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Effects of fuel properties and free stream turbulence on characteristics of bluff-body stabilized flames

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ABSTRACT

An experimental investigation of the effect of fuel properties and different levels of free stream turbulence intensities on the structure of bluff body stabilized lean, premixed flames is reported. The diagnostic techniques involving simultaneous imaging of hydroxyl (OH) and formaldehyde (CH_2O) by planar laser induced fluorescence and particle image velocimetry (PIV) were used to study the interaction between the flame and the flow field. CH_2O fluorescence and the pixel-by-pixel multiplication of OH and CH_2O fluorescence signals were utilized to mark preheat and heat release regions, respectively. As the turbulence intensity increased from 4% to 14%, pronounced formation of cusps and unburnt mixture fingers were observed along the flame front. For the intense turbulence conditions, different characteristics of the flame front were observed which strongly depended on the properties of fuel/air mixture. For lean methane/- and ethylene/air ($\phi = 0.85$), localized extinctions along the flame sheet and flamelet merging were observed which created isolated pockets of reactants in the flame envelope with heat release regions along their boundary. In addition to these features, propane/- and ethylene/air ($\phi = 0.655$) flames exhibited the occurrence of flame fragmentation events which created multiple islands of OH filled regions separated by thick layers of CH_2O. The overall flame shape for these conditions was observed to change intermittently from symmetric to asymmetric mode with increasing turbulence intensity. Several properties were measured to characterize the effects of turbulence–flame interaction which includes the preheat and reaction zone thicknesses, 2-D strain rate, burning fraction, flame brush thickness, flame surface density and turbulent to laminar flame area ratio.

1. Introduction

Stricter regulations on acceptable emission levels from combustion are being put in place, and as a result innovative technologies must be developed and employed to meet these new emission standards. To achieve this, focus in combustion engineering has shifted towards implementing lean, premixed combustion technologies [1]. Premixed operating conditions allow for better control of combustor temperature and reduce NO_x emissions; however premixed combustion schemes can result in flame stability issues within the combustor. In modern power generation and propulsion devices, combustion typically takes place under highly turbulent conditions. The turbulent flow conditions arise from high-speed turbulent inlet flow (free stream turbulence) as well as turbulence generated by the flame stabilization scheme. In addition to turbulence, characteristics of premixed flames are strongly governed by the properties of fuel–air mixtures. While many turbulent flame configurations have been studied in the literature, the effects of free stream turbulence and properties of fuel/air mixtures on bluff-body stabilized premixed flame characteristics have not been systematically investigated. Significant progress has been made recently on high-fidelity numerical simulations of turbulent premixed flames. Therefore, fundamental insights on local flame structure and variation of the various statistical flame parameters under highly turbulent conditions are not only useful for detailed physical understanding but also for validation of numerical simulations.

A number of experimental studies have been performed to investigate the effect of turbulence on premixed flames as summarized in the review papers of Driscoll [2], Clavin [3] and Lipatnikov and Chomiak [4]. Based on the different flame geometries, they can be classified as the “Envelope” (Bunsen-type flames), “Oblique” (V-shaped flames), “Unattached” (low swirl or counterflow flames) categories and propagating flame kernels [2]. The present study focuses on the canonical configuration of a bluff body stabilized inverted conical flame. Several studies have focused on the

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characteristics of planar V-shaped flames subject to different levels of free stream turbulence [5–12]. In these studies, flame front topology along with the variation of different statistical parameters – flame brush thickness, flame surface density, area ratio (A_T/A_L), 2-D curvature and displacement flame speed have been studied by employing laser tomography techniques. In practical devices, combustion occurs under highly turbulent conditions where both the velocity fluctuation (u') as well as integral length scale of the flow (l_o) are large. However, in all of these previous studies of V-shaped flames, the free stream turbulence intensity has been limited to ∼17% and integral length scales of the flow were smaller than those present in practical combustors.

In our recent work [13,14], detailed characteristics of lean propane/air flames subjected to low (∼4%), moderate (∼14%) and intense (∼24% and 30%) levels of turbulence have been investigated by simultaneous OH PLIF, CH_2O PLIF and particle image velocimetry (PIV). At low turbulence intensity, flame front featured weak corrugations and mostly symmetric flame structures with continuous heat release regions. Pronounced formation of cusps and unburnt mixture fingers were observed as the turbulence intensity was increased from 4% to 14 % without discontinuities in the heat release front. The local flame structure was found to be strongly modified for the intense turbulent conditions with the occurrence of flamelet merging, localized extinctions along the shear layer and flame fragmentations. The general shape of the flame intermittently switched from a symmetric (varicose) to asymmetric (sinuous) mode which had previously been observed for flames near blowoff [15,16].

In addition to the characteristics of the flow field, fuel/oxidizer composition has a strong influence on the behavior of premixed flames [17]. The fuel/oxidizer composition sensitivities are related to fuel oxidation chemistry and diffusive (differential diffusion and Lewis number) effects. For example, several numerical [18–20] and experimental [21–26] works have focused on the effect of Lewis number on turbulent premixed flames. The primary objective of these works was to develop an understanding of the physical mechanisms through which the thermal-diffusive properties of the mixture influence the overall turbulent burning rate. Bradley [21] and Abdel-Gayed et al. [22,23] developed a correlation for turbulent flame speed on the basis of their experiments performed in a fan-stirred chamber using fuel/air mixtures with non-unity Lewis numbers. The effect of turbulence (up to $u'/S_L = 25$) and elevated pressure on the burning velocities of lean methane, ethylene and propane air mixtures have been measured by Kobayashi et al. [24,25] for Bunsen-type turbulent premixed flames stabilized in a high-pressure chamber. In a recent work by Tamadonfar and Gülder [26], the effect of mixture composition and turbulence intensity on the flame front structure and burning velocities of hydrocarbon/air Bunsen flames have been studied in detail by laser tomography technique. For identical free stream turbulence levels, the influence of Lewis number on the variation of the flame front characteristics – brush thickness, flame surface density and wrinkled flame surface area have been clearly illustrated. However, the turbulence intensity in this work was limited to ∼9% and the integral length scales were limited to ∼3 mm.

In the present work, characteristics of bluff body stabilized lean methane/- and ethylene/air subjected to low (4%), moderate (14%) and intense (24% and 30%) levels of turbulence are reported and compared with the features of the lean propane/air flames reported earlier [14] under identical flow conditions. These fuels were selected owing to the differing thermal-diffusive properties and their representation of practical fuels and fuel components. Methane is the simplest hydrocarbon with high H/C ratio and a Lewis number less than unity and it is a main component of natural gas used for power generation in land-based gas turbines. Lewis number less than unity flames have been shown to behave differently when subjected to hydrodynamic strain relative to those having Lewis number greater than unity [27]. Ethylene has faster chemistry than methane and propane and is an important component in the oxidation mechanism of complex hydrocarbons [28,29]. Detailed characterization of the turbulence–flame interaction has been performed by simultaneous OH PLIF, CH_2O PLIF and particle image velocimetry (PIV). Measurements of 2-D strain rate, burning fraction, preheat and reaction zone thicknesses, flame brush thickness, flame surface density and the ratio of turbulent to laminar flame surface area have been obtained for a range of experimental test conditions.

2. Experimental methodology

This section outlines the experimental setup, measurement techniques and the experimental conditions tested in the present study.

2.1. Experimental setup

The layout of the experimental setup is shown in Fig. 1. A conical brass burner with an exit diameter of 40 mm and 3.2:1 nozzle diameter contraction ratio was used. A disk-shaped bluff-body with a diameter of 10 mm (shown in the inset of Fig. 1) was concentrically fitted at the burner exit using a rod of 6 mm in diameter. The air flow was supplied by a twin-screw air compressor (Gardner-Denver, Model ECHQHE) which was dried by a refrigeration dryer (Hankinson Model 80200) and then metered by a bank of critical flow orifices to obtain the desired nozzle exit velocity. Instrument-grade propane and chemically pure grade methane and ethylene (supplied by CT Airgas) were used as fuels. Fuel–air mixture was prepared in a mixing chamber containing a series of baffles and perforated plates and fed into the burner, upstream of the contraction section. The fuel flow rate was metered by using a set of mass flow controllers that were interfaced to a DAQ board and the data acquisition computer.

The free stream turbulence intensity levels of the incoming fuel–air mixture were varied stepwise from 4% to 30% by employing a combination of perforated plates, slotted plates, radially symmetric jets and mesh screens as described in detail in [14].

2.2. Characterization of the turbulent flow field

The turbulent flow field was characterized by using hot wire anemometry and high speed PIV. The radial profiles of mean and RMS velocity were uniform at the nozzle exit as presented in [14]. The integral length scale was determined by optimally fitting the inertial range of the power spectrum to the Von Karman's turbulence spectrum [30]. Additional flow field measurements were performed with a high-speed PIV system and the integral length scales computed from the spatial autocorrelation of the PIV data were found to be within 8% of those obtained from the hot film data.

2.3. Simultaneous PIV and PLIF imaging of OH and CH_2O

To locate the heat release region as well as to study the flame–flow interactions, simultaneous PLIF imaging of OH and CH_2O and particle image velocimetry (PIV) was performed. Two regions of interest were selected – Near the bluff body (spanning from 2 to 21 mm above the bluff body, 40 mm wide × 19 mm high) and far from the bluff body (spanning from 21 to 40 mm above the bluff body, 56 mm wide × 19 mm high). 600 images sets were obtained at each test condition to ensure convergence of different statistical parameters.