Experimental and numerical investigation of the effect of diffusive air injection on turbulence generation and flashback propensity in swirl combustors

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Abstract

Combustion instabilities are considered one of the most serious challenges for developing combustion systems through the years. Undesirable issues linked to these phenomena represent a risk for such systems especially in gas turbines and propulsion devices where the propagation of these instabilities can even lead to considerable damages. Flame flashback from the combustion chamber into premixer represents one of the most important combustion instability issue in swirl combustors used in gas turbines.

This study proposes an experimental and numerical approach to validate the use of a central air injection in swirl combustors to reduce flame flashback propensity via controlling the turbulence generation at the tip of the flame while pushing the CRZ, thus retarding the appearance of the CIVB, to mitigate the progression of combustion into the system. Results showed the potential of this technique to affect turbulence generation and pushing back the flame into the combustion chamber, increasing operability limits. Very good agreement was achieved between experimental and numerical results, demonstrating that the use of injection through the central core of the system not only controls the position of the recirculation zone but also affects turbulence and mitigates other forms of flame flashback.

Introduction

The public efforts towards mitigating the greenhouse gases emission such as NO_x and CO is increasing. Recently, Paris agreements emphasized on holding the increases in the global temperature which is one of the consequences of high pollutant emissions. Thus to achieve this target more developments in combustion systems are needed and urgent. Employment of lean premixed combustion in gas turbines has proven a successful technology that can achieve low-level emission and economic power generation. Nevertheless, this technology has some drawbacks with the combustion system becoming prone to flame flashback due to the existence of fuel-oxidizer mixtures upstream of the stable flame position [1, 2].

Swirl combustors are the dominant combustion technology in gas turbines due to their flame stabilisation capabilities over a wide range of equivalence ratios thanks to the formation of coherent structures, especially the well-known central recirculation zone CRZ which promotes the flame stability downstream the burner mouth by producing low or negative axial velocity regions and hence enabling flame local speed to match the local flow velocity, consequently anchoring the flame [3-5]. However, such combustors are frequently subjected to different combustion instabilities upstream the flame, producing phenomena such as flashback propagation from the stable flame position in the combustion chamber towards the premixing zone. One mechanism of propagation is through the Combustion Induced Vortex Breakdown CIVB, which is considered a fast acting flashback mechanism that appears in swirl burners as a consequence of the formation of the CRZ [6, 7]. Another mechanism that increases flashback trends is the appearance of highly turbulent combustion zones as a consequence of fuel properties, flow turbulence and other barely understood phenomena [8, 9]. These instabilities occur even when the incombustible mixture velocity is higher than the flame speed. Thus they can have dramatic consequences when high turbulent flame speed fuels such as those based on highly hydrogenated blends are used [3, 10].

Swirling flows are characterized by high complex phenomena because they are three-dimensional time dependent structures. Therefore the flow field manipulation, especially at the interaction region with the upstream flow field and the burner geometry, is of high importance in controlling flame stability downstream the burner nozzle. Previously, many studies investigated flame flashback mechanisms in swirl combustors and they suggested many techniques to mitigate flame flashback, either by doing some geometrical enhancement or by promoting flow field patterns. Flame flashback due to combustion induced vortex breakdown (CIVB) received special attention amongst other flashback mechanisms since it is one of the prevailing flashback mechanisms in swirl combustors and represents an obstacle in developing combustion systems, especially those fed by high flame speed fuels such as high hydrogen blends [5, 11].

Central fuel injectors or bluff bodies proved their potential ability in anchoring CRZ downstream the burner nozzle and their considerable flame flashback resistance, especially against CIVB. However, despite the vitality of this flame stabilization technique, it cannot totally mitigate flame flashback [7]. Moreover, the existence of bluff bodies or central injectors in touch with high flame temperatures for long period of time could lead to material degradation and hence, increasing maintenance cost [2, 12].

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Thus, promoting the flow downstream the burner mouth, especially close to the region of contact of the central recalculation zone CRZ with fresh upcoming mixtures, was one of the successful techniques that can effectively tackle CIVB. This method of flow field manipulation is based on injecting either fuel or air diffusively through the center of the vortex core in order to change the defect of negative axial velocity and turbulence characteristics. Diffusive fuel injection has been used by [6, 13], they found that the strong and coherent axial jet can effectively push downstream the vortex breakdown, consequently eliminating the possibility of CIVB. Nevertheless, injecting fuel diffusively can increase NO_x emission levels and degrade the degree of mixing. Thus, using axial air injection instead seems to be more efficient in this context, it can perform the required flame stabilization, in addition, to avoiding increasing pollutants level. Recently axial air injection as flame stabilization technique has been investigated by Reichel, Terhaar and Paschereit [14] and Lewis, Valera-Medina, Marsh and Morris [15]. This area of study still needs further investigations, especially for the optimum amount and position of the axial air injection. Thus this study proposes some experimental and numerical analyses of the effect of axial air injection on flow field characteristics downstream the burner mouth, especially the turbulence profile, negative velocity defects and the axial velocity gradient inside the CRZ.

Experimental setup

A 150 kW tangential swirl burner used in this work is illustrated in Figure 1.

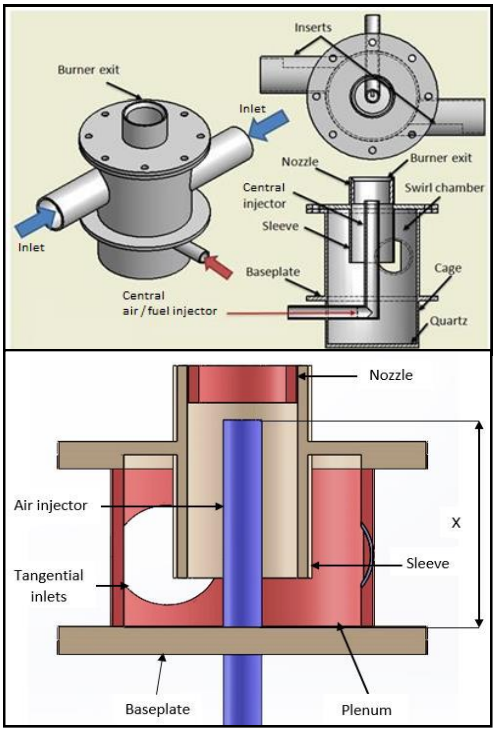


Figure 1. 150 kW tangential swirl burner

Other investigations on swirling flow stability have been undertaken previously using this combustion system [3, 16, 17]. The burner has two tangential inlets of 67 mm ID, the burner exit is 76 mm ID.

The diameter of tangential inlets can vary using different inserts, while the exit diameter can change using different nozzle configurations, thus it is possible to have variable geometric swirl number from 0.913 up to 3.65. However, in this work only a 0.913 swirl number has been used. The original base plate containing the fuel diffusive injector (Central injector), was replaced by a modified design that allowed axial air injection in addition to the fuel.

The air injector is fitted with an external screw inside a cylindrical pipe which is connected to the burner baseplate; this allows for vertical movement inside the burner plenum to give different positions (X) with respect to the tangential inlets.

Provisional tests revealed that it was difficult to obtain a stable swirl flame without the central fuel injector present, this was especially challenging when only air was injected into the central region. The absence of bluff body complicated the mechanism of flame anchoring and hence CRZ generation. A number of experiments were undertaken to obtain a suitable startup procedure to achieve a stable flame, eventually concluding that fuel must always be injected through the central injector at startup.

The instantaneous velocity components downstream the burner mouth has been measured by Laser Doppler Anemometry (LDA). The LDA system was one component Flowlight LDA (Dantec) operated at backscatter mode. The light source consists of an argon ion laser and the focal length of the lens was 500 mm. Aluminum oxide AL_3O_2 seeding was used in the experiments with a particle size of approximately less than 10μm. Velocity measurements have been done at three different levels downstream the burner damp plane. The system is connected to a PC to gather and analyze data via Dantec software.

Numerical approach

One-dimensional LDA measurements of axial velocity and hence turbulence intensity values can provide a good prediction of flow behaviour in both cold and combustion cases. However, three-dimensional characterisation is still required and important to emphasize the highly complex coherent structures of the swirling flow and the interaction between its elements. A lot of researchers and companies around the globe benefit from the use of CFD software in the design and developments of their products. ANSYS FLUENT 17.2 code has been used to simulate the cold swirl flow in the 150 kW tangential swirl burner. It is a computational fluid dynamics (CFD) code which involves broad physical modelling abilities and permits simulating problems of varying difficulty such as heat transfer, fluid flow, turbulence, and reactions within the computational models creating by users. The turbulent flows which occur in the opposite limit of high Reynolds numbers are characterized by large, almost random fluctuations in velocity and pressure in both space and time. These variations result from instabilities that finally are dissipated (into heat) viscosity effect. The popular turbulence models are the k-ε or the k-ω models which simplify the dilemma to the solution of two further transport equations and launch an Eddy-Viscosity (turbulent viscosity) to estimate the Reynolds Stresses. In this paper, k-ε turbulent models are performed to illustrate the turbulent flow behaviour. A very fine structured mesh was used. The total number of nodes of the grid used is 11,117,541 with elements 10,985,610 and minimum skewness of 0.3305726. Independency mesh analyses were performed to examine the mesh sensitivity using some experimental data for validation. Figure 4 illustrates the computational domain, the physical model, the generated mesh, and the axial velocity contour for the tangential swirl burner. The numerical approach has been conducted in parallel with an experimental campaign to investigate the effect of axial air injection on the three-dimensional swirl flow characteristics and correlate the three-dimensional results with one-dimensional experimental findings.

Results and discussion

The modified burner baseplate design allows the movement of a central air injector at different positions with respect to the base plate. However, in this study, just one position (X =150 mm) was used to investigate the effect of air injection downstream the burner mouth on the axial velocity and turbulence at different tangential flow rates. The amount of central air injection is crucial in obtaining flame stabilization, from one hand it should be strong and coherent enough to prevent upstream flame propagation, and on the other the ratio of axial to tangential injection must be kept as low as possible to avoid swirl strength deterioration. The geometric swirl number S_g mentioned in the experimental setup is determined based on burner geometry, inlet conditions and neglecting pressure variations [18]. Thus for isothermal conditions where density is assumed to be constant S_g can be defined according to the following equation [15]:

$$S_g = \frac{A_o * R_t}{A_t * R_o} \left(\frac{Q_{ta}}{Q_{to}}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where:

A_o is the nozzle burner area at the exit (m^2)
A_t is the area of tangential inlets (m^2)
R_t is the effective radius of the tangential inlets (m)
R_o is radius of burner nozzle exit (m)
Q_{ta} is tangential flow rate (m^3/s)
Q_{to} is total mass flow rate (m^3/s)

Thus, based on this equation when there is no axial air injection the total mass flow rate is the same of tangential, hence swirl number is 0.913. However, upon using axial air injection, swirl is reduced. Nevertheless, the minimum swirl number (at minimum tangential flow rate) is 0.75 which is still producing strong swirl coherent structures [4]. Based on preliminary tests it is found that the optimum amount of central air injection is (50 l/min), this ratio represents 3-10 % of the total mass flow rate at different inlet tangential flow rates.

Figure 2 illustrates the effect of axial air injection on the defect of axial velocity at the centre of vortex core, since the defect of the axial velocity is responsible for the generation of the vortex bubble at the tip of the recirculation zone, thus, injecting small portions of air diffusively can produce a positive flow velocity, consequently pushing up or totally preventing the CIVB conditions.

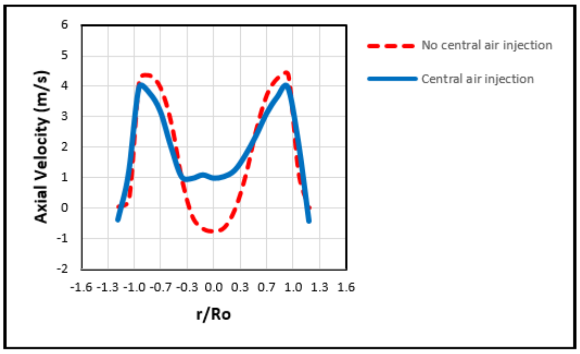


Figure 2. LDA results, effect of air injection on axial velocity downstream burner mouth (Y/D=0.0816)

The effect of axial air injection extends further downstream the nozzle exit damp plane. It considerably reduces the negative flow velocity values of the central recirculation zone or in other words pushes the CRZ downstream in such way that the vortex bubble is still slightly away from the nozzle exit plane, hence reducing the possibility of CIVB. Figure 3 shows the axial velocity magnitudes measured by LDA at different distances (Y/D) downstream the burner mouth, where Y is the axial distance downstream the burner nozzle and D is the nozzle exit diameter. It is clear that axial air injection can significantly affect axial velocity values downstream the nozzle. By comparing the negative flow velocity region with and without air injection, it is obvious that regions of negative velocity magnitude reduce when axial air injection is used.

However, this effect is just for a one-dimensional flow field, for axial velocity profiles. Three-dimensional verification is crucial in investigating this effect, as there is an increase of negativity in the CRZ close to the burner mouth. CFD results for three-dimensional swirl flow confirmed this effect too. Figure 4 shows how axial air injection pushes the CRZ downstream the burner mouth.

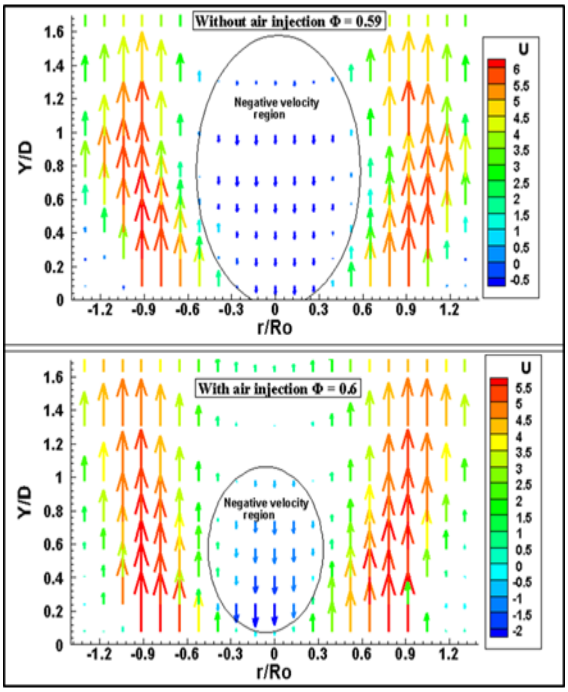
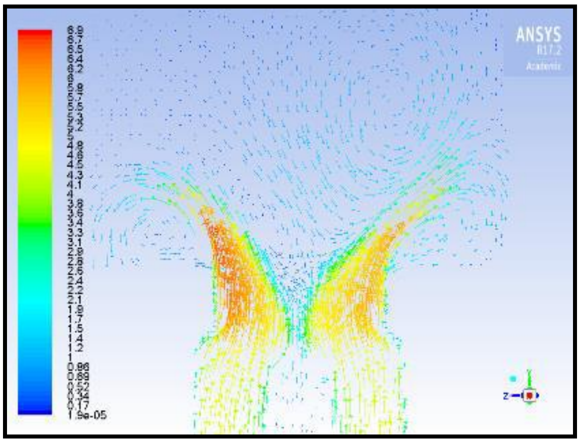
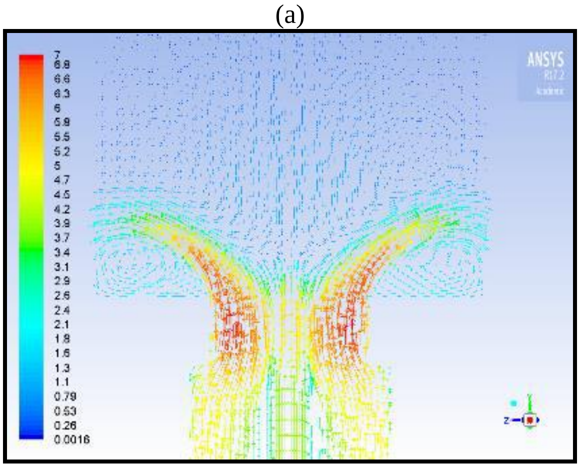


Figure 3. LDA results, effect of air injection on axial velocity magnitude downstream burner mouth at different distances (Y/D)



(a)



(b)

Figure 4. CFD results, (a) without air injection (b) with air injection, diffusive air injection pushes the CRZ downstream, consequently, prevent CIVB.

An interesting effect is that the negative velocity of the CRZ increases exactly at the bottom of collision point between the structure and the injected air. This shows that the recirculation zone is in effect a structure that is being compressed by both the surrounding pressure and the air injection.

Although decreasing negative velocity defects is important in maintaining stable flame downstream the burner mouth, moderate axial velocity gradients streamwise is also crucial in preventing upstream flame propagation [19]. Thus, since the axial air injection affects the axial velocity magnitude and the strength of the CRZ, it changes the velocity gradient in the axial direction.

Figure 5 shows the difference in axial velocity gradient at different positions (Y/D)) downstream the burner mouth inside the negative velocity region.

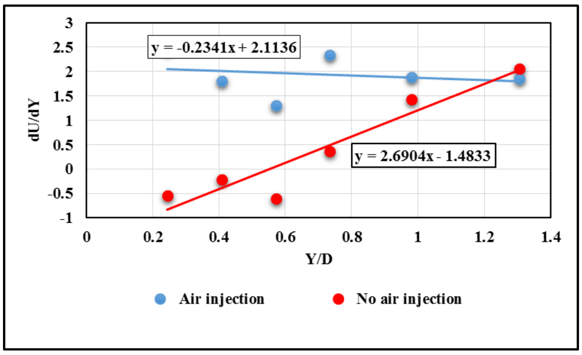


Figure 5. LDA results, variation of axial velocity gradient downstream burner mouth

It can be seen that introducing axial air injection considerably reduces the downstream velocity gradient along the burner axis.

This difference in velocity gradient downstream is of crucial effect on the upstream movement of the vortex breakdown. High velocity gradients (red line figure 5) mean that the vortex breakdown or CRZ can propagate faster which lead to a reduction of the time required for reaction at the tip of the recirculation bubble. This in turn reduce the heat generated at this region, hence decrease volume expansion, consequently producing negative vorticity values which lead finally to the onset the CIVB.

Contrary, when central air injection is used, lower downstream velocity gradients are observed which provide the conditions of balancing between volume expansion and baroclinic torque and keep positive azimuthal vorticity, consequently more resistance to CIVB can be achieved.

The change in velocity gradient has a direct impact on the values of axial velocity close to flashback conditions. Figure 6 shows the change in axial velocity of flame propagation when the equivalence ratio is increased from stable operation to that close to flashback conditions when no central air injection is used.

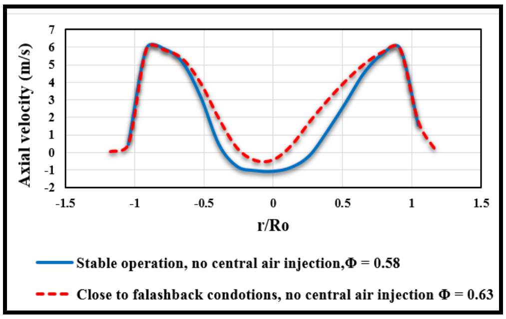


Figure 6. Change in axial velocity when equivalence ratio increased from stable to flash back conditions (no central air injection).

As can be seen from figure 6, axial velocity increase by 0.5 m/s close to flashback conditions. This increment in axial velocity reflects the change in turbulent velocity when moved from stable to flashback conditions.

However, upon using central air injection the change in axial velocity between stable and flashback conditions is much less acute than that when no air injection is used despite running at higher equivalence ratios. Figure 7 shows the difference in axial velocity values when moving from stable to flashback conditions when central air injection is used.

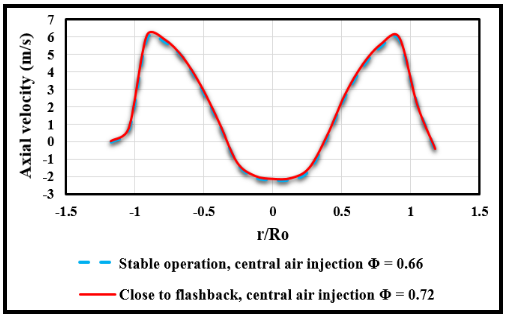


Figure 7. Change in axial velocity when equivalence ratio increased from stable to flash back conditions (with central air injection).

It appears from figures 6 and 7 that using central air injection can significantly change the axial velocity values and improve flashback, phenomenon caused by the reduction of the amount of axial velocity gradient with the reduction of turbulent flame speed even under flashback conditions.

Conclusions.

1. Using central air injection can significantly increase flame flashback resistance, it pushes the recirculating bubble and reduces the defect of axil velocity downstream the burner mouth.
2. The optimum amount of central air that can provide good flame stability whilst maintain appropriate swirl strength is 3-10% of the total mass flow rate, however, this amount can be varied according to burner size and configuration.
3. Velocity gradient downstream the burner mouth is a crucial factor in provoking flame flashback, this gradient can reduce considerably upon injecting air centrally, consequently the change of local axial velocity values hence turbulent flame speed when increasing equivalence ratio from stable to flashback conditions became less intense.

Acknowledgments

Fares Amer Hatem and Ali Safa Alsaegh gratefully acknowledges the receipt of a scholarship from the Iraqi Government and for the great assistance Malcolm Seaborne and Paul Malpas during the setup of the experiments.

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