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EXPERIMENTAL INVESTIGATION ON EFFECTS OF BLUFF-BODY SIZE AND AXIAL AIR INJECTION ON BLOWOFF LIMITS IN SWIRL BURNERS

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Abstract

The stability limits of swirl combustors have been considered as a crucial factor for obtaining a wide stability operation map. The present global consideration is towards using low-carbon emission fuel in gas turbine production sector and, many other combustion systems. However, the demands of introducing low-carbon emission fuels impose a considerable modification in the combustor hardware; consequently, the variation of burner stability operation map. Blowoff and flashback are two parameters that determined the margins of stability operation in swirl burners, when correlated with equivalence ratio and inlet tangential or bulk velocity. This study investigates the effect of hardware modification with different bluff-body sizes (external diameter) and flow-field manipulation like using axial air injection on blow-off limits in swirl combustors. The first part of this study has demonstrated that variation of bluff-body diameter alters the blowoff limits significantly. Small central injector (bluff-body) diameter displaces blowoff limits towards leaner equivalence ratios with (Φ= 4 to 4.2); which is favourable for low emission demands. However, the stability map became narrower regarding inlet tangential velocities with (w=2.7 to 4.2), consequently reducing output power. In contrast, bigger injector diameter leads to having blowoff limits occur at a wider range in term of inlet tangential velocity(w=2.5-4.5) which means high output power, despite slight displacement to the rich region, Φ= 0.5 at high tangential velocity. The second part of this work has proposed, a new technique that can replace hardware (bluff-body) by axial air-jets which can simulate the physical shape of bluff-body. Using axial air jets results in wider operation map, the inlet tangential velocity range is (w=2-8 m/s) compare with bluff-body case (w=2.5-4.5 m/s), hence increasing the burner output power while keeping its size. The position of air-jet opening inside burner plenum alter blowoff limits, baseline L_o=0 and L_o=150 extend the range of inlet tangential velocity at which the blowoff occurs, almost (2-8 m/s). While the other three positions revealed less range of inlet tangential velocities, as the affected by aerodynamic perturbations arise from the clash between axial jets and inlet tangential flow.

Keywords: Blowoff, Axial air-jets, Bluff-body, Premixed swirling flames.

1. Introduction

The concerns about keeping or reducing the pollution level in the atmosphere imposed strict emission regulations on the energy production market. Thus, most of the OEMs (Original Equipment Manufacturer) has been putting significant efforts to meet environmentally friendly requirements that set out by either local governments or international organizations. Almost all combustion systems, primarily that operated on fossil fuel are needed to fulfil low emission standards. Gas turbines are receiving special attention among other combustion systems due to their contribution to the energy market. Introducing alternative fuels that produce lower harmful pollutants require intensive consideration to employ such fuels safely in gas turbines with the achievement of optimum performance and output power. The combustor is an essential part of gas turbines that needs to be investigated in this context.

The broad stability operation map is one of the main factors that address the perfect performance of modern gas turbines combustor. Fulfilment of this target requires considerable modification of system hardware and careful flow field manipulation of the premixed mixture are considered as crucial factors. However, any of the variations mentioned above must take into consideration many operational factors, such as quality of mixing, flame length, uniformity of fuel distribution, temperature distribution, flame dynamics and flame attachment [1- 4]. Bluff-bodies, central fuel injectors and solid obstacles are considered as the traditional technique for flame anchoring and hence downstream static stabilisation of swirling flames [5-9]. They can also be employed for supplementary firing in some industrial burners [10-12].

The fundamental function of central bodies is physically anchoring premixed flames, it can also affect the downstream combustion process. The contact between the bluff-body, fresh mixture and combustible mixture can play an important rule regarding heat exchanging between the flame and the bluff-body itself, consequently the characteristics of the coherent structure, density ratio, pressure distribution and blockage ratio [4, 13-15]. Thus bluff-bodies governing blowoff limits physically represented by flow-field manipulating and chemically through heat transfer with combustion mixture. Many studies have investigated both effects, many studies about employment bluff-bodies for flame stabilisation requirements have been carried out [16-21].

The geometry and position of the bluff-body govern the shape and position of the shear layer [22]. Nair and Lieuwen [19] investigated the effect of the bluff-body on flow field characteristics. They realised that flame near to the cylindrical bluff-body mounted at the middle of the burner reveals high vorticity magnitudes, so higher fluid mechanics stretch. This factor links directly to flame extinction, hence blowoff mechanism. This factor has also previously explained by Yamaguchi et al. [23]. Chaudhuri and Cetegen [20] studied the characteristics of bluff-body stabilized conical premixed flames. They have found a gradual narrowing of the flame cone before blowing off. They also observed that the lean fuel region of the outer flow cannot sustain the combustion process. Shanbhogue et al. [10] further proposed blowoff mechanism with using bluff- bodies. They stated that it occurs in multiple steps; in the beginning, there was local extinction alongside the flame sheet, then large-scale wake disruption and finally flame blew off.

Although the considerable efforts had done to achieve the best employment of the bluff-bodies for flame stabilization demands with combustion systems used premixed swirling flames. However, there are still many issues associated with this technique; for instance, introducing high hydrogen-containing fuel characterized by high flame speed and temperature. It shifts the stability operation map of the burner towards the lean region to avoid potential risks like an explosion. Additionally, most bluff-bodies are subjected continuously to a harsh environment due to direct contact with flame. Therefore, the formation of soot and NO_x emission, consequently, increase maintenance cost of life degradation [11, 24, 25]. Moreover, in industrial swirl burners bluff-bodies also used for injecting diffusive fuel. It can reduce the quality of mixing accompanied by a significant increase of pollutants. This mode of combustion is strongly conflicted with ever-growing public demands for lowering greenhouse emissions. Hence, all these issues impose performing more investigations either by hardware modification or flow field manipulating.

Still, there is a lack of entire understanding of the relationship between blowoff mechanism and bluff-body geometry. This relation governs by physical parameters, such as the bluff-body size or factors that influence fluid mechanics. Therefore, it worthy of investigating the effect of such parameters, it is useful to find an alternative mechanism for flame holding and stabilisation to replace the hardware (bluff-body) by another technique. This alternate technique can perform the same function, while keeping a low level of emission with a reduced maintenance cost of combustors.

The present work consists of two methods of investigations; the first part of this study is a continuation exploring of the effect of bluff-body geometry representing by the outside diameter central fuel injectors on blow-off limits. The second part explores the difference in a blow-off mechanism and its limits when using axial air jets for simulating bluff-bodies virtually in swirl burners.

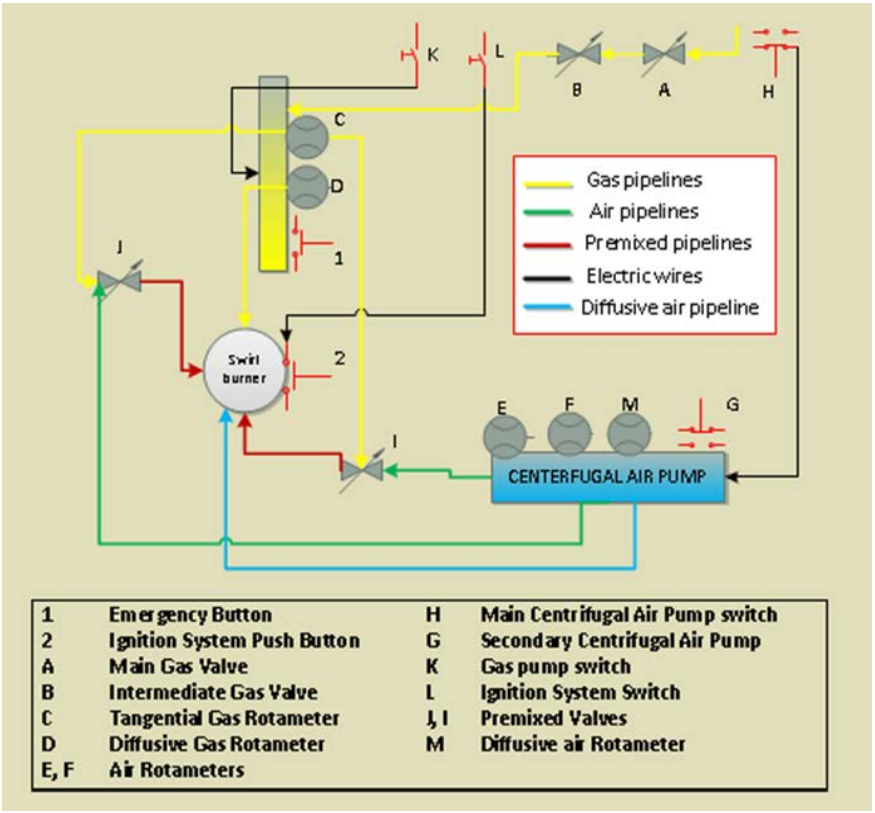
2. Experimental Setup

The testing rig was consisted of tangential swirl burner (150 kW, maximum output thermal power), gas rotameters, air rotameters, gas valves, air valves and LDA system. Figure 1(a) shows the testing rig and Fig. 1(b) illustrates the arrangement of the testing rig during the experiments.

The tangential swirl burner is illustrated in Figure 2. Some studies have already used this burner to investigate different flame characteristics [24, 26, 27]. In this burner, there are two tangential inlets, inlet diameter (*ID*) is 67 mm for each, opening inside the plenum, while the exit diameter is 76 mm, to change the inlet diameter of the inlets, different inserts have been used, while different nozzle configurations have been used to vary the exit diameter. As different swirl numbers can be achieved from 0.9-3.6 and a low swirl number (0.9) was used in current study.

The Laser Doppler Anemometry (LDA) Dantec system was used to measure the instantaneous vorticity magnitude downstream the burner mouth, this system is one component flow light and working on backscatter mode.

(a) Testing rig.



(b) Illustrates the arrangement of the testing rig during the experiments.

Fig. 1. Experimental setup.

The calibration uncertainty of this system is 0.067%. The measurements method was implemented based on introducing seeding particles (Aluminum Oxide AL_3O_2 of size ~ 10 μm) to the flow downstream burner mouth. LDA detected these particles (measuring points), and the average 10,000 measuring points was used in this study.

In the first part of this study, the burner baseplate was utilised to allow different diameters of central fuel injector (bluff-body). In this study six bluff-body (central fuel injector) of different outside diameter 7,12.5,16,19,21, and 23 mm have been tested. The results presented in this study are based on just three injectors (12.5,21 and 23 mm) as they reveal the most pronounce difference regarding blowoff limits.

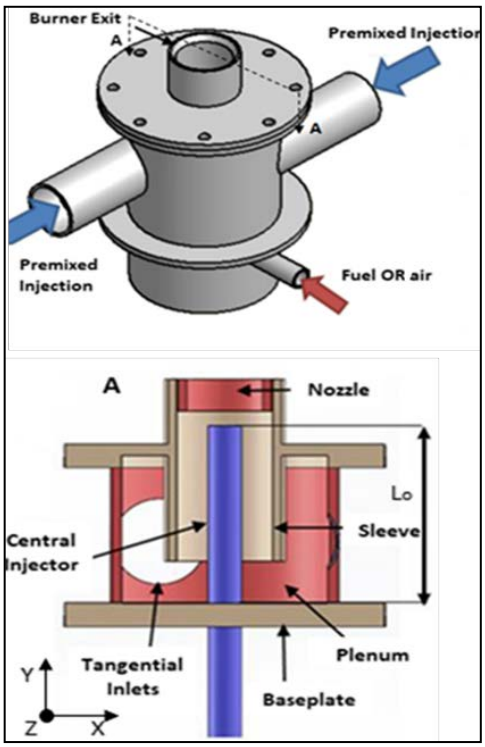


Fig. 2. Tangential swirl burner.

In the second part of this study, another baseplate was used to allows axial injection of air jets. The design enabled axial air jets repositioning in the vertical direction at different L_o positions.

All experiments were implemented under atmospheric conditions without air preheating and natural gas (90% methane) was used as fuel. A centrifugal fan was used for feeding the system via flexible hoses with two banks of rotameters to control the flow rate. There was one bank for fuel injection control. The readings errors were ~3% for both air and gas flowmeters. The ranging of flow rate for different operation conditions was from (Reynold number) *Re*~10500 to 30,000.

The following two modes of fuel injection were used.

- Premixed mode at the entrance of the tangential inlets of the burner.

- Diffusive mode via the central injector (this mode just for start-up).

The overall equivalence ratio (Φ) that considers tangential and central flow rates were controlled by decreasing/increasing the airflow in the blend while keeping a constant fuel flow rate.

The following equations were used to determine the equivalence ratio of all testing conditions.

$$\Phi = \frac{FAR_{act}}{FAR_{st}} \tag{1}$$

where FAR_{st} is the stoichiometric fuel to air ratio. This ratio can be determined according to the equation of the chemical reaction.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{2}$$

Based on the calculation of the molecular weight of the reactants (methane and oxygen) and by considering that oxygen ratio in the air which is almost (23.2%) and assume stoichiometric combustion (the condition for complete combustion). Burning 1 kg of methane requires 17.2 kgs of air. Thus, the stoichiometric fuel to air ratio is:

$$FAR_{st} = \frac{1}{17.2} = 0.058 \tag{3}$$

Actual fuel to air ratio is calculated by measuring the mass flow rates of fuel and air according to the following equation:

$$FAR_{act} = \frac{\dot{m}_{fuel}}{\dot{m}_{air}} \tag{4}$$

where the mass flow rate is calculated by measuring the volume flow rate directly from rotameters, thus equivalence ratio can be determined for each flow rate. It is worth mentioning here that in the case of using axial air jets, the amount of air is determined for the total air mass flow rate, the tangential and axial.

The inlet tangential velocity is determined according to the continuity equation depending on the total mass flow rate of the mixture and the entire area of tangential inlets of the swirl burner.

3. Results and Discussion

3.1. Effect of bluff-body size

Blowoff limits of three central fuel injectors size (diameter) have been determined. A dimensionless parameter λ which represent the ratio between the bluff-body diameter and the nozzle inside diameter, has been used for the analysis. Table 1 denotes various λ values.

Table 1. Various λ values

Bluff-body diameter(mm)	λ (Bluff-body diameter/Nozzle inside diameter)
12.5	0.205
21	0.345
23	0.378

As in previous studies, the mean velocities of fuel-air mixtures feed through the tangential inlets have been used for representing results [24, 26]. Thus, allowing a fair comparison between cases regardless variation in *Re* at burner exit arises with different bluff-body diameter. Moreover, depicting data based on the correlation of inlet tangential velocity with equivalence ratio (Φ) ease comparison other swirl burners regardless of their size or power.

To determine the blowoff limit for each case, stable operation was achieved. Then inlet tangential fuel was reduced until the flame is eventually blowing off. This procedure was repeated for flow rates until obtaining all blowoff limits. Then the measurements were repeated for other bluff-bodies. Figure 3 illustrates the blow-off limits of the three bluff-bodies. As can be seen, small values of λ (0.205) results in leaner operation region of the burner (Φ=4 to 4.2), which is favourable to meet low emission requirements. The inlet tangential velocity range was narrow (w=2.7 to 4.2 m/s) which reduced output power of the burner.

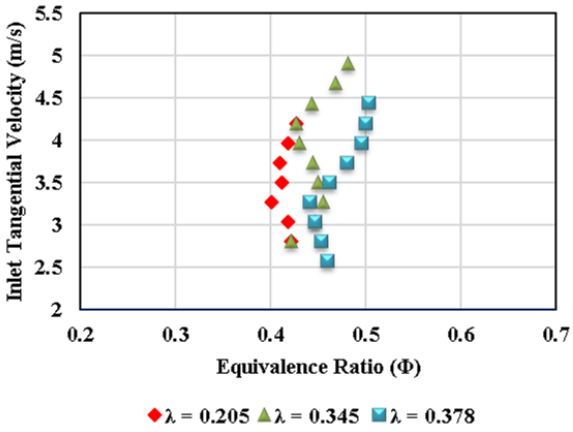


Fig. 3. Effect of bluff-body diameter on blow-off limits.

Increasing λ (0.345) produces a significant raise in the range of burner operation regarding inlet tangential velocity (w=2.7 to 4.5 m/s). However, there is a noticeable fluctuation of equivalence ratio values from Φ= 0.42 to 0.49. This variation is not desirable in terms of stable operation demands of gas turbine combustors.

Further increase of λ (0.378) results in a steady growth of inlet tangential velocity values (w=2.5-3.5 m/s) at almost constant equivalence ratio, Φ= 0.45. Then, the inlet velocity values increase linearly with equivalence ratio values Φ= 0.45-05, before it is showing a steady increase from w=4 m/s to 4.5 m/s at constant Φ= 0.5. The third type of bluff-body (λ =0.378) seems reveal the best performance, as it achieves a wider operation region regarding inlet tangential velocity with less equivalence fluctuation. Although increasing λ (outside diameter of the bluff-body) moves blow-off curves to the rich region. It leads to a considerable extending of the stable operation in terms of inlet tangential velocity. Having a wider operation region is interesting for high power operation or fuel switching demands as provide in [28].

The reason behind this difference in blowoff limits is explained here. For a small size bluff-body, the flame is shifted downstream towards low-velocity region upon decreasing equivalence ratio to the global limits, to maintain a kinematic

balance between the upstream fresh mixture velocity and flame speed. The repositioning of the flame leads to overlapping of the flame edge with shear layer vortices and high strain field and so higher stretch rate along the flame edge which consolidates the local extinction conditions, hence early blowoff.

Conversely, the flame can maintain the equilibrium with upcoming flow velocity in the further upstream position with increasing bluff-body diameter. Hence, flame edges became less affected by shear layer vortices, as a result, reduce local extinction, consequently, blowoff limits delay to higher inlet tangential velocities.

3.2. Effect of axial air injection

Introducing axial air injection to simulate bluff-body for stabilizing premixed swirling flames can control the position of the CRZ and other swirl coherent structures. Hence it can govern the blowoff limits considerably. However, the ratio of axial air injection to the total mass flow is crucial in this context; a higher flow rate could lead to avoiding swirl strength deterioration and lack of mixing. Thus, based on the previous study [24], the ratio of axial air jet of the total mass flow rate (3-10%) was used in this study. Figure 4 illustrates the differences in blow-off limits between bluff-body (central fuel injector) and axial air injection. Axial air injection extends blow-off limits to higher inlet tangential velocities (w=2-8 m/s) at constant equivalence ratio (Φ=0.53. It extends the inlet tangential velocity almost three times compare the bluff-body case, (w=2.5-4.5 m/s). This significant variation in blow-off mechanism is important, especially for industrial applications required increasing burner power while keeping constant (Φ).

The effect of axial air jet was noticeable when considering the significant variation of vorticity magnitude downstream nozzle exit and around shear layers. Figure 5 illustrates the vorticity magnitude measured by the LDA system and depicted using Tecplot 360 EX 2015. Introducing axal air jets into swirling flow, produces a smooth variation of vorticity magnitude between shear layer regions and the central recirculation zone (CRZ). Thus, it reduces the possibility of local extinction and flame stretch rate that can lead to an early blowoff when reducing the equivalence ratio.

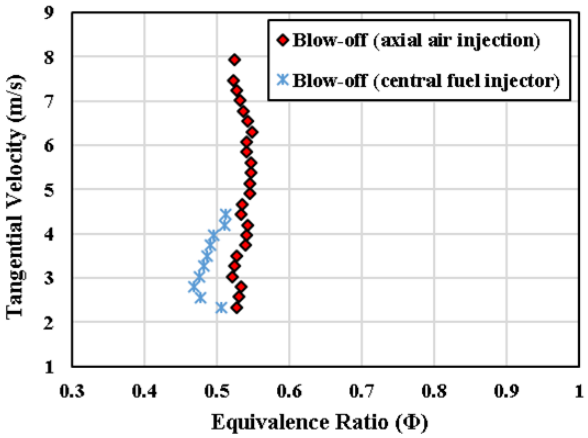


Fig. 4. Effects of axial air injection on blow-off limits compare with the bluff-body.

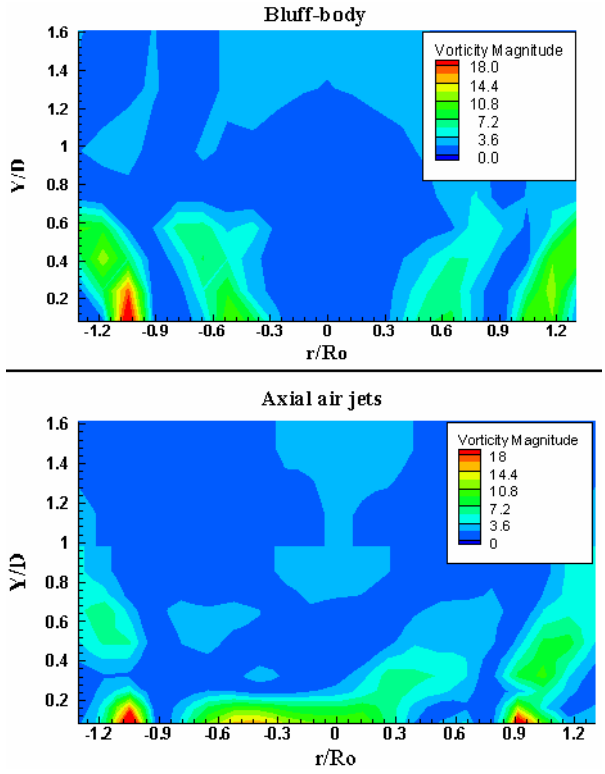


Fig. 5. LDA measurements depicted using Tecplot 360 EX 2015 R1, the differences in vorticity magnitude between bluff-body and axial air jets.

Moreover, it seems that the dilution of swirling flame downstream due to air-jet govern the density jump, and baroclinicity attenuates that can initiate shear layer roll-up, consequently local instability around CRZ [20]. Figure 6 illustrates the effect of air injection on the local mixture dilution and interaction between the CRZ and shear layers, Fig. 6(a) represents the case of swirling combustion without axial jets (no dilution) and Fig. 6(b) depicts the case when an axial air jet is introduced to swirling flame, the dilution of swirling flames is obvious.

It can also conclude that heat loss from the flame to the air jet results in flame anchoring slightly downstream than that of the bluff-body case. Which, in turn, lowering vorticity dilatation in the upstream region and allow the flame to withstand in higher flow strain closer to the shear layer [13].

Air injection position inside burner plenum for tangential inlets of the swirl burner can alter the blow-off limits. Five vertical positions (L_o=0, 29, 75, 110 and 150 mm) of air-jet have been investigated. Figure 7 shows the effect, for the baseline case L_o=0 mm, all blowoff limits were recorded at equivalence ratio Φ~0.53, with a good range of inlet tangential velocity w=2.8-8 m/s. However stable operation for low flow rates at this position is difficult to achieve due to aerodynamic perturbations arise between air jet and tangential flow rate.

The next three positions, L_o=29, 75 and 110 mm, the effect of aerodynamic turbulence became more obvious, leading to a reduction in the range of inlet

tangential velocity w=2.5-7 m/s accompanied with a noticeable fluctuation of equivalence ratio values. For L_o=150 mm, the air jet became coherent at this position and less affected by turbulence, consequently, reveal wide range of inlet tangential velocity values w=1.9-8 m/s.

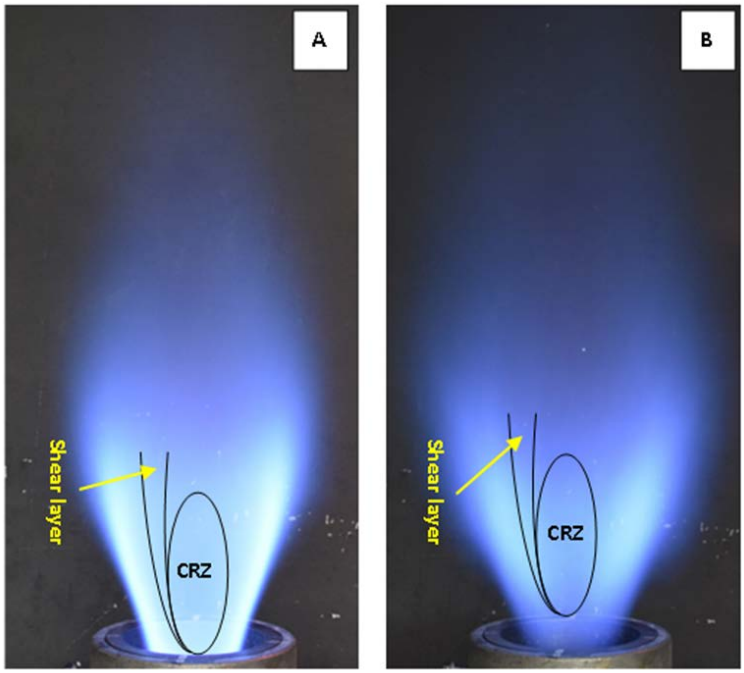


Fig. 6. Effect of axial air jets on the local mixture dilution and interaction between CRZ and shear layers (a) without axial air jets no dilution; and (b) with axial air jets produces dilution of flame. Images were taken by Nikon D7200.

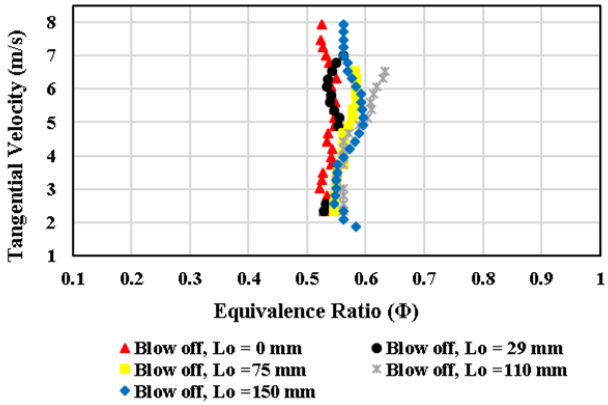


Fig. 7. Effect of air injection position on blow-off limits.

Thus, this position is considered as the optimum blow-off limits in terms of wide stability operation margin, although some fluctuation of equivalence ratio values at moderate inlet tangential velocity values w=4.5-6.

4. Conclusions

This study provides an experimental approach to study the effect of bluff-body size and axial air jets on blow-off limits in premixed swirling flames. The first part of this study revealed that the outside diameter of cylindrical bluff-body could considerably alter blow-off limits. Small size bluff-body (λ =0.205) moves blow-off limits to the leaner region with (Φ=4 to 4.2); the stability map became narrower regarding inlet tangential velocities with (w=2.7 to 4.2), in other words, limited burner output power. Moderate bluff-body size (λ = 0.345) can increase the range of inlet tangential velocity range, almost 1 m/s higher than small size and it reveals a considerable fluctuation in terms of equivalence ratio values. Bigger bluff-body diameter (λ=0.378) produces the optimum operation, a reasonable range of inlet tangential velocity values (w=2.5-3.5) accompanied with an almost steady increase of equivalence in the range of (Φ=2.5-4.5).

The second part of this work reveals that axial air jets can be employed successfully in swirl burners to simulate bluff-body physically, hence perform the flame holding and stabilization function. They can also control the flow field and flame-flow interaction by altering the characteristics of coherent structures downstream. Wider operation stability map revealed the feasibility of using this technique in industrial swirl combustors, and it seems a promising technique to enable combustion systems to be work with different blends, especially high hydrogen fuels. Axial air injection extends blow-off limits to higher inlet tangential velocities range of (w=2-8 m/s) at almost constant equivalence ratio (Φ=0.53), this range of inlet tangential velocity is almost three times compare the bluff-body case, (w=2.5-4.5 m/s).

The position of opening air-jet inside burner plenum plays important rule regarding stability operation map and can alter blowoff limits. The base-line case L_o=0 mm and L_o=150 mm revealed a wide range of inlet tangential velocity. Nevertheless, for the base-line case, it is pretty difficult to achieve stable operation at a low flow rate (low inlet tangential velocities) due to subjected to turbulence arise from the clash between air-jet and tangential flow rate. Conversely, the turbulence effect is not pronounced for L_o=150 mm position, as it opens slightly far from the turbulence perturbations region, hence it is considered as the optimum case. Other three positions show a narrower range of inlet tangential velocity with an equivalence ratio fluctuation, the reason behind that is at these positions air jet is opened at regions closer to tangential inlets of the burner; hence they are affected by high aerodynamic perturbations at this region.

Nomenclatures

D	The nozzle inside diameter, mm
ID	Internal diameter of tangential inlets, mm
L_0	Injector positions mm
$\dot{m}_{air}$	Air mass flowrate, kg/s
$\dot{m}_{fuel}$	Fuel mass flow rate, kg/s
w	Inlet tangential velocity, m/s
Y	Vertical distance downstream burner exit, mm

Greek Symbols

Φ	Equivalence ratio
λ	The ratio between bluff-body diameter and nozzle inside diameter

Abbreviations	
CRZ	Central recirculation zone
LDA	Laser Doppler Anemometry
LPM	Litter per minute

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