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Effects of high shear on the structure and thickness of turbulent premixed methane/air flames stabilized on a bluff-body burner

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The effects of preferential transport and strain on the scalar structure (profiles of major species, elemental ratios) of turbulent premixed bluff-body stabilized flames are examined using line-imaged Raman/Rayleigh/CO-LIF diagnostics combined with crossed-planar Rayleigh imaging to determine the 3D flame orientation. Comparison of the experimental measurements with laminar flame calculations shows strong effects of preferential diffusion on the flame structure and the product state in lean and rich flames. Measurements of the flame orientation show a strong correlation between the flame-front normal angle and the strength of the preferential transport effects. As the flame-front angle decreases (by increasing the reactant velocity or decreasing the distance from the surface), the coupling between the preferential diffusion through the flame brush and the recirculation region is increased, enhancing the preferential transport effects. Spatial profiles and flame thickness measurements are discussed to evaluate how the strain and the turbulence affect the flame. In fuel-lean flames, as the velocity increases, eddies smaller than the flame thickness, but larger than the reaction layer, penetrate the preheat zone, improving the mixing and thickening the flame. Higher velocities are associated with higher levels of strain, which mitigate the thickening effect of the turbulence. Increases of the flame thickness up to 10% were observed. In fuel-rich flames, both the strain and the turbulence contribute to the thickening of the flame, and a flame thickness up to 2.5 times larger than the unstrained laminar thickness is observed. Changes are not limited to the preheat zone, but affect the entire flame structure. Progress variable scalar dissipation rate profiles are also discussed.

1. Introduction

In practical premixed combustors the turbulent flame brush is often stabilized in a region of high shear by contact with recirculating combustion products, so there is motivation to better understand the effects of high shear on the flame structure. Bluff-body burners reproduce some of the effects of high shear and product recirculation encountered in such combustors, but the simpler geometry makes acquisition and interpretation of experimental results easier [1]. Most et al. [2] investigated flame lift-off mechanism in premixed CH_4–air flames stabilized over a bluff-body, using OH planar laser-induced fluorescence (OH-PLIF). Hartung et al. [3] applied stereoscopic PIV and OH PLIF to study the effect of heat release on turbulence and scalar-turbulence interaction in a premixed ethylene–air flame stabilized over a bluff-body. Nandula et al. [4] performed single-point Raman/Rayleigh measurements of temperature and major species concentrations in an enclosed, bluff-body stabilized, lean premixed CH_4–air flame. Extensive experimental studies, including laser Doppler velocimetry [5], 2D Rayleigh scattering, single-point [6] and 1D Raman/Rayleigh measurements [7], have been performed on the TECFLAM flame, a swirling natural gas/air premixed flame, stabilized over a bluff-body. Similarly, extensive experimental studies have been conducted on stratified and homogeneous flames stabilized on a bluff-body burner developed by Cambridge and Sandia [8–10]. Piloted Bunsen flames, such those investigated by Chen et al. [11] using line imaged Rayleigh/Raman/OH LIF, are also relevant to the topic of this paper, because of the high shear near the base of the flame.

Although several of the studies mentioned above involved Raman/Rayleigh measurements, spatial resolution and measurement precision sufficient to investigate the instantaneous internal scalar structure of premixed flames has been achieved only recently [12]. Using this improved 1D Raman/Rayleigh/CO-LIF instrument coupled with cross planar OH imaging, Sweeney et al. [9,13] obtained measurements of temperature, major species concentration, flame orientation, and scalar dissipation on the

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Cambridge/Sandia stratified swirl burner. Barlow et al. [8] compared species concentrations and atom ratios from the Cambridge/Sandia burner and from a simple premixed bluff-body burner to unstrained laminar calculations, and they observed that C/H and C/O atom ratios were not conserved going from reactants to products across the flame brush. This was attributed to preferential diffusion of H_2 and H_2O through the preheat zone, ahead of CO_2 and CO, followed by convective transport downstream and away from the flame brush. Furthermore, the preferential transport effects were shown to be enhanced when the flame brush was located in the high shear region adjacent to the bluff-body recirculation zone. As noted in [8], measurements in a pilot-stabilized annular flame did not show measurable changes in the flame structure or product composition due to preferential diffusion effects, reinforcing the interpretation of the key role played by the recirculation zone. Additional experiments [14] covering a wider range of flow parameters showed that the atom imbalances reached a limiting state as velocity continued to increase, suggesting that preferential transport effects may extend to the high Reynolds number encountered in practical applications, and motivates further studies. Numerical simulations by Katta et al. [15] of a fuel-lean methane flame on a similar bluff-body burner confirmed that atom balances are altered in this configuration and showed that preferential transport effects are strongest at axial locations close to the corner of the bluff-body.

The effects of preferential species diffusion on the flame structure and the propagation rate of turbulent premixed flames have been the subject of many numerical and experimental studies. A comprehensive review by Lipatnikov and Chomiak [16], summarizes findings from several numerical and experimental studies, showing that preferential transport effects can remain important in moderately and highly turbulent flames. Formation of super-adiabatic pockets has been observed in lean hydrogen–air flames [17–19] and rich hydrocarbon flames [20,21], as a consequence of preferential diffusion. DNS studies [22,23] showed that focusing and defocusing of fast diffusing species strongly affects the flame structure. Studies in premixed H_2–air flames reveal the importance of the Lewis number, defined as the ratio of the thermal to the fuel mass diffusivity, in determining the topology and the propagation speed of premixed flames [16–19]. Several models that account for the effects of Lewis number in turbulent premixed flames have been developed [16,24], and recent LES studies have successfully modeled the effects of preferential transport of profiles of equivalence ratio in the Cambridge/Sandia flames [25].

The present study examines in more detail the effects of preferential transport and high shear on the scalar structure of bluff-body stabilized flames. A simple annular bluff-body burner similar to that of [8,14] is used, and the Raman/Rayleigh/CO-LIF multi-scalar diagnostic system used in the previous experiments is combined with Cross-Planar Rayleigh Imaging (CPRI) for instantaneous measurements of the flame-front orientation. This allows quantitative determination of flame thickness and the 3D gradient in progress variable. We present results from fuel-lean ($\Phi = 0.75$) and fuel-rich ($\Phi = 1.23$) flames, each at three bulk reactant velocities. Measurements are obtained across full radial profiles at six axial locations, ranging from 5 mm to 20 mm from the surface, whereas previous measurements focused just on the flame zone at a distance of 10 mm from the surface. With this more complete mapping of the recirculation region and with the addition of flame orientation measurements, several questions raised by the previous studies are addressed.

First, numerical simulations by Katta et al. [15], performed on a similar bluff-body burner but for laminar flow, showed significant spatial variation in the effects of preferential transport on atom imbalances, with the largest effects seen near the corner of the bluff body. Here we show full radial profiles of temperature and major species mass fractions as function of the reactant velocity, the distance from the burner, and the equivalence ratio. In particular, the varying effects of the preferential transport on the gas composition in the recirculation region are discussed.

Second, it was reported in [14] that, at the highest velocity considered, the CO_2 and O_2 mass fraction profiles in temperature space have a near-linear trend, typical of highly strained flames. Profiles from laminar flame calculations at various strain rates were presented to show a qualitative similarity in the scalar structure to the experimental flame. The product state of the numerical simulation was set to the adiabatic temperature and composition, so a direct comparison with the measurements was not meaningful. In the present work we discuss the role of strain on the flame structure by comparing the measured profiles to opposed flow calculations with the product state matching the measured composition.

Third, Dunn et al. [14] plotted radial profiles of temperature, CH_4 mass fraction, and C/H atom ratio measured in the fuel-rich bluff-body stabilized premixed CH_4–air flame at high reactant velocity, and they observed a thickening of the flame compared to spatial profiles from laminar strained and unstrained calculations. However, this comparison was only qualitative because the flame orientation was not measured, and spatial profiles could not be projected onto the flame-normal coordinate. The spatial structure of the flame is useful to assess the effects strain and the level of interaction between turbulence and flame properties, which is critical information for modeling turbulent premixed flames. In the premixed flame literature, different burning regimes have been identified [26], distinguished by the shape of the flame-front and by the spatial structure of the flame. Diagrams proposed to identify the burning regime based on the turbulence and flame properties are often inadequate to predict the flame structure, and experimental measurements are preferred. For example, in the thin reaction regime introduced by Peters [27], eddies smaller than the flame thickness, but larger than the reaction layer, penetrate into the preheat zone and transport the hot fluid away, enlarging the preheat zone but leaving the thickness of the reaction layer unaltered. Both thickening [28–30] and thinning [31,32] have been observed in turbulent premixed flames belonging to the thin reaction regimes of Peters' diagram [33]. In this work we map instantaneous spatial profiles onto the flame-normal coordinate before comparing the measured spatial structures of the flame-front to laminar strained and unstrained calculations in order to determine the importance of turbulence and strain as function of equivalence ratio, reactant velocity, and distance from the bluff-body surface.

Finally, measurements of the 3D scalar dissipation of the progress of reaction variable c are presented. The scalar dissipation rate is representative of the rate at which scalar fluctuations are destroyed. It appears in most models of turbulent premixed and non-premixed combustion [34,35] and is useful for development and validation of numerical models. Measurements of scalar dissipation rate in premixed flames are relatively scarce because of the high spatial resolution required to resolve structures within the flame front [13,31,36,37].

2. Experimental methods

The bluff-body premixed burner (Fig. 1) used for this study is an improved version of the one used in the previous studies discussed above [8,14]. It consists of a 12.7 mm center-body surrounded by a premixed flow passing through a 6.3 mm annular gap. A perforated plate placed in the annular gap, 35 mm upstream of the exit, acts as turbulence generator. Similar to the Cambridge/Sandia swirl burner [13], the improved version of the simple bluff-body burner features a ceramic bluff-body cap that replaces the stainless steel center-body of [8,14]. Another improvement with respect to the