Blowoff characteristics of bluff-body stabilized conical premixed flames with upstream spatial mixture gradients and velocity oscillations

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Abstract

This experimental study concerns determination of blowoff equivalence ratios for lean premixed conical flames for different mixture approach velocities ranging from 5 to 16 m/s in the presence of spatial mixture gradients and upstream velocity modulation. Conical flames were anchored on a disk-shaped bluff body that was attached to a central rod in the burner nozzle. A combustible propane–air mixture flowed through a converging axisymmetric nozzle with a concentric insert, allowing radial mixture variation by tailoring the composition in the inner and outer parts of the nozzle. The radial mixture profiles were characterized near the location of the flame holder by laser Rayleigh light scattering. Additionally, a loudspeaker at the nozzle base allowed introduction of periodic velocity oscillations with an amplitude of 9% of the mean flow velocity up to a frequency of 350 Hz. The flame blowoff equivalence ratio was experimentally determined by continuously lowering the fuel flow rates and determining the flame detachment point from the flame holder. Flame detachment was detected by a rapid reduction of CH* emission from the flame base imaged by a photomultiplier detector. It was found that the flame blowoff is preceded by progressive narrowing of the flame cone for the case of higher inner jet equivalence ratios. In this case, the fuel-lean outer flow cannot sustain combustion, and clearly this is not a good way of operating a combustor. Nevertheless, the overall blowoff equivalence ratio is reduced by inner stream fuel enrichment. A possible explanation for this behavior is given based on the radial extent of the variable-equivalence-ratio mixture burning near the flame stabilization region. Fuel enrichment in the outer flow was found to have no effect on blowoff as compared to the case of uniform mixture. The results were similar for the whole range of mean flow velocities and upstream excitation frequencies.

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1. Introduction

Stabilization of flames in premixed combustion mode, particularly for high-velocity flows, has been an important subject for combustion research over the past several decades. Practical applications in-
clude flame stabilization in afterburners of military aircraft, gas turbine combustors, and industrial furnaces. Flame stabilization schemes that have been widely used in such applications mainly involve bluff-body or swirl stabilization or a combination of both. Among these, the bluff-body flame stabilization scheme typically employed in turbojet and ramjet afterburners is of particular interest in the context of this study. The physical process that anchors a premixed flame behind a bluff-body flame holder involves mixing of the combustible mixture with the hot combustion products residing in the recirculation zone, facilitating continuous ignition of the premixed reactants in its vicinity. The global flame-holding characteristics have been elucidated in a number of seminal works by Zukoski and Marble [1–3], Williams et al. [4], and Longwell [5]. In these studies, blowoff criteria were established for flame holding in uniform homogenized 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 and different bluff-body geometries, as well as pressure and temperature effects. In some of these studies, effects of fuel droplet vaporization and mixing were considered, as these issues relate to flame holding in aircraft gas turbine combustors. Recently, Nair and Lieuwen [9,10] studied the dynamics of bluff-body stabilized flames near blowoff. Their study showed that the transient dynamics of these flames near blowoff occurs in two distinct stages, first by emergence of localized flame extinction regions and then by violent flapping of the flame front.

Under steady conditions, the simplified view of bluff-body flame holding is that the residence time of the reactant mixture in the shear layer bounding the recirculation zone containing the hot product gases has to be longer than the chemical reaction induction time of the mixture, which is a function of the mixture equivalence ratio. In other words, \( t_{res} = \frac{L_{recirc}}{U} \geq \frac{1}{\tau_{chem}} \equiv \frac{L_{recirc}}{Da} \geq 1 \), where \( L_{recirc} \) is the streamwise length of the recirculation zone and \( U \) is the characteristic velocity that scales with the approach velocity, \( U_{in} \). However, this simplified time-averaged view of flame stabilization does not account for the unsteady flame dynamics, including unsteady vortex shedding and the increased unsteadiness exhibited near flame blowoff. These unsteady effects are believed to play an important role in the onset of flame lifting off the flame holder, leading to blowoff. In fact, Nair and Lieuwen [10] analyzed the flame acoustic emission due to unsteadiness near blowoff as a possible precursor of detecting the impending flame blowout.

Another dimension of unsteady effects on flame-holding behavior is the combustion dynamics encountered in compact combustors operating in the lean premixed mode. Combustion dynamics has been extensively studied and an excellent review of the topic was given by Candel [11]. Candel and his co-workers also studied the response of laminar conical flames to periodic oscillations and characterized the flame/flow coupling in conical and inverted conical flames [12,13]. The presence of oscillatory flow conditions influences the flame blowoff equivalence ratio as described by Chapparo and Cetegen [14,15], who presented an experimental study of the blowoff characteristics of bluff-body stabilized conical premixed flames under upstream flow modulation. It was found that flow oscillations can have a measurable effect on blowoff equivalence ratios that is dependent on the modulation frequency and approach velocity.

These effects were attributed to the recirculation zone flow dynamics and the unsteady straining effects. This and all other previous studies in the literature have focused on flame stabilization in flows with uniformly premixed reactants. However, there are many practical combustion conditions wherein a significant fuel/air composition gradient may exist just upstream of the flame holder. The flame blowoff phenomenon in the presence of both upstream spatial composition gradients and temporal flow oscillations is therefore of significant practical interest. Furthermore, characterization of the precursor events just prior to flame liftoff and blowout can be useful in avoiding the impending flameout by rapidly changing the upstream flow conditions (e.g., the equivalence ratio of the mixture). To this end, analyses of the time-resolved CH* emission signal from the vicinity of the flame stabilization region as the flame approaches the blowoff point can be useful for extracting signal features that can be associated with the impending flame blowout. Signal analysis in the frequency domain using Fourier or wavelet transforms can be employed. Such a study of near-blowoff instability of swirl-stabilized flames was performed by Nair and Lieuwen [10] using different signal processing techniques, among which wavelet transform methods yielded the best results.

In this article, effects of the spatial fuel/air mixture gradient on flame blowoff conditions are investigated for the steady and periodically modulated flow conditions. Spatial mixture gradient profiles were created by altering the upstream fuel/air mixing profiles and characterizing these mixture profiles by laser Rayleigh light scattering. The blowoff characteristics of the inverted conical flames stabilized by a disc-shaped bluff body were then determined for different
Fig. 1. Schematics of the experimental setup.

2. Experimental systems

The burner nozzle, shown schematically in Fig. 1, primarily consisted of two concentric converging nozzles. Both nozzles had a diameter contraction ratio of 3.2:1, with the outer brass nozzle and the inner aluminum nozzle having diameters of 40 and 20 mm, respectively, at the nozzle exit. Propane–air mixture was fed through seven 0.95-cm diameter radial inlets on the sidewalls of the brass nozzle below the contraction section at a base equivalence ratio of $\phi_b$. The eighth inlet port fed into the hollow center rod, enabling fuel enrichment in the inner nozzle, to create a radial mixture gradient in the mixture approaching the bluff body attached to the center rod. Small holes on the wall of the hollow center rod allowed radial jets of fuel to mix with the inner nozzle flow as shown in the inset of Fig. 1. In this configuration, the flow approaching the flame holder could be enriched by additional fuel beyond the base equivalence ratio by $\Delta\phi_i$. Fuel enrichment in the outer nozzle was achieved by feeding additional fuel through eight equally spaced 0.32-cm-diameter radial fuel injection lances with 1-mm lateral orifices on either side. These lances were aligned perpendicular to the main flow to allow effective mixing. A 2.5-cm-high stainless steel rim with the same inner diameter as that of the outer nozzle was attached at the burner exit. It contained a 13-mm-thick honeycomb with a cell size of 1.5 mm sandwiched between two layers of stainless steel mesh screens. This arrangement allowed straightening of the flow nonuniformities and management of the turbulence intensity downstream. At the bottom of the nozzle, a loudspeaker (Infinity Model 6012i) with a diameter of 12.7 cm was attached to introduce periodic velocity oscillations in the flow. A sine wave generated by a signal generator and amplified by an audio amplifier (Audio Source, Model AMP 1/A) was used as the input signal to the loudspeaker. An oscilloscope monitored the signal characteristics for effective control of the output. The loudspeaker response was calibrated in the frequency range of interest to maintain a constant flow velocity modulation amplitude with respect to the mean flow velocity $(u_{rms}/U_m) \sim 0.09$ with $\pm 5\%$ error. The flow modulation amplitude was limited by the maximum...
level that can be attained by the loudspeaker system for the range of mean flow velocities studied. Both \( u_{\text{rms}} \) and \( U_m \) were measured with a calibrated hot film anemometer probe (TSI Model 1210-20) and IFA 100 signal processing system. The probe was placed at an axial location 1 mm above the level of the disc-shaped bluff body and was mounted on a micrometer stage for radial traversing. The measurements at each location were taken over a period of 10 s to capture the turbulence characteristics. Air flow was supplied by a twin-screw air compressor (Gardner–Denver, Model ECHOHE) with a maximum mass flow rate of 0.1 kg/s. 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. Instrument-grade propane with 99.5% purity from 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. The output signal of a photomultiplier tube (Ealing Electro Optics, Model S20 UV), equipped with a narrow bandpass filter at \( \lambda = 430 \pm 10 \text{ nm} \), viewed the \( \text{CH}^* \) chemiluminescence at the base of the flame to determine the blowoff point as the fuel flow rates were slowly reduced. The PMT view field was masked to view a downstream distance of about 20 mm from the flame-holder tip. As the data acquisition computer ramped down the fuel flow rate and monitored the decrease of fuel flow rate simultaneously with the PMT signal, the flame blowoff point was unambiguously determined when the PMT output was suddenly reduced. The whole experiment was controlled by a LabView software interface. Different rates of fuel flow rate decrease were first employed to determine the sensitivity of the measured blowoff equivalence ratio due to time delays associated with the response of flow controllers and flow convection. It was found that a rate of mixture equivalence ratio decrease of \( d\phi/dt = 0.01 \text{ s}^{-1} \) provided consistent blowoff results. Furthermore, the field system time constants were calculated along with the mass flow controller response time to ensure that the system response delays did not bias the blowoff results.

The spatial distribution of the fuel concentration profiles just downstream of the bluff body was measured by a laser Rayleigh light scattering technique. The beam of a 10-Hz Nd:YAG laser (Continuum, Model Surelite I) at a wavelength of 532 nm was aligned in the diametric plane and the Rayleigh signal was detected by a CCD camera (Photometrics, CH 250) through a laser line bandpass (532 ± 10 nm) filter. In these nonreacting mixing experiments, air was replaced with high-grade nitrogen to prevent Mie scattering from particles often found in air. The Rayleigh signal can be converted to propane mole fraction because of the differing Rayleigh scattering cross sections of propane and nitrogen. The CCD camera exposure was set to 30 s in complete darkness, capturing an average of 300 laser pulses. A laminar jet flow of pure propane was placed at the edge of the view field to normalize and calibrate the Rayleigh signal.

3. Results and discussion

In this section, we first describe the flow-field characteristics before presentation of the flame blow-off data. Subsequently, an analysis of the \( \text{CH}^* \) emission signal near flame blowoff is presented.

3.1. Velocity field characteristics

Fig. 2 shows the profiles of mean velocity and turbulence intensity measured by hot-film anemometry from near the flame holder tip to the outer edge of the nozzle. The experiments were performed at three nominal mean velocities of 5, 11, and 16 m/s. The mean velocity profiles were found to be relatively uniform, with the possible exception of the highest-velocity case exhibiting a mild radial velocity gradient toward the flame holder. The velocity profile near the location of the inner nozzle wall was found to be minimally affected, as the wake velocity profile is rapidly dissipated. Turbulence intensities ranged from about 2.5 to 5% for nominal mean flow velocities from 5 to 16 m/s. In order to provide a constant relative amplitude of velocity fluctuations, the driving voltage for the loudspeaker was adjusted as a function of frequency. The signal generator was calibrated at different frequencies to maintain a constant \( u_{\text{rms}}/U_m \sim 0.09 \) with ±5%. Here, the \( u_{\text{rms}} \) is given by \( u_{\text{rms}} = \left[ \int_0^\tau (U(t) - U_m)^2 \mathrm{d}t \right]^{1/2} \). Characterization of the velocity field in the absence of the flame was for the purpose of documenting the nozzle exit flow conditions. When the flame is present, the flow field will be somewhat modified and the effects of flame on the upstream flow divergence needs to be separately quantified, for example, by particle image velocimetry.

3.2. Spatial mixture gradient profiles

Laser Rayleigh light scattering was utilized for measuring the spatial fuel concentration distributions as described earlier. In the present study, three different spatial mixture distributions were considered. These were (i) uniform fuel/air mixture identified with the uniform base equivalence ratio, \( \phi_b \); (ii) higher concentration of fuel in the inner stream,
identified as \( \Delta \phi_i \) above the base equivalence ratio; and (iii) higher fuel concentration in the outer stream identified as \( \Delta \phi_o \) above the base equivalence ratio. \( \phi_b \) is determined based on the total airflow rate and the fuel flow rate supplied to the fuel/air mixing chamber. \( \Delta \phi_i \) and \( \Delta \phi_o \) are calculated based on the nominal air flow rate in that flow stream and the additional fuel flow rate supplied to it. The mixing profiles were characterized under cold flow conditions. Care was taken to minimize the background scattering effects. The Rayleigh intensity data were processed to obtain the fuel mole fraction as 

\[
\chi_m = \frac{I_m - I_N}{I_f - I_N},
\]

where \( I_m, I_f, \) and \( I_N \) are the measured Rayleigh intensities for the mixture, pure propane, and nitrogen, respectively. Mixture profiles are shown in Fig. 3 for fuel-rich inner jet, uniform composition, and fuel-rich outer jet. All the profiles were measured 2 mm above the top surface of the bluff body. The results show the distributions of fuel composition in terms of the mixture equivalence ratio for \( \phi_b = 1 \) and the cases where \( \Delta \phi_o \sim 0 \) and \( \Delta \phi_i \sim 0.3 \). It was found that the outer fuel enrichment remains predominantly outside the inner nozzle boundary in the flame stabilization zone. For the inner fuel gradient case, shown in Fig. 3c, the central part of the inner jet is significantly richer than the average expected value of \( \Delta \phi_i \sim 0.3 \). This is because the fuel jets injected through the center body that enrich the inner stream do not mix uniformly throughout the inner flow stream, but produce a fuel-richer central stream in the inner nozzle. The ratio of this inner stratification is \( [\Delta \phi_i]_{\text{max}} / [\Delta \phi_i]_{\text{average}} \sim 1.34 \). Similar results were also observed for the outer enrichment case.

3.3. Visual characteristics of bluff-body stabilized flames

Before we present the blowoff data for the studied flames, it is instructive to study the visual characteristics of these flames. Fig. 4 shows the flame images with base equivalence ratios of \( \phi_b = 0.9 \) for the outer stream fuel stratification (top row), uniform mixture (middle row), and inner stream fuel stratification (bottom row). When the flame shapes are compared for the uniform, inner, and outer equivalence ratio gradients, the richer outer equivalence ratio case exhibits flames that expand downstream with vigorous burning on the upper periphery, as compared to higher inner equivalence ratio cases. These flames are significantly noisier than the uniform and centrally fuel-enriched flames due to vigorous burning toward the top of the flame cone, even without any upstream flow excitation. Flames with inner equivalence ratio gradient are found to be typically more compact, and burn vigorously near the center. Upon flow modulation at different frequencies, flames interact most strongly between 100 and 200 Hz. Luminous heights of these flames slightly decrease with increasing modulation frequency. Additionally, flames become narrower with increasing excitation frequency for the uniform and the inner gradient cases. In the case of richer inner stream, flames are confined to the central
part of the flow and much of the lean outer mixture passes without combusting when the outer stream is very fuel lean. As will be discussed later, the approach to blowoff under these conditions results in a progressive narrowing of the flame and final blowout. Fig. 5 exhibits this behavior for the case where the base equivalence ratio is reduced progressively while maintaining the gradient magnitude $\Delta \phi$ constant. It is seen that the flames progressively narrow as blowoff is approached, particularly for the uniform and inner gradient equivalence ratio cases.

3.4. Flame blowoff characteristics

Blowoff equivalence ratios of these inverted conical flames at different frequencies were measured by noting the equivalence ratios at the point corresponding to the rapid reduction of the PMT signal from the data acquisition system. An example of the time variation of fuel flow rate and the PMT signal is shown in Fig. 6 as the blowoff is approached. In this manner, the blowoff equivalence ratios can be precisely determined. Determination of the blowoff point is un-
ambiguous for spatially uniform mixtures, as the mixture equivalence ratio is reduced gradually to the point of flame blowoff. The change in the mass-flow rate and the mean flow velocity due to decrease in the fuel-flow rate as the flame blowoff is approached was calculated to be less than 2% for all experimental conditions.

For the experiments with mixture gradients, two different methods could be employed for the blowoff measurements. One method is to reduce the base equivalence ratio while maintaining the magnitude of the equivalence ratio difference, $\Delta \phi$. Another way is to maintain the base equivalence ratio constant and reduce the fuel enrichment magnitude, which will result in diminishing equivalence ratio difference as blowoff is approached. In the reported experiments, we took the first approach of reducing the base equivalence ratio while maintaining the magnitude of the inner or outer equivalence ratio enrichment. In the experiments, the base equivalence ratio was gradually reduced by lowering the fuel-flow rate in the base mixture, as depicted in the photographs of Fig. 5.

The blowoff equivalence ratios were determined at least twice for each experimental condition without upstream velocity modulation as well as at each modulation frequency ranging from 75 to 350 Hz for the three nominal mean flow velocities 5, 11, and 16 m/s. All the flames were initiated with a base $\phi_b = 1.0$ and this $\phi_b$ value was slowly lowered at a constant rate until blowoff. For several cases, the blowoff equivalence ratio was determined 10 times and the 95% confidence interval was estimated to be $\pm 1.5\%$ about the mean measured value.

The sensitivity of the blowoff equivalence ratio to flow modulation amplitude was first characterized as shown in Fig. 7. It was found that the blowoff equivalence ratio increases with increasing velocity modulation intensity at 100 and 200 Hz for $U_m = 5$ m/s. This is based on the higher level of unsteadiness that the flame base experiences and this finding is consistent with that of Balachandran et al. [16]. While it would have been desirable to determine blowoff behavior at different modulation levels throughout the frequency range of interest, limitation of the loudspeaker excitation precluded such a study.

Fig. 8 shows the flame blowoff characteristics for $U_m = 5$ m/s nominal approach velocity at a velocity modulation amplitude of $u_{rms}/U_m \sim 0.09$. Flame blowoff equivalence ratio behavior for the uniform mixture exhibits a slight increase of the blowoff equivalence ratio followed by a reduction of about 6% at high excitation frequencies similar to the results obtained before [14]. There are some differences between that study and the current one in the way the blowoff was detected. In the previous study [14], blowoff was visually detected while manually reducing the flow rate of fuel metered by the flow controller. In the present case, a fully automated approach was utilized as described earlier in this article. As can be seen in Fig. 8, enrichment of the outer stream has been found to have virtually no effect on the blowoff, as the data match the uniform mixture case within measurement error. To investigate the influence of outer mixture gradient further downstream, flame holder position was extended by 20 mm, so that further mixing of the fuel-rich outer stream with the inner mixture stream could potentially affect the flame holding...
Fig. 4. Flame images for outer gradient, uniform, and inner gradient equivalence ratios at $\phi_b = 0.9$ at $U_m = 11$ m/s at different excitation frequencies.

characteristics. The results shown in Fig. 8 (labeled as extended) indicate that there was virtually no influence of the outer stream fuel enrichment even at this farther downstream location. However, the flame with the enhanced fuel concentration in the outer nozzle exhibits a widening of the flame downstream, caused by the combustion of the richer mixture in the outer nozzle. The flame is also acoustically more active in
Fig. 5. Flame images as blowoff is approached. Top row: Outer stream fuel enrichment. Middle row: Uniform fuel concentration. Bottom row: Inner stream fuel enrichment.

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<td>$\phi_a = 0.9; \Delta \phi_a = 0.3$</td>
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<td>$\phi_a = 0.75; \Delta \phi_a = 0.3$</td>
<td>$\phi_a = 0.9$</td>
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<td>$\phi_a = 0.8$</td>
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<td>$\phi_a = 0.5; \Delta \phi_a = 0.3$</td>
<td>$\phi_a = 0.4; \Delta \phi_a = 0.3$</td>
<td>$\phi_a = 0.3; \Delta \phi_a = 0.3$</td>
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All cases, with and without upstream flow excitation. This can be attributed to the higher heat release in the periphery of the mixture jet and the interaction with the vortical flow field in this region.

Fuel enrichment of the inner stream mixture makes a substantial difference by lowering the base equivalence ratio at blowoff. There is a gradual increase of the base equivalence ratio at blowoff with
increasing excitation frequency and a greater degree of data scatter is observed as compared to the uniform mixture case. The low values of the base equivalence ratio for the inner fuel enrichment case can be explained by the presence of a favorable combustible mixture equivalence ratio gradient near the flame-holding region in this case. Obviously, the external part of the mixture flow cannot burn at these low equivalence ratios, as also evidenced by the flames becoming progressively narrower with reduction in the base equivalence ratio, as shown in Fig. 5.

The results are shown in Figs. 9 and 10 for mean flow velocities of 11 and 16 m/s, respectively. At 11 m/s, the blowoff equivalence ratios increase with increasing upstream velocity modulation frequency for the uniform and the outer mixture gra-
Fig. 8. Variation of base mixture equivalence ratio for uniform, fuel-rich inner stream, and fuel-rich outer stream at $U_m = 5 \text{ m/s}$ as a function of upstream velocity modulation frequency for $u_{rms}/U_m \sim 0.09$. For inner and outer stream enrichment, $\Delta \phi = 0.3$.

Fig. 9. Variation of base mixture equivalence ratio for uniform, fuel-rich inner stream, and fuel-rich outer stream at $U_m = 11 \text{ m/s}$ as a function of upstream velocity modulation frequency for $u_{rms}/U_m \sim 0.09$. For inner and outer stream enrichment, $\Delta \phi = 0.3$.

dient cases. The blowoff equivalence ratio increase between the 350-Hz modulation and no-excitation cases is about 8% and 7% for the 11 and 16 m/s approach velocities, respectively. This level of change is substantially higher than the uncertainty in the determination of blowoff equivalence ratios. Under all three mean velocity conditions, there is virtually no distinction between uniform and outer gradient base equivalence ratios at blowoff. Similarly to the 5 m/s case, the extension of the flame holder location downstream by 20 mm showed no discernible effect on flame blowoff equivalence ratios for 11 and 16 m/s cases. All these results suggest that the mixing between the inner and the fuel-rich outer streams over this distance is not sufficient to influence the flame-holding characteristics. As also observed for the 5 m/s approach velocity case, the inner equivalence ratio gradient shows a significant decrease of the base equivalence ratio, $\phi_b$, with respect to the uniform case (note the scale change), an increasing trend with modulation frequency, and a higher degree of data scatter.
In order to provide a possible explanation for these seemingly ambiguous results as shown in Figs. 8–10 for the inner gradient cases, one can analyze the fuel–air mixture profile at the base of the flame near the flame-holding zone. Fig. 11 shows the time-averaged flame shapes for the three mean velocity conditions without and with velocity modulation, obtained from time-averaged photographs of these flames. The corresponding mixture profile is shown in the lower panel of that figure. As the average flame shape becomes narrower with increasing velocity, the reactant mixture flow that burns near the recirculation zone is expected to become more fuel-rich. This enables flame holding at very low base equivalence ratios, effectively resulting in a piloting effect. The difference between the blowoff equivalence ratio for uniform mixture and the inner gradient cases is plotted for all cases in Fig. 12a. As it is seen, these values range from about 0.4 to 0.6 and depend on the mean velocity condition and to some extent on the excitation frequency for the case of the lowest mean velocity. If it is assumed that the flame blowoff is controlled by the mean mixed equivalence ratio of the mixture that is being consumed near the recirculation zone, one can calculate the radial extent of the mixture that is responsible for this difference. Assuming that the axial flow velocity is relatively uniform in this region, the radial extent of the mixture to account for the equivalence ratio differences shown in Fig. 12a can be computed. As shown in Fig. 12b, it is found that the 5 m/s mean velocity case has the largest radial extent, as this flame has the widest angle at the base. With increasing mean flow velocity, the radial extent diminishes, which is consistent with the decrease of the flame angle at its base. It is also interesting to note that there is an increasing trend of the radial extent with increasing excitation frequency for the \( U_m = 5 \text{ m/s} \) case.

3.5. Analysis of near blowoff behavior by wavelets

One of the important aspects of flame stabilization is the detection of the impending flame blowoff as the flame approaches this condition. If it is possible to detect identifiable events that precede flame blowoff, then corrective measures may be taken to prevent it. In this context, Nair and Lieuwen [10] recently looked at the dynamics of bluff-body stabilized flames near blowoff, utilizing acoustic and optical emission signals analyzed by wavelets. They found that flame blowoff is preceded by emergence of localized flame extinction regions followed by violent flapping of the flame front. In our experiments, we monitored the CH* chemiluminescence signal from the flame spanning a region from 5 to 40 mm downstream of the bluff body by a photomultiplier (PMT) detector with a bandpass filter centered at a wavelength of 430 nm. PMT signal was collected at 1 kHz frequency, which allowed a frequency resolution up to 500 Hz. The data from the PMT detecting this chemiluminescence were continuously acquired as the equivalence ratio of the mixture was reduced toward the blowoff condition. Postprocessing of these data was then performed to identify any features that may be utilized for blowoff detection. The PMT signal was first normalized with the short time-averaged local signal intensity to remove the CH* chemilumi-
nescence variation. Then complex continuous wavelet transform with progressive wavelets was utilized to analyze the normalized signal. The unique property of the complex progressive wavelets is that the quadrature phase shift between its real and imaginary parts removes the wavelet oscillation while observing the wavelet coefficient modulus [17,18].

The complex frequency B-splined wavelet was chosen as the functional wavelet for the present study. The functional form of these wavelets can be written as [19,20]

$$\psi(t) = \sqrt{f_b} \left( \text{Sinc}\left( \frac{f_b}{m} \right) \right)^m \exp(2i\pi f_c t),$$

where three parameters completely define the function: $m$ is the integer order parameter ($m \geq 1$), $f_b$ is the bandwidth parameter, and $f_c$ is the wavelet center frequency. The relationship between the wavelet scale and frequency is given by $f_a = f_c / (a \cdot \Delta)$, where $a$ is the scale, $f_a$ is the frequency of the dilated wavelet corresponding to local signal frequency, and $\Delta$ is the sampling period.

The strategy adopted for extracting new frequency content as blowoff is approached is as follows. Initial signal processing was done on signals obtained at stationary equivalence ratio conditions. Two uniform equivalence ratios were chosen for a mean velocity condition of 11 m/s. The first case, as shown in Fig. 13a for $\phi_b = 0.9$, represents conditions far from blowoff, whereas the second case, shown in Fig. 13b for $\phi_b = 0.73$, represents near-blowoff conditions under which wavelet coefficients at lower scales, i.e., at higher frequencies, become dominant, unlike the case far from blowoff, where wavelet coefficients at lower frequencies become more dominant. Naturally, the chemiluminescence intensity at $\phi_b = 0.9$ is much higher than that for $\phi_b = 0.73$. In order to make the wavelet transforms of the respective signals comparable, the signals were normalized with respect to the total power by

$$P = \sqrt{\frac{1}{10T} \int_0^T \int_{\text{CH}^+}(t) \, dt},$$
where $T$ is the total period of the collected signal, $I_{CH^*}$, and the factor 10 appears as a result of normalization. Fig. 14 shows the equivalence ratio variation, the time variation of the CH* signal, and the modulus of the wavelet coefficients as a function of scale (or frequencies) for $U_m = 11$ m/s. It is found that higher scales (or lower frequencies) dominate the spectrum with much smaller moduli at lower scales (or higher frequencies) away from the blowoff. However, as the flame blowoff is neared, higher moduli of lower scales (or higher frequencies) begin to dominate, as seen in Fig. 14. Based on this observation, normalized power distributions at low (5 to 10 Hz) and high frequency (20 to 50 Hz) were determined. To minimize the fluctuations in these power distributions, the wavelet power in a given scale range
Fig. 13. (a) Flame dynamics at constant equivalence ratio, $\phi_b = 0.9$, typically representing far from blowoff case; (b) flame dynamics at constant equivalence ratio, $\phi_b = 0.72$, typically representing near-blowoff case.

(a) is computed as $\sqrt{\frac{1}{a_2-a_1} \int_{a_1}^{a_2} C^2(a, t) \, da}$, where $C(a, t)$ are the wavelet coefficients as a function of scale $a$ and time or $\phi$ equivalently. The probability density functions of the ratio of the higher frequency (20–50 Hz) to lower frequency (5–10 Hz) powers were first obtained in small ranges of equivalence ratio ($\Delta \phi = 0.02$), and are shown in Fig. 15. In all cases, the high probabilities at low ratios decrease with diminishing equivalence ratios and the probability density distribution becomes broader with lower
Fig. 14. Near-blowoff flame base dynamics using wavelet analysis of the CH\textsuperscript{*} chemiluminescence.

peak values as the flame blowoff is approached. Typically, the ratios are near a value of 0.2 far from blowoff, but shift to higher values as blowoff is neared. These features are consistently evident in all cases and can possibly be used as the basis for flame blowoff detection. For example, the two measures (the most likely value of the power ratio and its standard deviation) can be utilized for this purpose.

4. Concluding remarks

In this study, blowoff conditions of bluff-body stabilized premixed turbulent flames with upstream flow modulation were studied as a function of upstream spatial mixture gradients and periodic velocity oscillations. The effect of the spatial fuel concentration gradient on the flame blowoff equivalence ratios was confined to the inner stream fuel enrichment. The base equivalence ratio at blowoff was significantly reduced for higher inner equivalence ratios. Fuel enrichment in the outer stream away from the recirculation zone was found to change the overall flame structure, but it did not affect the flame-holding characteristics because of the inability of the outer richer mixture to influence the flame stabilization zone. The different mixture composition profiles employed in the experiments were characterized by laser Rayleigh light scattering. The effects of the variable equivalence ratio profile were attributed to the contribution of the fuel-richer inner mixture to a more robust flame bounding the recirculation zone behind the bluff body. Additionally, the CH\textsuperscript{*} chemiluminescence signal from the base of the flame was analyzed using wavelet transforms to determine a precursor condition that can be possibly utilized to detect an impending flame blowout. It was suggested that the spectral power contained in the low and higher frequency ranges can be monitored for this purpose. However, the generality of this criterion needs to be further explored by additional experimentation.
Fig. 15. Probability distribution of higher frequency (20–50 Hz) to lower frequency (5–10 Hz) wavelet power ratio as a function of equivalence ratios at mean velocities of (a) $U_m = 5 \text{ m/s}$, (b) $U_m = 11 \text{ m/s}$, and (c) $U_m = 16 \text{ m/s}$. 
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