Investigation of Boundary Layer Flashback Enhancement in Swirl Burner Using Woven Wire Mesh.

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Abstract

Operation stability problems are amongst the main concerning issues during successful gas turbine design. Extensive studies are dealing with problems such as unstable phenomena caused by new blends or power conditions to find the best and most economical solution. Flashback is one of the main operation stability problems that represent a real challenge for gas turbine designers when using fast reacting fuels. One mechanism that has shown to considerably contribute to flashback 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. In order to produce controlled changes to the boundary layer, the internal side of the burner was covered by a 50 µm woven wire steel mesh. 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 result shows a good enhancement of the system to boundary layer flashback, and a new map of the combustion stability of the rig has been produced.

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 air. Flashback occurs when the flame propagates upstream from the combustion chamber into the premixing section [2]. Flashback has different propagation mechanisms in swirling flows, however 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 corner stone 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 BL 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 laminar flashback. It was proposed that a turbulent flame near flashback stabilized 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 [9] 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, where 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 presence of a diffuser [3]. A µ-PIV experimental study [10] showed that the flame near the wall leads to streamline 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 visualize different flashback mechanisms for H2/CH4 mixtures in variable swirl burners using high speed OH chemiluminescense imaging [2]. 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. [11]. 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 optimizing the system against one mechanism worsens the system against the other. In a more recent study [12] air was injected at the centre of the burner at different positions of a central injector to the baseplate of the burner. The study showed that using axial air injection enhances the CIVB

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resistance limits. Thus, the technique can be used to minimize the CIVB effect whilst designing for the reduction of BLF.

Thus, in order 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 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 [13]. 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 [14].

From all above studies the effect of the burner surface pattern on boundary layer flashback has not been considered yet. Thus, this study was intended to perform studies on the effect of having a microsurfaced wall in a swirling burner under conditions close to boundary layer flashback. Experimental trials took place on the same experimental rig of [12] 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 in flows [15].

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 [12, 16, 17]. 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.

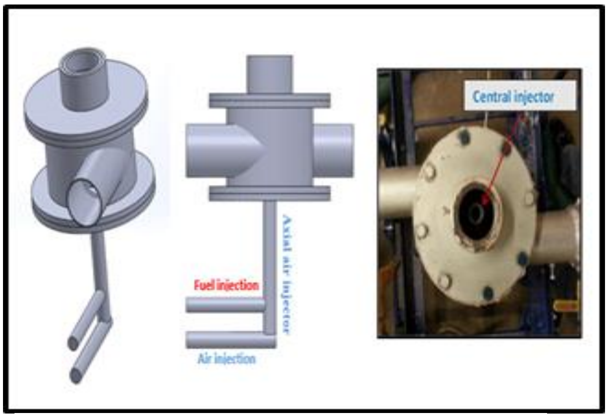

Figure 1 A 150Kw tangential burner

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 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. A piece of stainless steel (316) woven wire mesh was fitted firmly to the internal wall of the nozzle, Figure 2.

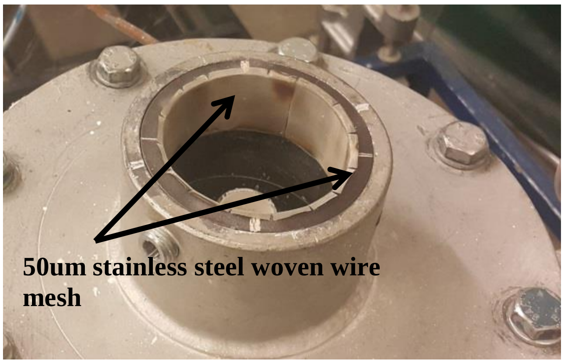

Figure 2 woven wire steel mesh underlying nozzle inner wall.

The wire mesh was 50um in diameter and 200 holes per square centimetre in total. The mesh was 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 mesh.

Theoretical background

Flame flashback mechanisms can be significantly affected by any change in the geometry of the combustor. Burner geometries and configurations play an important role in the operation stability layout; in swirl combustors the interaction of these geometries with swirling flows can alter the flow field characteristics significantly. Many configurations can be used to achieve good stability limits. However, flame flashback mechanisms in swirl combustors are so complicated that to achieve good flame flashback resistance geometrical changes should be able to support a good resistance to different phenomena. Using central fuel injectors as bluff bodies or central air injection can increase flame flashback resistance against turbulent core and combustion induced vortex breakdown flashback; however, these two passive controllers will have drawbacks in terms of boundary layer flashback BLFB, as the existence of a central fuel injector can enforce the upstream propagation to occur via the annular flow region. Therefore, any combustor should have good flame flashback resistance for both turbulent core and boundary layer flashback at the same time. In this work a central fuel injector and diffusive air injection have been used to support flashback resistance against turbulent core or CIVB flashback which in turn enforce the flashback mechanism to occur via boundary layer.

A microsurface that ensured a “sharkskin” effect to increase the resistance to boundary layer flashback was then employed. The boundary layer is generated when a fluid passes over or gets in contact with a solid surface or other different density fluids at different velocities. Boundary layers could be laminar or turbulent depending on fluid flow circumstances. A laminar boundary layer transits to turbulent due to kinetic energy transmission from the free stream flow into turbulent fluctuations and then dissipates into internal energy through viscous action as a drag force. The drag force is commonly categorized into pressure and skin friction drag. Thus, sharkskin riblet microstructures generally reduced the skin friction drag by effectively controlling the naturally occurring turbulent velocities, which lead to less momentum transfer and shear stress. Effectiveness of riblets on drag reduction is directly connected to their shape. In a previous work, the authors showed in a numerical simulation that the best shape for drag reduction is a blade shape where the reduction was around 11% [18].

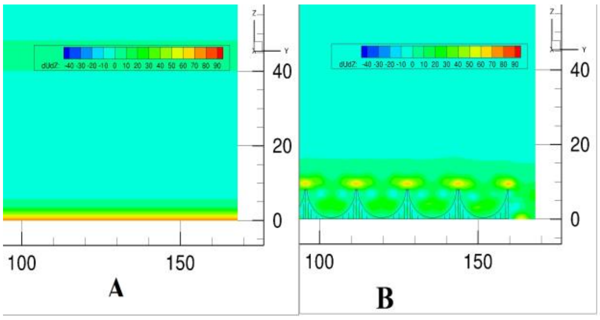

Figure 3 Velocity gradient at wall for flat plate (A) and scallop riblet (B) [18]

However, blade riblets are very weak structures and very difficult to manufacture especially on metallic surfaces. Therefore, other more “manufacturable” surfaces were assessed and experimentally tested to determine turbulent intensity and boundary layer thickness for isothermal air flows as shown in Figure 3. The tested shapes (i.e. diamond, louts and scallop) were manufactured using Wire Eddy Discharge Machining (WEDM) [18].

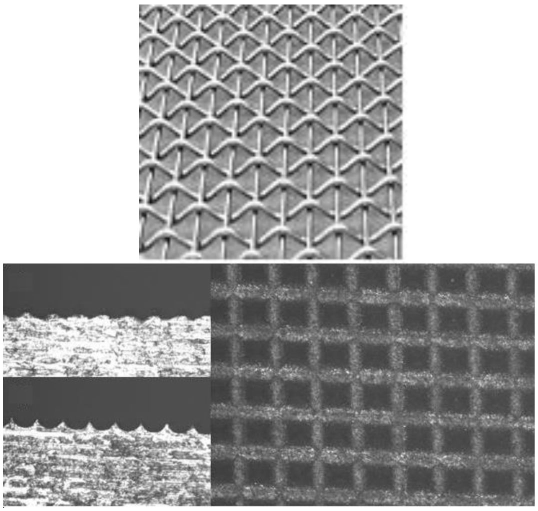

Figure 4 The structure of woven wire mesh (up) and louts riblet structured by WEDM (down)

Experimental results showed that the louts and diamond structure had a good reduction on turbulent intensity near the wall which led to a good drag reduction. However, WEDM is limited by the wire diameter, structured dimensions, corners, curves sharpness and access to the work piece itself. Therefore, construction of louts or diamond riblet shapes inside a burner tube was nearly impossible. The alternative way to have a structure with nearly similar patterns inside the burner nozzle was by using a woven wire stainless steel as shown in Figure 2. The shape of plain woven stainless steel and the louts’ structure are shown in Figure 4, denoting a good correlation between both. The wire mesh of 50um in diameter, i.e. similar to the lotus design in size and protruding shape [18], was used as an internal nozzle liner. The effects on BLFB were investigated.

Results

Figure 5 illustrates the flame flashback mechanism of the tangential swirl burner using three different configurations.

When the central fuel injector is used to promote flame stability (configuration 1), the flame flashback trends are located at an equivalence ratio ranging from Φ = 0.6 at low flow rates to Φ= 0.8 at high flow rates. The flashback trend remains up to tangential velocity values of Wt =4.7 m/s, after which no flashback is observed and stable flame was achieved.

When using a metal grid as interior liner of the nozzle (configuration 2), the flame flashback slightly enhances. This occurs at slightly higher equivalence ratios with a tangential velocity of Wt =3.7 m/s after which no flashback was observed.

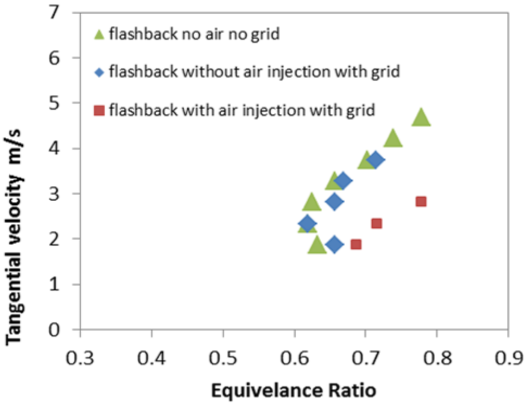

Figure 5. Flashback trend using different configurations, above the trend points the area is represent stable operation

The last configuration (configuration 3) used a central fuel injector, central air injection and boundary grid. Considerable enhancement in flame stability was achieved, as flashback occurs at limited low flow rates, and the configuration enables stable burner operation from Wt =2.7 m/s onwards. Despite of some upstream flame propagation towards the nozzle via boundary layer, even at higher flow rates the existence of the grid prevents upstream propagation as can be seen in Figure 6. This outcome of the effect of using different configurations to achieve wider operability is of high importance in terms of possibility to switch from one fuel to other while maintaining constant output power. Thus, effects of this configuration on burner stability are more obvious when correlating the total mass flow rate with equivalence ratio.

Figure 6. The flame rests out the tube burner rim. The air injector resists CIVB and the grid fights the BLFB.

Conclusions

Three configurations were used to study the effect of burner tube internal micro-riblets on the boundary layer flashback in a swirl burner system. The first configuration used the default system which is comprised by the swirl burner without air injection and without microsurfaced liner. The second configuration used microsurfaced linear and no air injection, while the third configuration used the microsurfaced liner and central air injection. The results show a good enhancement in stability region for the second configuration and excellent stability region enhancement for the third configuration compared to the default configuration. This is a consequence of an improvement on the resistance of the Boundary Layer Flashback due to an enchanced boundary layer at the nozzle of the system.

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