Blowoff dynamics of bluff body stabilized turbulent premixed flames

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ABSTRACT

This article concerns the flame dynamics of a bluff body stabilized turbulent premixed flame as it approaches lean blowoff. Time resolved chemiluminescence imaging along with simultaneous particle image velocimetry and OH planar laser-induced fluorescence were utilized in an axisymmetric bluff body stabilized, propane-air flame to determine the sequence of events leading to blowoff and provide a quantitative analysis of the experimental results. It was found that as lean blowoff is approached by reduction of equivalence ratio, flame speed decreases and the flame shape progressively changes from a conical to a columnar shape. For a stably burning conical flame away from blowoff, the flame front envelopes the shear layer vortices. Near blowoff, the columnar flame front and shear layer vortices overlap to induce high local stretch rates that exceed the extinction stretch rates instantaneously and in the mean, resulting in local flame extinction along the shear layers. Following shear layer extinction, fresh reactants can pass through the shear layers to react within the recirculation zone with all other parts of the flame extinguished. This flame kernel within the recirculation zone may survive for a few milliseconds and can reignite the shear layers such that the entire flame is reestablished for a short period. This extinction and reignition event can happen several times before final blowoff which occurs when the flame kernel fails to reignite the shear layers and ultimately leads to total flame extinguishment.

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1. Introduction

Premixed flame stabilization in high speed flows has been an important topic of inquiry in combustion research over the past several decades. Practical applications include flame stabilization in afterburners of military aircraft, gas turbine combustors and industrial furnaces. Flame stabilization schemes that have been widely used in such applications primarily involve bluff-body and swirl stabilization. In this work, we focus on bluff body stabilization. The physical processes that anchor a premixed flame behind a bluff body flame holder involve the combustible mixture being in contact with the hot combustion products residing in the recirculation zone and continuous ignition of the incoming mixture in shear layers bounding the recirculation zone. The global flame holding characteristics have been investigated in a number of seminal works by Zukoski and Marble [1–3], Williams et al. [4], and Longwell [5]. In these studies, a flame blowoff criterion was established for flame holding in uniformly premixed gases, and the effects of different bluff-body geometries on flame holding were identified. Among other investigations, Plee and Mellor [6], Rao and Lefebvre [7], and Rizk and Lefebvre [8] considered the lean blowoff limits for different combustible mixtures, bluff body geometries, and variable pressure and temperature. In some of these studies, effects of fuel droplet vaporization and mixing were considered as these issues relate to aircraft gas turbine flame holding.

Longwell [5] suggested that blowoff occurs when it is not possible to balance the rate of entrainment of reactants into the recirculation zone, viewed as a well-stirred reactor, and the rate of burning. An alternative view is that the contact time between the combustible mixture and hot gases in the shear layer must exceed a chemical ignition time [9–11]. According to Zukoski [9], ignition of the incoming fresh reactant mixture occurs in the shear layer as it mixes with combustion products from the recirculation zone behind the bluff body. Several studies have proposed a flamelet based description of local extinction by excessive flame stretch as suggested by Yamaguchi et al. [12] and Pan et al. [13] and others. Lieuwen and coworkers recently collected blowoff data from over fifty sources and developed correlations based on extinction time scales and extinction stretch rates from Chemkin calculations [14]. However, the details of the blowoff mechanism particularly the flame dynamics just prior to blowoff still remain elusive.

Recently, we studied experimentally the behavior of turbulent conical premixed flames anchored at their apex by a bluff body flame holder. These studies included flame blowoff characteristics under upstream flow oscillations [15] and spatial equivalence ratio gradients [16,17], their transfer function characteristics [17,18] and the effects of lateral flame confinement [19]. Although a significant amount of research has focused on investigation of
the blowoff mechanism in bluff body stabilized flames, a complete physical understanding of the final blowoff mechanism is still lacking. Significant contributions have been made recently by Nair and Liewen [20,21] who characterized two stages of near blowoff events. The first stage of flame blowoff is marked by localized extinction along the flame sheet, namely the formation of flame holes, their convection along the flame, and their subsequent heating towards a continuous flame surface. Although this stage acts as a marker towards flame blowoff, it has been suggested that the flame can survive indefinitely in this stage. The second stage is characterized by a more violent flapping of the flame front and an asymmetric mode of flame shape oscillations [16]. It should be noted that in a non-reactive cold isothermal flow separated by a bluff body, a three dimensional helical mode of absolute instability dominates the flow field characterized by convection of a sinuous vortex street, along with a weaker convective Kelvin–Helmholtz instability. For the two-dimensional case, the asymmetric vortex shedding is the well known von Kármán vortex street. For axisymmetric cases, a helical mode of vortex shedding is observed. When viewed across a two dimensional projection, they appear similar to the von Kármán vortex shedding [22]. On the other hand, for a reactive flow with sufficiently high heat release across the shear layers, shear layer generated vorticity is damped due to the effects of dilatation, production of baroclinic vorticity, and increase of viscosity. Thus, for a stable and robustly burning flame, absolute instability and the associated asymmetry is lost and only convective instability in the form of symmetric Kelvin–Helmholtz vortices appear along the shear layer.

It has been observed experimentally and also demonstrated computationally that a reversal to asymmetry can occur near flame blowoff or flames burning at low dilatation ratios [23]. Asymmetric flame behavior has been attributed to near unity global temperature ratio levels [23], although a wide variation exists in the reported values of temperature or density ratio thresholds. Thus, the parametric limits of the inception of asymmetry in the flow field are not well established and likewise, the role of this asymmetry in the flame blowoff mechanism is not clear.

In this article, we examine flame blowoff based on the flame/flow interaction obtained by time-resolved chemiluminescence imaging and simultaneous particle imaging velocimetry (PIV) and OH planar laser-induced fluorescence (PLIF) imaging. The experiments show that near blowoff, extinction of the flame along the shear layers leads to reaction of fresh mixture within the recirculation zone, which normally contains combustion products for a stably burning flame away from blowoff. The flame kernel survives for several milliseconds in the recirculation zone before annihilation of the entire flame, i.e. blowoff. This phenomenon of extinction along the shear layers is acknowledged to be a major cause of blowoff, which occurs due to the induction of excessive stretch rates by the shear layer vortices coupling with the flame front as flame blowoff is approached.

2. Experimental method

Two different experiment diagnostics were used for studying the bluff-body stabilized flames in the same axisymmetric burner used in previous studies [16–19], the detailed schematic of which is shown in Fig. 1. The first one involved chemiluminescence imaging using both a high speed camera and a photomultiplier tube (PMT) detector. The second involved a combined PIV–PLIF system used to extract velocity fields and qualitative OH distributions from which flame positions and strain rates along flame boundaries were determined.

The air flow was supplied by a 0.1 kg/s capacity compressor (Gardner–Denver, Model Electra-ECHQHE). The compressor air discharge was first dried by a refrigeration-type dryer (Hankinson Model 80200) and metered by a bank of critical flow orifices to obtain the desired air mass flow rate or nozzle exit velocity. Fuel (instrument grade propane, 99.5% purity) was metered using a set of mass flow controllers (Porter Instruments Model 202). Fuel and air were premixed in a mixing chamber containing a series of perforated plates and baffles to completely mix the fuel and air streams before the mixture entered the axisymmetric contoured burner nozzle through eight radial ports. Extensive mixing diagnostics using Rayleigh scattering were utilized to measure the fuel concentration profile and to test for any non-uniformity of the mixture. These results were presented in Fig. 3a of Ref. [16]. Those measurements showed a uniform equivalence ratio profile for the present case of interest. A 10 mm disk shaped bluff body was placed at the exit of the 40 mm diameter nozzle outlet shown in the inset in Fig. 1.

All the results discussed in this paper correspond to experiments performed at an inlet velocity of $U_{\text{mean}} = 10$ m/s with a turbulence intensity around 5% of the mean. These values are nearly uniform along the radial direction, confirmed via hot-film anemometry measurements, [16]. The inlet temperature was 298 K. The Reynolds number was 6293 based on the diameter of the bluff-body, $d = 10$ mm. For these conditions the DeZubay parameter [24] is 8.437 with the fuel to air ratio at blowoff being 0.049. This is in close agreement with the experiments performed by DeZubay [24]. However, the DeZubay number is an empirical correlation that does not take into account the chemical time scales comprehensively. As such the authors have adopted to use a correlation suggested by Shanbhogue al. [14]. The lean blowoff equivalence ratio of the present study agrees very well with data from other sources with respect to this parameter. The Damkohler number based on lip velocity is 2.5 with a corresponding Reynolds number of 6293. It falls very close to the linear trendline given by $Da_{\text{lip}} = f \left( Re^{0.67} \right)$ and is within the limits of scatter in the experiments reported by DeZubay [24]. For chemiluminescence measurements, a monochromatic high speed camera, Motion Scope (Redlake Imaging, Model 8000), optically coupled to a DEP-Gen II image intensifier was focused on the bluff-body wake. Images were gathered at 500 frames per second. Gate timing of the intensifier was controlled using a delay generator (Stanford Research System, Model DG535) with time gate width set to 700 µs. For acquisition at 500 Hz, the CCD size was reduced to 512 x 512 pixels. The images were continuously recorded into the buffer for a maximum recording time of 8.192 s. The PMT, with a 432-nm bandpass filter and an objective lens was configured to view the bluff-body wake, providing a signal of the CH* chemiluminescence from this region. The PMT signal, gathered at 5000 Hz, was recorded continuously and used to monitor the flame presence. When the flame extinguished for a period of longer than 100 ms, an output trigger was sent to the camera to terminate image acquisition and store the images saved within the camera buffer. These images were representative of the final eight seconds prior to complete blowoff.

The simultaneous PIV–PLIF system was comprised of a stand alone PIV system from LaVision Inc. The LaVision system consisted of a dual-cavity 50 mJ/pulse Nd:YAG laser (New Wave Solo PIV III), a frame-straddling 1024 x 1280 CCD camera (Flow Master 35), and DaVis 7.0 post-processing software. The PIV camera was coupled with a Nikon 50-mm lens and a 532-nm optical line filter to allow for imaging of scattered laser light downstream of the bluff body. In each case, 100 image pairs were collected for velocity averaging. The interrogation window for the PIV algorithm used a 16 x 16 pixel region, based on an initial 128 x 128 fixed window, with 50% overlap. Due to the readout time of both acquisition buffers on the frame-straddling PIV camera, the combined data acquisition rate was 2.5 Hz.
A laser sheet was created by using a \( f = -20 \text{ mm} \) cylindrical lens to expand the beam to the desired width, while an adjustable spherical lens was used to focus the expanded sheet as it passed through the region of interrogation typically comprising 5 mm to 40 mm along the main flow direction. The laser was passed through the region of interrogation using a 5 cm diameter 532 nm laser line mirror. The time between laser pulses was set to 10 \( \mu \text{s} \) for each measurement and timing was controlled by the LaVision Programmable Timing Unit (PTU). This pulse separation was determined based on the mean velocity upstream of the bluff-body measured by a hot-film anemometer in the unseeded flow, together with the final interrogation window size used for analysis. Particle seeding of the flow was accomplished using a fluidized bed particle seeder (TSI Model 9310) filled with approximately 1 \( \mu \text{m} \) alumina seed particles. The air supply from a separate air compressor was passed through the seeder before passing to a manifold which distributed the air to multiple inlets of the burner. Seed density was controlled by adjusting the powder dispensing rate along with the adjustment of its vibration frequency.

The PIV system was combined with the PLIF system for measurement of hydroxyl distributions within the flame. The PLIF system consisted of an Nd:YAG laser (Continuum, Model Surelite II) operating at 10 Hz and pumping a dye laser (Lumonics Model HD-500) containing Rhodamine 590 dye. The generated laser beam tuned around 560 nm was then passed through a doubling crystal in a frequency conversion unit (Lumonics Model HyperTrax-1000) to create the UV beam needed for excitation of OH. Beam energy was about 3 \( \text{mJ} \) per pulse with a wavelength at 282.67 nm in air, to create the UV beam needed for excitation of OH. Beam energy in a frequency conversion unit (Lumonics Model HyperTrax-1000) was then passed through a doubling crystal containing Rhodamine 590 dye. The generated laser beam operating at 10 Hz and pumping a dye laser (Lumonics Model CH 200). Timing of the pump laser was set such that the PLIF excitation pulse was temporally centered between the two PIV laser pulses.

Fluorescence signal was collected using a lens system coupled with an image intensifier to a separate CCD camera (Photometrics, Model CH 200). Light transmitted to the intensifier was filtered using a filter (Semrock Bright Line Model FF01-320/40-25) with a central wavelength of 320 nm and a width of \( \pm 40 \text{ nm} \) where transmission is greater than 70\%, allowing for OH fluorescence transmission while eliminating any laser scatter from the burner surface. The intensifier was gated for a duration of 80 ns to minimize chemiluminescence interference with the fluorescence signal. The region of interest of the CCD camera was confined to 500 \( \times \) 600 pixels to keep readout times less than 200 ms in order to enable the same 2.5 Hz sampling rate as for the PIV system. The camera was focused on the phosphor side of the image intensifier using a Nikkor 50 mm lens.

The laser beam energy profiles were measured prior to each data set so that the region of maximum intensity could be aligned with the region of interest above the bluff body. The profile measurement involved passing the UV beam through a removable UV-transparent cuvette placed on the bluff body. The cuvette was filled with a fluorescent solution diluted with water to maintain the linearity of fluorescence. Fluorescence from the cuvette was imaged using the same camera and intensifier used for OH fluorescence collection; however, the filter was replaced. For beam correction, the same CH\(^+\) filter used for chemiluminescence measurements with the PMT was placed in front of the image intensifier. Each profile was measured by averaging five sets of 100-shot accumulated images on the CCD with an intensifier gate time of 1 \( \mu \text{s} \). The laser profile was then taken as the area normalized profile extracted from the cuvette fluorescence.

The OH PLIF images represent the location of flame front including the hot combustion products and the recirculation zone. These images were used to extract flame edge locations. Velocity fields from the PIV data were further processed by extracting velocities along these flame edges. Extraction of a flame edge from a PLIF image involved background subtraction and correction for laser intensity distribution. Filtering of the image was performed by convoluting a two dimensional Gaussian filter kernel over the entire image to reduce noise. After filtering, a set threshold of 50\% of the maximum fluorescence intensity was used to binarize the image by redefining each pixel as either 1 (greater than the threshold)
indicating the presence of a flame or hot products or 0 (less than the threshold) indicating no combustion or hot products. Edge locations were then defined as the locus of points with a change from 0 to 1 in the flame map. These points were then used in conjunction with PIV data to determine the strain rate information along the flame front and also to evaluate extinction time scales based on the vorticity around the flame edge. Two-dimensional strain rate information was calculated using \[ J = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} + (1 - n_x^2) \frac{\partial v}{\partial x} + (1 - n_y^2) \frac{\partial u}{\partial y}, \] where \( u \) and \( v \) are the velocity components in the \( x \) and \( y \) directions, respectively, and \( n_x \) and \( n_y \) are the \( x \) and \( y \) components of the flame surface normal vector, \( n \). This strain is the hydrodynamic portion of the overall flame stretch. In this work, the additional effects of stretch via flame curvature are not considered and only this two-dimensional strain rate information was calculated using [25].

Fig. 2. Near blowoff symmetric and asymmetric modes at \( \phi = 0.775 \).
dimensional hydrodynamic stretch rate accessible via PIV is computed.

The flame edge map was used to determine the normal direction for strain rate calculations. A scanning polynomial fit was performed along the flame edge in which the shape of the flame front within a 20 pixel window centered about each edge point was used to determine the normal components, \( n_x \) and \( n_y \), of the flame surface. The direction of the normal vector was found such that the normal vectors pointed into the region where no flame was present (toward 0 in the flame map).

3. Results

In the following section, results from high speed imaging are first described, upon which the flame dynamics near blowoff are elucidated. These results are then analyzed and validated using simultaneous two-dimensional PIV and OH PLIF data. Experiments reported here were performed at a mass averaged inlet velocity of 10 m/s and a turbulence intensity of around 5% at the burner exit as determined from hot-film anemometer measurements.

Fuel–air mixture equivalence ratios of \( \phi = 0.9 \) and \( \phi = 0.775–0.770 \) were studied representing the flame conditions far from and near blowoff cases, respectively.

3.1. High speed chemiluminescence imaging

High speed images of flame chemiluminescence without any spectral filtering at 500 frames per second were obtained, as shown in Figs. 2 and 3. These example images were obtained near flame blowoff at equivalence ratios decreasing from 0.775 in the initial frames to 0.770 (the final blowoff point) in the later images. The experiments were repeated numerous times and similar observations to those presented here were found in each case. The flame appeared to exhibit a sinuous mode in some of the images (Figs. 2e–f), a phenomenon observed in several prior studies [19,20]. In the following paragraphs, an explanation of the switch from the varicose (symmetrically distorted flame structures) to sinuous (sinusoidal flame structures) flame shapes is given, which not only appears to be valid in this axisymmetric case but also at higher Reynolds number two-dimensional cases dis-

Fig. 3. Final moments through blowoff at \( \phi = 0.77 \).
Fig. 4. Two typical images of simultaneous OH PLIF and PIV for a stable flame at $\phi = 0.9$. Left panel: OH PLIF (normalized from 0 to 1) distribution superimposed on velocity vectors colored by $x_z$ (normalized from $-1$ to 1). Right panel: flame edges superimposed with vorticity contours.

Fig. 5. Two typical images of simultaneous OH PLIF and PIV for an unstable flame at $\phi = 0.775$. Left panel: OH PLIF (normalized from 0 to 1) distribution superimposed on velocity vectors colored by $x_z$ (normalized from $-1$ to 1). Right panel: flame edges superimposed with vorticity contours.
cussed in detail elsewhere [26]. However, chemiluminescence may not be a good marker for the flame edge because the obtained images are line-of-sight integrated; thus, this explanation is later supported and quantified by simultaneous PIV and OH PLIF measurements.

Fig. 3 shows a sequence of twelve images 50–0 ms prior to blowoff. The first four images in this sequence (50–44 ms) show weaker shear layers as compared to a stable flame. The next set, comprised of images from 42 to 36 ms, show large regions of extinction developing periodically, as also seen in Fig. 2b–d. This may be attributed to the weakly reacting shear layers as evidenced by little or no CH* emission; the reactivity of which essentially determines the connectivity of the flame surfaces, as discussed subsequently. The images at 34 and 32 ms are characteristic of the images captured for flames approaching a global blowoff event. They demonstrate that the shear layers around the wake are non-reacting or weakly reacting based on the low CH* chemiluminescence levels observed and the flame resides near the tip of the recirculation zone. When the incoming reactants are not burnt in the shear layers the reactants can then reach into the wake. In the next image at 30 ms, it is observed that instead of propagating downstream, the heat release zone is pulled back into the recirculation zone, producing chemiluminescence in the wake which under stable (far from blowoff) burning conditions, contains combustion products and is mostly non-luminous (e.g., Fig. 2a). It should be noted that this luminosity is not from the front shear layers, and if reacted, would have produced lower chemiluminescence intensity as observed from the stable cases. The same behavior is observed from high speed images from a 2D case, as discussed in another article [26].

From observations of the wake region of the flame in Fig. 2a at 6804 ms prior to blowoff, it is clear that the non-luminous recirculation zone is surrounded by luminous (reacting) shear layers due to CH* chemiluminescence from those regions. Since this is an axisymmetric flame, shear layer development is circumferential with smaller contributions from the near centerline regions due to line-of-sight integration effect. Lower chemiluminescence in the recirculation zone is also observed for stable flames far from blowoff (φ = 0.9). At a later instant (2476 ms prior to blowoff, Fig. 2b) examination of a series of sequential images 2 ms apart reveal interesting features. From 2476 to 2472 ms in Figs. 2b–d, it was found that a large region of flame extinction has developed just downstream of the recirculation zone and this extinguished region convected downstream. However, it is not clear at this stage whether a varicose or sinuous mode is prevailing as the flame was mostly extinguished. It was observed that one shear layer (on the right in this example) became progressively weaker and finally extinguished at 2472 ms, Fig. 2d. In the next image at 2470 ms, it was found that with the right shear layer still non-reacting and the left shear layer reacting, a sinuous mode developed. This mode was clearly observed in the next image at 2468 ms with most of the flame being reignited, indicated by a large rise in the total chemiluminescence signal, while the right shear layer was still non-reactive. The next image at 2466 ms shows that both shear layers were then reactive and symmetry was restored to some extent due to a reestablishment of combus-

Fig. 6. Two typical images of simultaneous OH PLIF and PIV for an unstable flame at φ = 0.770 showing extinction along shear layers. Left panel: OH PLIF (normalized from 0 to 1) distribution superimposed on velocity vectors colored by \( \omega_z \) (normalized from –1 to 1). Right panel: flame edges superimposed with vorticity contours.
tion and heat release on both sides. Thus, it appears that once a shear layer becomes non-reactive it becomes absolutely unstable, where the flame can no longer be sustained. On the other hand if the shear layer is reactive, then it is convectively unstable where vortices originating from the flame holder propagate along the flame front. Due to its inherent nature and greater strength, the absolute instability dominates the convective instability over the entire flow field. If the flame survives these larger flow instabilities, it leads to a sinusoidal structure referred to as “Stage 2” of near blowoff dynamics as discussed in recent experimental studies by Lieuwen and co-workers [14,21], Kiel et al. [27] and in LES studies of a near blowoff flame by Smith et al. [28]. This event precedes the final blowoff which occurs when all parts of the shear layers are extinguished and fail to reignite.

It was also observed that this event of the flame burning within the recirculation zone does not always lead to final blowoff as this sequence of images was observed in several other repeated experiments. The flame may reach this condition but still reignite to a fully developed state, as shown in the movie provided as supplementary content. Whether the flame will survive or completely blowoff depends on the possibility of reignition of the shear layers and heat losses near the flame holder. If the shear layers reignite, the flame survives. If not, it proceeds to blowoff as seen in the images 26–0 ms before blowoff, where the reaction zone within the wake shrinks and finally extinguishes.

The strongest fluid mechanical evidence that extinction within the shear layers is the ultimate cause of flame blowoff is the observation of a reactive recirculation zone just prior to flame blowoff. For a flame away from blowoff, the recirculation region just downstream of the flame holder is always non-luminous. This is because the fresh mixture is consumed along the reactive shear layer to feed hot products into the recirculation zone. It should also be

![Fig. 7. Left panels: mean axial velocity from PIV superimposed with OH fluorescence signal from PLIF. Right panels: mean out of plane vorticity superimposed with OH fluorescence, both at axial locations of 10, 20 and 30 mm for \( \phi = 0.9 \) stable flame case.](image-url)
noted that the only way the unburnt mixture could get entrained into the recirculation zone is by convection through the shear layers surrounding the recirculation zone. Therefore, a wake can be highly luminous only if fresh mixture passes through the non-reacting shear layers and burns in the recirculation zone. The reason why the flame settles within the recirculation zone is due to the low velocities and the favorable flow residence times in the wake.

3.2. Simultaneous PIV and OH PLIF measurements

The observations from the previous section utilized chemiluminescence imaging which is limited by its line-of-sight nature and the qualitative interpretation of those results. In this section, results from simultaneous two-dimensional PIV and OH PLIF imaging are presented to qualitatively and quantitatively understand the interaction of flow dynamics and flame during the final stages of flame blowoff. Two equivalence ratios, $\phi = 0.90$ and $\phi = 0.775–0.770$ are investigated, representing a robustly burning stable premixed flame and a flame approaching blowoff at $\phi = 0.770$. The main motivation for these measurements was to further develop and validate the observations of the final stages of blowoff based on the insights gained from the high speed imaging. However, while the velocity and OH fields are spatially and temporally resolved at the same instant, two consecutive image pairs are 400 ms apart due to the 2.5 Hz maximum feasible image sampling rate. Therefore, consecutive images pertain to non-consecutive instants in the flame evolution. Frames containing simultaneous PIV and OH PLIF data were extracted from a large number of data sets obtained from numerous blowoff events. This was necessary since the particular phenomena leading up to blowoff such as burning within the recirculation zone, re-ignition, and final blowoff events are random in nature in a turbulent flow field even within a small

![Fig. 8.](image) Left panels: mean axial velocity from PIV superimposed with OH fluorescence signal from PLIF. Right panels: mean out of plane vorticity superimposed with OH fluorescence, both at axial locations of 10, 20 and 30 mm for $\phi = 0.77$ near blowoff flame case.
equivalence ratio window, typically $\phi = 0.775–0.770$ in this case. For this reason, approximately 1000 images of PLIF and PIV near blowoff were examined.

Another point worth noting is that OH PLIF is not an exact marker for the reaction zone. Although OH is abundantly present at superequilibrium concentrations in the reaction zone and its highest intensity resides along the flame front, it is also present in high temperature near equilibrium products. However, it is clear that regions with no OH mark those regions containing no reaction or hot products. Thus, the OH PLIF essentially provides a limiting representation of the reaction zone boundaries.

Left panels in Fig. 4 display the simultaneous single shot OH PLIF intensity at $\phi = 0.9$ (normalized from 0 to 1, based on background and maximum signals) superimposed on PIV vector fields with vectors colored by the out of plane vorticity (normalized from −1 to 1, based on maximum vorticity magnitude). The OH PLIF intensity of 1 corresponds to $\sim$250 counts in a single shot image after background and laser beam corrections. The figures on the right show the extracted OH edges representing the flame edges superimposed with vorticity contours. The left images clearly show that for a stable flame, the maximum OH signal resides along the shear layers marked by high vorticity regions with low OH intensities within the recirculation zone, as also observed in the high-speed chemiluminescence images. The images on the right show that the flame edges are smoothly wrinkled due to convecting Kelvin–Helmholtz vortices in the shear layer and most importantly, these vortices are almost entirely enveloped within the flame edges.

Fig. 5 shows a set of two typical PIV–PLIF images in the same format, but near blowoff at $\phi = 0.775$. It is observed that the flames are narrower in shape with more corrugated OH PLIF edges along the shear layers. In both images (top and bottom), slight asymmetric behavior of the flame is also observed. Fig. 6 shows PIV–PLIF images of the flame near blowoff where extinction along the shear layers is more pronounced as observed from the absence of OH fluorescence signal in the high vorticity shear layer zones. Also, the flame edges are much more corrugated in these cases. Unlike the $\phi = 0.9$ case (Fig. 4), the maximum OH signal is not observed along the shear layers; but rather it is distributed within the recirculation zone for the $\phi = 0.775$ case. Moreover, the right pair of images for both Figs. 5 and 6 indicate that the flame is not enveloping the shear layer vortices as in the $\phi = 0.9$ case; rather the vortices are overlapping the flame front resulting in higher stretch rates as discussed later in this paper. It is shown that higher strain or hydrodynamic stretch rates induced locally on the flame front exceed the corresponding extinction stretch rates and cause local flame extinction along the shear layers. This allows fresh mixture to pass through the shear layers unburnt to reach into the recirculation zone to react there in the recirculation zone.

Fig. 7 shows the mean axial velocity profiles (left) and mean out of plane vorticity profiles (right) superimposed with profiles from the mean OH PLIF images at three axial locations of 10, 20 and 30 mm above the bluff body for $\phi = 0.9$. At all the axial locations, a bimodal distribution of OH PLIF signal is found, suggesting that the peak OH levels occur in the flame front located along the shear layers. Locations of high OH concentration are also located at radial locations where the mean vorticity is at its maximum. This also shows that the flame envelopes the high shear regions on a time-averaged basis.

Fig. 8 illustrates the superimposed mean velocity/mean vorticity with mean OH PLIF at axial locations of 10, 20 and 30 mm above the bluff body near blowoff for $\phi = 0.775–0.770$. The height of the recirculation zone was determined by the point on the centerline where mean vertical velocity becomes positive. The extent of the recirculation zone for the $\phi = 0.9$ case is 34.8 mm and for the $\phi = 0.77$ case is 28.79 mm. Although there is no considerable change in the flow profiles except for shortening of the recirculation zone for lower equivalence ratios due to lower dilatation, significant changes in the mean OH profile shape are observed. The bimodal shape of the OH profile observed in the $\phi = 0.9$ case changed to a unimodal Gaussian shape for the axial locations of 20 and 30 mm above the bluff body near blowoff showing a retreat of the reaction fronts along the shear layer and maximum OH levels within the recirculation zone. This is a consequence of shear layer extinction as only then it is possible for the fresh mixture to react within the recirculation zone.

This feature of OH encapsulation within the recirculation zone is also apparent by examination of the mean joint probability density function (pdf) of vorticity and OH PLIF as shown in Fig. 9a and b and mean pdf of absolute magnitude of vorticity conditioned on OH PLIF signal as shown in Fig. 9c and d. The top row corresponds to the case of $\phi = 0.9$ (Fig. 9a and c) and the bottom row corresponds to $\phi = 0.775–0.770$ (Fig. 9b and d). Once again, a bimodal distribution is observed for the $\phi = 0.9$ case where joint occurr-
rences of high OH and high vorticity have finite probabilities, which is not the case for $\phi = 0.77$ where high OH values are only associated with near zero vorticity values. The maximum of the joint pdfs in the $\phi = 0.9$ case is associated with OH values of around 0.2 and $\omega_z$ values less than ±2000. This is attributed to the recirculation zone being enveloped by the flames residing in the shear layers. This region contains combustion products only, hence near equilibrium low OH concentrations and relatively low vorticity. This behavior is better visualized in the conditional pdf images shown on the right for $\phi = 0.9$ (Fig. 9c) and $\phi = 0.77$ (Fig. 9d). These conditional pdfs are obtained by normalizing the mean joint pdf images with mean OH pdfs and considering only the absolute value of $\omega_z$-vorticity such that it can be associated with eddy turnover time scales (dimension of $\omega$ is $s^{-1}$) thus giving pdf ($|\omega_z[OH]$). In Fig. 9c, it is found that given high OH values, it is probable to find high vorticity magnitudes, i.e. a flame can exist in the high vorticity regions of the shear layers. However, for Fig. 9d corresponding to the $\phi = 0.77$ case, given high OH it is only probable to find vorticity with low magnitudes; i.e., reactions can only occur in low vorticity regions that are typically found within the recirculation zone. The noise present in these images result from conditioning on higher values of OH that have low occurrence; thus, the pdf is normalized by small values accentuating noise in the measurement of vorticity.

It has been suggested by both the high speed chemiluminescence images and the combined PIV and PLIF imaging that flame extinction in the shear layers leads to flame recession into the recirculation zone that precedes the final flame blowoff event. The cause for shear layer extinction can be further examined using strain rates measured along the flame surface. Fig. 10 shows the pdfs of hydrodynamic stretch rate obtained from processing PIV data using Eq. (1). This was performed along the leading edges in the OH PLIF images that are assumed to correspond to the flame edge. Figs. 10a and b show the pdf of the hydrodynamic stretch rate $\kappa_s$ with the scattered data points marking the pdf from each instantaneous PIV–PLIF image and bold lines marking the mean pdf obtained over a set of 100 images for two cases of $\phi = 0.90$ (stable flame) and $\phi = 0.775–0.770$ (near blowoff), respectively. Fig. 10c shows the comparison of the mean pdfs of $\phi = 0.90$ and $\phi = 0.775–0.770$ superimposed with their respective extinction stretch rate (ESR) values shown by corresponding vertical lines as obtained from OPPDIF [29] calculations for a premixed propane-air flame using the San Diego mechanism [30]. As blowoff is approached with reduction of $\phi$, the $\kappa_s$ pdf shifts towards higher stretch rates and the ESR shifts towards lower stretch rate values. This opposing advancement of $\kappa_s$ and ESR creates a limiting condition that results in extinction along the flame edges. It is observed that for $\phi = 0.77$, a significant portion of the $\kappa_s$ pdf exceeds the extinction stretch rate.

The shift in the $\kappa_s$ pdf toward higher $\kappa_s$ values may be explained by comparing the simultaneous PIV–PLIF images of Figs. 5 and 6 with Fig. 4. For a stably burning flame at $\phi = 0.9$, the flame front envelops the shear layer vortices as shown in the right panel images of Fig. 4. As the equivalence ratio is lowered and the flame approaches blowoff, the flame speed decreases which results in a reduction of the global flame angle. Also to maintain kinematic balance between the velocity component normal to itself and its corresponding flame speed the flame shifts towards lower velocity regions and interacts more intimately with the shear layer emanating from the bluff body. Consequently, the flame edge overlaps the shear layer vortices and this high strain field induces higher hydrodynamic stretch rates along the flame edge to cause local extinction as shown in the pdfs of Fig. 10.

Fig. 11 shows almost total extinction of shear layers and its associated recirculation burn event. As expected from the analysis, maximum OH intensity is obtained from near axial locations of the recirculation zone. This is most pronounced in the bottom panel of Fig. 11 where almost the entire flame has blown off and the flame is reduced to a very small reaction front within the recirculation zone accompanied with development of slight asymmetry in the non-reacting flow field.

Fig. 10. Probability density function of $|\kappa_s|$ at (a) $\phi = 0.9$ (b) $\phi = 0.77$ and (c) mean pdfs of $|\kappa_s|$ at $\phi = 0.9$ and $\phi = 0.77$. 

Fig. 11. Two typical images of simultaneous OH PLIF and PIV for an unstable flame at $\phi = 0.770$ showing total extinction along shear layers and reaction within the recirculation zone. Left panel: OH PLIF (normalized from 0 to 1) distribution superimposed on velocity vectors colored by $\omega_z$ (normalized from $-1$ to 1). Right panel: flame edges superimposed with vorticity contours.

Fig. 12. Flow diagram illustrating the hypothesis for lean blowoff mechanism.
4. Conclusions

In this study, time resolved chemiluminescence imaging and simultaneous PIV and OH PLIF have been utilized to investigate the final blowoff mechanism in bluff body stabilized turbulent premixed flames. The sequence of events have been summarized in the flow diagram shown in Fig. 12. It was found that with reduction of equivalence ratio as blowoff was approached, the flame shape changed from a conical to a more columnar shape and the degree of interaction of the flame front with the shear layer consequently increased. Near blowoff, the flame front and convecting Kelvin–Helmholtz vortices along the shear layer overlap to induce high local strain or hydrodynamic stretch rates that exceed the corresponding extinction stretch rates, resulting in local flame extinction along the shear layers. Following shear layer extinction, fresh reactants entrain through the shear layers to react within the recirculation zone due to favorable residence time there. This flame kernel within the recirculation zone may survive for several milliseconds and can reignite the shear layers such that the entire flame is reestablished temporarily. This extinction and reignition event can happen repeatedly before final blowoff which occurs when the flame kernel fails to reignite the shear layers.

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Appendix A. Supplementary material


References