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Experimental study to enhance swirl burner against boundary layer flashback

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Abstract

In gas turbine systems, operation stability represents the major challenge to any successful device deployment. Climate change combined with fossil fuel pollution has led to the need of considering high hydrogen content fuels, thus putting more pressure to stabilise gas turbines at operation conditions. Flashback is one of the main operation stability problems that represent a real challenge for gas turbine designers when using fast reacting fuels with high hydrogen content. One mechanism that has shown to contribute to flashback considerably is the propagation of the flame through its boundary layer. Although the latter has been studied, there are still several unknowns in its evolution through the system. Thus, boundary layer flashback of a swirling turbulent flame was investigated in a 150 kW tangential swirl burner previously characterised. To produce controlled changes to the boundary layer, the internal side of the burner was covered by woven wire steel mesh to mimic biological skin techniques in flow drag improvement. Two different wire meshes were used to study the effect of the regular roughness size on the boundary flashback. Moreover, the effects of using the wire mesh in such swirling flow with and without central air injection for reduction of other flashback phenomena were studied. The results show good enhancement of the system to boundary layer flashback, and a new map of the combustion stability of the rig has been produced.

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Keywords: BLF, Woven grid mesh, swirl burner, velocity gradient.

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1. Introduction

The ambition to develop gas turbines that are capable of using different fuels ranging from natural gas to syngas with high hydrogen content usually collides with operability issues in the form of instabilities such as blowoff, combustion instability, autoignition or flashback [1]. Flashback and autoignition represent high-risk phenomena for hydrogen-containing fuel mixtures as a consequence of both fast chemical reaction rates and high flame speed of hydrogen in the air. Flashback occurs when the flame propagates upstream from the combustion chamber into the premixing section [2]. This instability has different propagation mechanisms when swirling flows have been imposed. The most common are core flashback, combustion induced vortex breakdown (CIVB) and boundary layer flashback (BLF) [3].

Flashback in the boundary layer was firstly studied by Lewis and von Elbe for laminar flames [4]. 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. Later this formula held a cornerstone position in most of the boundary layer flashback studies. This model was developed even further in term of the pressure effect on the velocity gradient in laminar flames [5]. 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 [7]. Thus, the relation between pressure and flashback in laminar and turbulent flames was studied deeply by Fine [8] who reported that at a constant pressure the critical boundary velocity gradient for turbulent flashback was significantly larger than that for a laminar flashback. It was 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 [1] in a study of turbulent wall flashback of H_2 flames using a temperature controlled rim burner. However, this ratio varies with equivalence ratio, especially towards the rich mixtures. Models and corrections were performed based on ambient, preheat mixtures, atmospheric and experimental pressure. The critical velocity raised up to 60 percent due to pressure raising from atmospheric to engine pressure which required reduced equivalence ratios to avoid boundary layer flashback, as boundary layer flashback propagates in the wall boundary layer in the presence of a diffuser [2]. A μ-PIV experimental study [3] showed that the flame near the wall leads to streamlining curvature and to the formation of a separation bubble upstream of the flame followed by Wall BLF if the reactant production exceeds a threshold value.

Other experimental studies have been conducted to visualise different flashback mechanisms for H_2/CH_4 mixtures in variable swirl burners using high speed OH chemiluminescence imaging [4]. For the boundary layer flashback, the authors stated that flashback started in the low-velocity region of the boundary layer and the flame inclined towards the wall of the premixing tube. A study injecting additional fuel tangentially in the swirl burner was conducted by Sattelmayer et al. [5]. The purpose of the study was to achieve a better flashback resistance than in the premixed case by creating a radial fuel distribution at the mixing tube outlet. The study focused on the interaction between CIVB and wall boundary layer flashback and showed that optimising the system against one mechanism worsens the system against the other. In the same tone, the air was injected at the centre of the burner at different positions of a central injector to the baseplate of the burner[6]. The study showed that using axial air injection enhances the CIVB resistance limits. Thus, the technique can be used to minimise the CIVB effect while designing for the reduction of BLF. 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, where the flame starts to generate a conical flame bubble in the centre of the downstream flame zone.

The velocity gradient at the wall in swirling flows is determined by the wall shear stress, not by the local shear stress, suggesting the influence of wall shear stress as a dominant parameter and that it determines the near-wall flow even in flows with curvature and pressure gradient [7]. It is known that the shear stress can be reduced through using micro extended surfaces from the wall. Such a reduction leads to better velocity gradient at the wall with drag reduction in the flow [8]. In previous work, the authors show that using combined burner nozzle with regular roughness wall and central air injection improve a swirl burner against boundary layer flashback and CIVB[9].

Microsurfaces for drag reduction to increase resistance to boundary layer flashback have been well reported [10]. A laminar boundary layer will transit to turbulent due to kinetic energy transmission from the free stream flow into turbulent fluctuations and then dissipated 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 flow the laminar sublayer thickness is very small which means that the tips of the microsurface would penetrate the layer, thus allowing the grooved surface to play a role of damping turbulence and reducing drag [11, 12] . Effectiveness of ribblets on drag reduction is directly connected to their shape. A small patch of ribblets with different shapes in different patches in a fully turbulent duct flow was simulated. Initial correlations were performed to compare previous works with the numerical approach carried out in this study. The findings demonstrated good correlation showing that a blade shape microsurface can reduce drag up to 11% [13].

Thus, this study was intended to extend studies on the effect of having a micro surface wall in a swirling burner under conditions close to boundary layer flashback. Experimental trials took place on the same experimental rig of [6] after modifying the internal burner walls to enhance the system resistance to boundary layer flashback using a woven wire steel mesh. Air central injection was used to avoid CIVB propagation. The study covered the effect of using regular or pre-shaped surfaces and how these enhance the fluidic properties of the field based on many studies that use small riblets on surfaces to enhance the reduction of drag resistance inflows [14].

2. Experimental setup

The 150 kW tangential swirl burner used in this work is illustrated in Figure 1. Many investigations on swirling flow stability have been performed using this combustion system [6, 15, 16]. The burner has two tangential inlets of 67 mm in diameter; the exit diameter is 78 mm. The diameter of the tangential inlets can be varied using different inserts, while the exit diameter can be changed using different nozzle configurations. Thus it is possible to have variable geometric swirl numbers from 0.913 up to 3.65, Figure 1.

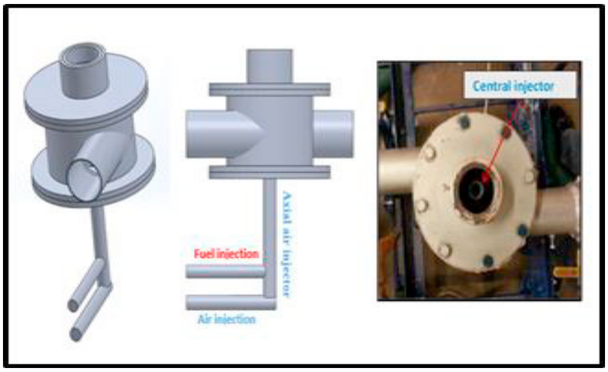

Figure 1. 150kW tangential swirl burner.

The burner uses a dual fuel-air injector at the centre of the baseplate. To start combustion, fuel is injected first through the injector. Then, the central injector is shut once the tangential premixed fuel is supplied, ensuring stable combustion conditions. In this study, the air was also injected through the injector in the axial direction after the fuel was shut down. A 62.4mm in diameter and 25mm in depth nozzle was used. Two pieces of stainless steel 316 woven wire meshes were fitted firmly to the internal wall of the nozzle, Figure 2 and Figure 3.

The wire meshes were 50μm and 150μm in length between valleys. The mesh were cut and fixed firmly to the inner wall of the nozzle to ensure the aerodynamic stability of the flow and to provide flow conditions close to the ones without the meshes. An LDA system was used to obtain the isothermal velocities downstream the nozzle. A matrix of point with variable distances was used to record the velocity values from 1mm to 15mm downstream the nozzle, then the recorded points were transferred to TECPLOT360 R2 to plot the results and obtain a contour distribution for the velocity.

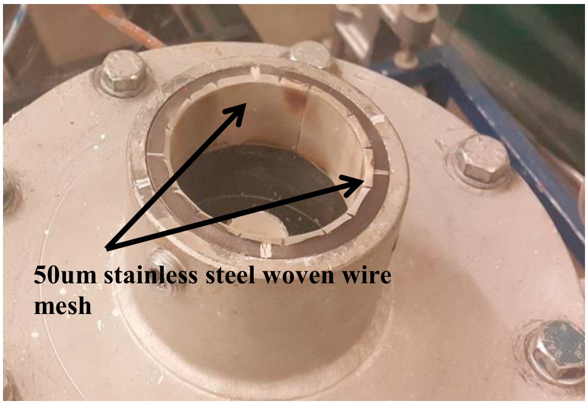

Figure 2. Woven wire steel mesh underlying the nozzle inner wall.

Figure 3. Nozzle with 150µm wire mesh.

3. Results and Discussion

In figure 4, the axial velocity downstream the nozzle is ploted. The results show that the axial velocity gradient is affected by changing the wire mesh. The results show that the velocity gradient in the radial direction was decresed with the increase of the wire mesh as shown in figure 5, which means that the high velocity region is shifited towards the nozzle wall as shown in figure 4. The velocity gradient in the downstream direction shows some important results regarding the impact of these structures on the flow. The velocity gradient in the downstream direction for the nozzle with the 150 µm mesh is less than the velocity gradient for the 50 µm mesh, which means that the wall effect on the near wall layer of fluid is less than the effect in case of the 50 µm, also the outer fluid interaction with the swirl flow is less when using a 150 µm geometry, with a lower velocity decay downstream. This result is important because it explains the improvement in boundary layer flashback when using these mesh wires. 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.

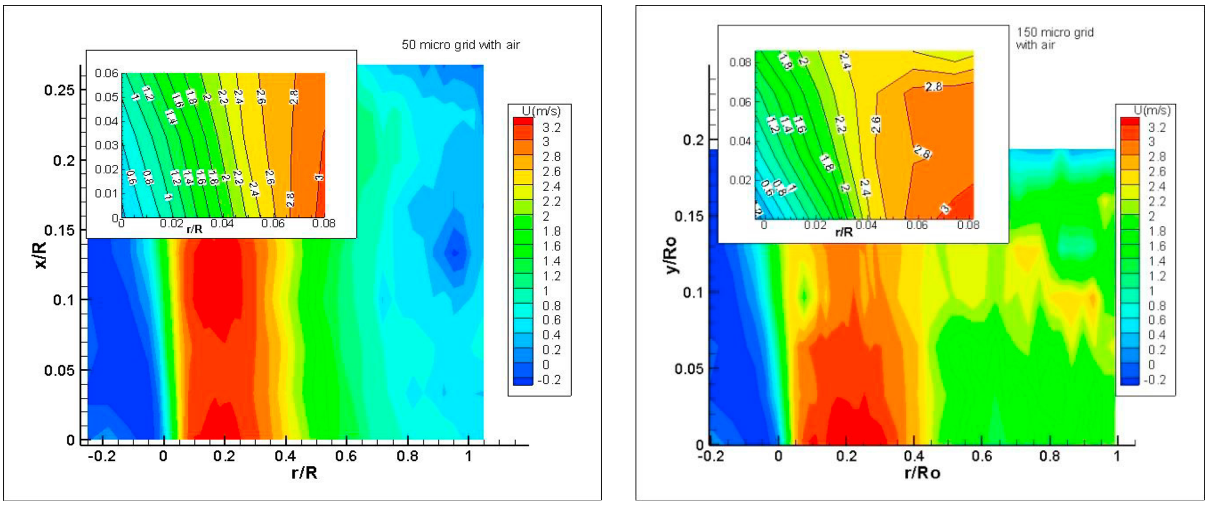

Figure 4. Axial velocity downstream the nozzle with 50 µm (left) and 150 µm (right).

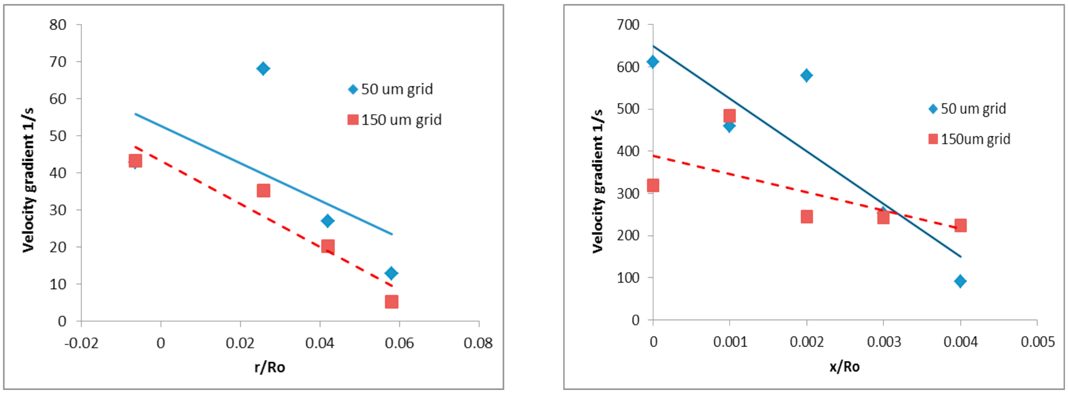

Figure 5. Velocity gradient in the radial direction (r/Ro) (left), and in downstream direction (x/Ro)(right).

4. Conclusion

The effect of the wall roughness on the boundary layer flashback in a tangential swirl burner was studied using stainless wire mesh liners from 50 µm to 150 µm. The regular roughness that is provided by the wire mesh helps to alter the velocity gradient near the nozzle wall. The velocity gradient in the radial direction shows that the smaller wire has greater gradient values than the larger one, althougth the value of the velocity is higher in case of the larger mesh. The velocity gradient in the downstream direction was sharp for the case with a small wire, which means that the velocity decays faster compared to the case that used the 150µm mesh. The results shown in this work support the result that have been published in previous works.

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