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Effects of different nozzle configurations on swirl flow topology in tangential swirl burners

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Abstract

Flame flashback is one of the central combustion instabilities, especially when it appears in the form of boundary layer flashback (BLF) or combustion induced vortex breakdown (CIVB) flashback, some of the most common instabilities in swirl combustors. This paper focuses on mitigating the phenomenon of CIVB and BLF flashback mechanisms using different nozzle configurations while using central air injection. Studies were conducted on a 150-kW tangential swirl burner manufactured and previously characterised at Cardiff University. The effects of different nozzle heights (h_n) with and without microstructure on the swirl flow characteristics were investigated experimentally by utilising an LDA system. Different strip heights (h_m) of a wire woven mesh have been employed as a liner on the smooth nozzle to change its surface roughness. It was found that longer smooth nozzles (h_n/R_o=2.3) led to promotion of stability in the swirl burner by minimising the axial velocity defect while decreasing turbulence downstream the dump plane. Moreover, the average measurements show that the burner nozzles with microstructured surfaces enable improvements in controlling the BLF flashback and hence reduces outflow drag. It was found that the microstructured mesh alters the flow structure near the wall by increasing the velocity adjacent to this region delivering further resistance to BLF. On the other hand, using both central air injection and the nozzle with and without the microstructured surface can affect the operability of the gas turbine combustors.

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Keywords: Swirl flow; gas turbine; CIVB flashback, boundary layer flashback, axial air injection system, laser Doppler anemometry.

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1. Introduction

Gas turbine designers are targeting developments in thermal efficiency while controlling emissions, constraints that represent a significant challenge as both are controlled in opposite manners. From most of the available means to achieve these objectives, lean premixing (LPM) is an efficient technique that has been used to reduce NOx emissions and increase power outputs. However, this technique still requires further analyses to prevent instabilities such as extinction, flashback or thermoacoustics when using alternative fuels that still represent the deciding issue limiting the improvement of the gas turbine combustion systems. Therefore, These systems should be entirely designed and developed to meet many essential design elements. A well-designed gas turbine combustors will fulfil the high requirements of a vast spectrum of gas turbine applications regarding efficiency, reliability, fuel flexibility and environmental compatibility. Swirl combustors represent the most significant improvements to the gas turbine combustion system due to their flame stabilisation capabilities over a wide range of equivalence ratios. 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 of the swirling flow while the second employs alternative fuels [1]. However, performing modifications on swirl burners and achieving the requirements of efficient gas turbine combustion systems is difficult due to many combustion problems such as extinction, low reaction rates, mild heat release, instabilities, emissions and mixing issues [2]. Flashback is an instability of premixed combustion systems in gas turbines that may occur under a variety of conditions as the flame may stabilise where fuel and oxidiser mix, upstream of the reaction zone, which might cause considerable damage to the combustion system with increase in pollutant levels [3]. Flashback may happen via various mechanisms prone of turbulent swirling flows such as turbulent flame propagation in the core flow, flashback by autoignition, combustion instabilities leading to flashback, a flashback in the boundary layers (BLF), and flashback induced by vortex breakdown (CIVB) [4, 5]. It was proposed that multiple mechanisms can trigger the flashback at the same time. However, the BLF and CIVB flashback mechanisms receive particular attention as they commonly happen in swirl combustors [6].

Many techniques can efficiently mitigate CIVB flashback by doing some geometrical modifications or by raising flow field patterns [7]. These techniques range from using diffusive fuel injection to push the vortex breakdown downstream or employing bluff bodies as stabilisers to the swirling flow [2]. Recently, central air injection systems have been designed and employed to mitigate the CIVB flashback in tangential swirl burners [8]. It was found that using the central air jets affect the defect of negative axial velocity and turbulence characteristics and hence promote the CIVB flashback resistance with wider operability limit [9]. However, using such methodology for the mitigation of CIVB flashback mechanism will lead to BLF. Regarding boundary layer flashback, the geometry of the nozzle and its wall properties play an essential role in upstream flame propagation during BLF [10]. Furthermore, the interaction between nozzle wall surface and the parallel flow generates a viscous drag that produces an adverse pressure gradient, consequently promoting velocity gradient. The degree of wall roughness is of particular importance in this context as it promotes the amount of heat transfer, hence decreasing or increasing the shear wall stress [11]. The contribution of the effect of the surface type on the mean velocity profile and hence the wall turbulent boundary layer usually is described by a roughness function which represents the difference in normalised velocity distribution between smooth and rough surfaces [12]. It is known that the shear stress can be reduced using micro extended surfaces from the wall, and such reduction leads to better velocity gradient at the wall and a drag reduction in the flow [13]. In a more recent study, it was noticed that the high turbulent velocity fluctuation near the burner wall increases the tendency to flashback. Thus, to avoid flashback, it is required that the local premixed flow speed is higher than the flame speed. This concept is valid for all flashback mechanisms except for the CIVB [14].

This study aims to expand the understanding of the role of different burner nozzle configurations with/without microstructured surfaces in improving the system against different flashback mechanisms, mainly CIVB and BLF flashback, in conjunction with central air injection. A stainless steel woven mesh was employed to accomplish the research goal and served as a liner for the nozzle burner with different heights (hm) to examine their effects on the swirl flow characteristics near the burner rim. Experiments are conducted using Laser Doppler Anemometry (LDA) to measure the average velocity distribution close to the nozzle wall and downstream the burner exit.

2. Configuration and experimental setup

Testing at Cardiff University's combustion laboratory took place to promote the stability of the previously designed 150 kW tangential swirl burner. The details of the burner are illustrated in figure 1(a). This burner has been re-developed to allow the positioning of an axial fuel/air injector to move vertically inside the plenum for different positions (X) with respect to the base plate. For this study, X=150 mm as depicted in figure 1(b). The outer diameter of the central air injector was set at 21 mm as this diameter sets the flashback transition from BLF Flashback to CIVB mechanism as proved by a previous study [15]. A 25%-25% insert selected to have the suitable geometric swirl numbers (*Sg*=0.9) where vortex breakdown coherent structures exist in the flow. Two nozzle configurations with different heights (h_n) have been tested, the old design with h_n=25 mm while the second new one was h_n=70 mm, both with inner diameter equal to 61 mm as pointed in figure 1(b).

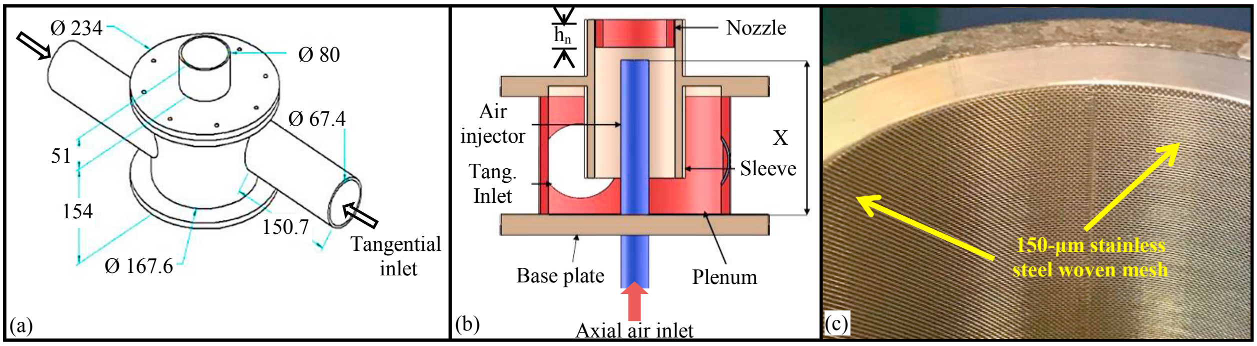

Fig. 1. (a) Sketch of the test rig (mm) (b) front section of the burner [16], (c) nozzle with 316 stainless steel woven wire as a liner.

Getting a machined microstructured surface can be costly to produce and it can difficult or even impossible to introduce inside a circular nozzle. Therefore, a woven wire 316 stainless steel mesh with 150 µm in length between valleys has been employed to examine the effect of surface roughness on the swirl flow, hence the flashback resistance, as it presents some structural similarities with diamond and lotus geometries [10]. Three different heights (h_m) mesh strips, i.e. 25, 40, and 70 mm, were fitted firmly to the internal wall of the nozzle as a liner to increase the roughness of its smooth surface as shown in Fig. 1(c).

3. Results and Discussion

The primary objective of this research is to observe the impact of different nozzle heights (h_n) on the swirl flow characteristics under isothermal (no combustion) and atmospheric conditions. Average axial velocities ($\bar{u}$) and the velocity fluctuations (u_{rms}) have been determined to show the axial velocity and turbulence distribution at the dump plane (Y=3 mm downstream the burner rim) for different nozzle heights (h_n=25 and 70 mm). Two tangential flowrates 800 and 1000 LPM with and without central air jets were used to set different operating conditions. The amount of the injected air was equal to 50 LPM that was enough to maintain the coherent air jet and avoid swirl strength degradation [8].

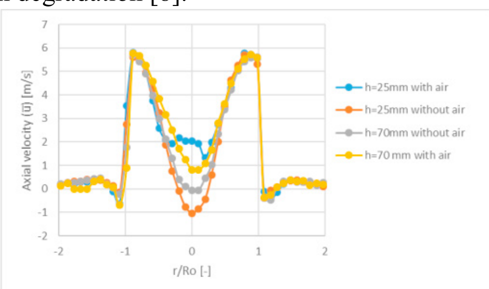

Fig. 2. Axial velocity for different nozzle heights (h_n), 800 LPM inlet tangential, X=150 mm, with and without air injection.

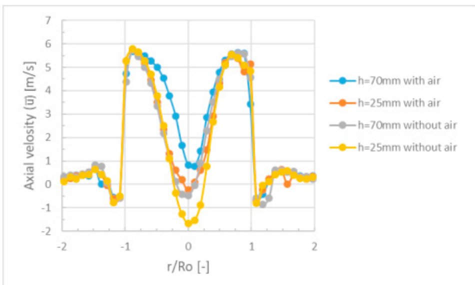

Fig. 3. Axial velocity for different nozzle heights (h_n), 1000 LPM inlet tangential, X=150 mm, with and without air injection.

Figure 1 demonstrates the amount of the reduction in axial velocity defect (negative region) under moderate inlet tangential flowrates (800 LPM) with (X=150 mm) for two nozzle heights with and without central air jet. It is apparent that for the case of no air injection, the long nozzle (h_n=70 mm) is significantly effective in lessening the axial velocity defect at the tip of the central recirculation zone (CRZ) which is one of the main reasons leading to swirling flow instabilities. Moreover, under the effect of the axial air jet, the long nozzle also played a significant role in axial velocity defect reduction and in preventing the distortion in the axial velocity profile while avoiding the swirl strength degradation caused by the axial momentum of the central air jet. For higher tangential inlet (1000 LPM), the effects of the long nozzle became more influential for velocity defect reduction as depicted in figure 2. The axial velocity defect is minimised by 50% at the CRZ tip under the simultaneous effects of the long nozzle (h_n=70 mm) and the central air jet as compared with the short nozzle (h_n=25 mm) without axial air injection. These hydrodynamic effects will undoubtedly promote the stability limit of the burner as proved in previous studies [17, 18].

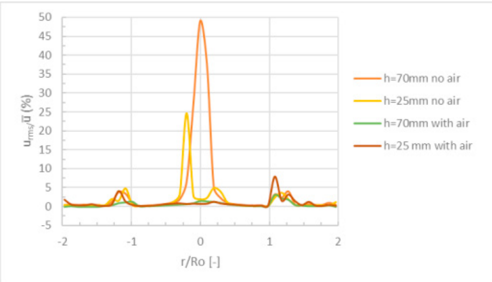

Fig. 4. Turbulent intensity for different nozzle heights (h_n), 800 LPM with and without air injection at and (X=150 mm).

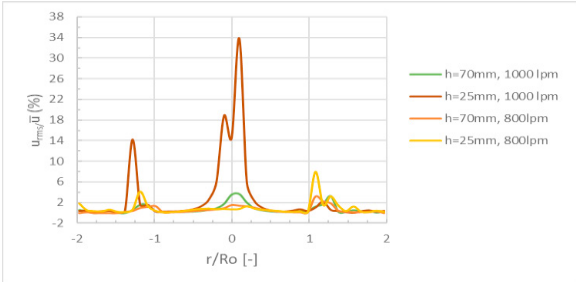

Fig. 5. Turbulent intensity for different nozzle heights (h_n) and different inlet tangential flowrates with air injection at (X=150mm).

Turbulent intensity at the dump plane was calculated from the experimental results by dividing the root mean square of the axial velocity fluctuations by the average axial velocity gathered from the LDA system. Isothermal experiments for 800 LPM inlet tangential, figure 3, show that the central air injection in general for short and long nozzles reduces turbulence at the burner exit and ensure greater stability, consequence of the interaction at different magnitudes between nozzle geometry, central air injection and tangential air flowrate. The higher inlet tangential flowrate (1000 LPM), the better positive effects of the long nozzle on the turbulence intensity and then on the stability of the swirl burner as illustrated in figure 4. This fact looks very promising as actual gas turbine combustors operate on high flowrate and pressurised conditions. Moreover, the long nozzle (h_n/Ro=2.3) can be used as an alternative technique to the central air injection system especially for high inlet flowrate to promote the resistance to CIVB flashback, reducing cost and complexity of the swirl burner design, and minimizing swirl strength degradation caused by the central air jet. However, using both techniques at the same time will produce better effects regarding the axial velocity defect reduction, minimizing turbulent intensity and hence achieving swirl flow stability while covering a wide range of operating conditions from low to high inlet flowrates.

Although using the simultaneous actions of the long nozzle and the central air injection which can considerably raise the swirl flow field patterns and tackle the upstream flow propagation through the central core, some drawback can arise, as the system could be likely subjected to wall boundary layer flashback (BLF) mechanism, especially at high flowrates. As a result, the second objective of this paper was to improve the BLF resistance by changing the surface properties of the long nozzle (h_n=70 mm) and test the effects on the flow field adjacent to the nozzle's wall. This goal has been achieved by using three different woven wire mesh configurations (25 mm, 40 mm, and 70 mm) which served as a nozzle liner to investigate the effects of surface roughness on the swirl flow characteristics near the wall. The tests were performed for 800 LPM inlet tangential flowrate with and without central air injection through the central injector. A 50 LPM axial airflow rate was used for the case under the air jets effect. The influence of the geometrical shape of those grids has been analysed using numerical simulation by other authors. Details of the numerical approach and results are discussed in [10].

Under the effect of central air injection, figure 5, shows that for long smooth nozzle (without mesh lining), the wall effect is clear and represents a decline in axial velocity due to the viscosity and wall shear stress. On the other hand, using woven wire meshes as lining regardless height causes limitations of wall defects, keeping the axial velocity with relatively high values near the wall. Such behaviour could be explained using the concept of antifouling surfaces, which use regular surface roughness as a passive control on boundary layer. Also, the height of the lining has a small effect on overall velocity values. A wide strip of the mesh caused a drop in the flow while the short one did not produce such noticeable reeducation in overall velocity. It was seen that the better in eliminating the wall effect and increase the BLF resistance, the shorter lining strip was required (25 mm). This looks quite promising since there is no need for a lengthy and costly micro surfaced burner nozzle.

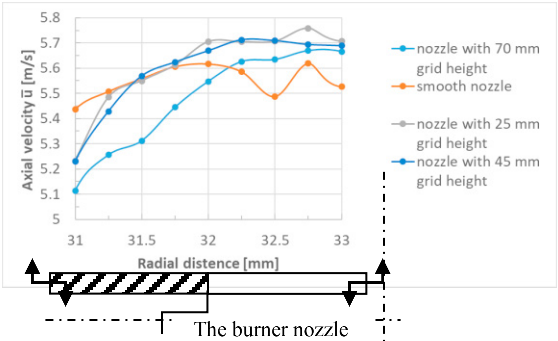

Fig. 6. Axial velocity downstream the burner nozzle for different surface roughness with 50 LPM axial air jet.

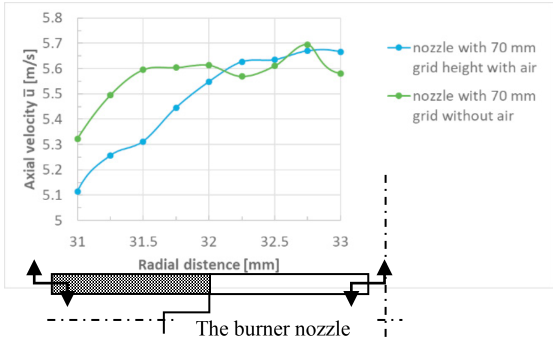

Fig. 7. Axial velocity downstream the burner nozzle under the effects of 50 LPM axial air jet.

Figure 6 shows the axial velocity values at 3mm downstream the burner exit with and without central air injection (50 LPM) for a surface roughness lining with 70mm height. As depicted in figure 6, the velocity gradient is dropped to its minimum value at the wall under the effect of air injection. The effect of the axial air injection and the surface roughness is plausible. As a result, using both techniques, axial air injection and surface roughness effects, can promote the resistance of the burner for both BLF and CIVB flashback with wider stability margins due to the hydrodynamic effects of both approaches on the swirl flow field. In figure 7, the axial velocity downstream the nozzle is plotted. The results show that the axial velocity gradient is affected by changing the lining height. The results show that the velocity gradient in the radial direction was decreased with the short lining grid (25 mm), which means that the high-velocity region is shifted towards the nozzle wall. The velocity gradient in the downstream direction shows some significant results regarding the impact of these structures on the flow. This result is important because it explains the improvement in boundary layer flashback (BLF) when using the shorter mesh. According to the Lewis von Elbe formula for the laminar flame speed, the sharp velocity gradient increases flashback, where the flame attacks the low-velocity region near the wall to penetrate towards the premixing channels.

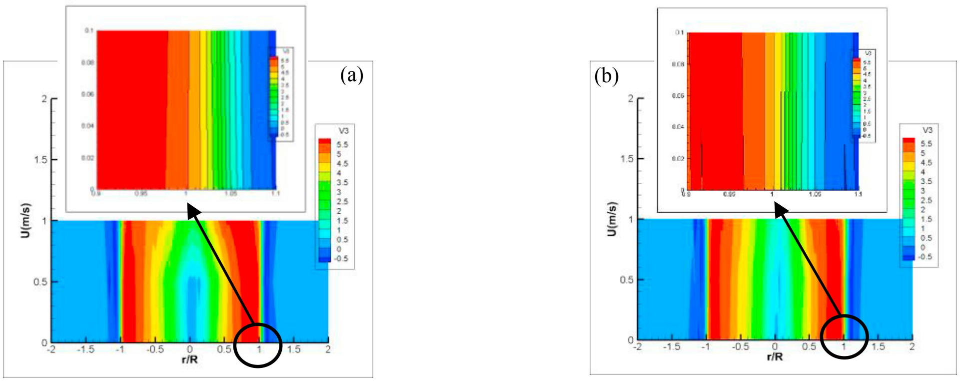

Figure 8. Contour of axial velocity downstream the nozzle (a) lining grid height (25 mm), (b) lining grid height (70 mm)

4. Conclusions

Two different nozzle heights (h_n=25 mm and 70 mm) have been tested to promote CIVB flashback resistance in a tangential swirl burner under the effect of central air injection system. It was observed that the longer nozzle increased the resistance to CIVB flashback and minimised the swirl strength degradation caused by the central air jet. Using both techniques, i.e. the long flat nozzle (h_n=70 mm) with central air jet, will give more substantial effects regarding axial velocity defect reduction, minimizing turbulent intensity and hence achieving swirl flow stability while covering a wider range of inlet flowrates. On the other hand, a new technique inspired by biomimetic engineering has been developed and tested using 3 different strip heights (h_m) of microsurface to improve the burner against BLF phenomena. It was found that the height of the micromesh is essential. The 25 mm strip height of micromesh gave better results than the longest one (70 mm) as the former produced the best shift of the velocity gradient close to the wall. The optimum stability could be achived when using the different techniques at the same time, i.e. central air injection, the long nozzle and microstructured surface to provide additional resistance to CIVB and BLF.

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References

[1] D. G. Lilley, “Swirl Flows in Combustion: A Review,” *AIAA J.*, vol. 15, no. 8, pp. 1063–1078, 1977.

[2] T. Lieuwen, V. McDonell, D. Santavicca, and T. Sattelmayer, “Burner Development and Operability Issues Associated with Steady Flowing Syngas Fired Combustors,” *Combust. Sci. Technol.*, vol. 180, no. 6, pp. 1169–1192, 2008.

[3] C. Mayer, J. Sangl, T. Sattelmayer, T. Lachaux, and S. Bernero, “Study on the Operational Window of a Swirl Stabilized Syngas Burner Under Atmospheric and High Pressure Conditions,” *J. Eng. Gas Turbines Power*, vol. 134, no. 3, p. 31506, 2012.

[4] Y. Sommerer, D. Galley, T. Poinsot, S. Ducruix, F. Lacas, and D. Veynante, “Large eddy simulation and experimental study of flashback and blow-off in a lean partially premixed swirled burner,” *J. Turbul.*, vol. 5, 2004.

[5] G. Baumgartner and T. Sattelmayer, “Experimental Investigation of the Flashback Limits and Flame Propagation Mechanisms for Premixed Hydrogen-Air Flames in Non-Swirling and Swirling Flow,” in *Volume 1A: Combustion, Fuels and Emissions*, 2013, p. V01AT04A010.

[6] E. Tangermann, M. Pfitzner, M. Konle, and T. Sattelmayer, “Large-Eddy Simulation and Experimental Observation of Combustion-Induced Vortex Breakdown,” *Combust. Sci. Technol.*, vol. 182, no. 922482307, pp. 505–516, 2010.

[7] T. Sattelmayer, C. Mayer, and J. Sangl, “Interaction of Flame Flashback Mechanisms in Premixed Hydrogen-Air Swirl Flames,” *J. Eng. Gas Turbines Power*, vol. 138, no. January, pp. 1–13, 2014.

[8] A. S. Alsaegh, F. Amer Hatem, and A. Valera-Medina, “Visualisation of Turbulent Flows in a Swirl Burner under the effects of Axial Air Jets,” *Energy Procedia*, vol. 142, pp. 1680–1685, 2017.

[9] F. A. Hatem, A. S. Alsaegh, M. Al-Faham, and A. Valera-Medina, “Enhancement flame flashback resistance against CIVB and BLF in swirl burners,” in *Energy Procedia*, 2017, vol. 142.

[10] M. Al-Fahham, A. V. Medina, F. A. Hatem, S. Bigot, A. S. Alsaegh, and R. Marsh, “Experimental study to enhance resistance for boundary layer flashback in swirl burners using microsurfaces,” in *Proceedings of the ASME Turbo Expo*, 2017, vol. 4A–2017.

[11] D. Ebi and N. T. Clemens, “Experimental investigation of upstream flame propagation during boundary layer flashback of swirl flames,” *Combust. Flame*, vol. 168, pp. 39–52, 2016.

[12] R. A. Antonia and P. Krogstad, “Turbulence structure in boundary layers over different types of surface roughness,” *Fluid Dyn. Res.*, vol. 28, no. 2, pp. 139–157, 2001.

[13] C. T. DeGroot, C. Wang, and J. M. Floryan, “Drag Reduction Due to Streamwise Grooves in Turbulent Channel Flow,” *J. Fluids Eng.*, vol. 138, no. 12, p. 121201, 2016.

[14] V. Hoferichter, C. Hirsch, and T. Sattelmayer, “Prediction of Confined Flame Flashback Limits Using Boundary Layer Separation Theory,” *J. Eng. Gas Turbines Power*, vol. 139, no. 2, p. 21505, 2016.

[15] N. Syred, F. A. Hatem, A. Valera-Medina, R. Marsh, and P. J. Bowen, “Experimental Investigation of the Effects of Central Fuel Injectors on Premixed Swirling Flames,” *53rd AIAA Aerosp. Sci. Meet.*, pp. 1–8, 2015.

[16] A. Valera-Medina, N. Syred, and A. Griffiths, “Visualisation of isothermal large coherent structures in a swirl burner,” *Combust. Flame*, vol. 156, no. 9, pp. 1723–1734, 2009.

[17] A. S. Alsaegh, F. Amer Hatem, and A. Valera-Medina, “Visualisation of Turbulent Flows in a Swirl Burner under the effects of Axial Air Jets,” in *Energy Procedia*, 2017, vol. 142.

[18] F. Hatem, “FLASHBACK ANALYSIS AND AVOIDANCE IN SWIRL BURNERS,” PhD thesis, Cardiff University, 2017.