Blowoff characteristics of bluff-body stabilized conical premixed flames under upstream velocity modulation

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Abstract

This article presents experimental findings on the blowoff characteristics of conical premixed flames anchored at their apex by three different flame holders (rod, disk, and cone) in the presence of upstream velocity oscillations. Experiments were performed with propane–air mixtures at mixture velocities approaching the flame holder of 5, 10, and 15 m/s. The flow speed was modulated sinusoidally at frequencies up to 400 Hz with a constant-velocity modulation amplitude of \( u_{\text{rms}}/U_m = 0.08 \) upstream of the flame holder. It was found that the blowoff equivalence ratio exhibits a dependence on the flow modulation frequency. Specifically, at low approach velocities (5 m/s), the effect of upstream flow modulation is to improve flame stability as evidenced by lower flame blowoff equivalence ratios for all three types of flame holders considered. At higher approach velocities (10 and 15 m/s), the disk- and cone-shaped flame holders exhibit less stability with increasing excitation frequency. The rod-shaped flame holder behavior is different at these higher velocities in that the flow modulation still provides enhanced flame stability. The flame stability results are supplemented with a detailed analysis of the flow field in the flame stabilization zone obtained by particle image velocimetry.

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1. Introduction

Flame stabilization in premixed fuel–air streams has long been a subject of significant technological interest for a variety of applications, such as in gas turbine combustors, afterburners, and industrial furnaces. The two main flame stabilization schemes employed in premixed combustion systems include swirl and bluff-body stabilization. In both schemes, a zone of flow recirculation containing hot combustion products is created as a result of flow separation and reversal, thus enabling stabilization of the flame. In studies concerning bluff–body flame stabilization, starting with the seminal works of Williams et al. [1], Longwell [2], and Zukoski and Marble [3,4], many investigations have focused on establishing the blowoff parameters for uniform homogenized premixed gases and effects of different bluff-body geometries on flame holding (see, for example, references at the end of Plee and Mellor [5], Rao and Lefebvre [6], and Rizk and Lefebvre [7]). These studies have considered the lean blowoff limits for different combustible mixtures and different bluff-body geometries as well as pressure and temperature ef-
effects. Typically, blowoff characteristics of bluff-body stabilized premixed flames are determined for a given geometrical configuration in terms of flame blowoff equivalence ratio as a function of the gas-mixture approach velocity. In some of these studies, effects of fuel droplet vaporization and mixing have been considered, as these issues relate to gas-turbine flame stabilization. In addition to the 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 mass and heat between the reactants and the products. In the simplest physical model, advanced by Zukoski and Marble [3], the ability for anchoring a premixed flame in the wake of a bluff-body flame holder is related to the residence time of the incoming combustible mixture in contact with the hot combustion products residing in the recirculation zone and the chemical induction time for ignition of the combustible mixture. This model was refined and expanded to account for more detailed geometrical, fluid-mechanical, and chemical effects by Zukoski [8].

While they provide useful design information, the global flame stability studies had not considered the detailed instantaneous structure of the flame. Beyond the understanding developed based on the time-averaged picture of the flame-holding problem, the instantaneous flame-holding characteristics are responsible for the initiation of precursor events preceding the flame blowoff such as local flame liftoff and extinction in the flame-anchoring region. Furthermore, unsteadiness in the form of either turbulence or periodic flow oscillations can influence flame-holding characteristics through unsteady straining [9,10] affecting flame extinction behavior as well as modifications to mixing in the wake structure. These aspects of flame stabilization under oscillatory flow conditions are relevant to those combustion devices that may experience oscillations of the flow field either intentionally or unintentionally. For instance, pulsed combustion furnaces are designed to operate at a resonant frequency to promote better heat transfer [11,12], while some other combustion systems such as gas turbine combustors may encounter undesirable combustion oscillations in the lean-premixed operating mode [10]. Flow and mixture equivalence ratio oscillations can be present as a result of acoustic coupling of the flow and combustion processes in high-intensity combustors [10,12–17]. It is therefore important to characterize not only the static stability limits (i.e., blowoff and flashback limits under steady flow conditions), but also consider the blowoff and flashback events in the presence of time-varying flow oscillations. In this context, several different types of interactions may be envisioned. One concerns the periodic oscillations in the mixture velocity at a constant mixture equivalence ratio when premixing of fuel and air streams occurs in a decoupled manner from the downstream flow excitation. Another possibility is the presence of oscillations in the mixture equivalence ratio as a result of modulation in the fuel flow rate. The third possibility involves the simultaneous presence of both velocity and fuel–air mixture ratio fluctuations as the coupling occurs with the air and fuel supply systems.

A survey of recent literature reveals very little research on the detailed experimental characterization of bluff-body stabilized flames with modern diagnostic techniques while many such studies have been conducted for lifted or rim-stabilized nonpremixed jet flames (e.g., Chen et al. [18]; Bakrozis et al. [19]; Honore et al. [20]; Barlow and Carter [21]; Donbar et al. [22,23]). In one study by Most et al. [24], velocity and OH laser-induced fluorescence measurements were reported in a bluff-body stabilized premixed flame to test different flame blowoff models. However, their experimental configuration of a thin annular combustible mixture flow at the flame holder base surrounded by co-flowing air appears to be rather specialized and this configuration does not lend itself to a generalized interpretation of the blowoff phenomenon.

In this article, we first discuss the blowoff characteristics of conical turbulent premixed flames when controlled periodic oscillations in the upstream flow velocity are present at a constant fuel–air mixture composition. The results of experiments in which conical V-shaped flames are anchored at their apex by three different types of bluff-body flame holders (a circular cylindrical rod, a disk, and a cone) are presented in terms of flame blowoff equivalence ratio as a function of flow modulation frequency at constant modulation velocity amplitude and mean mixture velocity. Velocity field measurements using particle image velocimetry and the analysis of these data in the flame-anchoring region are subsequently presented to provide a detailed description of the flow field just prior to blowoff. The article is concluded by the key findings from this study.

2. Experimental

The experimental setup is schematically shown in Fig. 1. The burner is made out of brass with a 3.2:1 nozzle diameter contraction with an exit diameter of 40 mm. A stainless steel rim of height 2.5 cm and of the same diameter is attached to the burner exit to prevent damage to the brass burner in the case of flame attachment to the burner rim. The fuel–air mix-
Fig. 1. Experimental setup used in the study of the blowoff characteristics of turbulent conical V flames.

Flame stability was fed into the burner through eight equally spaced 0.95-cm-diameter radial ports on the side wall of the burner before the contraction section. A stainless steel circular rod sting with a diameter of 6.4 mm was centered at the burner exit and it was attached at the bottom of the burner. Upstream of the contraction, the burner contained a 2.5-cm-thick honeycomb flow straightener with a cell size of 4.0 mm and a stainless steel mesh screen above it to minimize the flow nonuniformities. Attached at the bottom of the burner was a loudspeaker cavity containing a 15.2-cm-diameter subwoofer (Kenwood, Model KFC-1656) to modulate the flow. The loudspeaker cavity was designed to allow free movement of the speaker diaphragm while preventing leakage of the combustible mixture through the speaker. The loudspeaker was driven by a sine wave generated by the data acquisition computer with the output signal first amplified by an audio amplifier before being fed into the speaker. Speaker performance was characterized as a function of the excitation parameters (frequency and amplitude) by measuring the velocity perturbation resulting from the modulation at the exit of the burner. A calibrated hot film probe was placed at the burner exit 18 mm upstream of the flame holder halfway between the inner wall of the burner and the flame holder stem. The hot film probe output was filtered by a first-order analog filter whose cutoff frequency was set to 1/2 of the sampling frequency to remove aliasing. In the reported experiments, the speaker excitation amplitude was selected to achieve constant flow-velocity modulation amplitude with respect to the mean flow velocity (i.e., $u_{rms}/U_m$) at different modulation frequencies. The air flow was supplied by a twin-screw air compressor with a maximum mass flow rate capacity of 0.1 kg/s. The compressor discharge air was first dried and then metered by a bank of critical flow orifices to obtain the desired air mass-flow rate. Instrument-grade propane (99.5% purity) was supplied from a tank and was metered using two electronic mass-flow controllers (Tylan Model FC-280 and Porter Model 202).
Three different flame holders, shown in the inset of Fig. 1, were tested. Each flame holder had the same blockage onto the oncoming flow with a diameter of 10 mm. Flame holders were installed onto the sting and protruded typically 5 mm above the nozzle exit. Determination of the flame blowoff equivalence ratio involved establishing a premixed flame at approximately stoichiometric conditions and slowly decreasing the fuel flow rate as controlled by the flow controllers until the flame blowoff occurred. The blowoff point was recorded as a function of bluff-body type, the mean mixture velocity, and the flow modulation frequency. The speaker excitation signal was adjusted at each modulation frequency to provide the desired constant velocity modulation amplitude.

The mapping of the instantaneous and time-averaged velocity fields was achieved by particle image velocimetry (PIV) utilizing an LaVision 2-D PIV system. The system consists of a 50-mJ/pulse dual-cavity Nd:Y AG laser, a 1024 × 1280 pixel frame-straddling CCD camera, a process timing unit, and cross-correlation PIV software. The timing unit also enables the phase-locked PIV imaging with respect to the speaker excitation signal. In these experiments, the air supplied to the premixer was seeded with small (less than 2-µm) titanium dioxide particles using a fluidized bed feeder (TSI Model 9310). The imaged region containing the wake of the bluff body spanned a width of 50 mm and a height of 65 mm. Both instantaneous and time-averaged velocity maps were gathered. For the time-averaged data, the instantaneous velocity vector maps were averaged over 50 PIV acquisitions.

3. Results and discussion

Experiments were performed wherein the premixed propane–air conical-flame blowoff equivalence ratios were determined by slowly decreasing the fuel flow rate until the flame was detached from the flame holder and blown off. The air-flow rate was kept constant in each experiment while the fuel flow rate was gradually reduced until the flame blowoff condition was reached. The nominal mean velocities of the fuel–air mixture at the burner nozzle exit were 5.0, 10.0, and 15.0 m/s.

3.1. Flow field characteristics upstream of flame holders

Fig. 2 shows the axial velocity profile measured using a calibrated hot-film anemometer 18 mm upstream of the bluff-body flame-holder tip between the nozzle inner wall and the bluff-body holder sting. The velocity profile exhibits a slight skewedness toward the center due to the contraction and the boundary layer growing on the inner wall of the burner. The turbulence intensity is below 3% in the core of the flow and it increases near the inner boundary layer up to 8%. The axial velocity variation at the midspan between the nozzle wall and the flame-holder sting is shown in Fig. 3 for 100-Hz modulation. The velocity modulation amplitude was maintained at a constant value of $u_{rms}/U_m = 0.08$. The selection of the velocity modulation amplitude was based on the maximum amplitude that can be generated by the loudspeaker. The speaker excitation signal was adjusted as a function of excitation frequency to maintain a constant value of $u_{rms}/U_m$.

![Fig. 2. Velocity profile 18 mm upstream of the flame-holder tip at the nozzle exit without flow modulation.](image-url)
3.2. Time-averaged visual characteristics of premixed conical flames

Fig. 4 shows long-exposure photographs of these conical premixed flames at different excitation frequencies for rod- and disk-shaped bluff bodies at a mean mixture velocity of 10 m/s. The luminosity of these conical V-shaped flames is mostly due to CH* chemiluminescence and can be correlated with heat release. In most cases, a nonluminous region appears in the wake of the flame holder, enveloped by the luminous wings on either side that delineate the flame front around the outer boundary of the wake. At 100 Hz excitation, the flame responds quite strongly to flow modulation with the lower part of the flame widening and the noise from the flame becoming stronger. This behavior is connected with the acoustics of the burner cavity, which has a resonance at around 100 Hz. In this case, the chemiluminescence in the wake region is similar to that of the no-excitation case. However, with increasing excitation frequency toward 400 Hz, the overall flame appearance changes to a narrower cone shape and the wake of the bluff body becomes more luminous. Based on the bluff-body diameter of 10 mm, the Strouhal number, $f d / U_m$, values are 0.8, 0.4, and 0.27 for 5, 10, and 15 m/s at a frequency of 400 Hz. It is thus possible that the increase of wake luminosity is connected with wake resonance [25] and the enhanced mixing in the wake under these conditions [26].

3.3. Flame blowoff under flow modulation

Three different bluff-body flame holders with the same projected blockage diameter to the flow of 10 mm were used in this study. Shown in the inset of Fig. 1, these flame holders are in the shapes of a cylindrical rod, a circular disk, and a circular cone with an included angle of 35°. Fig. 5 shows the results for the cylindrical rod-shaped bluff-body flame holder at three nominal approach velocities of 5, 10, and 15 m/s. At 5 m/s, the blowoff equivalence ratio decreases from its value for the unmodulated flow (shown as 0 Hz excitation) with increasing modulation frequency with a maximum reduction of about 10% in blowoff equivalence ratio at 400 Hz. This stability gain due to upstream flow modulation is connected with the modification of the bluff-body wake flow field and mixing at the high excitation frequencies. At 400 Hz excitation, the wake region becomes more luminous, indicating the presence of a higher concentration of CH* radicals in the wake region. At 10 and 15 m/s approach velocities, a slight increase in blowoff equivalence ratio (i.e., reduced flame stability) is followed by a reduction in the equivalence ratio with increasing modulation frequency. While the maximum reduction for the 15 m/s case amounts to about 7%, the 10 m/s case appears to exhibit a somewhat different behavior with maximum reductions in the blowoff equivalence ratio between 2.5 and 4%.

Fig. 6 shows the instantaneous flame images obtained during the PIV experiments. In these images the sudden change of seed density across the approximate flame front resulting from the gas-density change across the flame was utilized to identify the flame-front location as utilized in earlier studies [27,28]. Here, the negative images are shown to better display the flame. It is seen that the studied flames become progressively more turbulent with increasing approach velocities. The calculated Reynolds numbers based on the bluff-body diameter at STP are 3190, 6380, and 9570 for 5, 10, and 15 m/s mixture velocities, respectively. These values would be reduced by a factor of 25 if the Reynolds numbers were evaluated at the temperature of the wake region of about 2000 K. At the lowest velocity, the effect of
Fig. 4. Photographs of bluff-body stabilized premixed flame images at a mixture velocity of 10 m/s and $\phi = 0.9$. Top row: rod-shaped bluff body; bottom row: disk-shaped bluff body. The dashed horizontal line delineates the terminus of the bluff body.
periodic velocity oscillations is to modulate the continuous flame surface. At higher velocities, the flame breaks up and highly disconnected vortical structures appear for the higher frequency excitation cases. The flame near the bluff body is anchored in all cases and has a cylindrical shape. In all images, the outer boundary of the fuel–air jet is clearly visible and, in most cases, the coherent vortical structures resulting from the excitation is self-evident. As expected, the flame structures have a spacing scaled as $l = \frac{U_m}{f}$ while the outer vortices have half the spacing, due to their convection velocity being $\frac{U_m}{2}$.

The flame blowoff data for the disk-shaped flame holder are presented in Fig. 7. At 5 m/s, upstream flow modulation results in a stability gain of about 7% in the blowoff equivalence ratio, similar in magnitude to the rod-shaped flame-holder results shown in Fig. 5. There appears to be a plateau in the data trend between 100 and 200 Hz for the 5 m/s case for all the flame-holder results. In contrast to the data for 5 m/s showing a gradual decrease of blowoff equivalence ratio with increasing flow modulation frequency, the other two velocity cases show an increase of the blowoff equivalence ratio with increasing modulation frequency, i.e., flames becoming less stable upon excitation. Typical increase in the blowoff equivalence ratio at high frequencies is 4.4 and 7.0% for 10 and 15 m/s cases, respectively. It is also worth noting that the disk-shaped bluff body provides better overall flame stability than the rod-shaped flame holder, as evidenced by the lower magnitude of the blowoff equivalence ratios. This is due to the much more significant flow separation and higher degree of wake recirculation for the disk-shaped flame holder, as will be evident in the flow-field structure discussed later.

Fig. 8 displays instantaneous flame images for the disk-shaped flame holder, similar to the ones shown in Fig. 6. For the disk-shaped flame holder, the flame structures appear more coherent than the ones for the rod-shaped flame holder under excitation. The flame around the recirculation zone is of a more conical shape, indicating the stronger and larger extent of the recirculation zone. At high velocities and higher excitation frequencies, disconnected flame structures become omnipresent.

The experimental results are shown in Fig. 9 for the cone-shaped flame holder. The results are similar to those for the disk flame holder in that the 10 and 15 m/s data show an increasing trend for the blowoff equivalence ratio with modulation frequency. This flame-holder geometry was considered as the intermediate case between the rod-shaped and disk-shaped flame holders. The cone-shaped flame holder provides a more gradual flow divergence to the oncoming flow as compared to the more drastic flow separation experienced for the disk-shaped flame holder. Consequently, the flame blowoff data lie between those for the rod and disk flame holders. For example, the data trend for the 15 m/s case is similar to that of the disk flame holder. Yet the 10 m/s data exhibit the characteristics of the rod flame holder. In addition, the dependence of the blowoff equivalence ratio on the mixture velocity without excitation is more monotonic as compared to the disk flame holder. For the 5 m/s case, the maximum reduction in the blowoff equivalence ratio amounts to 7% as a result of flow modulation.
Fig. 6. Flame images obtained by reversing the Mie scattering images obtained during the PIV experiments for the 10-mm-diameter rod-shaped bluff-body flame holder (arrows show the length scale $l = U_m/f$).
3.4. Velocity, vorticity, and strain in the flame stabilization zone

Understanding of the flame blowoff data trends requires analysis of the underlying flow field in the region of flame stabilization. Particle image velocimetry was utilized to obtain the instantaneous velocity and vorticity maps downstream of the bluff-body flame holders under the conditions of the blowoff experiments. Figs. 10 and 11 show the velocity field (vectors) and vorticity (color contours) for the rod and disk flame holders at 5 and 15 m/s approach velocities with and without upstream velocity oscillations. Superimposed on these maps are the flame front locations as determined from the rapid change of seed density, as discussed earlier. General observations are that (1) high-vorticity regions are contained within the hot products region enveloped by the flame and (2) vorticity becomes more concentrated within the flame envelope with increasing approach velocity and increasing oscillation frequency. A closer look at the region within two bluff-body diameters for the two flame holders shows that the disk-shaped flame holder affords a wider region of vorticity contamination, as expected, since rapid upstream flow divergence is induced by this flame holder as compared to the rod flame holder with a growing upstream boundary layer on it. The effect of sinusoidal flow oscillation is to modulate the flame front as well as the flow field. This effect appears to be greater for the disk flame holder in terms of both the flame appearance (Figs. 6 and 8) and the modification of the vorticity field (Figs. 10 and 11) at the lower approach velocity of 5 m/s. At the higher approach velocity of 15 m/s, the vorticity is more confined near the flame front for the rod flame holder regardless of excitation frequency. However, significant flame-front modulation and breakup of the flame into pockets is evident at downstream distances of more than two bluff-body diameters, as can be also seen in Fig. 6. At 15 m/s for the disk flame holder, the vorticity-contaminated region is larger and becomes more concentrated near the flame front with increasing modulation frequency. It is also evident that the flame breaks up into pockets downstream.

The instantaneous velocity fields were also averaged to look at the time-averaged velocity field in the flame stabilization zone. For this purpose, 50 images obtained within 5 s prior to flame blowoff were averaged to determine the time-averaged flow field. Fig. 12 shows the results for the disk-shaped flame holder at velocities 5 and 15 m/s. It is evident from these data that the recirculation zone length decreases with increasing modulation frequency at both approach velocities. This change affects the characteristic residence time that the combustible mixture is in contact with the hot combustion products recirculating in the wake. Defining this time based on the simplified analysis of Zukoski and Marble [3,4] as $\tau_R = L/U_m$, where $L$ is the length of the recirculation zone determined from the time-averaged PIV images, this residence time is reduced with increasing frequency, which would make the flame more prone to blowoff. Fig. 13 shows the flame blowoff equivalence ratio as a function of this characteristic time for the
Fig. 8. Flame images obtained by reversing the Mie scattering images obtained during the PIV experiments for the 10-mm-diameter disk-shaped bluff-body flame holder (arrows show the length scale $l = U_m/f$).
rod- and disk-shaped flame holders. The general trend of decreasing blowoff equivalence ratio with increasing residence time is found for the disk flame holder at 10 and 15 m/s. However, the rod-shaped flame holder and the disk-shaped flame holder at 5 m/s follow a trend which exhibit a positive slope in this figure corresponding to a decrease of blowoff equivalence ratio with increasing frequency. This behavior is possibly connected with the changes in the mixing (species and heat transport) between the flame and the combustion products in the wake as alluded to earlier.

It is also interesting to compare the flow-field structure just prior to and after the flame blowoff. Fig. 14 shows the unforced flow fields for the disk-shaped flame holder at 5 and 15 m/s. It is seen that the recirculation zone extends farther for the case of flame as compared to the corresponding nonreacting flow by at least a factor of 2. The vortex shedding is apparent in the nonreacting flow whereas it is not present in the reacting flow as has been observed previously. The increased length of the recirculation zone is connected with the heat release accompanied by volumetric expansion. The lack of vortex shedding in the reacting case is related to the increase of viscosity, the reduction of Reynolds number, and the consequently diminished flow instabilities.

The flame blowoff data presented earlier are clearly influenced by the vorticity and the scalar transport in the vicinity of the recirculation zone. Vorticity in the wake region plays an important role in mixing which influences the temperature and species distributions in the flame stabilization zone. Additionally, the straining along the flame surface affects to the local flame extinction phenomenon as a precursor to blowoff. In this spirit, we have determined the instantaneous strain rates along the flame surface from the PIV data. Our approach follows that described by Donbar et al. [23] for a turbulent jet diffusion flame utilizing the generalized strain-rate expression developed by Candel and Poinso [29]. In this approach, the strain rate on a surface can be expressed as

\[
K = -n \cdot (n \cdot \nabla)u + \nabla \cdot u, \tag{1}
\]

where \(u\) is the velocity vector and \(n\) is the unit normal to the surface on which the strain is calculated. In the cylindrical coordinates, this expression takes the form

\[
K = -n_x u_r \left( \frac{\partial u_x}{\partial r} + \frac{\partial u_r}{\partial x} \right) + \left( 1 - n_x^2 \right) \frac{\partial u_x}{\partial x}
+ \left( 1 - n_r^2 \right) \frac{\partial u_r}{\partial r} + \frac{u_r}{r}, \tag{2}
\]

where the flame front is described by its outward unit normal vectors \((n_x, n_r)\) and \(u_x\) and \(u_r\) are the axial \((x)\) and radial \((r)\) velocity components, respectively. Caution should be exercised in identification of the flame front based on the PIV seed density change, since this marks the boundary between the hot combustion products and fresh reactants. In this work, such identification of the flame front was limited only near the base of the flame in calculating strain rates. In this region, the continuous flame front envelops the wake zone behind the bluff body.

Fig. 9. Blowoff equivalence ratio as a function of flow modulation frequency at \(u_{\text{rms}}/U_m = 0.08\) for the conical-shaped bluff-body flame holder.
Fig. 10. Instantaneous velocity field and vorticity maps for the rod-shaped bluff body before blowoff at flow velocities of 5 and 15 m/s and excitation frequencies of 0, 100, 200, and 400 Hz. Vorticity scale: top row, ±3500 s⁻¹; bottom row, ±12,000 s⁻¹.
Fig. 11. Instantaneous velocity field and vorticity maps for the disk-shaped bluff body before blowoff at flow velocities of 5 and 15 m/s and excitation frequencies of 0, 100, 200, and 400 Hz. Vorticity scale: top row, ±3500 s⁻¹; bottom row, ±13,000 s⁻¹.
Fig. 12. Time-averaged velocity field and vorticity maps for the disk-shaped bluff body before blowoff at flow velocities of 5 and 15 m/s and excitation frequencies of 0, 100, 200, and 400 Hz. Vorticity scale: Top row, $\pm 3500 \text{ s}^{-1}$; bottom row, $\pm 13,000 \text{ s}^{-1}$. 
Evaluation of strain rate from Eq. (2) was implemented by first discretizing the flame front onto a fine grid mesh (0.2-mm resolution) using AutoCad software. Subsequently, the velocity field on the unburned side was interpolated from its original spatial resolution of 0.5 mm onto this grid and the computation of $K$ was performed on this mesh. In order to avoid ambiguity of inadvertently sampling velocity data from the products region, the $K$ values were also evaluated along a contour parallel to the identified flame front but offset toward the unburnt side by 1.0 and 2.0 mm. Such comparisons ensured that obtained results did not suffer from such ambiguity. Fig. 15 shows an example of the strain rate along the flame front for the case of the disk flame holder at 5 and 15 m/s. It is found that the instantaneous strain rate along the flame front is highly nonuniform and can have very high positive and negative values. The magnitude of strain rate increases with approach velocity from $\pm 1500$ to 3000 s$^{-1}$ for the 5 m/s approach velocity to $\pm 10,000$ to 15,000 s$^{-1}$ for the 15 m/s cases. These instantaneous strain rates are much higher than the counterflow premixed flame extinction strain rates that are reported in the literature [30]. However, the configuration of a flame in contact with the hot combustion products of the recirculation zone is quite different from the counterflow flames established between two opposed jets of reactants, and is expected to be much more robust to extinction.

The positive strain rates are typically associated with the convex regions of the flame front toward the products (A, B, F) and the negative values are found in the concave regions such as C and E, shown in Fig. 15. Similar results have been reported by Carter and co-workers [23] for turbulent nonpremixed jet flames where highly fluctuating strain rates were found along the flame front. Additionally, the effect of flow oscillations on the strain rate appears not to be significant, with the strain rates being similar for both unforced and forced cases. It should also be pointed out that these high strain rates in the wrinkled-flame regions may not be sustained sufficiently long to cause local extinction. The characteristic time of these wrinkled regions is a fraction of a millisecond, considering the wrinkling scales of a few millimeters and the approach velocities.

3.5. Characteristic time scales

In the analysis of this problem, interaction and coupling of time scales need to be considered. For the bluff-body flame stabilization, two relevant characteristic time scales are the flame time scale, $\tau_{f} = \delta_{f} / S_{u}$, which is on the order of a millisecond based on the data available in the literature (cf. Ref. [31]), and the residence time between the hot combustion products in contact with fresh reactants, $\tau_{r} = L_{recirc} / U_{m} \approx 2d / U_{m}$ which ranges between 1.3 and 4.0 ms for 15 and 5 m/s, respectively. The flow excitation time scale is the inverse of the oscillation frequency, $\tau_{e} = 1 / f$; in the present case it spans 2.5 to 13.3 ms between 400 and 75 Hz. It is expected that when coupling of these time scales occurs, it leads to changes in mixing and flame blowoff characteristics. Furthermore, the Strouhal number of the wake, $fd / U_{m}$,
ranges from 0.06 to 0.8 depending on the excitation frequency (100–400 Hz) and approach velocity (5–15 m/s). The blowoff equivalence ratio behavior for the rod-shaped bluff body, which has the weakest recirculation strength of all flame holders considered, is found to be affected in a manner not captured by the classical characteristic time argument. This is believed to be due to alteration of the fluid mechanics and mixing of the wake in this range of Strouhal numbers.

Fig. 14. Instantaneous velocity and vorticity maps for the disk-shaped bluff body before and after flame blowoff. Vorticity scale: Top row, ±3500 s$^{-1}$; bottom row, ±13,000 s$^{-1}$.
4. Conclusions

An experimental study of flame-holding behavior for bluff-body stabilized premixed propane–air flames has been presented. Experiments were conducted under conditions of modulated and unmodulated flow upstream of the flame holder. The measured blowoff equivalence ratios for all cases indicate that the upstream flow excitation can have a significant influence on flame stability. At low approach velocities (5 \text{ m/s}), the effect of upstream flow modulation is to improve flame stability, as evidenced by lower flame blowoff equivalence ratios for all three types of flame holders considered. At higher approach velocities (10 and 15 \text{ m/s}), the disk- and cone-shaped flame holders exhibit less stability with increasing excitation frequency. The rod-shaped flame-holder behavior is different at these higher velocities in that the flow modulation still provides enhanced flame stability.

The flow field of the flame stabilization zone determined by particle image velocimetry shows that the vorticity is predominantly contained in the hot-products region enveloped by the premixed flame front. The vorticity becomes more concentrated near the flame front with increasing approach velocity and upstream flow excitation frequency. The time-averaged velocity field results indicate that the length of the recirculation zone decreases with increasing excitation frequency. This finding is consistent with the classical explanation of blowoff behavior at higher approach velocities for the disk flame holder. However, the blowoff trends for the rod-shaped flame holder with excitation frequency could not be explained in the same manner, and the influence of forcing of the wake may be responsible for this observed behavior. The instantaneous strain rates determined along the flame front show high-magnitude variations of both positive and negative strain rates. They oc-
cur in the cusped regions of the flame front and may lead to local flame extinction and re-ignition events. However, it is estimated that the short time scales over which these high strains act on the flame may not be sufficient for local extinction. Our ongoing work is focused on attaining a deeper understanding of the transport processes in the flame stabilization zone using laser-based spatially and temporally resolved diagnostics.

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