Study on the Blowout Mechanism of Turbulent Lifted Jet Flames

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1 Introduction

The stabilization of turbulent non-premixed jet flames has been the subject of many research efforts in the past few decades. It is well-known that as the fuel jet velocity increases, a non-premixed jet flame would first lift off from the burner rim then stabilizes as a lifted flame at a certain downstream location. A continuous increase in the jet velocity would eventually result in the blowout of the lifted flame. Many previous research efforts focused on stable lifted flames with both experimental and numerical studies on their characteristics near the flame base such as the velocity field and flow structure. Readers can refer to a recent review on this subject by Lyons [1].

However, there is still a limited amount of information available with regards to the behaviour of lifted flames near their blowout limits or at the instance of blowout. The study on lifted flame blowout revolves primarily around the prediction of the blowout limits. It is of practical importance to develop a model that can predict the blowout limits based on the initial jet exit conditions only such as that of Kalghatgi [2]. His semi-empirical correlation was derived based on the notion that fuel and air are completely premixed at the base of a lifted flame and blowout occurs when the local gas velocity exceeds the turbulent burning velocity at the flame base. Subsequent arguments suggesting that there is not enough residence time for a complete premixed fuel-air mixture to exist at the base of a lifted flame have arisen, which led to the development of an alternate model based on the large-scale mixing theory [3]. Nevertheless the success of Kalghatgi's model in predicting the blowout limits of free jet flames [4] has proven that the premixed flame propagation model has a certain degree of merit. However, this model cannot be applied directly in the case of lifted jet flames in a co-flowing air stream.

The first objective of the current study was to develop a similar model for the case of coflowing lifted jet flames and to compare the predicted blowout limits with experimental data obtained over a wide range of operating conditions. The second objective of this study is to capture the velocity field at the flame base just prior of blowout as well as at the instance of blowout using a high-speed PIV system. These experimental results can shed light on the blowout mechanism of lifted flames and the validity of the turbulent flame propagation theory [2].

2 Experimental Method

Fuel is discharged from a nozzle into a co-flowing air stream in a 127 mm x 127 mm stainless steel chamber. The nozzle diameter varies from 2 mm to 2.8 mm. Windows are installed on the sides of the chamber for visualization and imaging. Blowout limits over a wide range of co-flow velocities have already been determined and reported in a previous study [5]. For the high-speed PIV measurements, the co-flowing air is seeded with olive oil droplets with a nominal diameter of 0.8 µm. Olive oil evaporates at approximately 600K, which is the temperature characteristic of a lifted flame base [1], and therefore the lifted flame base can be clearly identified in the images as the region without any seeding oil droplets. The velocity field upstream of the flame front is measured using a high-speed PIV system, which consists of a digital high-speed CMOS camera (Photron Fastcam APX RS) and a Nd:YLF diode pumped laser (Photonics DM 20). The laser and the camera can be synchronized at the same frequency up to 10 kHz. The velocity field can be obtained from the cross-correlations between consecutive images. All data acquisition and post-processing is performed using the software DaVis 7.2.



Figure 1. Experimental setup.

3 Results

The location of blowout is not as definite as the lift-off height of a stable lifted flame. It was shown [6] that during the blowout process, the triple flame structure disappears and the flame base becomes "disk-like" instead of the typical hollow cone structure. This corresponds to the onset of lifted flame receding. The lifted flame then continues to travel downstream and becomes extinct eventually at the tip of the lean flammability limit contour. It is thus reasonable to consider the tip of the stoichiometric contour as the characteristic location of blowout at which the blowout criterion is to be evaluated. As the lifted flame is receding downstream, the jet velocity immediately upstream of the flame base must be greater than the flame propagation velocity. Without the triple flame structure as a flame base anchor where the local jet velocity is notably reduced, it can then be postulated that the flame base

propagates at the turbulent burning velocity. Therefore a critical blowout condition can be defined as is that the local jet velocity $U_{b,j}$ is equal to the turbulent burning velocity S_T at the tip of the stoichiometric contour. The local jet velocity was calculated using a RANS model (realizable k- ϵ) for a cold jet, and the turbulent burning velocity was estimated using Bray's model as a function of laminar burning velocity S_L , turbulent velocity u' and the Karlovitz number K [7]:

$$\frac{S_T}{S_L} = 0.875 K^{-0.392} \frac{u'}{S_L}$$

where K is the Karlovitz number defined as follows [8]: $K = 0.157 (u'/S_L)^2 (v/u'l)^{1/2}$

The integral scale l is the half jet width and v is the kinematic viscosity. Applying the critical condition, $U_{b,i} = S_T$, the blowout limits for methane and methane-diluent mixtures have been predicted as shown in Figure 2. Results indicate that the effects of diluents and co-flow velocity on the blowout limits can be predicted quite well. It should be noted that there are different complex phenomena with regards to the stability of lifted flames that have not been accounted for in the current analysis. For example, the structure of a lifted flame base is not exactly a one-dimensional planar premixed flame in a homogeneous turbulent flow. The presence of large-scale structures near the flame base is also playing a prominent role in affecting the stability of a lifted flame. Despite the complexity of the problem, the difference between the calculated local jet velocity and turbulent burning velocity for all the cases considered is comparable to the scatter in the experimental measurements of turbulent burning velocity. This suggests that the current simplified approach is still capable of providing a reasonable approximation of the blowout limits for a variety of conditions. Other important feature of this approach, it does not require input of any experimental blowout data for calibrating any constant or stability criterion in the model. Although the current approach tends to underestimate the experimental blowout limits, nonetheless it can provide a very good prediction on the effects of coflow stream velocity, diluents present in both the fuel and in the co-flowing stream and nozzle diameter.



Figure 2. Experimental and calculated blowout limits for methane and methane-diluent mixtures for two nozzle diameters: (a) 2 mm and (b) 2.38 mm.

A sample of the high speed PIV results are shown in Figure 3, which show the velocity field superimposed on the raw images. The flame zone can be identified as the region where seeding particles are absent. The sample images were snapshots taken from a sequence of 3360 images at a frame rate of 5 kHz, which capture the blowout process. The sequence of images clearly shows the

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flame base as it is receding downstream until it is completely out of the field of view. The blowout conditions were for methane discharging from a nozzle of 2.38 mm in diameter at a velocity of 36 m/s, while the co-flowing air velocity is 0.22 m/s. The location of the jet axis is at the radial position of 63.5 mm. Figure 3a shows the onset of blowout when the flame zone widens into a "disk-like" structure. It is evident that the instantaneous velocity entering the flame base is quite high, which is close to the turbulent burning velocity estimated in previous calculations. Figure 3b shows the flame base after a time period of 146 ms, where the flame base continues to recede downstream.



Figure 3. Instantaneous velocity field superimposed on the raw images obtained with a high-speed PIV system at blowout conditions. a) the onset of blowout; b) 146 ms after the onset of blowout.

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