt and unburnt fluid samples reveal separate trends: while the levels of χ remain similar for burnt samples, unburnt fluid experiences increasing levels of χ as the flames approach blow-off.

1. Introduction

Compositional inhomogeneity is common in practical turbulent combustion systems due to the inherent difficulty associated with achieving uniform mixing within limited times or lengths. The possible formation of acoustic instabilities and flow pulsations only adds to this problem with their tendency to form concentration gradients [1,2]. As such, understanding the mechanisms that drive stability of these flames and developing reliable predictive tools for mixed-mode combustion are integral parts of improving their design. Key prerequisites for achieving these objectives are an improved understanding of mixed-mode flames and the generation of reliable datasets for representative conditions that form a platform for model validation. The Sydney piloted burner with inhomogeneous inlets provide such a platform because of its capability to stabilize flames ranging from homogeneously non-premixed to mixed-mode flames that also span a wide range of turbulence-chemistry interactions. The burner has two concentric pipes within the pilot stream where the inner pipe, which carries fuel, can be recessed within the outer pipe, which carries air, hence introducing compositional inhomogeneity at the jet exit plane.

Previous studies in this burner [3–6] have shown that for a variety of fuels, a significant improvement in flame stability can be observed at an intermediate recess distance of the inner jet, and hence at some optimal level of compositional inhomogeneity in the inlet profile. Previous measurements of Rayleigh scattering at $x/D = 0.5$ [4] taken at Sydney and species concentration and temperature at $x/D = 1$ [3,5] taken at Sandia, at these conditions, have shown that samples adjacent to the hot pilot stream are more likely to be within the fuel flammability limits. These measurements have also shown the primary upstream combustion mode of these flames with improved stability is premixed after which they quickly transition to a diffusion dominated mode further downstream.

This paper complements the already substantial data set existing for flames stabilised on this burner by presenting novel measurements of three-dimensional mixture fraction dissipation rates, χ, and joint statistics of mixture fraction, ξ, and reaction progress variable, c. Mixture fraction dissipation is referred to simply as scalar dissipation in the rest of this paper. All these parameters, χ, ξ and c are important for modelling approaches to mixed-mode combustion [7]. In non-premixed flames, the interactions between

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chemical reaction and mixing rates may be significant depending on the magnitude of the relative time scales that is expressed in terms of a Damkholer number [8]. The scalar dissipation rate, provides a measure of the rate of mixing expressed in terms of a local diffusivity and the extent of the concentration gradients at the location of the reaction zone. When mixture fraction is employed, the square of its spatial gradient is used in the definition of the scalar dissipation rate. In flows with compositional inhomogeneity such as those considered here, the concept of scalar dissipation remains valid as long as gradients in mixture fraction exist. In fully premixed pockets, the extent of burning is expressed in terms of the reaction progress variable which in turn is affected by local strain and curvature. Depending on the modelling approach, a flame indicator may be need to distinguish between premixed and non-premixed modes of burning and the nature of the extent of the correlation between mixture fraction and reaction progress variable becomes interesting.

The data presented here are extracted from measurements of temperature and major species composition made using the multi-scalar diagnostics system at Sandia National Laboratories [9–11]. Key to these diagnostics and the subsequent analysis is an improvement in measurement resolution using a wavelet adaptive threshold and reconstruction technique, and insight into flame front orientation using cross planar OH-LIF in addition to combined Raman/Rayleigh/CO-LIF diagnostics.

The first section of this paper focuses on scalar dissipation rates and takes advantage of the improvements in diagnostic techniques over previous measurements of these flames to provide more quantitative analysis. This includes determining the effect of these diagnostic improvements and understanding their importance for future reporting of scalar dissipation rates. The next section focuses on the contrast between the standard piloted jet case, when the mixture at the jet exit plane is homogeneous, and the compositionally inhomogeneous flames. The previous assumption that the increased probability of flammable mixtures upstream in the flame results in greater levels of heat release near the jet exit, enhancing overall flame stability, is examined more deeply. Conditional statistics of mixture fraction and a recently developed oxygen based progress variable designed for use with Raman and Rayleigh diagnostics have allowed a closer look at these flames. The use of greater conditioning confirms earlier theories on the importance of inlet inhomogeneity in piloted jet flames on flame stability, and subsequently analogous systems.

2. Experimental setup

2.1. Burner design

The burner used in this study has been described in detail elsewhere [3–5] and only a brief description is given here. As shown in Fig. 1, it consists of two concentric tubes surrounded by an 18 mm pilot. The 4 mm inner diameter (0.25 mm wall thickness) central tube can be recessed within the ID 7.5 mm (0.25 mm wall thickness) outer tube. By controlling the recession distance, L_r, the homogeneity at the exit plane can be varied from fully non-premixed at $L_r = 0$ mm to near homogeneous at $L_r = 300$ mm with intermediate distances exhibiting compositionally inhomogeneous mixtures

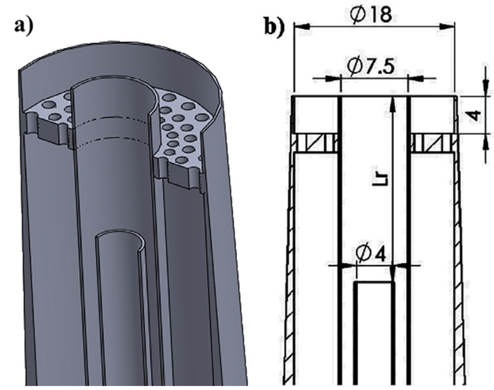

Fig. 1. Isometric (a) and schematic (b) view of the modified Sydney piloted jet burner.

at the exit plane. For the flames studied in this paper, fuel issued from the central jet and air from the annular jet. The burner was placed in 300 mm x 300 mm co-flow with a velocity of 15 ms^{-1}.

Four flames are investigated here, listed in Table 1, three having inhomogeneous mixtures at the inlet but varying departures from blow-off and one with near homogeneous inlet conditions. These four flames have been investigated previously [3–5] alongside an additional case with the reverse air/fuel configuration, fuel issuing from the annulus and air from the inner jet. The reverse configuration is not discussed here due to differences in velocity fields hampering useful comparison in this context. Note the full case names are listed in the table but, for brevity, abbreviated versions are used later on with the cases distinguishable by their velocity and recession. All flames have an air/fuel volume ratio of $V_A/V_F = 2$ using methane as fuel that corresponds to a bulk jet equivalence ratio, $\phi_j = 4.76$. The pilot, consisting of a mixture of acetylene, hydrogen, air, nitrogen and carbon dioxide, provides a heat release rate of $H_r = 2.2$ kW, and is designed to have the same C/H ratio and adiabatic equilibrium temperature as a stoichiometric methane/air mixture. Velocities given in Table 1 are calculated using the volumetric flow rates divided by the appropriate cross sectional area. For the bulk jet and blow off velocities, U_j and U_{bo}, that is the total volumetric flowrate and the jet area at the exit plane. Bulk velocities U_A and U_F use the air and fuel volumetric flowrates and annulus and inner jet areas respectively. The Reynolds number is calculated using the bulk jet velocity, $U_{j,}$ and the nner diameter of the outer jet, $ID_o = 7.5$ mm. Heat release rate is calculated from the flow rate of fuel and the lower heating value of methane.

2.2. Laser diagnostics

The multi-scalar measurements presented here were taken at the Turbulent Combustion Laboratory (Sandia National Laboratories) using combined line imaging of Raman and Rayleigh scattering, and laser induced fluorescence of CO, and crossed planar OH LIF [9–12]. This provides single shot profiles of temperature and seven major species (O_2, N_2, CH_4, H_2O, H_2, CO_2 and CO) across 6 mm long segments, and instantaneous information on the flame orientation using OH iso-contours. Groups of 300-500 shots were

Table 1
Selected cases.

Cases	L_r (mm)	U_j (m/s)	U_{bo} (m/s)	U_j/U_{bo} (%)	U_A(m/s)	U_F(m/s)	Re_j	Hr (kW)
FJ200-5GP-Lr300-59	300	59	84.3	70	61.5	69.2	27600	28.5
FJ200-5GP-Lr75-57	75	57	114.3	50	59.5	69.0	26800	27.6
FJ200-5GP-Lr75-80	75	80	114.3	70	83.4	93.8	37500	38.6
FJ200-5GP-Lr75-103	75	103	114.3	90	107.2	120.6	48300	49.6