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Proceedings of the Combustion Institute 36 (2017) 1737–1745

Proceedings of the Combustion Institute

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Turbulent flames with compositionally inhomogeneous inlets: Resolved measurements of scalar dissipation rates

H.C. Cutcher [a,*], R.S. Barlow [b], G. Magnotti [b], A.R. Masri [a]

[a] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006 Australia
[b] Combustion Research Facility, Sandia National Laboratories, Livermore, CA 94550, USA

Received 4 December 2015; accepted 24 July 2016
Available online 8 November 2016

Abstract

Highly resolved measurements of scalar dissipation rates in turbulent piloted CH_4/air flames with compositionally inhomogeneous inlets are presented. These were performed using Sandia's Raman–Rayleigh–LIF system but with data acquisition and processing strategies that result in enhanced spatial resolution and reduced noise. They complement earlier measurements with coarser resolution. The burner stabilising these flames enables variability in the mixture fraction profile at the exit plane. Earlier studies have shown enhanced stability at an optimal compositional inlet profile that leads to multiple modes of combustion, with premixed-stratified flames close to the jet exit but transitioning to diffusion-dominated burning downstream. It is found that at upstream locations, for jets with homogeneous inlets as well as for the high-temperature regions of flames with inhomogeneous inlets, both fine and coarse measurements of scalar dissipation rates yield similar results, giving confidence that measurements resolve the local dissipation scales. Downstream locations in homogeneous mixtures also show similar results for both coarse and fine measurements across all mixtures. Differences arise in the rich, inner regions of turbulent flames with inhomogeneous inlets, where the fine resolution measurements are more reliable due to the existence of steep gradients in composition. Both data sets provide a comprehensive platform to enhance the modelling of turbulent flames in the presence of multi-modes of combustion.

Keywords: Turbulent flames; Scalar dissipation rates; Partially premixed flames; Inhomogeneous composition

1. Introduction

The scalar dissipation rate, a highly relevant parameter in turbulent combustion modelling [1,2] continues to challenge the combustion diagnostics community despite recent advances in laser imaging techniques [3,4]. The difficulty lies in the need to resolve the relevant dissipative flow structures yet maintain high signal to noise ratios (SNR) to enable a reliable measure of scalar

* Corresponding author to: School of AMME, Faculty of Engineering and IT, Building J07, University of Sydney, NSW 2006, Australia.
E-mail address: hcut6115@uni.sydney.edu.au (H.C. Cutcher).

http://dx.doi.org/10.1016/j.proci.2016.07.093
1540-7489

gradients. There have been numerous attempts to measure scalar dissipation rates in turbulent flames [5–11], most with somewhat limited spatial resolution of 0.2–0.3 mm, resulting in potentially significant spatial averaging affects. More recently, modification of the optical set-up at Sandia's Combustion Research Facility enabled multiscalar line measurements with 0.1 mm data spacing [12]. Advances in data acquisition and processing strategies [13] yielded data spacing of 20 microns, improved SNR, and spatial resolution approaching 60 microns. These techniques have been applied in the present measurements of turbulent piloted flames of methane with compositionally inhomogeneous inlets.

The burner, developed at the University of Sydney, enables variability in the mixture fraction profile issuing from the jet exit [14]. This is achieved by placing two concentric tubes within the pilot annulus, such that the inner tube can translate upstream of the burner exit. Varying the recess distance of the inner tube, varies the extent of mixing between fuel and air, leading to conditions not unlike those found in practical combustors. With fuel delivered through the inner tube and air through the outer, maximum flame stability was found to occur at some intermediate recess distance where compositional inhomogeneity is optimal [14–16]. Detailed measurements of species concentration and temperature at these conditions have revealed that fluid mixtures in the region adjacent to the hot pilot stream are generally close to stoichiometric, and this leads to additional heat release which augments flame stability [15,16]. Within the first 5–10 diameters from the jet exit plane a transition takes place from this mode of premixed-stratified combustion to diffusion-dominated combustion.

These earlier measurements suffer from two drawbacks. First, estimates of turbulent length scales suggested that 0.1 mm resolution would be insufficient to measure scalar dissipation in the near field. Second, an insufficient number of radial scans were acquired at axial locations close to the jet exit, where significant changes in flame structure and the mode of combustion occur. The measurements reported here include more profiles within the near field, and they were taken using methods of spatial oversampling and wavelet denoising [13] that improve measurements of scalar gradients. The first section of the paper confirms key phenomena seen in the earlier measurements by showing selected scatter plots of temperature. The focus then shifts to scalar dissipation rates where the highly resolved measurements are compared with earlier measurements at lower resolution, analogous to a grid convergence test in simulations. New features of conditional scalar dissipation rates related to both flame conditions are highlighted.

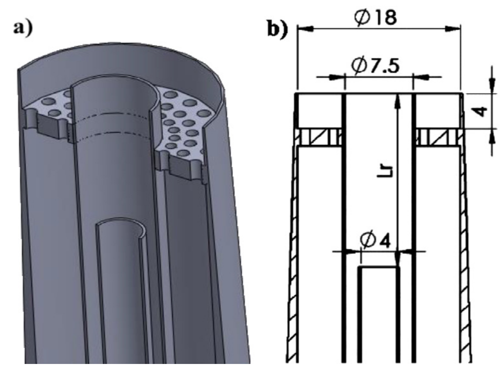

Fig. 1. Schematic (b) and isometric (a) view of modified Sydney piloted jet burner.

2. Experimental

2.1. The burner

The Sydney piloted inhomogeneous burner, shown in Fig. 1, is fully described elsewhere [14–16] and only brief details are given here. The inner tube (4 mm inner diameter, 0.25 mm wall thickness) can be recessed at a distance, L_r, within the outer tube (7.5 mm inner diameter, 0.25 mm wall thickness). By varying the recession distance the degree of mixing can be controlled when fuel and air are delivered separately. For sufficiently large recess distances ($L_r > 300$ mm) the mixture is nearly homogeneous at the burner exit. For $L_r = 0$ the flows are purely non-premixed. Intermediate recess distances lead to compositional inhomogeneity reflected in varying gradients in the mixture fraction profile at the exit plane. Maximum flame stability was noted for flames of methane at $L_r = 75$ mm and for flames of compressed natural gas methane at $L_r = 100$ mm, both with volumetric air/fuel ratio, $V_A/V_F = 2.0$. The burner was located centrally in a 254 mm × 254 mm wind tunnel giving a 15 m/s uniform air co-flow.

Five of the flames studied previously [15] are further investigated here, and relevant properties are listed in Table 1. FJ refers to cases with fuel (99.97% CH_4) issuing from the central tube (fuel in inner jet), while FA refers to fuel in the surrounding annulus and air issuing from the central tube. The volumetric air/fuel ratio of 2 is denoted by the '200' in the case codes. Three cases (FJ200-5GP-Lr300-59, FA200-5GP-Lr75-45, and FJ200-5GP-Lr75-80) were selected to have different inhomogeneity but the same departure from blow-off, a discussion of which is presented elsewhere in more depth [15,16]. The other two cases, FJ200-5GP-Lr75-57 and FJ200-5GP-Lr75-103, have the same inlet configuration as FJ200-5GP-Lr75-80 but different bulk jet velocities and different departures