# Enhancing flame flashback resistance against Combustion Induced Vortex Breakdown and Boundary Layer Flashback in swirl burners

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## ABSTRACT
Swirl combustors have proven to be effective flame stabilisers over a wide range of operation conditions thanks to the formation of well-known swirl coherent structures. However, their employment for lean premixed combustion modes while introducing alternative fuels such as high hydrogenated blends results in many combustion instabilities. Under these conditions, flame flashback is considered one of the major instability problems that have the potential of causing considerable damage to combustion systems hardware in addition to the significant increase in pollutant levels. Combustion Induced Vortex Breakdown is considered a very particular mode of flashback instability in swirling flows as this type of flashback occurs even when the fresh mixture velocity is higher than the flame speed, a consequence of the interaction between swirl structures and swirl burner geometries. Improvements in burner geometries and manipulation of swirling flows can increase resistance against this type of flashback. However, increasing resistance against Combustion Induced Vortex Breakdown can lead to augmentation in the propensity of another flashback mechanism, Boundary Layer Flashback. Thus, this paper presents an experimental approach of a combination of techniques that increase Combustion Induced Vortex Breakdown resistance, i.e. by repositioning a central injector and using central air injection, while simultaneously avoiding Boundary Layer Flashback, i.e. by changing the wall boundary layer characteristics using microsurfaces on the nozzle wall. Results show that using these techniques together has promising potentials regarding wider stable operation for swirl combustors, enabling them to burn a broader variety of fuel blends safely, while informing developers of the improvements obtained with the combined techniques.

**Keywords:** Swirl, instabilities, CIVB, BLF, flashback, central injection.

## INTRODUCTION
In most practical combustion systems achievement of high flashback resistance depends on flame stabilisation which rests on the equilibrium between flame speed and incoming flow velocity at the reaction zone both in magnitude and direction. This balance, in turn, is a function of different parameters such as burner configuration, degree of mixing, fuel type, etc. Furthermore, swirl combustion, the most employed technology in current gas turbine burners, creates tri-dimensional structures that add further complexity to this balance [1].

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However, avoiding flame flashback by controlling the equilibrium between incoming flow velocity and flame speed is not always manageable [2]. Thus, flashback mechanisms can lead to dramatic consequences when high, turbulent flame speed fuels such as those based on highly hydrogenated blends are used [3]. One of these mechanisms, Combustion Induced Vortex Breakdown (CIVB) [4], is considered a fast-acting flashback mechanism that appears in swirl burners as a consequence of the formation of the Central Recirculation Zone (CRZ) [5] that can eventually propitiate the movement of the flame inside of feeding passages, leading to CIVB. The phenomenon is particularly important in swirling flows, which are characterised as highly complex phenomena because of their inherent three-dimensional time-dependent structures. Many studies have investigated flame flashback mechanisms in swirl combustors suggesting many techniques for mitigating flame flashback either by doing some geometrical enhancements or by promoting flow field patterns [6]. Flame flashback due to CIVB received particular 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 highly reactive blends [7].

Of particular interest for applied concepts to reduce flashback, central fuel injectors or bluff bodies have proved their potential ability in anchoring the CRZ downstream the burner nozzle [8] with a considerable flame flashback resistance, especially against CIVB. Most investigations in this context have largely concentrated on the effect of bluff body geometries on blowoff limits [9], with findings that suggest phenomena related to the creation of regions across the flame that are unable to “self-heal” on the basis of critical parameters [10] resultant from blend reactivity and combustion conditions [11]. However, the high complexity of swirling flows under lean conditions goes further with phenomena still not entirely understood that can propagate through the flow field producing either blowoff or flashback [12]. For example, some other studies [13] have investigated the effect of position and geometry of bluff-bodies on flow aerodynamics and flashback resistance. However, employing bluff- bodies in gas turbines do not fully mitigate the risks of flashback [14]. Unfortunately, centre-body devices can also undergo material degradation due to the harsh environmental conditions produced by high temperature flames, especially when high hydrogen content blends are used [15, 16]. Therefore, flow field manipulating has been considered as one of the effective techniques that can inhibit flame flashback propagation [17]. Fritz, et al. [5] studied the effects of using axial fuel injection with variable orifices in swirl burners for flashback resistance. Konle, et al. [18] used unswirled core flows (axial injection) to control the position of swirling coherent structures. They found that an increasing axial fuel jet diameter produces a more coherent and strong axial jet flow, which in turn pushes back the vortex breakdown downstream, consequently optimising flashback resistance.

However, whereas injecting fuel axially in the centreline demonstrated a wider operability consequence of improving CIVB flashback resistance, the technique can lead to significant increase in the level of NOx emissions [19]. Moreover, central fuel injection cannot completely mitigate flame flashback as most of the previous applications suffered degrading of mixing considerably. Thus, using central air injection is considered a suitable alternative to central fuel injection to reduce NOx, where distributed reaction conditions in the combustor can be achieved via controlling the air injection velocity [20], although this can lead to mixing degradation, topic that requires deeper understanding. However, this state-of-the-art technique has been barely investigated for flashback resistance. Reichel et al. [21] found that a high amount of central air injection could effectively influence the CRZ position and improve flashback resistance with a considerable reduction in NOx levels. This technique can significantly produce wider operation stability maps in gas turbines, critical concept regarding the possibility of switching to different blends for flexible power plants. Central air injection can also be employed in colourless distributed combustion (CDC) [22], where air jets can support dilution of the

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blends to enable lower temperatures and highly distributed reactions in these systems, consequently reducing emissions [23] even with high hydrogen content blends [24] that tend to raise temperature profiles over combustion processes. However, to the knowledge of the authors, studies performed by Reichel et al. [21] seem to be unique in this area of research.

The above methods of flow field manipulation are based on injecting either fuel or air axially through the centre of the flow field. Nevertheless, although axial injection can compensate the defect of the velocity at the burner centre-line, it could enforce the flame to propagate via another flashback mechanism known as wall Boundary Layer Flashback (BLF). Therefore, it is essential to focus on improving Boundary Layer Flashback (BLF) resistance while trying to mitigate Combustion Induced Vortex Breakdown (CIVB) in a medium/high swirl combustion system.

Flame flashback via wall boundary layer depends on many parameters such as the flow field characteristics, equivalence ratio, pressure, temperature, wall temperature, confinement type, the state of the boundary layer and the geometry of interior liners in the burner nozzle [25]. Flashback in the boundary layer was firstly studied by Lewis and von Elbe for laminar flames [26]. In this pioneering work, a relation between the velocity gradient at the wall and the ratio of the laminar flame speed to the quenching distance was suggested. This model was developed even further in terms of the pressure effects on the velocity gradient in laminar flames [19]. In turbulent flame studies, the Lewis and von Elbe model also considered other works [6], but some studies reported that the flashback limit could not be explained by the original concept of velocity gradient due to the very thin boundary layer in turbulent cases [27]. Thus, the relation between pressure and flashback in laminar and turbulent flames was studied deeply by Fine [28] who proposed that a turbulent flame near flashback stabilised in the laminar sublayer, concluding that a turbulent flame could penetrate around three times closer to the wall than a laminar flame. The same ratio was suggested by others [29] in a study of turbulent wall flashback of hydrogen flames using a temperature-controlled rim burner, as hydrogen flames present flame speed values an order of magnitude greater than most fossil gaseous fuels, thus increasing their propensity to flashback. However, this ratio varies with equivalence ratio, especially towards the rich mixtures. The geometry of the nozzle wall also plays an important role in upstream flame propagation during boundary layer flashback, i.e. the interaction between nozzle wall and flame can affect directly the amount of heat flux, which consequently changes the wall quenching distance [30]. The interaction between nozzle wall surface and the parallel flow generates a viscous drag which produces an adverse pressure gradient, consequently promoting velocity gradients that will lead to flashback.

In swirl burners, the presence of flame near the wall of the burner nozzle is usually affected by the flow characteristics upstream the nozzle exit close to the boundary layer [31]. Thus, influencing this boundary layer to modify BLF resistance needs innovative research. For such a reason, research on the area for Boundary Layer stabilisation has been conducted using biomimetic applications, concept that to the knowledge of the authors of this work has never been attempted before. Microsurfaces for drag reduction to increase resistance to boundary layer flashback have been well-reported [32]. A laminar boundary layer will transit to turbulent due to kinetic energy transmission from the free stream flow into turbulent fluctuations and then dissipate into internal energy through viscous action as a drag force. The drag force is commonly categorized into pressure and skin friction drag. Thus, ribblet microstructures generally reduce skin friction drag by effectively controlling the naturally occurring turbulent velocities, which leads to less momentum transfer and shear stress. In fully turbulent flows the laminar sublayer thickness is very small which means that the tips of the microsurface would penetrate the layer [33], thus allowing the grooved surface to play a role of damping turbulence and reducing drag [34].

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Therefore, due to the need for improving flashback conditions in swirl burners, this study seeks to fill gaps of knowledge directly linked to these phenomena. To the knowledge of the authors, combination of parameters such as properly positioned central injection and microsurfaces has never been attempted. Although these works are based on natural gas (NG) fuelling to reduce risks towards both equipment and researchers while validating the concept, the final aim of the proposed combined technique is to employ the concept in systems fuelled with high hydrogen content blends which are particularly disposed to flashback due to the higher flame speeds that these flames possess.

## EXPERIMENTAL SETUP

The 150-kW tangential swirl burner used in this work is illustrated in Fig. 1. The burner has two tangential inlets of 67 mm internal diameter (ID); the burner exit is 76 mm ID. The diameter of the 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 numbers from 0.913 up to 3.65. However, in this work, only a 0.913 swirl number has been used. The base plate was fitted with a central injector that allowed both air and fuel injection. The central injector can be moved up or down to different "$L_o$" positions, Fig. 1. A 150 µm micromesh grid, Fig. 2, has been used as a liner located over the nozzle internal wall to investigate the change of nozzle surface and its impacts on the boundary layer. The liner thickness was scanned by Shared Labs Europe LTD via non-destructive MLP-3 micro-scanning. The wire mesh structure provides small holes that trapped the air inside and helped to make a fluid cushion that separates the high-velocity region and the wall. This microsurface was numerically simulated and assessed somewhere else [35].

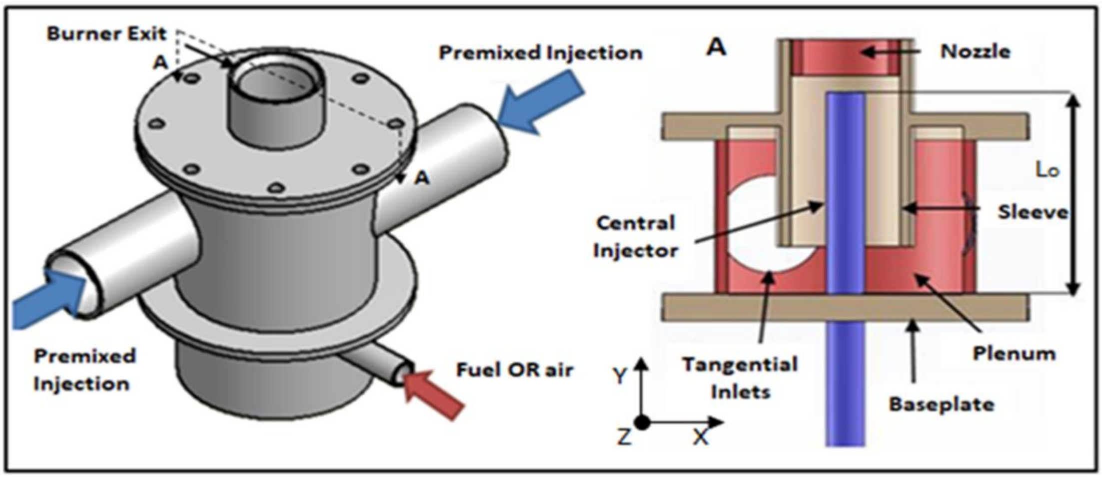


**Fig 1.** 150 kW tangential swirl burner.

Experiments were conducted under both isothermal (no combustion) and combustion conditions under atmospheric pressure with no air preheating, using NG (90% methane) as fuel for the combustion trials. The system was fed by a centrifugal fan providing air flow via flexible hoses and two banks of rotameters for flow rate control and a further bank for the injection of natural gas. The errors in air and gas rotameters readings were ~3%. Flowrates ranging from 400 LPM to 1200 LPM (Re ~ 10,500 to 30,000) were employed to set different operating conditions. Fuel was added both in premixed mode (i.e. being premixed exactly at the entrance of the tangential inlets of the rig) and diffusive mode (i.e. through the central injector, just for start-up). The overall –i.e. that takes into account central and tangential flows- equivalence ratio (Φ) was controlled by slowly reducing/increasing the airflow in the blend while keeping the fuel flowrate constant.

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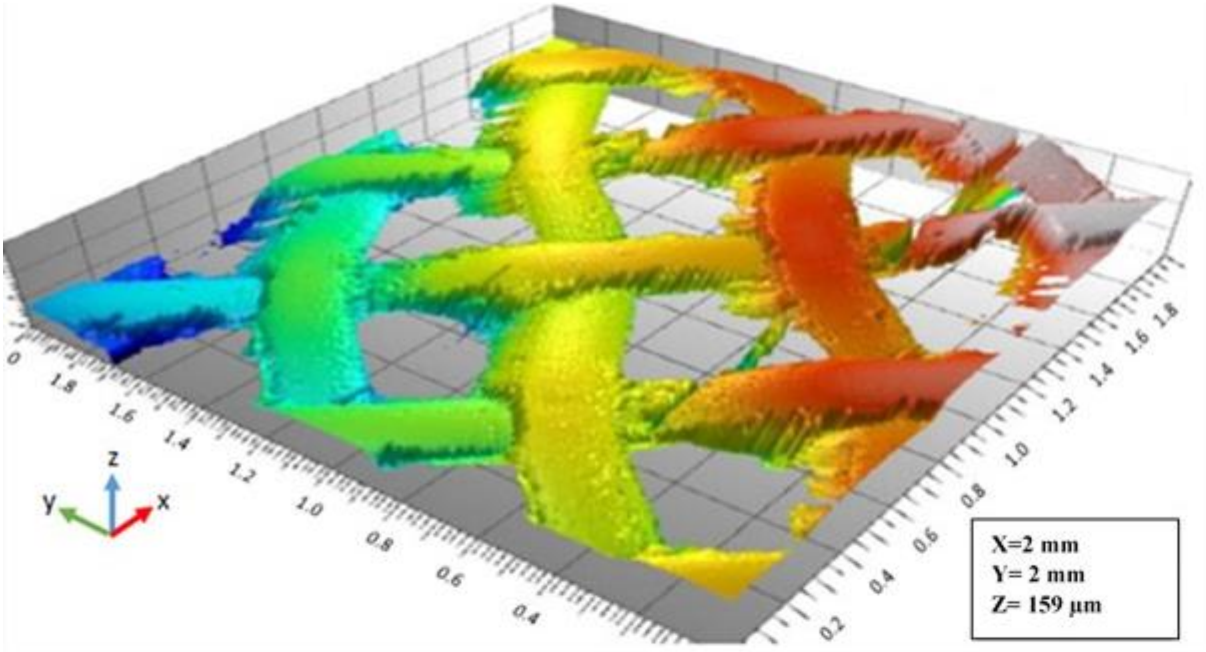


**Fig 2.** Scanned microsurface geometry.

The instantaneous velocity components downstream the burner mouth have been measured by Laser Doppler Anemometry (LDA). The LDA system used was a one component Flowlight LDA (Dantec) operated at backscatter mode. The system offers a calibration uncertainty of 0.067%. It is recognised that swirling flows are 3-dimensional in nature. However, the results provided an initial insight into the phenomena occurring through the flow field under different experimental conditions. The expander ratio during the isothermal test was equal to 1.0, and the probe volume dimensions were (dx=0.338 mm, dy=0.388 mm and dz=8.919mm). However, to increase the data rate during the combustion test, the expander ratio was increased to 1.5, and hence the probe volume was decreased (dx=0.225 mm, dy= 0.226 mm and dz= 3.968 mm). Velocity measurements were performed at different levels downstream the burner dump plane -i.e. plane located exactly at the exit of the rig-, being Y=5 mm from this plane the closest plane possible for measurements. The LDA system has been recently calibrated to operate with 50,000 measuring points before moving to the next measuring point for isothermal conditions and 10,000 measuring points for combustion conditions. The rationale of this change in measuring conditions was the change in density of the flow, thus less available points for measurement under combustion conditions, combined with the reduced seeding employed in the presence of a flame to minimise heat transfer losses to the seeding particles. The light source consists of an argon ion laser, and the focal length of the lens was 500 mm. Aluminium oxide seeding was used in the experiments with a particle size <10µm, and the injection point located 2m away from the burner to reduce impacts on the flow field.

## *Experimental Methodology*

As in previous studies [36], results were tabulated using the mean velocities of the air and fuel mixture fed through the tangential inlets. This parameter will be named for simplicity "Tangential velocity", which has previously proven to allow correlation with other similar burners and characterise fundamental patterns regarding the various effects produced through the inlet port of this device [37]. The parameter "Axial velocity" will be only employed to show the velocity distribution in the Y axis at different injection conditions. The internal diameter of the central air injector was chosen to be 19 mm based on a previous study [38] where this diameter sets the flashback transition from Wall

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Boundary Layer Flashback (WBLF) to CIVB flashback. For the experiments, different "$L_o$" positions were investigated, Table 1.

**Table 1**. Air injector positions with respect to the burner baseplate

| no | $L_o$ (mm) | From outlet (mm) |
|---|---|---|
| 1 | 0 | 205 |
| 2 | 29 | 176 |
| 3 | 48 | 157 |
| 4 | 75 | 130 |
| 5 | 110 | 95 |
| 6 | 150 | 55 |

Provisional tests revealed that it was difficult to obtain a stable swirling flame without the central injector or bluff body. Since only air was injected into the central region, this problem was more pronounced. A number of experiments were undertaken to obtain a suitable start-up procedure to achieve a stable flame, eventually concluding that fuel must always be injected through the central injector during start-up for this geometry.

The blowoff point was determined when the flame zone was visibly lifted from the burner mouth. For flashback, the points were defined when the flame zone appeared to retreat into the plenum. Both envelopes, i.e. flashback and blowoff, were deduced and compared between cases. In order to check accuracy of results, experiments were repeated five times, showing deviations not greater than 5%.

In turbulent flames, the high level of turbulence can increases the flame speed, consequently the possibility of flashback initiation [39]. The relation between turbulence intensity and turbulent flame speed is described as follows [2],

$$S_T \propto S_L + u'$$

Where
$S_T$ : turbulent flame speed [m/s]
$S_L$ : laminar flame speed [m/s]
u' : velocity fluctuations [m/s]

According to the previous equation, any increase in turbulence intensity will consequently be followed by an increase in turbulent flame speed. Hence if this increment occurs at some weak regions inside the swirling flow, especially at the tip of the CRZ, there is a strong possibility of upstream flame propagation caused by turbulence effects in the flame. Thus determining and correlating turbulence intensity with combustion instabilities, especially flame flashback, has significant potential. However, methods of measuring turbulence intensity mainly depend on the flow characteristics. Thus, in this study the used method describes the instantaneous changes in turbulence intensity at the exit of the dumping plane, and consequently, correlation between those changes and combustion instabilities. Turbulence intensity was calculated according to the following equation,

$$T_u = u_{rms} / \bar{u}$$

Where,
$u_{rms}$: Root mean square value in the axial direction measured by LDA
$\bar{u}$: Mean axial velocity measured by LDA

It must be recognised that the position of the central injector plays an important role in the final location of the CRZ, as the closer the injector is to the dump plane, the further away the CRZ is pushed back into the combustion zone. Therefore, measurements of turbulence at the plane of interaction between the central jet and the CRZ were difficult to correlate between cases. However, the intention of those tests was to determine the turbulence of the flow close to the dump plane (Y=5 mm) as a parameter for flashback propagation/avoidance.

## RESULTS

### *Central air injection effects on burner operation*

Initial studies were carried out to observe the impact of central air injection in the burner operability. Figure 3 shows the relationship between flashback and blowoff limits at various equivalence ratios and tangential velocities for two conditions, i.e. with and without central air injection. These tests were conducted without central injector to observe the effects caused by the injected airflow. Stable operation is to the right and left sides of the blowoff and flashback regions, respectively. Above these points unstable conditions were observed leading to a complete loss of the flame.

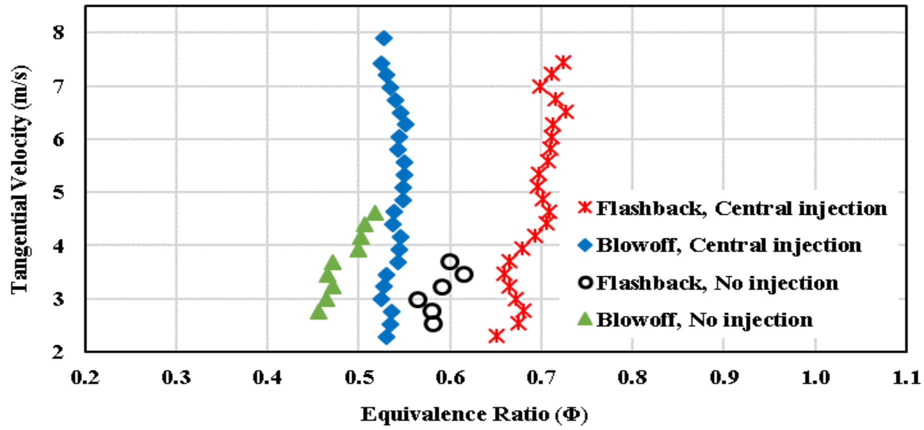


**Fig 3.** Burner stability operation region (effect of using central air injection), $L_o$=0 mm.

The improvement in operability is caused by the use of central air injection that simulates the physical shape of a central injector, allowing wider range of operation (0.55> Φ <0.7) over a tangential velocity ranging from 2.5 m/s to 7.5 m/s. When there is no central injection, operability limits are narrower (0.48> Φ <0.57) over a smaller tangential velocity range of only 2.5 – 4.0 m/s, after which no stable flame can be achieved.

### *Effect of the central injector position*

The position of the central injector inside the burner plenum with respect to the baseplate was then mapped. The amount of central air injection is crucial in obtaining a stable flame. From one hand, it should be robust and coherent enough to prevent upstream flame propagation, and on the other hand, its ratio to the tangential injection must be kept as low as possible to avoid both swirl strength deterioration and lack of mixing between reactants, i.e. excessive dilution at the tip of the CRZ. It was found that the optimum amount of central air injection required to achieve a coherent air jet and avoid swirl strength degradation was ~50 LPM, flowrate kept for all the experiments that follow. This ratio represents 3-10% of the total mass flow rate at different inlet tangential flow rates.

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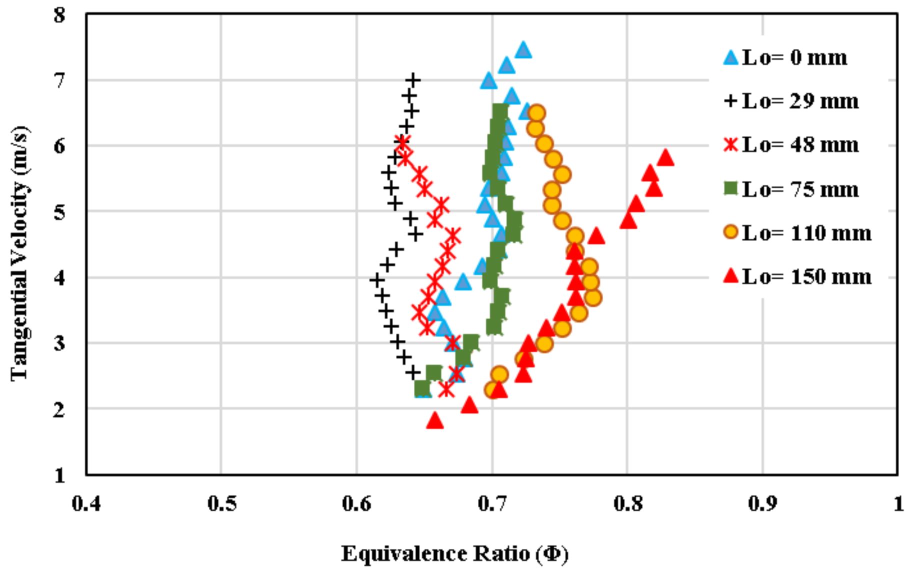


**Fig 4.** Flame flashback trends at different central injector positions.

Figure 4 shows the flame flashback trends for six different positions of the central injector with respect to the baseplate. When air is injected directly from the burner baseplate ($L_o$=0 mm), the flame flashback margin is around Φ=0.7 over inlet tangential velocities ranging from 2.5 to 7.5 m/s. However, when the position of the central injector opening is parallel to the bottom edge of the tangential inlets ($L_o$=29 mm), flashback trends are affected significantly and shifted to the leaner region. At $L_o$=48 mm, the flashback behaviour is like that of $L_o$=0 mm at low-velocity rates of 2.0-3.0 m/s. However, upon increasing flow rates the overall turbulence generated at the bottom of the burner sleeve produces an aerodynamic flow fluctuation leading to earlier flashback compared to that of $L_o$=0 mm but slightly richer than the flashback for the $L_o$=29 mm case. When the central injector is located further downstream inside the burner sleeve at $L_o$=75 mm, the flame flashback trend recovers and by large concurs with the trend shown at $L_o$=0 mm, albeit some difference in the tangential velocity range of 3.0-4.0 m/s.

Furthermore, enhancement of flashback resistance is observed at $L_o$=110 mm where the stable operating regime became wider as both the air injection and sleeve promote flame stability. This stability limit is almost similar to $L_o$=150 mm. However, flashback limit shifts to a richer region at higher flow rates (5.0 m/s tangential velocity). Interestingly, no flashback was observed beyond this point. This outcome is of importance regarding the possibility of switching to higher power operation.

A closer analysis to the velocity profiles close to the exit dump plane, Fig. 5, shows how the position of the central injector is critical in re-establishing the recirculation zone to enhance flashback. As the central injector is closer to the dumping plane, the axial momentum of the former remains strong enough to push back into the combustor the CRZ, which due to its negative velocity seeks to reposition itself closer to the burner exit. However, as the central injector is located closer to the baseplate ($L_o$=0 mm, Fig. 5a) the negative profiles, similar to those without central air injection and with clear presence of a CRZ, reappear, denoting that the use of the central injection technique is barely affecting the position of the central recirculation zone. On the other hand, as the injector is closer to the dump plane (i.e. $L_o$=150 mm, Fig. 5b), negative profiles are eliminated at the central axis.

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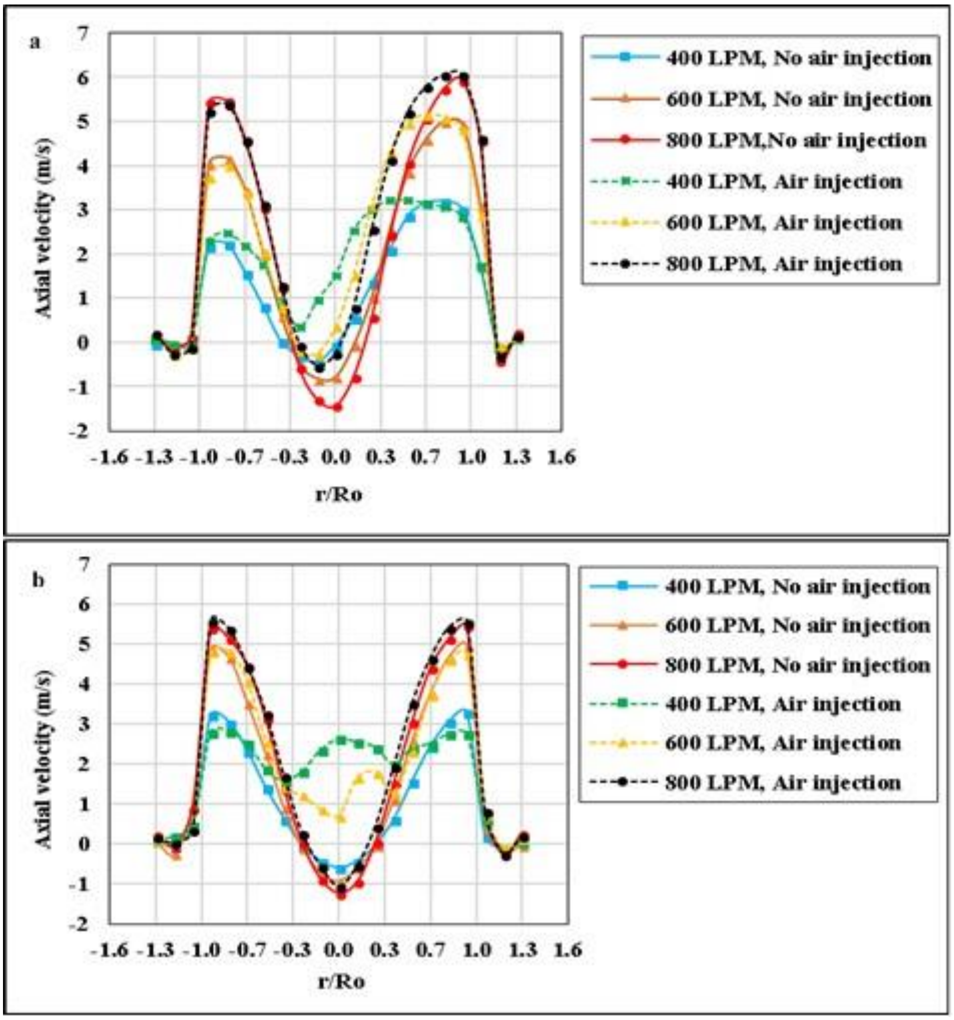


**Fig 5.** LDA Results, effect of both the position of the central air injector and total airflow rate on the location of the CRZ, a) $L_o$=0 mm; b) $L_o$=150 mm. Isothermal conditions, Y=5 mm.

As for the turbulence, results demonstrate that the increase in turbulence plays also an important role in flashback resistance. Isothermal tests, Fig. 6, show that the location of the central injector enhances (i.e. $L_o$=0 and 29 mm) or reduces ($L_o$=150 mm) turbulence at the dump plane, consequence of the interaction at different magnitudes between geometry, central air injection and the tangential air flowrates.

However, the previous results could have been obtained at the tip, inside or outside the CRZ, thus showing details of different phenonema, i.e. CRZ, central air jet, mixing layer between structures, etc. Since the CRZ has been pushed back into the combustion zone to different locations across the flow field depending on the central injector position, it was still unclear that measurements were done inside or outside of the CRZ for each case, limiting correlation between conditions. Thus, a turbulence map of the entire flow field was reconstructed for two different central injector positions, i.e. $L_o$=29 mm and 150 mm, Fig. 7. It is clear from the results that the levels of turbulence caused by the $L_o$=29 mm injector are considerably higher than those by the injector located closer to the burner exit. When considering the region between r/Ro= 0.3 to 0.9 at $L_o$=29 mm, it appears that the RMS values are about 1.7 m/s compared to RMS ~1.0 m/s in the same region for $L_o$=150 mm.

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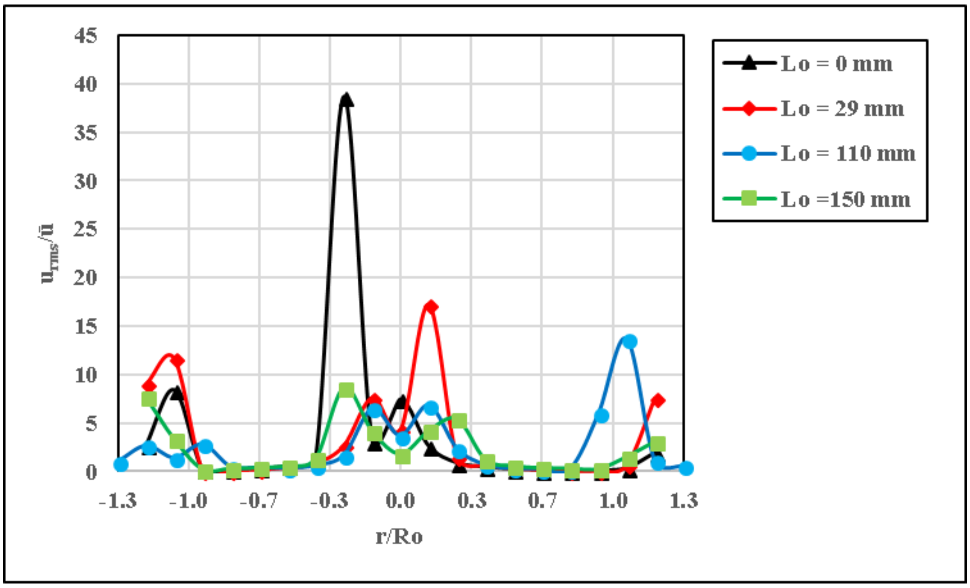


**Fig 6**. LDA results, effect of central injector position on turbulence, 800 LPM tangential flow rate, isothermal conditions, Y=5 mm.

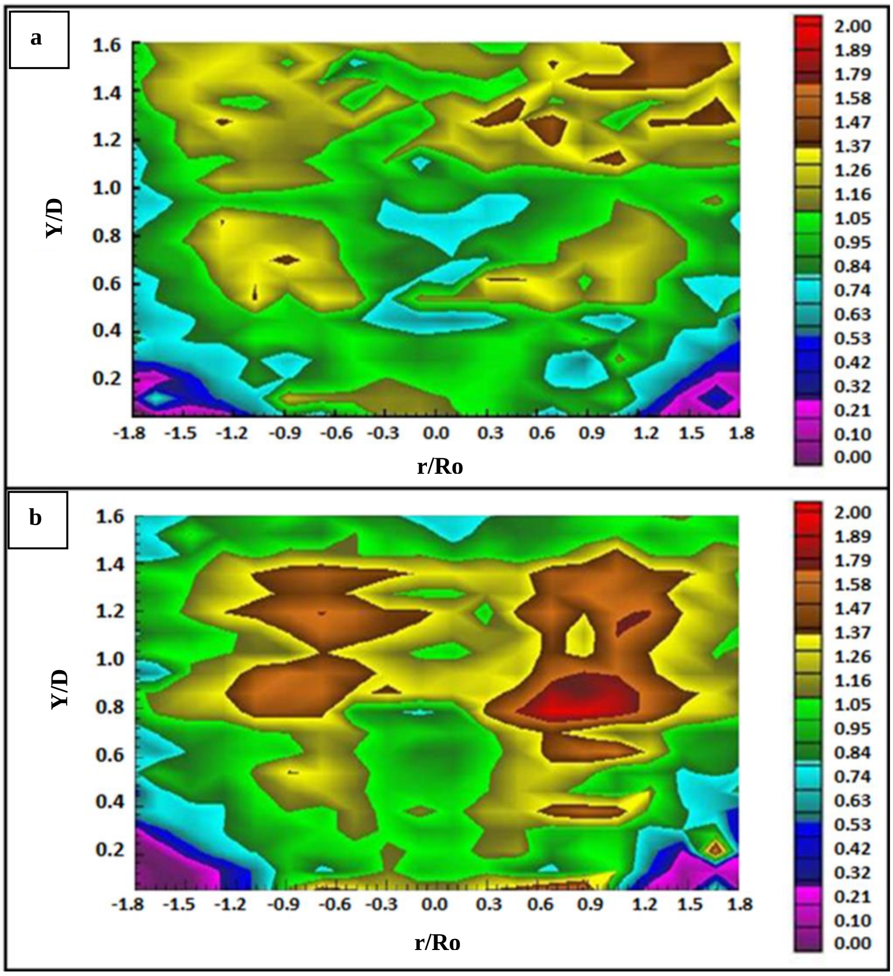


**Fig. 7.** Turbulence results with central air injection using a central injector at a) $L_o$=150 mm, and b) $L_o$=29 mm, isothermal conditions.

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*Central air injection combined with best central injector position*

Previous results demonstrated a better resistance to flashback when using a $L_o$=150 mm position. Therefore, the $L_o$=150 mm configuration was employed for the remaining of the experimental campaign.

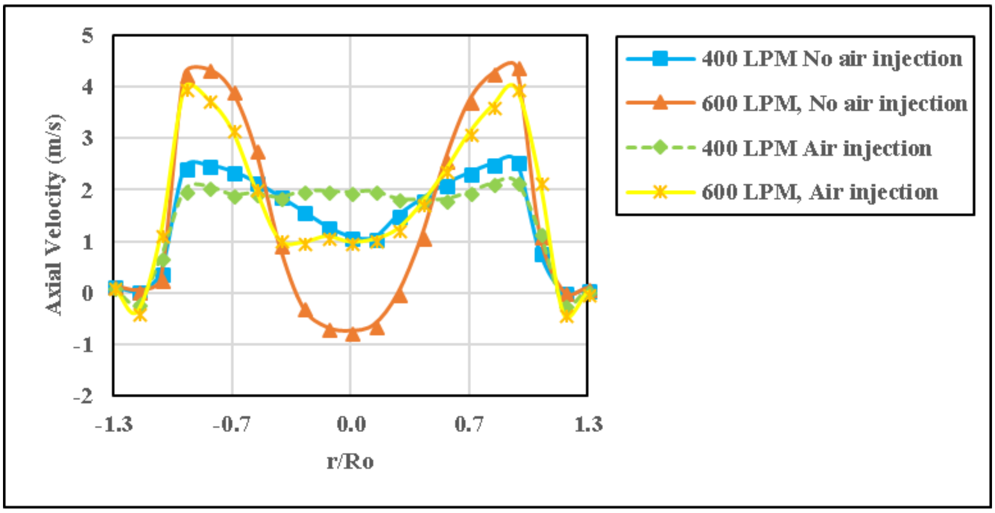


**Fig 8.** Effects of axial air injection on the defect of axial velocity, $L_o$= 150 mm, Y=5 mm, combustion conditions.

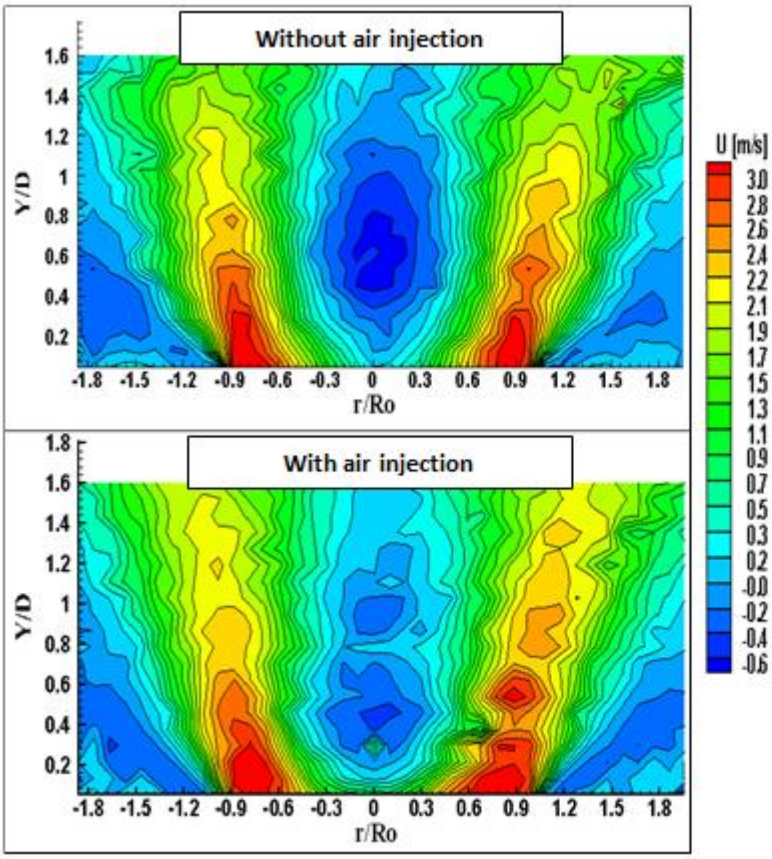


**Fig 9.** LDA results, Isothermal conditions. Effect of axial air injection on the velocity downstream the burner mouth and the position of the CRZ. Tangential flowrate 800 LPM.

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Figure 8 shows the amount of reduction of axial velocity defects (negative regions) under two moderate inlet tangential flowrates (combustion conditions). As previously documented, Fig. 5, higher flowrates are barely effective in reducing these defects at the tip of the central recirculation zone. Nevertheless, further analyses at higher flowrates, Figs. 9 and 10, show that although the tip of the CRZ has regained strenght and strong negative defects at this flowrate, a narrower vortex core appears in the flow field with central air injection.

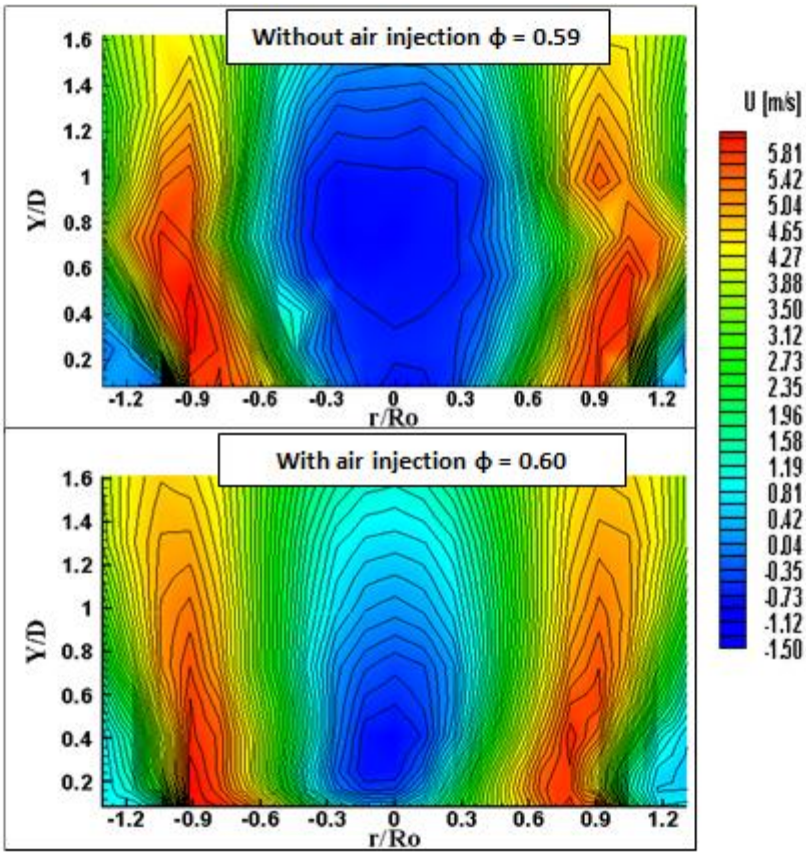


**Fig 10.** LDA results, Combustion conditions. Effect of axial air injection on the velocity downstream the burner mouth and the position of the CRZ. Tangential flowrate 800 LPM.

Velocity gradients, important parameters in flashback stability, were also considered. Figure 11 shows the difference in velocity gradient profiles when air injection is used. As observed, the axial air injection produces a flat region with low velocity gradients close to the dumping plane compared to those observed in the same region without central air injection. Thus, flame propagation across the central region of the flow field will be enhanced without air injection, deteriorating operability.

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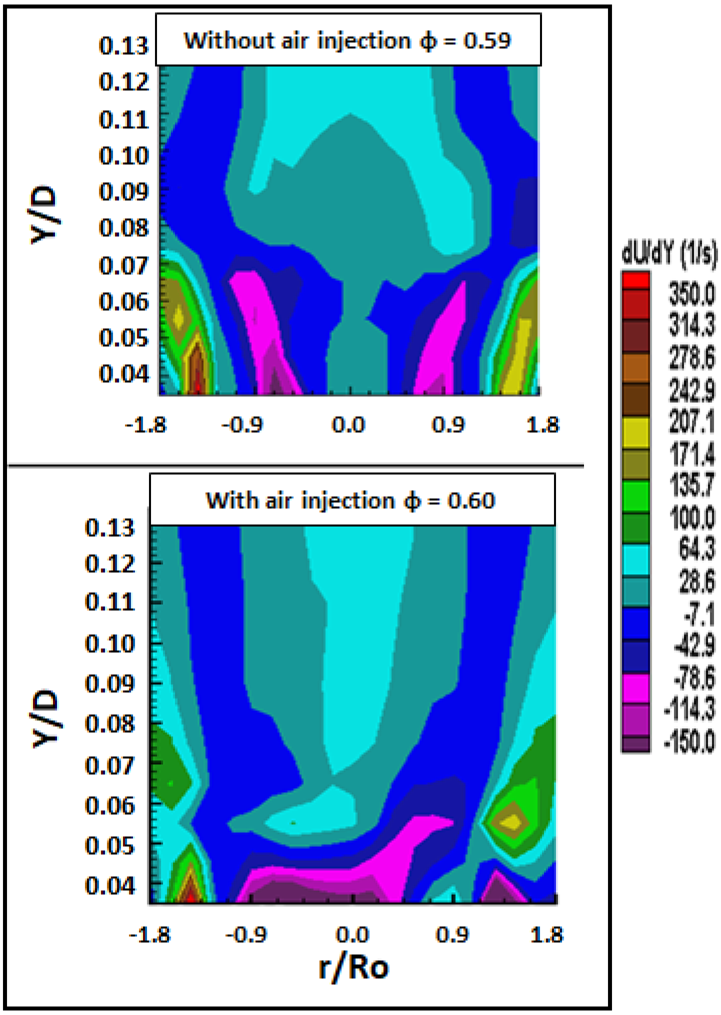


**Fig 11.** LDA results. Effects of air injection on the velocity gradient downstream the burner mouth (combustion conditions), 800 LPM.

## *Central air injection at best position combined with Microsurfaces for added BLF resistance*

Addition of microsurfaces to the best-placed central air injection was performed and analysed based on velocity gradient performance. Initial results show a sharp velocity gradient near the wall, or in other words, the velocity gradient becomes less than its critical value, hence initiating BLF, Fig. 12, without the use of microsurfaces and with central air injection located in its best position ($L_o$=150mm).

By increasing the nozzle wall surface roughness employing a 150 µm microsurface, the sudden variations from high-velocity values at the central axis of the nozzle to the low-velocity region near the wall are reduced, Fig. 13. The effect is related to the reduction of the boundary layer, which is controlled by the microsurfaces, as explained below. Consequently, lower gradients in the velocity values at the boundary layer region near the nozzle wall were achieved, overcoming the flashback event at this region, Fig. 13. Moreover, the use of the microsurfaces also had a positive impact on the reduction of the turbulence generated close to the nozzle, Fig. 14.

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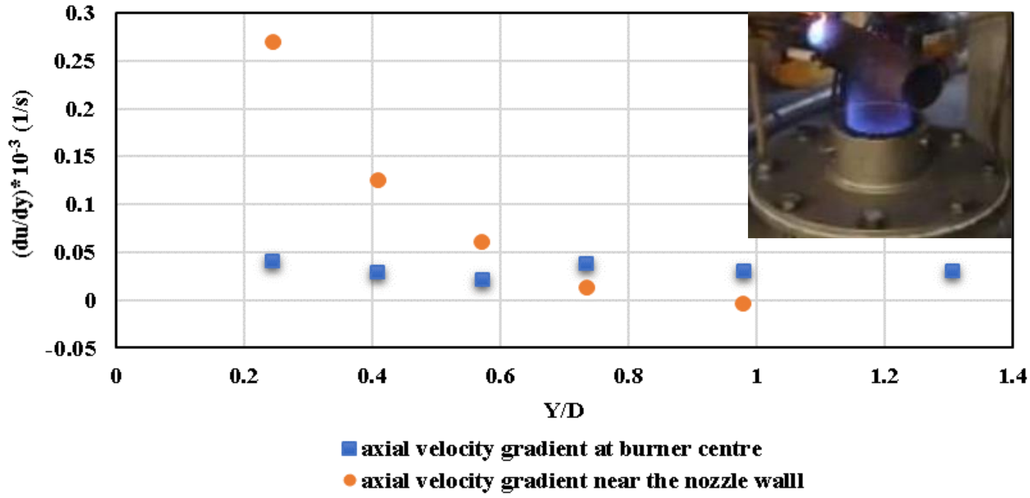


**Fig 12.** Difference in velocity gradient profiles at the centre and near the nozzle wall under the effect of central air injection during BLF.

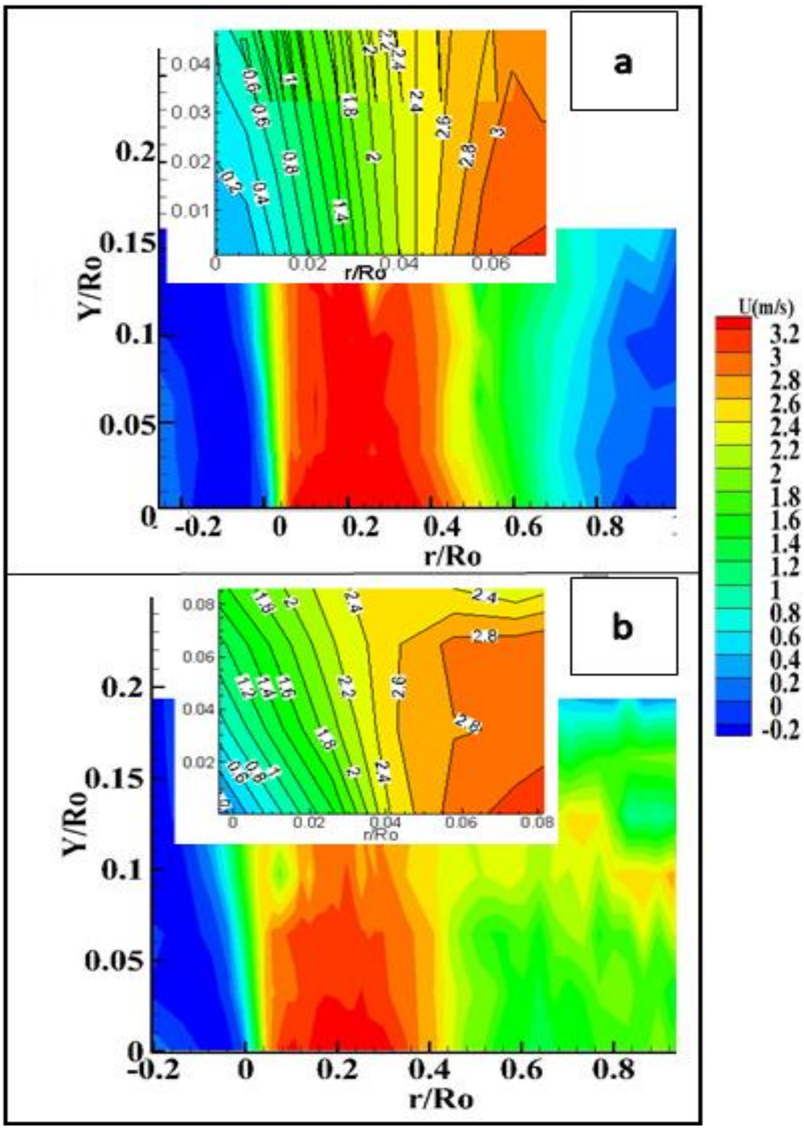


**Fig 13.** LDA results. Effects of nozzle wall surface geometry on velocity gradient close to the wall; a) smooth nozzle (no grid); b) with 150 μm microsurface.

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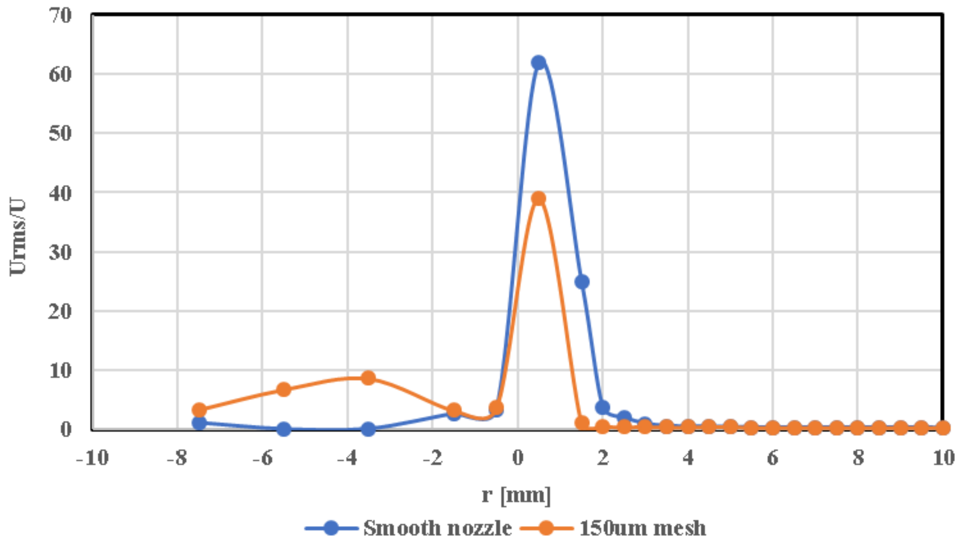
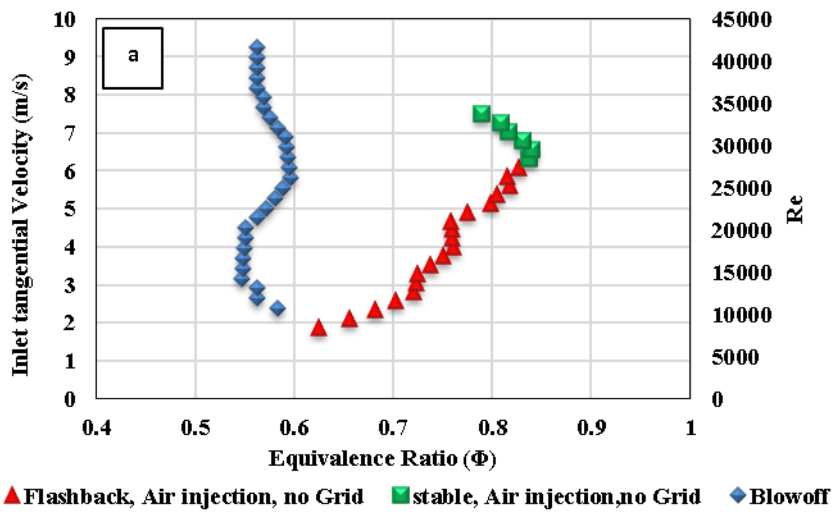



**Fig 14.** Effect of microsurfaces on turbulence intensity at the outelt of the nozzle.

Interestingly, the flame behaviour remained unchanged using the microsurfaces across the stable operational region. However, as the flame approached flashback, the flame became attached to the nozzle, thus modifying the behaviour of the flow field. The effect is demonstrated when considering the change in the burner stability map when using microsurfaces for additional flame stability. Figure 15 shows a comparison between two configurations, i.e. central air injection at best position and central air injection at best position plus microsurfaces. It can be observed that at a tangential velocity of 1.8 m/s (Re=10,783), blow off and flashback curves are very close to each other leading to a narrow stability region, Fig. 15a. Upon increasing equivalence ratio and tangential velocity (thus Re), the stability map became wider. However, there are still some limits over which the flame cannot remain stable, and a flame flashback occurs. The last condition where flashback is observed was a tangential velocity of 6 m/s (Re=32,932), Φ=0.83; beyond these values, no flashback was observed. However, when the microsurface was used for additional stability support, Fig. 15b, significant improvement in flashback resistance was achieved. The flame flashback was observed for inlet tangential velocity ranging from 2.0 to 2.8 m/s (Re=10,783 to 15,712); beyond this limit, no flame flashback occurs, and operation is stable for higher equivalence ratios and high tangential flowrates.



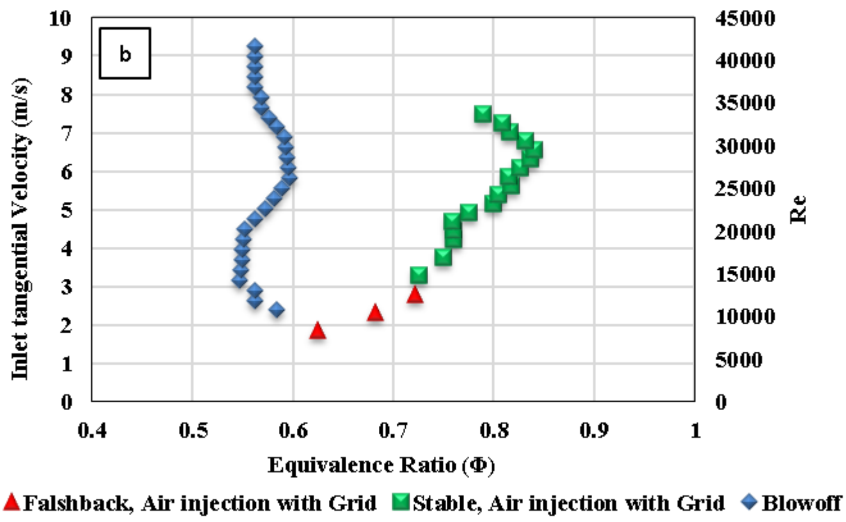



**Fig. 15.** Effect of using microsurfaces; a) central air injection without microsurface; b) central air injection with microsurface, respectively.

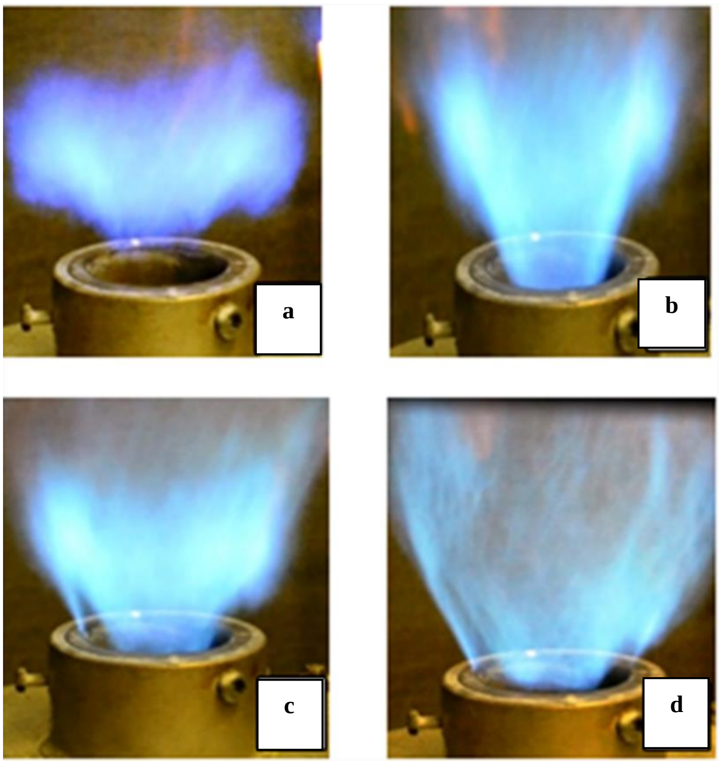



**Fig. 16**. Flashback resistance scenario for CIVB and BLF simultaneously.

Based on the previous results, it appears that the three flame flashback resistance mechanisms, i.e., central injector in the right position, central air injection and microsurfaces, can work together to achieve highly flame flashback resistance for BLF and CIVB. Figure 16 illustrates flashback resistance scenarios across different equivalence ratios, going from stable operation ($\Phi_{stable}$) to flashback conditions ($\Phi_{FB}$). Figure 16a represents stable operation where the flame is anchored downstream the nozzle. By increasing equivalence ratio, the flame propagates upstream, Fig. 16b. However, the axial air injection prevents CIVB. Upon increasing equivalence ratio, the axial air injection is still coherent enough to avoid upstream flame propagation, consequently enforcing the flame to propagate via outer shear layer, Fig. 16c. Further increase of equivalence ratio led the annular shear layer to become totally in contact with the nozzle microsurface, with no flame flashback noticed, Fig. 16d.

## DISCUSSION

After comparing previous studies with those performed in this work, it was recognised that consistency between theories is similar, i.e. improvement of wall boundary layers through the use of microsurfaces that led to better control of these regions, or the increase in flashback resistance in swirling flows via well positioned central injection. However, different to previous studies, these works combined these techniques increasing even further the final resistance as compared to those techniques used separately.

Initial data, Fig. 3, shows that the operating envelope shifts to richer conditions and becomes much wider over the equivalence ratio scale when central air injection is attained. Thus, stable operation with air injection is almost three times that of the central injector with no air injection. The phenomenon is linked to the relocation of coherent structures, i.e. which are pushed back into the combustion zone, and decrease of overal swirl number, i.e. extra axial air, which in turn reduce propensity of the CIVB. This outcome is of great importance due to the possibility of increasing power output while keeping the size and dimensions of the combustor, parameters necessary for aerospace propulsion applications. Moreover, since central air injection leads to wider operability margins, it enables smoother fuel switching, technical problem that has become one of the important milestones for modern, flexible gas turbines using alternative fuels [38]. Additionally, wider operation limits power input fluctuations, which is an important parameter when operating gas turbines on a baseload basis [40].

As previously presented, the study denotes a technique that employs central air injection to mitigate CIVB, phenomenon previously characterised somewhere else. While previous studies used this technique, they do not recognise that the central bodies can be subjected to harsh environments which in turn can lead to an increase in maintanance cost. Therefore, relocating the injector was also attempted, and interestingly, the relocation generated considerable variations in turbulence, thus affecting flashback propensity, a concept barely analysed and that through these works has been documented. The analyses demonstrated that the position of the central injector plays a major role in stabilising the flame. This is mainly because the central air jet is subjected to the high momentum tangential flow which in turn produces different pressure distributions and various turbulence intensities that are conveyed by the jet, leading to flashback occurring at lower/higher $\Phi$. As the central injector is moved upwards, operability increases. This behaviour is linked to the position of the central injector as it is protected from fluctuations generated from the interaction between flows, i.e. the incoming tangential air, central air and turbulence generated at the tip of the injector.

Combination of central air injection and position of the injector produce phenomena that affect flame stability based on two parameters, 1) how the central air pushes back the central recirculation zone to the burner with a decrease in swirl, and 2) turbulence generated at the dumping plane. Although the combined technique is effective at low/medium flowrates, greater tangential air flowrates (thus Re) produce greater impacts on the central air, probably by increasing mixing and turbulence, changing flame speed, reducing axial momentum and/or augmenting the strength of the CRZ.

As for turbulence, these assumptions can be correlated to the results in Fig. 7. Although the difference in RMS values between the two analysed cases ($L_0$ = 150 and 29mm) is not drastic, this phenomenon can produce a considerable change in turbulent flame speed values at the tip of the flame, thus also

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affecting the propagation of the flame inside of the burner as a consequence of an increase in turbulence, i.e. less resistance to flashback. Additionally, it is important to mention that this measuring position, i.e. Y=3 mm downstream the burner mouth, was difficult to obtain due to the reflection of one of the laser beams. Thus it is hypothesised that the region of high turbulence without injection extended towards the burner exit plane or even further inside the nozzle, hence increasing flashback. Although it is still unclear what structure/flow was measured in Fig. 6, it is evident that the profiles can be employed as an insight of the turbulence within the flowfield. Moreover, all the results confirm assertions on the turbulence parameter and how the location of the central air injector can lead to higher/lower turbulence, which in turn can affect combustion stability while promoting/reducing flashback via complex structure interactions that require further analyses.

As mentioned, central air injection promotes flame stability by affecting not only turbulence and mixing but also aerodynamic characteristics of the flow field downstream the burner mouth. It reduces the defect in the axial velocity at the tip of the recirculation zone with a decrease of turbulence, parameters that are the main reason leading to CIVB flashback [5]. It has also been elucidated that keeping the vortex core radius as constant as possible in the axial direction or at least decreasing with streetwise direction is recommended to achieve good stability conditions [43]. Moreover, central injection keeps the CRZ tip at a certain distance from the nozzle exit plane, Figs. 10 with injection, thus allowing an increase in volume expansion of the incoming flow under the effect of the heat generated from the flame, consequently preventing the formation of a strong recirculation bubble at the tip of the CRZ, which can lead to the onset of the CIVB [18]. Moreover, narrower CRZs product of the central injection lead to lower pressure gradients, consequently reducing the baroclinic torque and thus reducing the negative velocity of the recirculation bubble. This effect promotes better flame flashback resistance [41, 42].

Moreover, the study presents good correlations between effects of these techniques with the change of velocity gradients and turbulence generated across the central region of the flowfield and/or the zone located close to the wall boundaries, both characterised through this work and that demonstrated to be crucial for upstream flame propagation. Phenomena related to these effects have been poorly documented in previous studies, thus justifying the novelty and importance of the current works.

Since the velocity values change when the air is injected axially, it is predicted that velocity gradients change as well. Although higher variation in velocity gradients is one of the important features of swirling flows due to the existence of different coherent structures that have different velocity values and directions, this significant difference may promote sudden upstream flame propagation, especially CIVB. It has been reported that moderate increase of velocity in the streamwise direction characterises optimum velocity distribution for flashback resistance [43]. Thus, small velocity gradients product of a moderate, relatively constant axial injection are beneficial to improve CIVB flashback resistance. Moreover, the air jet at the burner axis can affect the mean pressure gradient; this in return enables suitable conditions for velocity to match the turbulent flame speed and hence allow stable flame operation.

Noticeably, using well positioned central injection alone produces wider operability, although the central jet forces the flow to propagate via wall boundary layer during the flashback event. Although using central air injection can considerably tackle upstream flame propagation through the central core, especially CIVB, some drawbacks can arise, as the system could be likely subjected to wall boundary layer flashback (BLF), especially at higher tangential flow rates. The reason for this effect is that the central air injection produces moderate velocity gradients at the burner central axis by affecting the local velocity values at the tip and inside the CRZ. Therefore, further mitigation of flashback can be attained by employing microsurfaces, leading to considerable enhancement of operability and reduced maintenance.

The use of microsurfaces reduces the shear flow layer between the flame and flow field, resulting in an environment more conducive for stabilisation of the flame. Another parameter observed on the flame behaviour was the reduced strenght of the central recirculation zone, Fig. 13.b, which is known to be a product of the baroclinic change in the flow region. Therefore, the decrease in velocity gradient produced by the microsurfaces might have the potential to even impact the formation and strengthenig of the CRZ, a point that requires further studies. Moreover, the use of the microsurface also had an impact on the turbulence generated close to the nozzle, Fig. 14. it is believed that the change in length scales product of the dissipation caused by the smooth surface will also have an impact on the improvement of the premixing of the reactants, thus enhancing flame speed at these locations and increasing flashback via BLF. Therefore, the use of microsurfaces shows a different effect, as the latter control eddies dissipation herain minimization of localized micromixing, hence promoting good flashback resistance.

Finally, the results showed that a combined technique that employs a properly located central injection with microsurfaces has the potential to considerably increase flashback resistance by enhancing three of the most commonly known mechanisms of propagation of such an instability, enabling researchers and industrials to keep moving forward towards the implementation of the concept in systems requiring more robust techniques to minimize the impacts of flashback, i.e. flexible, multi-fuel combustion system. This finding is of considerable interest for switching to higher power operations at constant equivalence ratios or switching to another fuel blend which might have stability operation regions overlapping with the original fuel stability margins [16]. Moreover, the high BLF resistance at high flow rates is very important in protecting the nozzle inside walls due to harsh environmental conditions or impingement effects when the flame comes in touch with the nozzle.

## CONCLUSIONS

This study provides a new alternative method for the avoidance of flashback in swirl combustors, increasing operability and leading to more flexible fuel usage with minimum retrofitting. Results demonstrate that by using central injectors at the correct position combined with central air injection can increase flame flashback resistance by pushing back into the combustor structures prone to Combustion Induced Vortex Breakdown while reducing the velocity gradient at the exit of the burner. Moreover, the position of the injector is crucial to decrease propagating turbulence that can impact on the flashback regime. Nevertheless, this method alone could lead to increase Boundary Layer Flashback as such stabilisation techniques force the flame to propagate via wall boundary layer. Therefore, increasing resistance to boundary layer flame flashback needs to be furtherely enhanced by restructuring the nozzle surface, which was accomplished using microsurfaces. The microstures have a direct impact on velocity gradient and turbulence intensity, which seem to be also affecting coherent structures such as the central recirculation zone, with beneficial effects on the stability of the flame close to flashback. The use of these three techniques combined showed a considerable increase on the stability limits.

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