Hindawi Publishing Corporation
International Journal of Reacting Systems
Volume 2008, Article ID 461059, 7 pages
doi:10.1155/2008/461059

Research Article

Observations on Jet-Flame Blowout

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Received 29 August 2007; Revised 16 November 2007; Accepted 14 January 2008

Recommended by Ishwar K. Puri

The mechanisms that cause jet-flame blowout, particularly in the presence of air coflow, are not completely understood. This work examines the role of fuel velocity and air coflow in the blowout phenomenon by examining the transient behavior of the reaction zone *at blowout*. The results of video imaging of a lifted methane-air diffusion flame at near blowout conditions are presented. Two types of experiments are described. In the first investigation, a flame is established and stabilized at a known, predetermined downstream location with a constant coflow velocity, and then the fuel velocity is subsequently increased to cause blowout. In the other , an ignition source is used to maintain flame burning near blowout and the subsequent transient behavior to blowout upon removal of the ignition source is characterized. Data from both types of experiments are collected at various coflow and jet velocities. Images are used to ascertain the changes in the leading edge of the reaction zone prior to flame extinction that help to develop a physically-based model to describe jet-flame blowout. The data report that a consistent predictor of blowout is the prior disappearance of the axially oriented flame branch. This is witnessed despite a turbulent flames' inherent variable behavior. Interpretations are also made in the light of analytical mixture fraction expressions from the literature that support the notion that flame blowout occurs when the leading edge reaches the vicinity of the lean-limit contour, which coincides approximately with the conditions for loss of the axially oriented flame structure.

1. INTRODUCTION

At a particular fuel velocity, a gaseous hydrocarbon jet-flame will detach from the burner and stabilize at some axial distance downstream. The reaction zone consists of a leading partially-premixed flame front and a trailing diffusion flame created at the vertically-oriented interface of the residual fuel not consumed by the leading flame front and air. A diffusion flame has no burning velocity so it is the premixed flame front that is generally assumed to act as a stabilizing anchor. Many studies, like that of Muñiz and Mungal [1] and Watson et al. [2–4], have investigated stable lifted flame reaction zone structures that settle at moderate downstream positions. If the reaction zone moves further downstream, it eventually enters a region that can no longer support combustion due to the low fuel concentration and all reaction abruptly ceases, a condition known as flame blowout (Kalghatgi [5], Pitts [6], Coats [7], Chao et al. [8, 9]. The term *blowout* seems more physically descriptive than the sometimes used *blowoff* since the global reaction zone does not seem to blow off the downstream end of the jet, but rather, to locally cease (Liñán and Williams [10]). Since the blowout phenomenon happens typically in an abrupt and unpredictable manner, its transient characteristics are difficult to study experimentally. Additionally, the large width of the fuel jet, the small gradients in the scalar and velocity fields, and the relatively low values of fuel concentration make the situation, in many ways, more challenging to fully characterize than the situations described in the studies of Watson et al. [2–4].

Theories have been developed to determine the mechanism controlling blowout. For a laminar propane jet flame, Savas and Gollahalli [11] studied the shape of the flame front and found that near blowout, the flame front became flat (an axially centered disk) and the chemiluminescence weakened. The blowout conditions were determined to be dependent on the fuel and oxidizer properties and on the burner geometry. Chung and Lee [12] showed similar phenomena also in laminar jet flames. For turbulent flames, Broadwell et al. [13] proposed that at the blowout velocity, the combustion ceases because there is not enough time for the ignition of incoming fuel/air mixtures by entrained hot products. This work and others (Miake-Lye and Hammer [14]) point to the primary role of large-scale structures in facilitating hot-product transport. Similarly, Dahm and Dibble [15] applied a blowout parameter from Broadwell et al. [13] for turbulent jets in coflow and showed that an increased coflow velocity decreased the jet blowout velocity. The blowout parameter, based on characteristic ignition time and mixing time ratios, predicts blowout trends correctly. More recently, Han and Mungal [16] also offered observations on flame blowout, but focused their explanations on the inability of the reaction zone to counter-propagate against incoming reactants at blowout. Burgess and Lawn [17], Brown et al. [18], Dahm and Mayman [19] and Montgomery et al. [20] discussed related elements of flame blowout; a recent overview of this previous research in blowout is contained in Chao et al. [9]. More recently, Wu et al. [21] report on lifted flames near blowout, with detailed comments on triple flames in the pulsating region, and describe a proposed mechanism of flame pulsation and blowout.

The current paper discusses an experimental study of the blowout phenomenon for a lifted methane-air diffusion flame in various coflow conditions. Rather than focusing on detailed instantaneous images of reaction zones, as has been our tact in the past, this effort has utilized time sequences of the reaction zone at blowout. The main focus is to investigate the transient behavior leading to global blowout. Instantaneous measurements at blowout prove to be quite difficult with the limitations of single-shot experimental techniques due to the abrupt onset of blowout. Two types of experiments are described that attempt to clarify the characteristics of flames during the blowout process, focusing on the behavior of the leading edge reaction zone and the trailing diffusion flame at blowout. Sequences of digital images of the lifted reaction zone are provided along with details of the flame movement for different combinations of fuel and coflow velocities. Interpretations of the data are discussed, utilizing a relation for the stoichiometry from Tieszen et al. [22]. This allows for the assessment of past theories and the development of a physically-based concept of flame blowout in turbulent jets, along with proposing a new signature which indicates the imminence of flame blowout.

2. EXPERIMENTAL SETUP

The experiments were performed at the Applied Energy Research Laboratory on the campus of North Carolina State University. A vertical jet flame burner with a fuel nozzle of 3.5 mm diameter was used to deliver 99% pure methane. The apparatus provides a *top-hat* velocity profile at the nozzle's exit. As shown in the schematic in Figure 1, the fuel nozzle is surrounded by an annulus of coflowing air with a diameter of 150 mm. Care was taken to minimize the effects of room currents on the flame apparatus by turning off laboratory ventilation during the recording of data and limiting activity near the burner. The height of the lifted flame, h, is the distance from the lowest part of the flame front to the nozzle.

For this investigation, images of chemiluminescence (Lyons and Watson [23]) from the methane jet near blowout conditions were obtained with a Panasonic Model PV-GS120 camera producing thirty frames per second (60 interlaced fields). The colors of the images were enhanced using Adobe Photoshop. A rotameter measured the fuel velocity, and the coflow velocity was measured using a TSI Veloci-calc model 8345 anemometer. The minimum and maximum coflow velocities used were 0 m/s and 0.65 m/s, respectively.

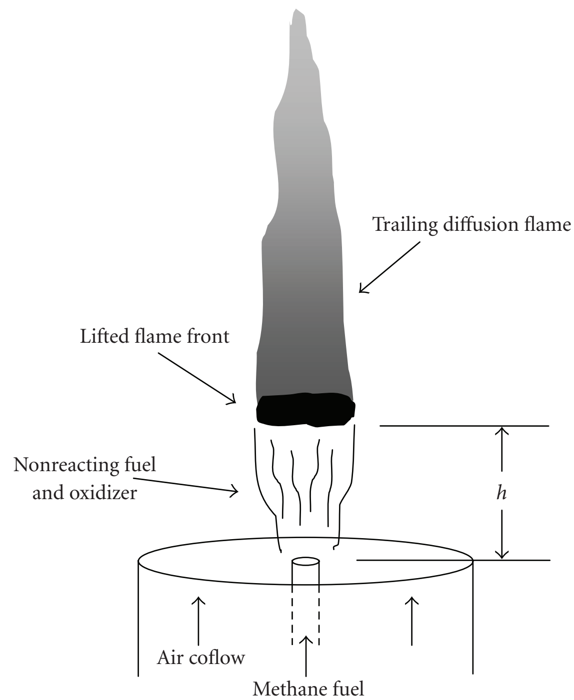


Figure 1: Methane is delivered from the nozzle that is surrounded by coflowing air. The conditions allow the flame to lift to some downstream position where there exists the lifted flame front and the trailing diffusion flame, before proceeding to blowout. The letter h is the distance from the fuel nozzle to the lifted flame front.

3. RESULTS AND DISCUSSION

Images of the blowout of a methane flame were obtained at various conditions during two different types of experiments. In the first series of experiments, blowout was brought about by a change in the flow conditions of a stable lifted flame. For a constant coflow velocity, the initial fuel velocity was set to allow the flame to stabilize at a lifted height of approximately 14.0 cm (or 40 nozzle diameters) above the nozzle. The same stable height was used throughout the first experiments and was chosen because a reaction zone at that height is stable (i.e., will not spontaneously blowout) and turbulent for each coflow velocity tested. The fuel velocity was then increased slightly until blowout occurred. The procedure was repeated multiple times to determine the lowest jet velocity at which the flame would consistently blowout. Table 1 contains examples of conditions that were digitally recorded, with the fuel velocities being the averaged values.

The data of Table 1 show that with increasing coflow, decreasing values of the methane jet velocity are needed for blowout to occur. Dahm and Dibble [15] proposed that this reduction in fuel velocity at blowout was due to the local

Table 1: Flow conditions for flame from (a) stable lifted positions (b) to blowout.

Coflow velocity (m/s)	*Lifted* 14.0 cm (*a*)		*Blowout* (*b*)	
	Fuel velocity (m/s)	*Reynolds number*	*Fuel velocity* (m/s)	*Reynolds number*
0.0	46.6	10114	50.4	10929
0.3	36.9	8013	41.7	9050
0.4	31.6	6848	35.6	7716
0.5	27.0	5855	31.6	6848

molecular mixing rate. In experiments by Brown et al. [18], a change in the coflow velocity had a greater effect on a flame, the further downstream the flame was stabilized, resulting in lower jet velocities for flame blowout. Additionally, the findings of Brown et al. [18] confirmed the data of the current study which show that for a given coflow velocity, the flame can on occasion extinguish at a slightly lower fuel velocity than the experimentally-determined average blowout velocity. In this regime (as witnessed in the current study), the coflow so dominates that it tends to be comparable to the jet velocity and the bulk coflow velocity carries the reaction zone downstream. As discussed elsewhere, it is proposed that at this downstream location the flame blows out as the lean limit is reached.

Images from these experiments were examined to determine the effect of coflow on the mechanism of blowout. Figure 2 shows two sequences of images of the flame proceeding to blowout. The images in Figure 2(a) are from a flame with 0.3 m/s coflow, corresponding to the data on the second line of Table 1. The sequence begins after the fuel velocity was increased from 36.9 m/s to 41.7 m/s. The image at time zero is the last one of the flame at the stable lifted height, immediately after which the flame begins moving downstream. The flame transitions from a stable lifted flame to a quasistable flame on the threshold of blowout. During this transition, the length of the diffusion flame decreases as the leading edge of the flame front drops downstream. The contrast in color for this sequence has been increased due to the faint chemiluminescence of the actual flame. The blue flame consists of a leading-edge flame front that anchors the trailing diffusion flame. Blowout occurs 1.50 seconds after the change in fuel velocity causes downstream movement of the flame.

In the second series of experiments, the fuel velocity was set at blowout conditions, predetermined by multiple tests, for a particular coflow velocity. With the fuel and coflow velocities held constant, the flame was reignited at the fuel nozzle and allowed to move downstream and eventually extinguish. Figure 2(b) shows one sequence of images from these experiments with the colors inverted and enhanced to counteract the faintness of the flame. The larger field of view includes the nozzle but it is not visible in the enhanced images. For this sequence, the flame was reignited from the nozzle with 0.55 m/s coflow and 34.3 m/s fuel velocity. After 3.53 seconds, the chemiluminescence witnessed from the trailing diffusion flame has been significantly reduced and the leading-edge of the flame front has moved 19.1 cm downstream. At 25.1 cm and 3.73 seconds, the diffusion flame is no longer visible. In the remaining 0.14 seconds until the flame entirely extinguishes, the flame front moves 6.7 cm. Thus, the flame moves further downstream much more rapidly in the absence of the trailing diffusion flame compared to when it is present. The last image in the series shows that complete blowout was achieved 3.87 seconds after reignition.

Table 2: Fuel velocity, U_0, and coflow velocity, U_{CF}, for a given stoichiometric contour velocity, U_S. Times given are from reignition to blowout based on digital images.

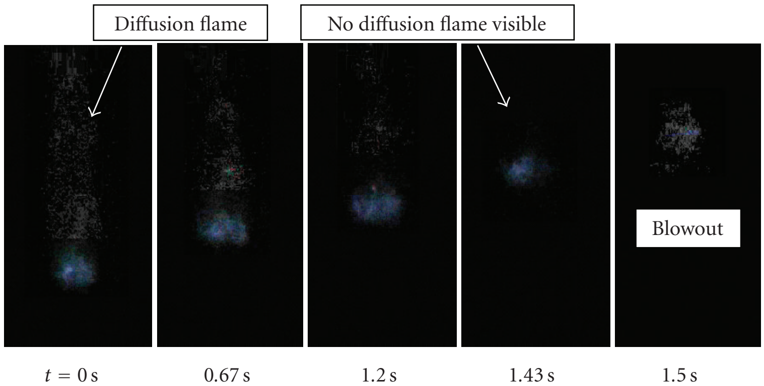
Fuel velocity U_0 (m/s)	*Coflow velocity* U_{CF} (m/s)	U_S (m/s)	*Time to blowout* (s)
36.9	0.4	2.4	No blowout after 60 s
36.0	0.45	2.4	20.5
35	0.5	2.4	2.47
35.0	0.55	2.4	3.87
33.5	0.6	2.4	2.03
32.6	0.65	2.4	1.00

Data from repeated tests for each of the flow conditions revealed no trend in the amount of time needed from reignition to blowout. However, similar characteristics of the flame were noticed regardless of the presence or magnitude of the coflow velocity or by which method blowout was achieved. At downstream locations, the flame front is witnessed to decrease its recession speed downstream as the diffusion flame diminishes. After the chemiluminescence from the trailing diffusion flame is no longer detected, the small region of flame at the leading edge (a *blue* flame ball) increases its recession speed downstream until the whole reaction is completely extinguished. Importantly, as Figure 2 shows and other experiments verify, blowout is *not* witnessed while the axially oriented diffusion flame is present.

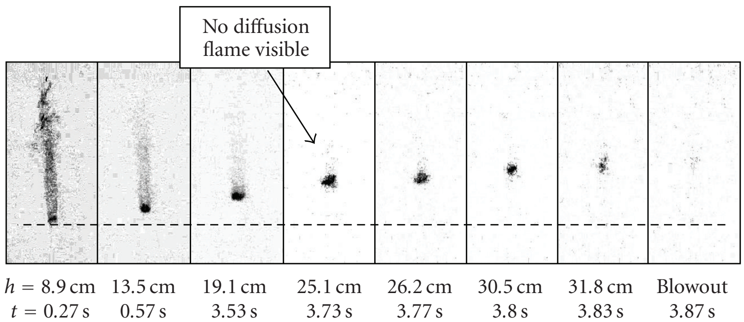
As suggested by Han and Mungal [16], the velocity of the stoichiometric contour can be estimated and used to approximate the amount of mixing between the fuel jet and the surrounding air. This velocity, U_S, can be calculated from

$$U_S = Z_S U_0 + (1 - Z_S) U_{CF}, \tag{1}$$

where Z_S is the stoichiometric mixture fraction (0.055), U_0 is the nozzle exit velocity, and U_{CF} is the coflow velocity. To test for blowout dependence on the stoichiometric contour velocity, the coflow and fuel velocities were varied such that U_S remained the same, beginning with 0.50 m/s coflow and 35 m/s fuel giving U_S = 2.4 m/s, as seen in Table 2. Despite starting at a blowout condition and keeping U_S constant,



(a)



(b)

Figure 2: (a) Enhanced images of the flame receding downstream for 0.3 m/s coflow. The fuel velocity was increased from 36.9 to 41.7 m/s to cause blowout (line 2, Table 1). The entire flame is blue in color. (b) Inverted images of the flame after being reignited at time zero, with 34.3 m/s fuel velocity and 0.55 m/s coflow (line 4, Table 2). The distance, h, from the fuel nozzle to the lifted flame front is measured for each.

Table 3: Comparison of theories on blowout from past publications.

	Blowout concepts supported	*Proposed blowout mechanism*
Broadwell et al. [13]	Large-scale structures move hot product to flame leading edge	Mixing between hot products and unburned fuel allows insufficient time for combustion to occur
Dahm and Dibble [15]	Molecular mixing rate	Reduction in the fuel velocity with increased coflow velocity corresponds to a consistent blowout parameter
Tieszen et al. [22]	Local flow velocity exceeds turbulent flame speed	Turbulent flame propagation towards the outer edge of the reaction zone stabilizes flames near blowout
Han and Mungal [16]	Flame propagation against incoming reactants	Flame base moves into a higher-velocity region due to a change in the stoichiometric velocity of the flame surface
Wu et al. [21]	Triple flames/flame pulsation	Lessening of the stoichiometric branch of the triple flame leads to downstream recession and eventual blowout

the flame's behavior was not consistent. At the lowest coflow velocity, the flame stabilized and was not seen to blowout for an extended amount of time in spite of being at a higher fuel velocity than a comparable flame in Table 1. Added to the unpredictable nature of blowout, a difference in experimental procedures cannot be ruled out as a cause of some discrepancy. Blowout occurred in one second at the highest coflow velocity. These variations in behavior predict a lack of dependence of blowout on U_S. As implied in previous studies by Han and Mungal [16] and Watson et al. [3], U_S is a useful quantity for estimating the axial velocity at the stoichiometric contour of the *already* established portions of the flame; the leading edge of the flame has been found to favor lower speed regions (S_L to $3\,S_L$) typically less than U_S.

4. ANALYSIS OF THE SCALAR FIELD

An analysis of the scalar field for the turbulent methane jet flame indicates a correlation between the downstream appearance of the flame and the value of the local mixture

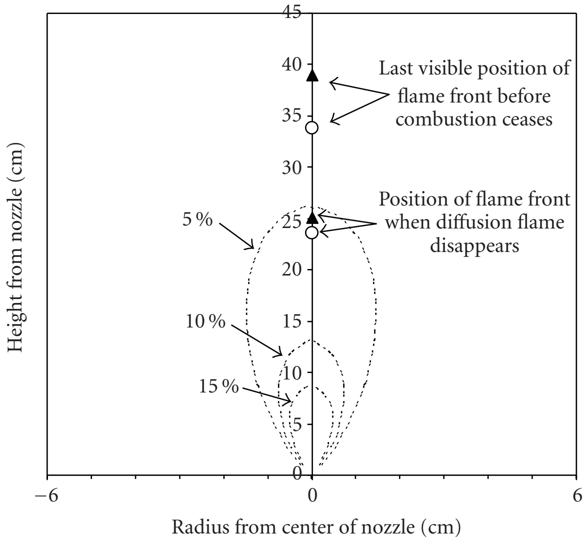


Figure 3: Position of the flame leading edge relative to the mean fuel concentration as calculated from the approach of Tieszen et al. [22] for two cases without coflow. For Case 1 (circles), the fuel velocity is increased from 46.6 m/s to 50.4 m/s (line 1, Table 1) from the first series of experiments. For Case 2 (triangles), the fuel velocity is 54.3 m/s from the second series. What is notable is that the position where the axial oriented flame is lost corresponding to the approximate position of the lean limit.

fraction. The scalar field of methane issuing into quiescent air is determined from the method used by Tieszen et al. [22]. The time-averaged mass fraction of fuel, Y, into air with no coflow present is represented as

$$Y = 10\cdot\left(\frac{\rho_0}{\rho_\infty}\right)^{1/2}\left(\frac{r_0}{z}\right)\exp\left\{-57\left(\frac{r}{z}\right)^2\right\}. \tag{2}$$

This equation, a function of the ratio of the densities of methane ρ_o and air ρ_∞ and the nozzle diameter r_o, is used to estimate the fuel concentration at a particular downstream location z for a given radial position r. It assumes self-similarity and is derived from the concentration profile developed by Dowling and Dimotakis [24], thus a lack of dependence on the jet velocity. The stoichiometric contour and those indicating the 5 and 15% flammability limits of methane generated from this approach are shown in Figure 3. Also shown in Figure 3 are the axial locations of the flame front as the flame progresses downstream for two different cases. Because (2) is strictly valid only when no coflow is present, both cases have zero coflow velocity but slightly different fuel velocities, as each was achieved by one of the two different techniques explained above. For Case 1, the flame is at a stable lifted position before the velocity is increased from 46.6 to 50.4 m/s to induce blowout. For Case 2, the flame was reignited at the nozzle with the fuel velocity kept constant at 54.3 m/s. Blowout occurs at 33.8 cm for Case 1 and 38.9 cm for Case 2.

For both cases, the downstream location of the flame front when the diffusion flame disappeared was determined from the images. As seen in Figure 3, the location for Case 1 is 23.6 cm and for Case 2 is 25.1 cm. The location for both is just within the 5% methane contour, implying that the mixture fraction at the leading edge is found to be approaching the mean lean flammability limit contour (and moving downstream in a direction of decreasing mixture fraction) when the diffusion flame is witnessed to disappear and the flame to subsequently blowout. Data from multiple tests confirm that the disappearance of the diffusion flame occurs near the 5% methane contour. Tests conducted with coflowing air gave similar results; however, a more accurate representation for the flammability limits with coflow present is necessary before the results can be confirmed.

Equations for the time-averaged velocity profile of the flame (also from Tieszen et al. [22]) have been examined to verify the validity of (2) in this study. Data from numerous experiments utilizing particle image velocimetry to determine the velocity of the stabilized flame were compared to the estimates provided by the Tieszen velocity relation (Watson et al. [3], Su et al. [25], and Muñiz and Mungal [1]). The published PIV measurements for each agree with the estimated velocities predicted by (2), especially as the flame stabilizes further downstream. Each of these experimental studies used planar laser-induced fluorescence to determine the axial and radial location of the flame edge. Watson et al. [3] used the CH radical to locate the flame edge; thus the PIV measurements were greater than one could expect from using OH, due to the tendency of the CH zones to lie towards the centerline. To account for this, the locations of the rich flammability limits were used to estimate the velocities for these data sets and good general agreement was found, with better results further downstream. The agreement of the velocity estimates despite the presence of coflow supports the use of the similarly derived Tieszen relation (2) for the mass fraction.

These findings support the earlier interpretations based on the digital images, namely that the reduction and eventual disappearance of the diffusion flame indicates the onset of blowout. In addition, once the trailing diffusion flame is absent, the flame front is shown to move into a downstream region in which the mixture fraction is below 5%, and stable combustion is no longer possible. Blowout is found to be imminent for these conditions.

5. CONCLUSIONS

From the images generated by the two types of experiments, general conclusions can be drawn. As shown in Figure 4(a), a stable lifted flame consists of a premixed flame front and a diffusion flame. When the flame front moves downstream, due to the fuel being at the blowout velocity, the diffusion flame length begins to shorten, Figure 4(b). Once this trailing flame has disappeared, Figure 4(c), the reaction zone progresses downstream, being unable to stabilize, and eventually extinguishes, Figure 4(d).

The results of the study suggest that the trailing diffusion flame, specifically its disappearance, plays a useful function as a flame extinction precursor signature. The loss of the chemiluminescence from the trailing diffusion flame functions as an indicator of blowout being imminent. Only after

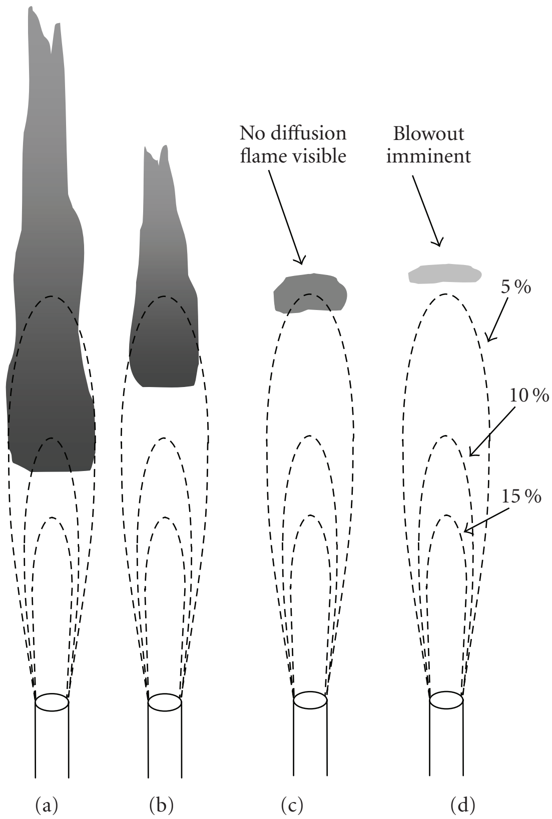


Figure 4: Schematic of the blowout mechanism relative to the flammability limits of methane. (a) A stable lifted flame, (b) the unstable flame has recessed downstream and the diffusion flame has shortened, (c) the diffusion flame has disappeared, (d) blowout occurs.

the diffusion flame disappears does blowout occur for all of the regimes studied.

It is concluded from the analysis that blowout occurs when the leading edge of the reaction zone moves to a downstream region where most of the fuel that is consumed is burnt locally near the leading edge, leaving little in the way of fuel-rich gases to feed the trailing diffusion flame, only large volumes of very fuel-lean gases. In this sense, blowout may be viewed for the cases studied as a lean-limit phenomenon (Williams [26], especially Glassman comments) and this simple analysis supports this conjecture, as well as the paper of Wu et al. [21], as shown in Table 3. The explanations in this paper do not explicitly address the mixing effects (Dahm and Dibble [15]) or the velocity field considerations (Han and Mungal [16]), nor do they contradict them, but rather offer an alternative way based on lean limits to describe blowout and report a new visually observable indicator that is compatible with concepts developed from the general approach of Broadwell et al. [13].

ACKNOWLEDGMENT

The research reported in this paper has been supported by the U. S. Army Research Office (Contract W911NF0510045).

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