



Effects of free stream flow turbulence on blowoff characteristics of bluff-body stabilized premixed flames

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ABSTRACT

In this article we report on an experimental investigation of a bluff-body stabilized lean premixed flame subjected to different levels of free stream turbulence intensities (4, 14, 24 and 30%) at conditions approaching blowoff. The mean flow velocities ranged from 5 to 15 m/s. The turbulence Reynolds number based on integral length scale and rms velocity ranged from 44 to 4280. Simultaneous imaging of hydroxyl (OH) and formaldehyde (CH₂O) by planar laser induced fluorescence and particle image velocimetry (PIV) was used to study the interaction between the flame and the flow field and determine the sequence of events leading to flame blowoff. CH₂O fluorescence and the pixel-by-pixel multiplication of OH and CH₂O fluorescence signals were utilized to mark the preheat and heat release regions of flame front respectively. The flame structure was observed to be strongly modified by the turbulent flow field which affects the lean blowoff limits. The flame blowoff equivalence ratio increased with increasing free stream turbulence levels owing to strong interactions of the turbulent flow with the flame and the resulting modification of flame surfaces and ensuing local flame extinction. For stably burning flames, the flame front predominantly enveloped the shear layer vortices for all the turbulent conditions. As blowoff was approached, the flame front and shear layer vortices entangled inducing high local strain rates on the flame front that exceed the extinction strain resulting in significant breaks along the reaction zone. At conditions near blowoff, wide regions of CH₂O and heat release were observed inside the recirculation zone. Velocity vectors near the flame holes indicate the penetration of the reactants into the recirculation zone. Several properties were measured to characterize the near blowoff flames which include the strain rate and curvature statistics along the flame front, burning fraction, asymmetric index and the average duration of the blowoff event.

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1. Introduction

Flame stabilization in high-speed flows is important for operation of a wide range of combustion devices, including gas turbine combustors, industrial burners, ramjets and afterburners. To make the modern power generation devices more compact, mixing is strongly enhanced by operating these devices under highly turbulent conditions. Flame stabilization schemes that have been widely employed in practical combustors include bluff-body or swirl stabilization, or a combination of both. The turbulent flow conditions arise from both high-speed turbulent inlet flows (free stream turbulence) as well as the turbulence generated by the flame stabilization scheme in a combustor. In this article, we report on the effects of free stream turbulence on flame characteristics near blowoff.

Stricter regulations on emission levels from combustion systems are being put in place including NO_x and CO emissions that has pushed the combustion technology to operate devices in lean, premixed combustion mode. Premixed operating conditions allow for better control of combustor gas temperatures, and reduce NO_x emissions; however premixed combustion schemes can result in stability and flame holding issues within the combustor. Flame stability and blowoff are critical issues that can arise during operation in lean premixed combustion mode. Therefore, an improved understanding of the dynamic flame stability and lean limit phenomena is important for development of better turbulent combustion systems with increased efficiency, broader stable operating range and reduced emissions.

Flame stabilization using a bluff-body flame holder is achieved by formation of a localized low velocity recirculation zone which is created by sudden flow divergence. Continuous ignition of the incoming mixture takes place in the shear layers bounding this recirculation zone containing hot products and results in a stable, anchored flame [1]. In the seminal works of Zukoski and Marble

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[1,2], Williams et al. [3] and Longwell [4], blowoff criteria were established for flame holding in uniformly homogenized premixed gases, and the effects of different bluff-body geometries on flame holding were identified. The issue of lean blowoff limits for different combustible mixtures, variable temperature and pressure, blockage ratio and the effect of fuel droplet vaporization and mixing have been considered in the works of Plee and Mellor [5], Rao and Lefebvre [6], Rizk and Lefebvre [7]. In addition to these experimental efforts, a series of models have been developed based on the competing time scales related to fluid mechanics in the vicinity of recirculating flow, chemical reaction or ignition time scales as well as the turbulent diffusion of heat and mass between the reactants and products. There have been also attempts to correlate flame blowoff data collected from many studies in the literature utilizing different correlation parameters [8] with limited success. In such efforts difficulty arises from lack of knowledge of detailed experimental conditions for each study and many different configurations and fuels utilized in them. Scatter in these data correlations is typically very large.

To explain the lean blowoff phenomena, various phenomenological theories have been proposed which primarily rely on the competition between a chemical time scale for the mixture and a characteristic fluid mechanical time scale near the recirculation zone. Longwell [4] viewed the recirculation zone as a well-stirred reactor and suggested that blowoff occurs when the rate of entrainment of fresh reactants and the rate of its consumption is not balanced. An alternate view was proposed by Zukoski and Marble [1,2] based on a critical time τ_{cr} required for ignition of the combustible mixture i.e. $\tau_{cr} = L_{RZ}/V_{B,O}$, where L_{RZ} is the streamwise length of the recirculation zone and $V_{B,O}$ is the measured blowoff velocity and blowoff occurs when the chemical ignition time exceeds the critical time. Yamaguchi et al. [9] has proposed a flamelet based description of local extinction by excessive stretch, followed by influx of cold reactants from the downstream end of the recirculation zone which may lower the temperature of the recirculation zone below a critical level required to sustain a flame.

More recently, the flame structure near blowoff has been studied by employing time resolved imaging. Significant contributions have been made by Kiel et al. [10], Nair and Lieuwen [11,12], Chaudhuri et al. [13,14] and Tuttle et al. [15,16] toward the understanding of the mechanism of blowoff process for lean premixed flames. They found that the flame front moves into the high vorticity region as blowoff is approached, resulting in localized flame extinction along the shear layer due to excessively high strain rates. This is followed by the recession of the flame into the recirculation zone with complete extinction occurring when the reignition of flame segments bounding the shear layers is no longer possible. However, these works have been limited to low free stream turbulence levels corresponding to a maximum turbulence Reynolds number of a few hundred. In these experiments, premixed flames were anchored on bluff bodies having small blockage ratios (~6–7%), producing flames that lie in the wrinkled and corrugated flamelet regimes of the turbulent flame regime diagram. The blowoff processes of short axisymmetric flames supported on bluff bodies with larger blockage ratio (~51%) have been studied recently by Dawson et al. [17] and Karuiki et al. [18–20]. Heat release images obtained in Ref. [19,20] show that at conditions approaching blowoff, localized extinctions occur along the shear layer, followed by reduction in flame height and entrainment of reactants from the top of the recirculation zone. The flames studied in Ref. [17–20] were also stabilized in approach flows with low free stream turbulence levels. These flames were typically in the thin reaction zone regime and the high velocity fluctuations were generated owing to large blockage ratio flame holders. Limited research has been done in studying the phenomena of flame extinction of the bluff-body stabilized flames under high turbu-

lent Reynolds number conditions. Ballal and Lefebvre [21] investigated the effect of free stream turbulence on the extinction limits of lean, premixed flames with the focus on developing relevant correlations for predicting the blowoff equivalence ratio. To the best of our knowledge, this is the only work in the literature where the turbulence intensities in the approach flow were varied up to 15%.

Visualization of the reaction zone in turbulent flames is fundamental to the understanding of flame-flow interactions. A useful diagnostic technique to achieve this objective is the simultaneous PLIF imaging of OH and CH₂O. Paul and Najm [22] demonstrated that the region derived from pixel-by-pixel product of sequentially obtained OH- and CH₂O PLIF images correlates well with the heat release zone in premixed laminar flames. The application of this diagnostic technique to turbulent flames was demonstrated by Böckle et al. [23]. In their work, simultaneous PLIF imaging of OH and CH₂O technique was used to obtain the reaction zones marked by the overlapping PLIF regions of OH and CH₂O intensities and was validated with simultaneous Rayleigh temperature measurements in a bunsen flame. Kariuki et al. [19,20] demonstrated the advantage of this diagnostic technique to study flame structures in the vicinity of blowoff events for bluff-body stabilized flames. The accuracy of this technique to obtain the spatial profile of the heat release regions in highly turbulent flames has been recently validated by the direct numerical simulation of the Lund University Piloted Jet burner [24] by Wang et al. [25].

In this paper, we examine the effect of different levels of free stream turbulence (turbulence intensity varying from ~4% to 30%) on flame blowoff phenomenon of lean, turbulent and nominally axisymmetric propane–air flames. Detailed study of the flame/flow interaction at conditions close to blowoff has been performed by simultaneous OH PLIF, CH₂O PLIF and particle image velocimetry (PIV) to examine the underlying physics. Measurements of strain rate and curvature statistics, burning fraction, asymmetric index and the average duration of the extinction event have been obtained for a range of experimental test conditions. The experimental methodology is discussed in the next section, followed by a discussion of the results and a summary of the important conclusions.

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. 1a. 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. 1a) was concentrically fitted at the burner exit using a rod of 6 mm diameter. The air flow was supplied by a twin-screw air compressor (Gardner-Denver, Model ECHQHE) with a maximum mass flow rate capacity of 0.1 kg/s. The compressor discharge air was first dried by a refrigeration dryer (Hankinson Model 80,200) and then metered by a bank of critical flow orifices to obtain the desired air mass flow rate or nozzle exit velocity. Instrument-grade propane with 99.5% purity (supplied by CT Airgas) was metered using a set of mass flow controllers (Porter Instruments, Model 202). Mass flow controllers were interfaced to a DAQ board (NI Model PCI-MIO-16E-1) and the data acquisition computer. Fuel–air mixture was prepared in a mixing chamber containing a series of baffles and perforated plates. The premixed propane–air mixture was then fed into the burner upstream of the contraction section.

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