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Visualisation of Turbulent Flows in a Swirl Burner under the effects of Axial Air Jets

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Abstract

Meeting emission regulations represents a real challenge in the power generation sector. Swirl combustors and their operation under lean premixed (LP) conditions are a step towards attaining low emissions, especially NOx formation, while ensuring high efficiency. However, performing modifications on combustors and reaching the requirements of efficient combustion systems is difficult due to many combustion problems such as extinction, low reaction rates, mild heat release, instabilities, and mixing issues. Thus, giving careful attention to the hydrodynamics design of the swirl burners with extensive testing methods in both experimental and numerical approaches is crucial to stabilise the combustion phenomena in gas turbines. As a result, this study employed the implementation of CFD simulations in the design of a 150 kW tangential swirl burner and considered the consequences of 50 LPM diffusive air injection at different positions on three-dimensional isothermal flow field characterizations, especially the turbulence, downstream the burner nozzle. Various mass flow rates from 600 to 1000 l/min were used at atmospheric conditions with a geometrical swirl number of 0.913. Experimental work was conducted with good correlation. It was found that using the air injection system could increase the flashback resistance by affecting the velocity defect downstream the burner nozzle. Moreover, the axial air jet reduces the flow field turbulence at the central recirculation zone (CRZ) tip and hence minimises the flow fluctuations and affect its size and position. CFD results show a very good agreement with Laser Doppler Anemometry (LDA) data acquired from the experimental work.

Keywords: CFD; ANSYS Fluent; swirl flow; gas turbine; diffusive air injection; flashback; Laser Doppler Anemometry.

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1. Introduction

Combustion involves severe impacts to the environment because of the pollutants it produces. Emission regulations and energy efficiency are of high interest due to associated issues of environmental pollution and energy consumption, respectively. As a result, the power generation sector has faced real challenges due to requirements to decrease combustion emissions. Combustion running under LP operation conditions can produce very low emissions due to low flame temperature and hence minimise NOx formation [1]. Also, LP combustion of hydrocarbons ensures the complete burnout of the fuel and reduces hydrocarbon and CO emissions [2]. On the other hand, using syngas instead of traditional fuels [3] or developing systems for hydrogen blends [4] are among the principal means of solving power generation challenges. However, the reliability of LP systems running on these blends is complicated as they operate close to the lean stability limit and are more sensitive to combustion instabilities. Swirl combustors represent the most significant improvements to the gas turbine combustion systems due to their flame stabilisation capabilities over a wide range of equivalence ratios. Frequently, they do not only improve combustion intensity by enhanced mixing and higher residence times while increasing the flame stabilisation thanks to the formation of coherent structures [5].

Combustion systems in gas turbines should be entirely designed and developed to meet many inconsistently essential design elements such as high combustion efficiency that are covering wide operating limits, low greenhouse gas emissions especially NOx, low lean flame stability limits, and low smoke. Many techniques can be used in developing conventional burner designs to ensure the stable operation of gas turbines and achieve fuel variability and flexibility. The first method is represented by developing the aerodynamics and hence the turbulence of the swirling flow field in the combustion chamber to wider the stability limit while the second is employing alternative fuels to reduce the combustion impact on the environment [6]. The flow turbulence is regularly altering the flame structure and affects the combustion process, hence affecting flame stabilities such as blowoff and flashback. Various mechanisms causing flashback were recognised in turbulent swirling flows such as flashback by autoignition, flashback in the boundary layer, turbulent flame propagation in the core flow, combustion instabilities leading to flashback and flashback induced by vortex breakdown [7]. Combustion Induced Vortex Breakdown (CIVB) flashback receives particular attention amongst other flashback mechanisms since it is one of the prevailing 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 [8]. Many techniques can effectively mitigate CIVB flashback mechanism and anchor CRZ downstream the burner nozzle either by doing some geometrical modifications or by raising flow field patterns. Firstly, the use of diffusive fuel injection can effectively push the vortex breakdown downstream and consequently eliminate the possibility of CIVB [9]. Secondly, bluff bodies can be implemented as stabilisers to the jet and swirling flow. However, these two vitality stabilisation techniques cannot completely tackle flame flashback. Moreover, using central fuel injectors could lead to increase of NOx emission levels and degrade the degree of mixing. On the other hand, the existence of bluff bodies or central injectors in touch with high-temperature flames for long times could lead to material degradation and hence increase in maintenance cost [10]. Thus, injecting air diffusively through the centre of the vortex core to change the defect of negative axial velocity and turbulence characteristics is another option to mitigate the CIVB flashback which seems to be more efficient in this context. It can perform the required flame stabilisation and avoid increasing pollutant levels. Recently axial air injection as flame stabilisation technique has been investigated by many researchers [11]. This area of study still needs further investigations, in particular for the optimum amount and position of the axial air injection.

Regarded to the numerical analysis, Reynolds Averaged Navier-Stokes equations (RANS) are originally used to describe the turbulent flow numerically and then employed to predict the properties of swirl flows due to its low computation cost and high reliability. The main point behind RANS is represented by the Reynolds decomposition, where the instantaneous quantity is decomposed into its time-averaged and fluctuating quantities [12]. Standard κ-ϵ equations have been assessed in a swirl or recirculating flows with great success [13]. Some works have also been conducted with other turbulence models with success [14]. Recently, large eddy simulation (LES) turbulence model, which resolves the eddies of the turbulence itself, has been used widely by several researchers to model swirling combustion dynamics. Consequently, it is the best CFD turbulence model to predict the 3D unsteady nature of the actual swirl flow in gas turbine combustors and the flame instabilities and it is more reliable than classic RANS models [8,15]. However, LES is more costly and needs advanced specifications for the computer hardware with much higher transient resolution. Therefore, in this study experimental and RANS based numerical results are presented and analysed to examine the effect of axial air injection on the isothermal flow field characteristics downstream the burner mouth, especially the turbulence profile and negative velocity defects within the CRZ.

2. Swirl burner and test conditions

Testing at Cardiff University's combustion laboratory took place to analyse the hydrodynamics effects of diffusive air jet on swirling flows. A previously designed 150 kW tangential swirl burner [2,15] has been re-developed to allow the positioning of an air injector of 21 mm outer diameter move vertically inside the plenum for different positions (X) with respect to the base plate as depicted in Fig. 1(a,b). Constant diffusive injection of 50 l/min air at atmospheric conditions via the central injection system was used for all swirling mass flow rates.

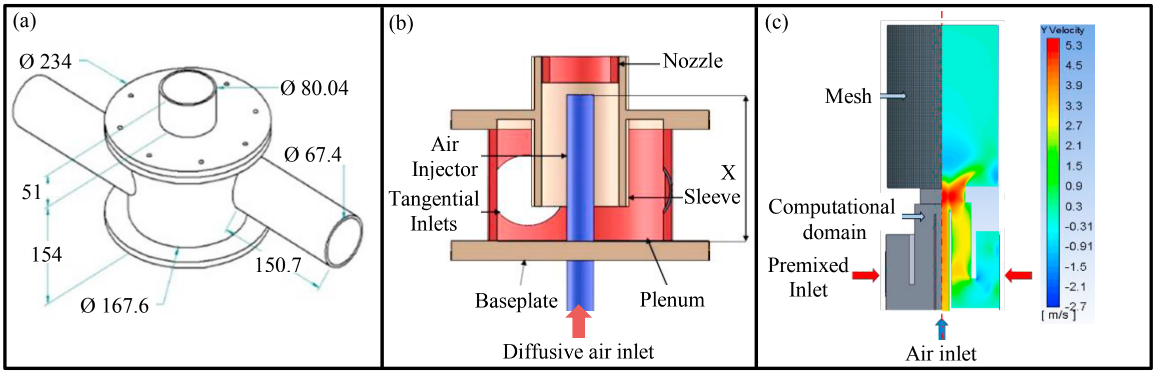

Fig. 1. (a) schematic of the burner (not-to-scale); (b) detailed view of the central injector; (c) computational domain and mesh quality.

Different tangential inlet flow rates were used in this study, i.e. 600, 800 and 1000 l/min. Pure methane open flames were tested in the experimental campaign at ambient conditions, while the isothermal flow modelling has been done to provide correlation with the cold flow experimental findings at the same test conditions in a three-dimensional format. One-dimensional LDA measurements of the instantaneous axial velocity and the turbulence intensity have been performed with a DANTEC Dynamics LDA system for both cases, isothermal and combustion conditions.

3. Modelling technique and mesh generation

The three-dimensional characterisation is still required and essential to emphasise the high complexity of the coherent structures of the swirl flow and the interaction between them. Turbulent combustion is the sequence of two interactions, turbulence and chemical reactions. If the flame is coupling with a turbulent flow effect, the reacting flow will be modified due to the dominant flow accelerations started by the heat released and the dramatic changes in the thermophysical properties, especially the viscosity. This interaction can develop the turbulence in the combustion process or diminish it in the flow field depending on burner configuration. The turbulent flow, which occurs at high Reynolds numbers, are characterised by random fluctuations in velocity and pressure in both space and time. It is therefore of great importance to set up a computational model, capable of capturing the main physical effects, that governs the hydrodynamics of the swirl flows. ANSYS Fluent 18 commercial code was used to simulate the isothermal swirl flow in the tangential swirl burner to study the effects of air injection on the swirl flow and to predict the turbulence change behind this effect. Popular turbulence models used to solve these conditions are the κ-ϵ or the κ-ω models which simplify the solution dilemma of two further transport equations while launching an eddy-viscosity (turbulent viscosity) constant to estimate Reynolds Stresses [16,17]. In this paper, κ-ϵ turbulent model was utilised to illustrate the turbulent flow behaviour in the tangential swirl burner under consideration. Care was taken to construct a high-quality mesh to choose high-order discretization schemes and a robust equation solver, and to ensure adequate convergence. A finely structured mesh was used and independence mesh analyses were performed to examine the mesh sensitivity using some experimental data for validation as see in Fig.1(c). As a result, the total number of nodes of the independent grid used is 11,117,541 with 10,985,610 elements. The Pressure-Implicit with Splitting of

Operators (PISO) pressure-velocity coupling scheme was employed as a solution method. Accurate results were achieved after the convergence was done with convergence criteria of 10^{-4}.

4. Results and discussion

Five planes were set out at the computational domain downstream the burner exit nozzle to calculate different unknown properties. These planes are P1=1mm, P2=5mm, P3=10 mm, P4=15 mm and P5=25 mm. As the first step of the numerical approach verification, Fig. 2 shows the CFD results of the axial velocity profile for 600 l/min tangential flow inlet at plane P2 without air injection and X=150 mm. The figure reveals an excellent agreement with the results using LDA measurements for isothermal swirl flow. Apparently, at the burner centerline, the axial velocity is decaying due to the presence of the vortex breakdown. The central air injection promotes flame stability by affecting the aerodynamics characteristics of the flow field downstream the burner mouth. It reduces the defect of the axial velocity at the tip of the recirculation zone which is one of the main reasons leading to CIVB flashback.

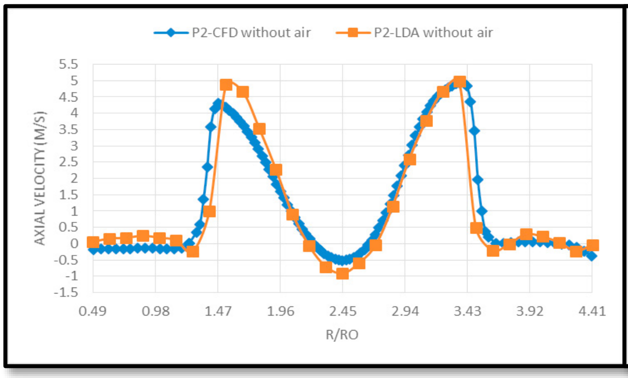

Fig. 2. Comparison of axial velocity calculated by LDA with CFD.

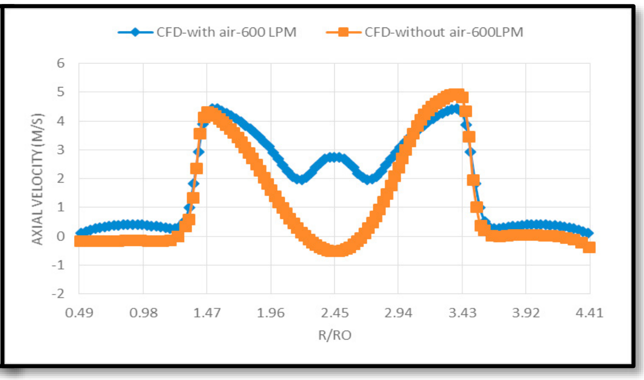

Fig. 3. Effect of air injection on the defect of axial velocity at P2.

Fig. 3 presents a comparison of the axial velocity profiles at plane P2 with and without air injection for 600 l/min inlet tangential flow rate and X=150 mm. In Fig. 4 contours of the mean axial velocity with and without air injection effects are revealed for the whole burner for the case of 600 l/min with X=150 mm. It is clear that the diffusive air pushed up the CRZ downstream the burner mouth due to hydrodynamics effect of the jet, affecting its size, shape and position by adding positive values to the negative axial velocity at the vortex core. Keeping the vortex core radius as constant as possible in the axial direction is recommended to achieve good stability conditions [18]. Thus, to achieve constant vortex core radius, the central air injection should still be effective at a certain distance downstream the burner centre. Fig. 5 illustrates the effect at four different planes downstream the burner mouth P2, P3, P4 and P5 for 600 l/min flow rate and X=150 mm. It can be seen that central air injection is still active on those planes. Nevertheless, the degree of the diffusive air injection effect on axial velocity defects is less than that of P2.

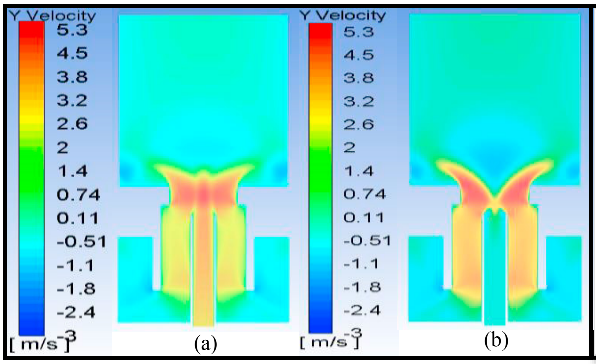

Fig. 4. Axial velocity contour (a) with air Injedction; (b) without air.

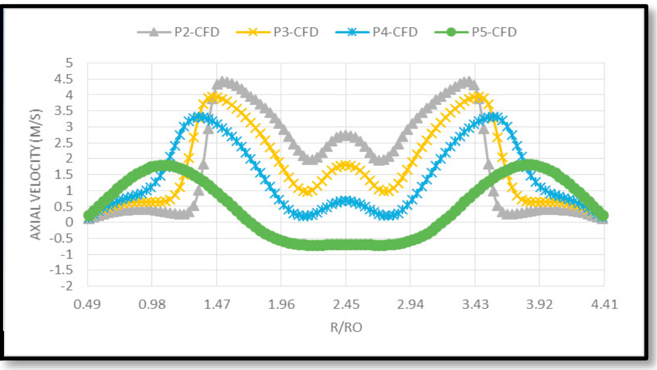

Fig. 5. Axial velocity at different planes from burner mouth.

A comparison between the axial velocities at P2 plane for various tangential flow rates, i.e. 600, 800 and 1000 l/min, with X=150 mm is presented in Fig. 6. Upon increasing inlet tangential flow rate, the effect of diffusive air became less pronounced. These findings suggest that the value of diffusive air injection must be proportional to the tangential flow rates. For instance, at low tangential flow rates, the amount of diffusive air injection is around 10% to achieve the required effect regarding flame flashback resistance. However, at high flow rates, the ratio is decreased to almost 4%. Thus, keeping the diffusive to tangential flow ratio at about 8-10% could achieve the stability operation.

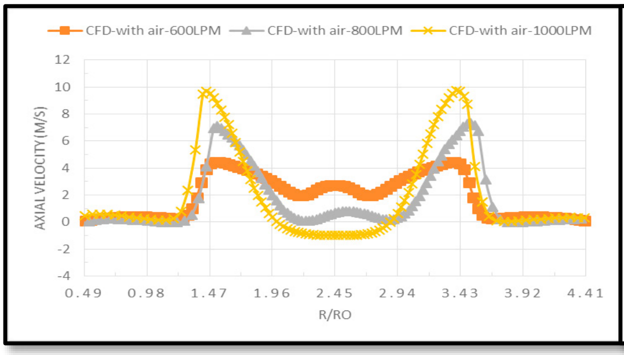

Fig. 6. Axial velocity comparison for different tangential inlets at P2.

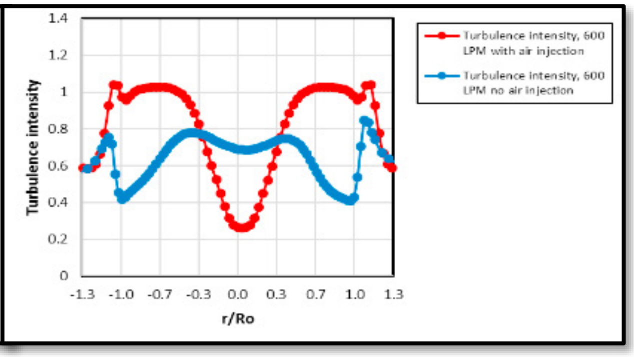

Fig. 7. 3D effect of central air injection on turbulent intensity.

The turbulent intensity downstream the burner mouth have significant consequences on the stability regime because it has a direct effect on the turbulent flame speed and hence the flashback propensity. It can be seen from Fig. 7 that without central air injection, high levels of turbulence intensity are observed at P2 for 600 l/min tangential flow rate and X=150 mm. This reveals the existence of the tip of the CRZ and its interaction with the incoming flow, producing high amounts of turbulence in this region.

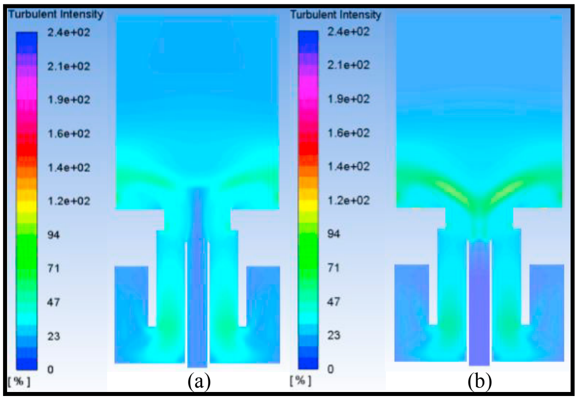

Fig. 8. Turbulent intensity contours (a) with air injection; (b) without air injection.

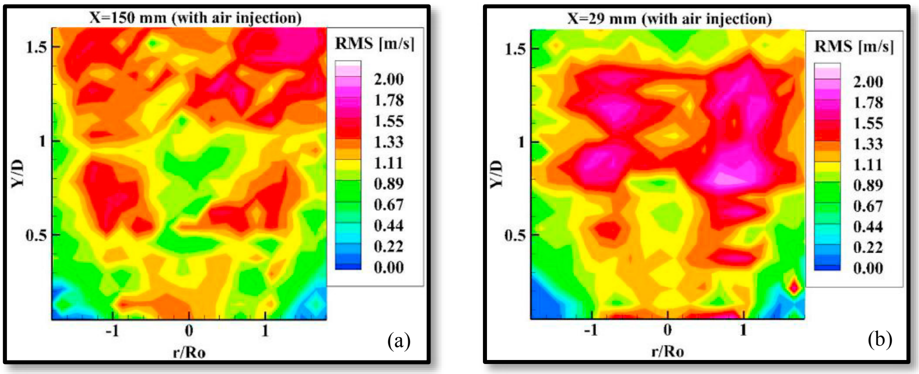

Fig. 9. Three dimentional effects of central air injection position on turbulent intensity (a) X=150 mm; (b) X=29 mm.

A clear image of the effect of diffusive air on the three-dimensional flow turbulent intensity contours appears in Fig.8 for the case of 600 l/min flow rate with X=150 mm. It is clear that the air injection reduces the swirl flow turbulence at the burner nozzle exit and hence increases flow stability. The effect of different positions of the air injector will be more obvious if it is represented by the changing in the turbulence level downstream and close the burner mouth. Fig. 9 shows the isothermal RMS values for two air injector positions, X= 29 and X=150 mm, aquired from the LDA system. From this figure, it can be observed that when air injector is positioned at X=150 mm, turbulence intensity levels are noticeably lower in all the flow field domain than those at X=29 mm. Low turbulence intensity means lower local turbulent flame speed and hence optimum flame flashback resistance.

5. Conclusions

Diffusive air injection via the central injection system changed the size, intensity and position of the central recerculaton zone. Moreover, the use of central air injection is a promising technology that can provide further resistance to flashback for wider operability limits. Consequently, investigating the swirling flow characteristics downstream the burner mouth, especially axial velocity and turbulence, proved to be a critical approach in determining the effects of diffusive injection on swirling flows and hence the operation stability regime of the combustor.

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