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Experimental investigation on effects of central air jet on the bluff-body stabilized premixed methane-air flame

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Abstract

Flame stabilized by a bluff-body is a common scene in many engineering applications due to the enhanced mixing characteristics, improved flame stability, and ease of combustion control. We recently designed a burner which has a conical bluff body with a central air injector. In the current work, effects of the central air jet on the heat load of the bluff body, the flame structures and the flame blowoff limits were investigated. It was found that the central air jet can significantly reduce the heat load to the bluff body. It is a considerable solution to the problem caused by the high heat load in practical applications. The flame structures and blowout limits were altered with the addition of central air jet as well. Different blowout behaviors caused by the air jet were observed and reported. The bluff-body could be cooled down by the center air injection but then it seems not to stabilize the flame any more.

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Keywords: Blow off; bluff-body; flame structures; premixed combustion.

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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, heat recovery steam generators, and industrial furnaces [1]. Bluff-body flame holder is a commonly employed practical methodology to stabilize the flame due to the enhanced mixing characteristics as well as the ease of combustion control. The recirculation of hot gas behind a bluff-body can help to reignite gas mixtures, and thus stabilize the flame [2].

Bluff-body stabilized premixed flame has been investigated in a number of seminal works by Zukoski [3],[4], Longwell [5],[6], Wright [7] and Pan [8]. The main focus of the bluff-body stabilized premixed flame was the blowoff mechanism or lean flame stabilization limits of the flame holder. Lefebvre et al. [9] summarized the effects of inlet air temperature, pressure, velocity, turbulence and bluff-body geometry on the lean blowoff performance of bluff-body flame holders supplied with homogeneous mixtures of gaseous propane and air. Moreover, Shanbhogue et al. [10] reviewed the dynamics of two-dimensional bluff-body stabilized flames and described the phenomenon of the blowoff process in the bluff-body. Chaudhuri et al. [11] claimed that the bluff-body stabilized flames had the features of a centrally piloted flame, with much of the outer flow remaining unburnt at low equivalence ratios. Chaudhuri et al. [12] also investigated the blowoff dynamic of bluff body stabilized turbulent premixed flame and illustrated the hypothesis for flame blowoff mechanism. A change of flame shape between conical and columnar shapes was also observed with the changing of equivalence ratio of the premixed fuel-air mixture. The unstable flame behavior (local extinction and re-ignition) near blowoff was recorded and presented as well. Fan et al. [13] claimed that the heat loss to the confinement wall have a negligible effect on the flame blowoff limits in the bluff-body stabilized micro-combustor. Additionally, Fan et al. [14] also concluded that solid materials of the bluff-body with relatively low thermal conductivity and emissivity were beneficial to obtain a large blowoff limit.

Usually the bluff-body used to stabilize the premixed flame is a simple solid cone or solid plate with different geometries. Whereas thebluff-body with a central jet is commonly employed to stabilize a diffusion flame. Roquemore et al. [15] tested the behavior of reacting and non-reacting flows in an axisymmetric bluff-body burner. Illustration of the time-averaged flow field of a bluff-body with a central jet from [15] is shown in Fig.1. The flow field downstream of the bluff-body was determined by the ratio of the annular and central jet velocities. Caetano et al. [16] presented three different flame types in the bluff-body flame holder in their experimental work and concluded that combustion presented a weak influence on the averaged velocity field. Based on the change of the central jet to annular air velocity ratio and the corresponding flow structures, Esquiva-Dano et al. [17] summarized six different regimes of non-premixed bluff-body stabilized flames. Tang et al. [18] investigated the effects of the Reynolds number of both central fuel and annular air jet on the flame structures and its dynamics. They concluded that the central fuel jet Reynolds number mostly determines the flame extinction phenomenon while the annular air Reynolds number influences the flame structures more.

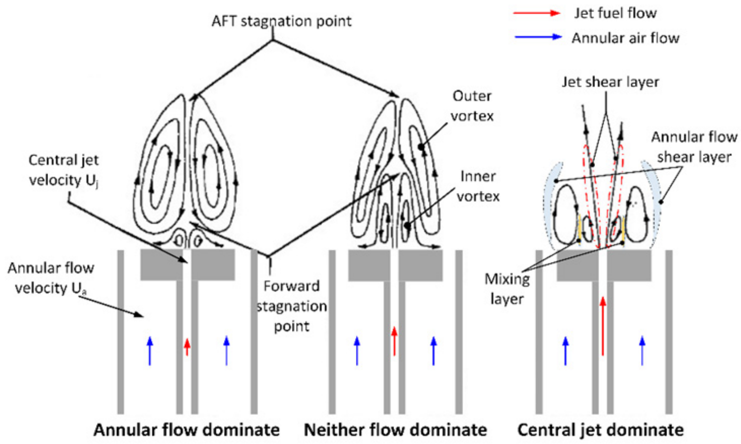


Fig.1. Illustration of the time-averaged flow field of a bluff-body with a central jet (reproduced from [15])

To the author's best knowledge, there is a limited amount of researches focused on the heat load to the bluff-body. Nishimura et al. [19] utilized a fine wire thermocouple to study the temperature fluctuations of the diffusion flame in a bluff-body burner. The temperature distribution along the axial line of the burner including the bluff-body surface was presented. But their focus was the interaction of the unstable flame and thermal structures. Euler et al. [20][21] measured the bluff-body surface temperature of the Cambridge/Sandia Stratified Swirl Burner using laser induced phosphor thermometry. Different premixed and stratification cases with/without swirl were tested. They found that the overall operation of the burner was adiabatic since the radiative and convective heat transfer by the bluff-body amounted to less than 0.5% of the thermal input from the combustion. They also mentioned that there were few measurements of the flame holder's temperature distribution whereas that temperature had a strong effect on the flame stabilization. In fact, in practical applications in Gas Turbine combustor, the challenge of the bluff-body is the sever heat load and extremely high temperature of the bluff-body surface. Temperature distributions along the surface of the bluff-body are important to the combustion system's lifetime [22]. Some practical methodologies to ease the heat load to the bluff-body surface are needed. But little effort has been made to understand the influence of the central jet on the bluff-body surface temperature and the premixed flame stabilization. In this paper, the effects of central air jet on the bluff-body stabilized premixed methane-air flame is investigated. Emphasis is made on the bluff-body surface temperature, flame structures, flame blowoff features and their interactions.

2. Experimental setup and methods

2.1. Experimental setup

The experimental setup and the bluff-body burner are schematically shown in Fig. 2. The burner is an annular channel with a 45 deg conical bluff-body located in the center. The inner diameter of the circular pipe for the premixed annular methane-air flow is 30 mm. The removable stainless steel bluff-body has a top diameter of 14 mm and an inner diameter of 4mm. The thickness of the central pipe wall is 2 mm. Premixed methane-air is fed into the annular channel while pure air is injected through the central pipe. A ceramic honeycomb is mounted in the annular channel to form a uniform annular flow and avoid flashback of the annular premixed flame.

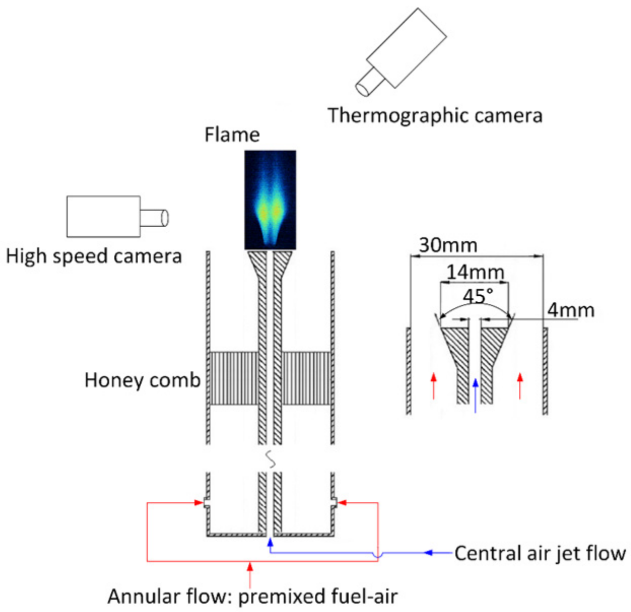


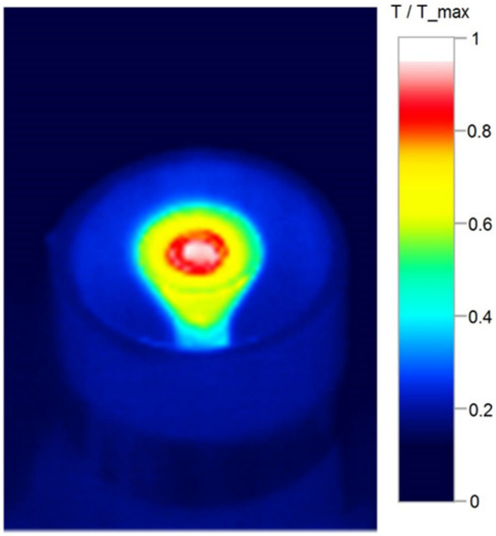
Fig. 2. Schematic of the experimental setup

Two Bronkhorst mass flow controllers are utilized to control the mass flow rates of the central air jet and the annular fuel flow. An Alicat (MCR 125) mass flow controller is employed to control the mass flow rate of the annular air flow rate. The mass flow rate controlled by Bronkhorst mass flow controllers are calibrated at 300 K with an uncertainty of 1%. The bulk velocity of the main premixed annular flow ranges from 1.85 to 2.77 m/s (Re-annular ranges from 1960 to 2940), and the equivalence ratio is set between Ø-annular = 0.64 to blowoff limit. The velocity of the central air jet ranges from 0 to 29 m/s (Re-jet <7690). The experiments are carried out without confinement in the atmosphere condition.

2.2. Methods

A high speed photography technique and a thermographic camera are adopted to study the flame structures and the temperature distribution of the bluff-body surface respectively. A high speed CMOS camera (Vision Research Phantom V611) with a resolution of 800×1280 pixels and a depth of 12 bit is utilized to record the full band chemiluminescence from the flame. Since the chemiluminescence from the flame varies with the equivalence ratio of the annular flow, the frame recording rate is set between 200 to 800 frames per second (fps) based on the signal intensity to freeze the unstable dynamics of the flame. Digital image process is fulfilled based on the DaVis (v.8.1.4) software and Matlab. Time averages and root mean square (RMS) values of the broad band flame chemiluminescence are used to evaluate the flame structure and its instabilities.

An infrared thermographic camera (Testo 881-3) is used to record the temperature distribution of the bluff-body surface. The burner is not confined which makes the recording of the temperature of the bluff-body surface practical and reliable. The thermographic camera is placed above the burner as shown in Fig. 2 The thermographic camera can record both infrared image (as shown in Fig. 3) and real image simultaneously with a spatial resolution of 160×120 pixels and 640×480 pixels respectively. The camera can measure the temperature ranged from 253 to 823 K, while the reading error for the measured temperature within 273 to 623 K is less than 2%. In order to obtain a thermodynamic equilibrium of the bluff body, the flame is maintained stable at least 10minutes and the maximum temperature showed in the thermographic camera stays constant at least 3 minutes. After this, the annular fuel is shut down and the temperature is recorded at a selected point as shown in Fig. 4.



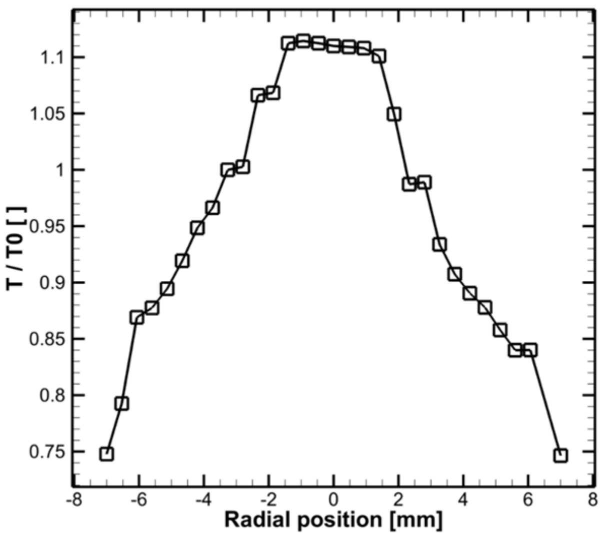


Fig. 3. Typical infrared image (left) and temperature distribution along the radius direction (right)

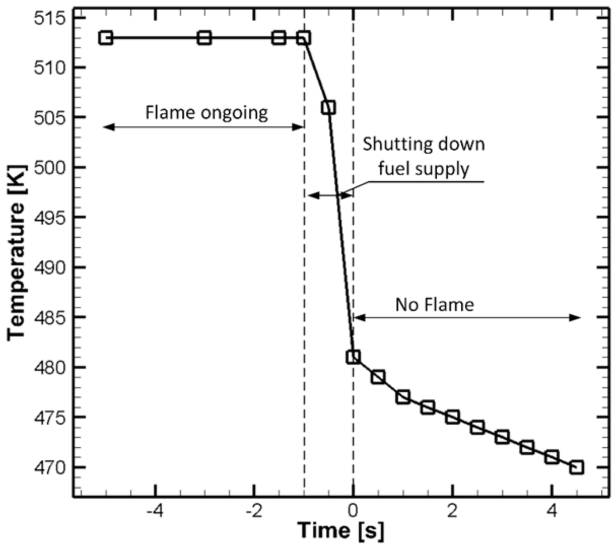


Fig. 4. Typical temperature changes of T_{apex} when shutting down the fuel supply

The same as presented in the literature [20], the temperature distribution peaks in the center of the bluff-body. But in the current study, the high temperature in the radial position -2<r<2 mm is caused by the reflection of infrared light from the curved inner wall of the injection hole. So here in the paper, temperature data in the center injection hole is ignored as noise. The temperature at the apex of the injection hole is selected and analyzed as the representative temperature T_{apex}. Based on data from [23], the emissivity (ε) of stainless steel type 301 is within the range of 0.54 to 0.63. Here ε = 0.58 is set as the emissivity of the bluff-body. Setting ε = 0.58, the annular flow equivalence ratio ∅-annular=0.64, U-annular = 2.77 m/s and U-jet = 0, the temperature at the apex of the bluff-body surface is approximately 480 K, which is referred as T_0 as the base case in this paper. In order to minimize the error caused by the selecting of the emissivity of the material, the ratio of local temperature to T_0 under different experimental cases is used to evaluate the temperature variances caused by the injection of central jet. The error of the temperature ratio caused by selecting the emissivity from 0.54 to 0.63 is within 2%. Fig. 3 also shows the distribution of the ratio of local temperature to T_0 along the radius direction at the bluff-body surface.

Since the flame could radiate infrared light and effect the result, the temperature is recorded continually since the flame is ongoing till manually shut down the fuel supply and flame is totally quenched. The recording rate of the temperature is 2 Hz. During that procedure, a typical temperature change of T_{apex} versus time is shown in Fig. 4. With the shutdown of the fuel supply, the temperature drops down and the gradient is sharp at first because of the weak flame remained attached to the bluff-body. This weak flame is the reaction of the fuel that is remained downstream of the mass flow controller in the annular channel. When the effect of the flame is totally vanished the surface temperature changes slowly with time due to the heat convection of the bluff-body to the environment. The temperature decreases with a rate of less than 4 K/s. So here we selected the temperature distribution of the bluff-body surface at time within 1 s after the flame is totally quenched. The error caused by the recording time is within 2%.

3. Results and discussion

3.1. Bluff-body Surface Temperature

Experiments reported here are performed holding the premixed annular flow velocity U-annular = 2.77 m/s and equivalence ratio ∅-annular = 0.64, while changing U-jet/U-annular = 0~8.8. The temperature of the inner apex of the bluff-body surface varies with the injection of the central air jet, as shown in Fig. 5.

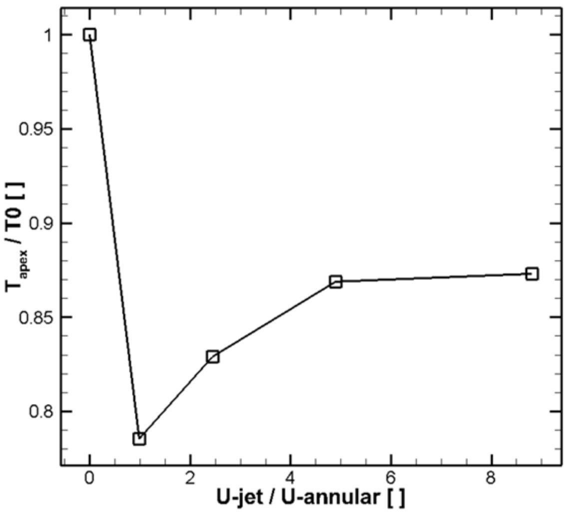


Fig. 5. Effects of central air jet on the temperature of bluff-body surface

It can be observed in Fig. 5 that with a small amount injection of the central air jet, the temperature of the bluff-body surface drops to less than 80% of T_0. But an increase of the central air flow makes the temperature ratio returns back to approximately 87%. The peak cooling effect caused by the central air jet (with U-jet/U-annular $\approx$ 1) may be explained by the local flow structures dominated by the annular flow near the bluff-body. With a small amount of central air jet, a fresh air layer is formed above the bluff-body surface preventing the heat convection from the flame to the bluff-body. The burnt product also gets separated by the cold air layer from the bluff-body. With the increase of central air mass flow rate, the cooling effect gets weaker due to the change of the flow field to neither flow dominate as shown in Fig. 1. When the flow field is central jet dominated, increasing the central jet mass flow rate does not significantly change the heat load to the bluff-body surface.

Just taking the temperature of the bluff-body surface into consideration, the central injection of air is a practical method to reduce the heat load to the bluff-body. But there are some drawbacks caused by the central jet in the bluff-body flame holder and they will be discussed later.

3.2. Flame Structures

With the injection of the central air jet, the flame structures changes. Effects of central air jet on the annular flame structures are shown in Fig. 6 holding U-annular = 1.85 m/s and Ø-annular = 0.64. The averaged and RMS of flame structures for different test conditions are shown in Fig. 6.

It can be observed from Fig. 6 that without the injection of the central air jet, the heat release zone on the center line downstream of the bluff-body. With the injection of the central air jet, the main heat release zone gets separated by the central air jet and the flame can be observed to be attached to the outer apex of the bluff-body. Similar to the findings presented in [12], the stronger luminous signal is found in the annular flow shear layer. However, different from [12], the non-luminous recirculation zone is believed to be filled with fresh cold air from the central jet. An increase of the mass flow rate of the central air jet makes the flame shorter and the open angle narrower due to the strong shear stress of the central jet. The flame becomes weaker and the size of the heat release zone becomes smaller with the addition of central air jet because of the overall leaner condition of the flame. This could be the reason for the lower temperature of the bluff-body with central air jet than T_0. The lowest temperature with U-jet/U-annular~1 in Fig. 5 (left) may be caused by the flow field which is dominated by the annular flow with small velocity ratios of U-jet/U-annular [15]. As shown in Fig. 1, when the annular flow dominates the recirculation zones downstream of the bluff-body, the small amount of central air jet may form a protection layer (with the locally extremely lean condition) to avoid the flame getting attached to the bluff-body. Moreover, the cold central air jet layer could reduce the heat convection of combusted products to the bluff-body.

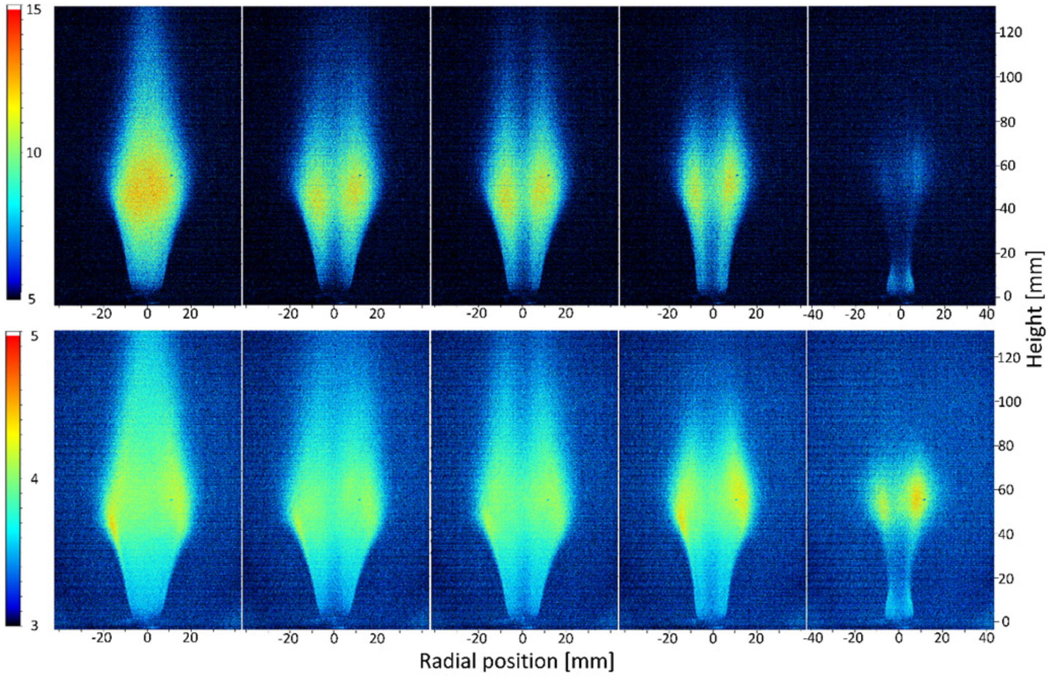


Fig. 6. Averaged (upper row) and RMS (lower row) images of the flame with conditions of U-jet /U-annular = 0, 0.79, 3.94, 7.87 and 13.22 (from left to right)

The flame neck, which is formed by the strong shear stress of the central jet, shows up with a large mass flow rate of the central air jet as shown in Fig. 6. When the mass flow rate of the central air exceeds a critical value, the flame is split into two parts by the high strain rate at the flame neck and this type of flame is called a split-flashing flame [18]. The upstream part of the flame is stable and called flame root, while the downstream part is highly unstable with local extinction and re-ignition. Increasing the central air jet further, the flame cannot get reignited in the downstream region and just maintains in the flame root attached to the bluff-body. The unstable flame behavior for U-jet/U-annular = 13.22 is shown in Fig. 7 with the recording rate of 200 fps (lower recording rate is due to the weak chemiluminescence). The unstable flame extinction and re-ignition behaviors are also observed in some other studies about bluff-body stabilize diffusion flames as reported in literatures [12] and [18]. In the literature [18], the maximum strain rate is found in the neck zone which makes the flame get split. The locally fuel lean condition and high strain rate (which is higher than the critical flame strain rate) are believed to be the reasons for the extinction downstream of the flame neck. The movements of the flame segments downstream are influenced by flame propagation, buoyancy and the bulk flow [18]. The flame root which is attached to the bluff-body acting like a pilot supplies the heat and radical sources to reignite the fresh fuel-air mixture downstream of the flame neck. The flame root is stabilized by the recirculation zone formed by the bluff-body and is not affected by the downstream unstable flame condition. The separated weak flame segments are generated from the flame root and after passing through the neck region they expand and fade out gradually before being extinguished. Moreover, the luminance intensity in the cross section vertical of the burner (r=3mm) could be used to represent the flame feature in each frame [18]. Data for flame lasting for the whole recording period is shown in Fig. 8. The stable flame root region, neck region and flashing region could also be seen in Fig. 8. It could be found that the flame root is stable which maintained in the whole recording period. The flame neck split the flame into two parts while the flame brush distributed in the downstream region occupied almost half of the recording period. The speed of the flame segments downstream could be estimated approximately from the slope of the oblique bright bands (which mark the evolution of the flame segments downstream) [18]. The speed of the isolated flame segments is approximately 1.1 m/s which is lower than the annular bulk velocity.

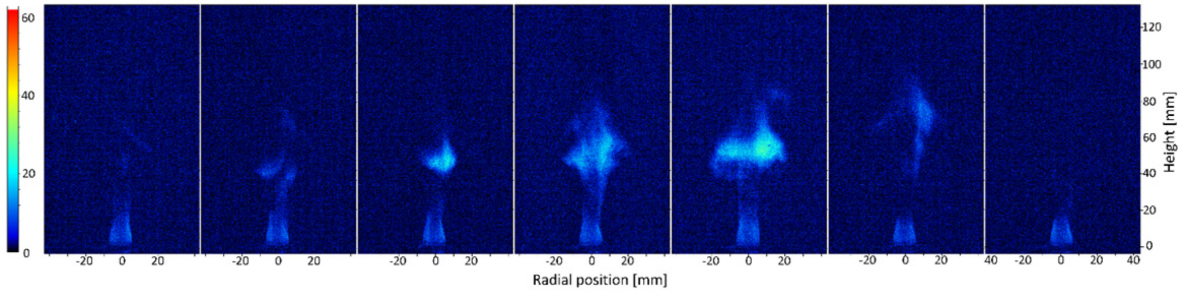


Fig. 7. Split-flashing flame instability near blowoff

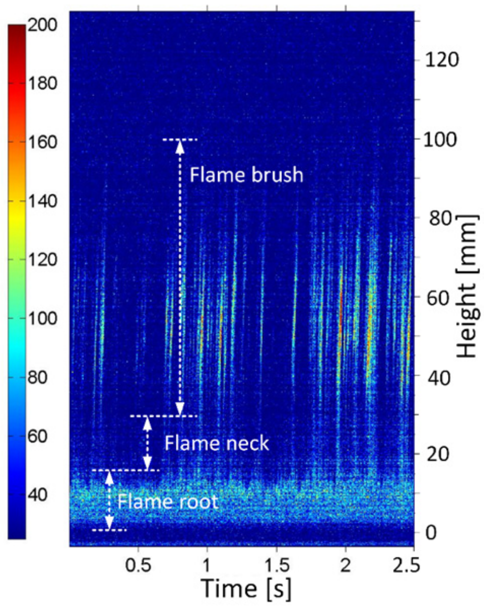


Fig. 8. Schematic of paths of flame segment for split-flashing flame

3.3. Flame Blowoff

Flame blowoff limit is another important feature to evaluate the performance of the bluff-body stabilized flame. The blowoff limits are the annular flow equivalence ratios at which the flame becomes visualized absence. Flame blowoff limits results under the condition of keeping annular mixture flow velocity U-annular ≈ 1.85m/s are summarized in Fig. 9. The flame blowoff limit was obtained by reducing the annular fuel flow rate from a stable flame condition (i.e. Ø-annular = 0.64) till the flame gets vanished. During the operation procedure of reducing the annular fuel flow by steps of 0.04 SLPM, the mass flow rate of the annular air and central jet are kept constant. At each step of varying the fuel flow rate, the fuel flow rate is kept constant for at least 3 minutes in order to achieve a thermal equilibrium.

It could be found from Fig. 9 that with the addition of the central air jet, overall the flame blowoff limit increases. That is the main drawback caused by the injection of the central air jet. The increasing of flame blowoff limit at the beginning may be also caused by the annular dominated flow structure as shown in Fig. 1. The central air jet formed a protection layer for the bluff-body and the size of the recirculation zone is small when the annular flow dominates the flow field. They in all makes the flame detached from the bluff-body and easy to blowoff. Increasing the mass flow rate of the central air jet further, the flame blowoff limit decreases. It could be explained by the alteration of the flow structures from annular flow dominated to neither jet dominated condition (as shown in Fig.1). Under conditions when neither jet dominates, the flame may get reattached to the bluff-body's outer apex. Increasing the central air jet velocity further, flame blowoff limits get increased almost linearly.

There are two different blowoff phenomenon observed during the experiments. When U-jet/U-annular < 5.5, the flame blowoff occurs without the appearance of the split-flashing flame. But when U-jet/U-annular > 5.5, reducing the equivalence ratio from the stable flame condition (i.e. $\emptyset$-annular = 0.64), the split-flashing flame (as shown in Fig. 70) shows up prior to flame blowoff. Further reducing the equivalence ratio, firstly the flame brush downstream of the flame neck gets totally extinct and could not be reignited, while the flame root keeps stabilized and maintained by the bluff-body. A little further reduction of equivalence ratio makes the flame root blowoff totally. As discussed above, the local flame extinction and re-ignition may be caused by the high local strain rate. With the increasing of the central air jet, the local strain rate of the flame brush gets higher and much easier to cause local extinction and blowoff.

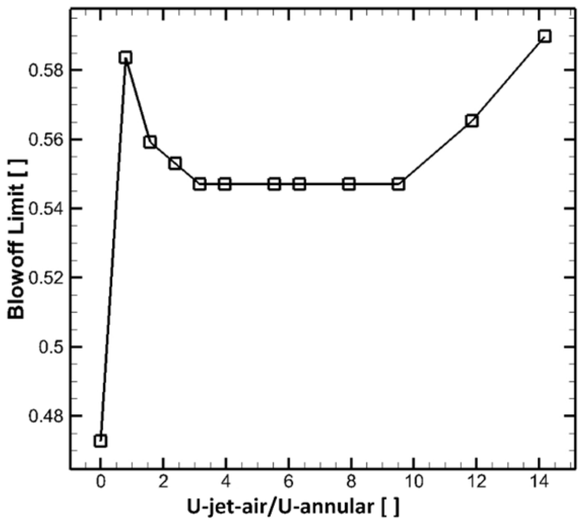


Fig. 9. Effects of central air jet on flame blowoff limits

4. Conclusions

Effects of central air jet on bluff-body stabilized flame are studied experimentally in the paper. The temperature of the bluff-body surface, flame structures and blowoff features are analyzed using the thermographic camera and high speed camera respectively. It is observed that the injection of central air jet eases the heat load to the bluff-body surface. But the injection of the air jet makes the flame more unstable. The central air jet causes the flame easier to blowoff. Two different blowoff phenomenon (with/without local quenching and re-ignition) are observed and presented. More detailed investigation of the flow structures and interactions of central jet and the annular flame need to be studied.

Acknowledgements

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