Effect of Nozzle Geometry on the Stability of a Turbulent Jet Methane Flame in Still Air

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1 Introduction

Turbulent jet (or diffusion) flames are studied considerably in the past and are still an attractive research topic. The common element of interest in a diffusion flame is particularly its stability, which includes its liftoff height and blowout, as well as pollutants formation. It is recognised that the fuel nozzle geometry and exit conditions can impact drastically the stability and other charactersitics of a jet flame. In the early studies of diffusion flames, jets issuing from circular (e.g. pipe) nozzles are traditionally used (see Ref. [1] and references cited therein). Kalghatgi [1], in his famous study, show that the jet flame liftoff height follows a linear pattern with the jet exit velocity independent of the nozzle exit diameter. Furthermore, Kalghatgi [1] finds that the flame liftoff height of most hydrocarbon fuels collapse onto a single, non-dimensionallinear line. Following Kalghatgi's work, several studies are undertaken to assess the effect of nozzle contraction and consequently turbulence on the general characteristics of a jet flame (see, for example, Ref. [2]). Coats and Zhao [2] report that there is no significant difference in the flame liftoff height between the pipe and contracted circular nozzle. Other non-symmetrical nozzle geometries have also been tested. For instance, recent studies report that there is an immense increase in entrainment rate from jets issuing from asymmetric nozzles as compared to those issuing from a pipe, as well as contracted circular nozzles [3-8]. Several other studies report an enhanced stability of asymmetric nozzles especially elliptic nozzles [9]. Note that the stability of these flames is judged in the context of liftoff and blowout.

To the best knoweledge of the authors of the present contribution, no known literature has studied the liftoff and blowout of a jet flame issuing from a triangular or a rectangular nozzle despite their overwhelming entrainment rates compared to other geometries [3-4]. Thus, the present study attempts to assess the stability of asymmetric nozzles with particular emphasis on the liftoff height and blowout of diffusion flames issuing from triangular and rectangular nozzles. In addition, the effect of a quarl, which is an extension of the nozzle exit cross section, is also investigated to determine its impact on the stability of diffusion flames.

2 Experimental Set-up

The burner consists of a central fuel nozzle surrounded by an annulus of swirling or non-swirling airflow. However, in this study no co-flow is employed. To ensure a well-developed gasflow in the pipe, the ratio of the length to diameter of the fuel pipe, *L/D*, is taken equal 150. The central nozzle, which is about 47 mm long and attaches to the gas pipe, is interchangeable where three nozzles with different geometries are tested in the present study (e.g. circular nozzle with contraction, rectangular and triangular). The gas pipe is used to convey either methane fuel to the nozzle for combustion studies or air for the cold jet flow measurement. The pipe nozzle has a

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diameter of 4.45 mm while the circular contracted nozzle has a diameter of 4.81 mm. The asymmetric nozzles have an identical equivalent diameter, D_e, (i.e the diameter of a round slot with the same exit area as the geometry in question) nozzle exit area. The rectangular nozzle has an aspect ratio of 2 (D_e = 4.71 with an exit area of 5.9×2.95 mm^2) whereas the equilateral triangle has an aspect ratio of 1 (D_e = 4.46 mm). It is important to mention that the gas velocities quoted in this study are averaged velocities based on readings from the gas flowmeters (i.e. rotameters) and the cross-sectional area at the burner exit. These rotameters have a very high accuracy (i.e. 0.5 % full scale). The jet flame liftoff is imaged by using a high-speed camera having a resolution of 1280 × 1024 pixel. A frequency of 60 Hz is employed for imaging flame liftoff at jet velocities beyond 40 m/s and a frequency of 30 Hz for flames having an exit velocity below 40 m/s. For each experiment, a total of about 1630 images are taken to determine the liftoff height for each test condition. Note that the relatively high number of images is chosen to statistically improve the accuracy of the fluctuating flame liftoff height. A ruler is first placed over the burner in order to calculate the height of a pixel. The height of each flame is measured from the nozzle exit plane. A MATLAB code is developed to analyse the images and hencedetermine the flame base, which is based on the brightness of each pixel, as well as the number of pixels between the nozzle exit and the flame base. A threshold is applied to separate the background from the real flame image. The MATLAB code assigns each pixel a brightness level from 0 to 256 with 0 being black and 256 being white. The number of pixels is then multiplied by the pixel height to determine the liftoff height. The imaging error is calculated by photographing a solid object of known height. The maximum error is found to be less than 2%. Two different burner arrangements/configurations are tested. One configuration has a quartz quarl mounted at the tip of the nozzle, and another burner configuration in which the quarl is taken off the nozzle. The quarl used in this study is a hollow cylindrical pipe made from quartz with an inner diameter of about 12 mm and a length above the nozzle exit that extends to about 12 mm. This arrangement is used to assess the effect of quarl on the liftoff height and blow out velocity of a turbulent jet flame issuing from a pipe or a non-symmetric nozzle.

3 Results

This section presents some sample results of the liftoff for turbulent methane jet flames in still air environment. Four different nozzles with and without quarl are tested, which are a pipe, a contracted pipe, a rectangular, and a triangular nozzle. These results are intended to show the effect of nozzle geometry (i.e. asymmetry and quarl) on the liftoff height, as well as the flame blow out limits.

Figure 1 shows the liftoff height of the four nozzles tested in this study. Note that the results presented in Figure 1 are for the nozzle configuration without a quarl. Figure 1 shows that, in general, the liftoff height of a jet flame increases with the exit velocity in accordance with the findings of Kalghatgi [1]. The current results for the pipe show a reasonably good agreement with those of Kalghatgi's data [1], which are also plotted in this figure. However, for the assymmetric nozzles the results shown in Figure 1 exhibit two distinct regions. In the region for which U < 40 m/s, the rectangular nozzle's liftoff height is higher than that of the triangular nozzle. This is the same region where the liftoff height of the asymmetric nozzles ceases to follow the straight line trend as a function of the exit velocity, U, as predicted by Kalgatgi's [1] correlation, but rather exihibits a change as U becomes high than 40 m/s, which is the second region. The cold flow results, which are not presented here, show that there are two different rates of entrainment and spreading that take place for the two regions. For example, at 30 m/s, which falls into the first region, there is less entrainment and spreading than at 65 m/s (i.e. which corresponds to the second region). Consequently, it appears this difference is what is responsible for a gradual reduction in liftoff height when the jet velocity increases from 40 m/s to 45 m/s.Nevertheless, the same figure shows clearly that overall the asymmetric nozzles' liftoff heights are much lower than that of their axisymmetric counterparts. Indeed, the rectangular nozzle has overall the lowest lift-off height, followed by the triangular and finally the contracted circular nozzle. The circular nozzle (with contraction), however, has a very similar liftoff height compared to the pipe, which is in good agreement with the findings of [1]. Finally, though not explicitly shown in the figure, there is a better flame stability exhibited by the asymmetrical nozzles. While the flame blows off for the pipe at 71 m/s, the asymmetric and contracted circular nozzles' flame still exists much beyond this velocity. The blow off velocity is approximately 89, 75, and 89 m/s for the rectangular, triangular, and contracted circular nozzles, respectively.

The effect of quarl is presented in Figure 2. It can be seen from this figure and Figure 1 that the presence of quarl reduces the liftoff height considerably. In addition, Figure 2 shows that the evolution of the lift-off height versus the exit velocity remains linear for all the nozzles tested. This indicates better stability for the quarl configuration when compared to that without quarl. One interesting observation in Figure 2 is that the liftoff height for the contracted cicrular nozzle is lower than that of the pipe. Moreover, the blowout velocity for the quarl configuration is significantly increased where the blow off velocity is 78.5, 99, 122, 95 m/s for the pipe, contracted pipe, rectangular and triangular nozzles, respectively. The reduced liftoff height and increased blowout velocity arises as a result of the improved entrainment engendered by the presence of quarl, thereby, causing better mixing properties and consequently improved combustion.

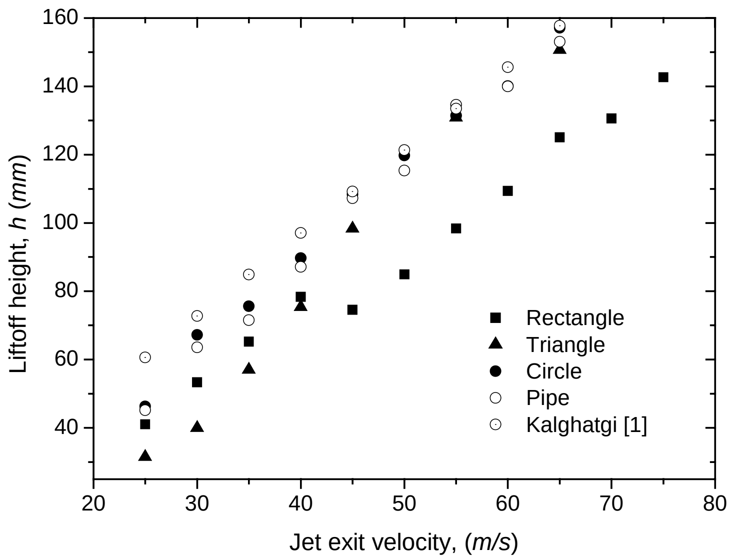

Figure 1. Turbulent jet methane flame's liftoff height for different nozzle geometries without quarl

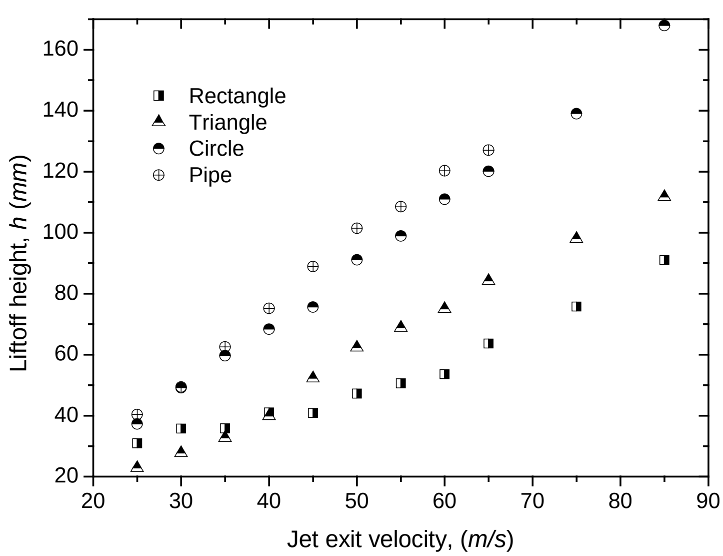

Figure 2. Turbulent jet methane flame's liftoff height for different nozzle geometries with the presence of quarl

4 Concluding Remarks

The major findings of the present study are that

- Asymmetric nozzles seem to enhance fluid entrainment which tends to stabilize better the flame, and
- The flame stability is further increased considerably when the quarl configuration is used. The latter reduces the flame liftoff height and enlarges the velocity range within which the flame could exist. The extent of the increase in entrainment by the use of quarl is substantial.

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References

[1] G.T. Kalghatgi GT (1984). Lift-Off Heights and Visible Flame Lengths of Vertical Turbulent Jet Diffusion Flames in Still Air. Comb. Sci. and Techno. 4: 17-29.

[2] Coats CM, Zhao H (1989). Transition and Stability of Turbulent Jet Diffusion Flames. Proceedings of the Combustion Institute 22: 685-692.

[3] Mi J, Nathan GJ, Luxton RE (2000). Cenetreline Mixing Characteristics of Jets from Nine Differently Shaped Nozzles. Exp. Fluids 28: 93-94.

[4] Quinn WR (2005). Measurements in the Near Flow Field of an Isosceles Triangular Free Jet. Exp. Fluids 39: 111-126.

[5] Zaman KBMQ (1999). Spreading Characteristics of Compressed Jets From Nozzles of Various Geometries. J. Fluid Mech. 383: 197-228.

[6] Gutmark E, Schadow KC, Wilson KJ (1991). Subsonic and Supersonic Combustion Using Noncircular Injectors. Journal of Propulsion and Power 27 (2): 240-249.

[7] Gutmark E, Schadow KC, Wilson KJ (1989). Noncircular Jet Dynamics in Supersonic Combustion. Journal of Propulsion and Power 5(5): 529-533.

[8] Gutmark E, Schadow KC, Parr TP, Hanson-Parr DM, Wilson KJ (1989). Noncircular Jets in Combustion Systems, Exp. Fluids 7: 248-258.

[9] Gollahalli SR, Khanna T, Prabhu N (1992). Diffusion Flames of Gas Jets Issued from Circular and Elliptic Nozzles. Comb. Sci. Techno. 86: 267-288.