Experimental Investigation of the Effects of Fuel Diffusive Injectors on Premixed Swirling Flames

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Abstract

The demand for alternative fuels has increased significantly during the previous decades in order to reduce pollutants and increase the amount of energy that can be generated from non-fossil fuels. However, the use of new fuels faces many issues especially the problem of stability of operation which sometimes can cause severe damages to the system hardware. Thus the development of flexible combustion systems for gas turbines becomes urgent in order to achieve high reliability with these new sources of energy.

Swirl stabilized combustion is the most widely spread deployed technology used to stabilize and control combustion in gas turbines and numerous other systems. However, the interaction of the swirling flows with the burner geometries is very complex and it has been proved that any change in the burner geometry can affect the flow field inside the combustion chamber, close to the burner mouth and downstream the combustion zone. Most burners are generally provided with a diffusive injector that centrally delivers well-known fuels allowing the stabilization of the system previous to entirely premixed conditions. Moreover, the injector anchors the central recirculation zone formed downstream of the nozzle. However, the use of injectors can also affect the stability limits of the system, especially the propagation of flashback through changes of shape of the shear layer since other structures such as the Combustion Induced Vortex Breakdown are suppressed due to the presence of this central body. However, the characterization of the flow and its impacts on the propagation of these and other flashback structures using different injectors has been briefly documented.

Thus, this paper presents a series of experiments using a well-characterized tangential swirl burner to determine the impact of different central injector geometries on the flow field characteristics which directly affect the flow stagnation point downstream of the burner mouth and consequently the propagation of the Combustion Induced Vortex Breakdown. Results show how the use of various injectors and swirl numbers can impact on the flashback limits with a minimum outside diameter before which the Combustion Induced Vortex Breakdown is altered.

Nomenclature

CIVB = Combustion Induced Vortex Breakdown
CRZ = Central recirculation zone
D = Burner exit diameter
HMFR = High momentum flow region
OD = Central injector outside diameter (m)
OD_M = Minimum diameter before transition (m)
R_e = Rynolds number
W_{in} = Inlet tangential velocity (m/s)
Φ = Equivalence ratio
χ = outside injector diameter to inside nozzle diameter ratio

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I. Introduction

The global trend towards using low NOx alternative fuels has increased significantly. Consequently the motivation to develop new flexible combustion systems has augmented. However, the improvement of these systems still faces a lot of difficulties related to operation stability. The flashback phenomenon is still one of the key operability issues amongst the stability limits of any premixed combustion system due to the possibility of damaging the system hardware. Swirl stabilized premixed combustion is the dominant technology used to get control stabilized combustion in gas turbines and other combustion systems. Nevertheless, swirl burners with lean premixed combustion are prone to the following flashback mechanisms [1],

-Flame propagation in the wall boundary layer

-Turbulent flame propagation in the core flow

-Combustion instabilities, and

-Combustion induced vortex breakdown (CIVB)

Combustion induced vortex breakdown [2] has been identified as one source of sudden flame transition and flashback in swirl combustors where this sudden transition can cause severe system failure due to the risk of overheating of upstream burner positioned components.There have been considerable efforts and research focused on the understanding of this phenomenon [2-8]. However, there are still areas of improvement that need to be assessed.

The earliest study that denotes this new type of flashback was carried out by Kröner et al[2]. The group studied the flashback limits of a swirl burner with a cylindrical premixing tube without using canter bodies. They found that the quenching of the chemical reactions is a governing factor for flashback limits. Another study [1] found that the propagation of the vortex breakdown was induced by the change of pressure boundary conditions at the combustion chamber inlet due to chemical reactions.

The group also used the vorticity transport equation [4] to analyse the source terms of the azimuthal components of the flow. They found that the CIVB is initiated by the baroclinic torque which produces considerable levels of negative axial velocity in the vortex core. The effect of changing the equivalence ratio on the axial position was correlated to the phenomenon of the stagnation of the recirculation zone. According to their investigation the distance between the upstream flame tip and the position of the stagnation point is a crucial factor which plays the main role in the onset of the CIVB. If the reaction zone can pass the stagnation point this leads to an increase in volume expansion, hence positive axial velocity thus preventing the onset of the CIVB. However, further upstream flame propagation (i.e. further increase in equivalence ratio) means an increase in the baroclinic torque, hence high possibility of CIVB occurrence, Konle et al [3].The analysis was carried out on the transient behaviour of the flame using high speed PIV and LIF measurements near the onset and during the occurrence of the CIVB. It was found that the CIVB flashback is governed by the interaction between turbulence and chemistry at the tip of the recirculation bubble.

All these works showed that the interaction between the flow field and the heat release from the combustion process is the crucial factor which defined the stability regime close to the burner mouth. This is governed by the fuel type, composition, unburned mixture conditions and local stoichiometry, meaning that it is necessary to understand the effect of fuel type as well as the swirl burner geometry in terms of their impacts on the turbulence close to the burner mouth.

The effects of fuel variability show this complexity when using blends with high hydrogen content where the percentage of hydrogen in the mixture plays the dominate role for the occurrence of the CIVB. Several authors [8-10] stated that the behaviour of fuel mixture can be significantly different than that of individual constituents. Syred et al [11, 17] showed considerable difference in flashback blowoff limits when increasing the hydrogen content of the fuel, whilst demonstrating that these limits could be correlated with the inlet tangential velocity level..

Regarding geometrical issues other works have investigated the effects with the change in geometry to find out the possible enhancement of flashback resistance. Axial injection was one of the successful mechanisms to reduce the possibility of flashback occurrence, although clearly we are now dealing with paretially premixed combustion. It was used by Reichel and Paschereit [12] to reduce the deficit in the axial velocity and change the location of vortex breakdown which positively influence flashback resistance. Other works[3] have found that the increase in the diameter of the central injector will increase the thickness of the vortex cores and strengthens the axial flow velocity thus the vortex breakdown is shifted downstream producing better flame stability. Another groups [13] investigated two types of fuel injection, i.e. axial and trailing. They found an improvement of the flashback resistance by using axial injection when compared to trailing injection. This was done by adding rows of injector holes placed along four trailing edges of a vaned type swirler.

Another study about the effect of diffusive injection of different fuel gases was carried out by Lewis et al[14]. They found that characteristic coherent structures change significantly according to the type of gas used. Moreover, a correlation about the mutual effect between the high momentum flow region and central recirculation zone was postulated. According to this theoretical correlation the combustion induced vortex breakdown occurs when the CRZ is squeezed by high momentum flow region (HMFR) that envolves with the flow.

Based on these works it appears that although considerable work has been done on the characterization of these combustive flows and associate coherent structures, there are still many unknowns. The effect of different geometries and fuels on flashback phenomenon is still generally only predictable in a qualitative sense.

The role that central injectors play in the propagation of flashback is of special interest as it could reveal the stability limitis associated with the CRZ, associated shear layer and how modes of flashback can change with geometry and fuel type. The shape and dimensions of the injectors need more research to find out the minimum and maximum limits at which the flashback resistance can be improved whilst keeping low emission levels. Another important feature that needs to be considered is the change of swirl number which can be considerably affected as a result of changes in geometry. Therefore the present work investigates the effect of different central injector geometries on flashback using a well-characterised tangential swirl burner, and uses earlier work to illustrate how the mode of flashback can alter as geometry and swirl number change.

II. Experimental setup

A 150 KW Tangential generic swirl burner was used, Fig. 1. This system has been extensively used to investigate flame characteristics and other combustion features by using different configurations[15-19]. It has two tangential inlets of 67mm diameter which can be changed by using different inserts blocking of 25%, 50% and 75% of their total area, giving swirl numbers ranging from 0.913 to 4.5, Table 1. The burner exit diameter is 76 mm, D, which can be changed by using different nozzle configurations, Fig. 2a. Seven central fuel injectors with different outside diameters (diffusive injectors; 7.0, 12.5, 16.0, 18.0, 19.0, 21.3 and 23.5 mm) and the same length (175mm) were used, Fig. 2b.

Fig. 3 shows the position of the injector inside the swirl burner. Experiments were done using all these injectors, nozzles and inserts without confinement. Air was provided by a centrifugal fan via flexible hoses and two banks of rotameters were used to control the air flow and natural gas injection, respectively. Two modes of fuel injection were utilized; a diffusive mode where the fuel is injected via the central injector, and premixed injection where the fuel is injected through the tangential inlets just before the inserts, fuel always being natural gas. The former is used to start up the system, and once a stable flame has been achieved premixing is added to the flame. Diffusive injection is slowly shut down once that stability with high premixed fuel rates has been achieved.

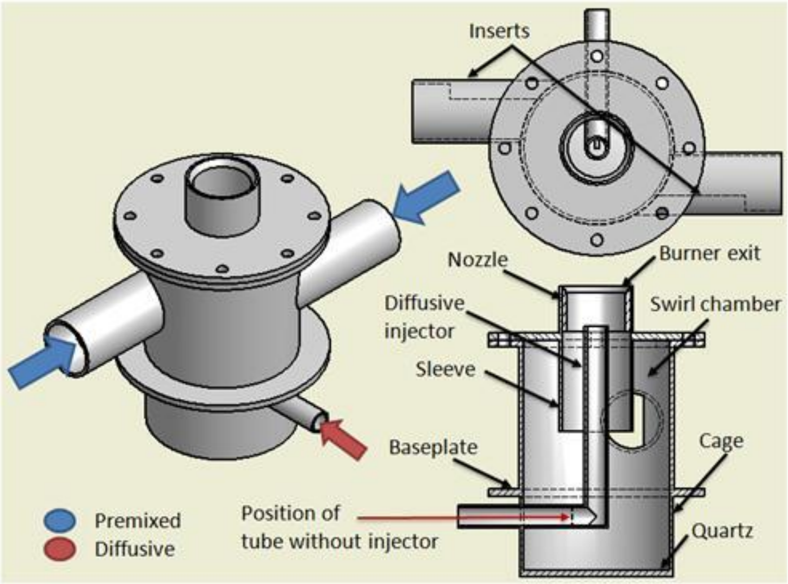

Fig 1. Generic tangential swirl burner.

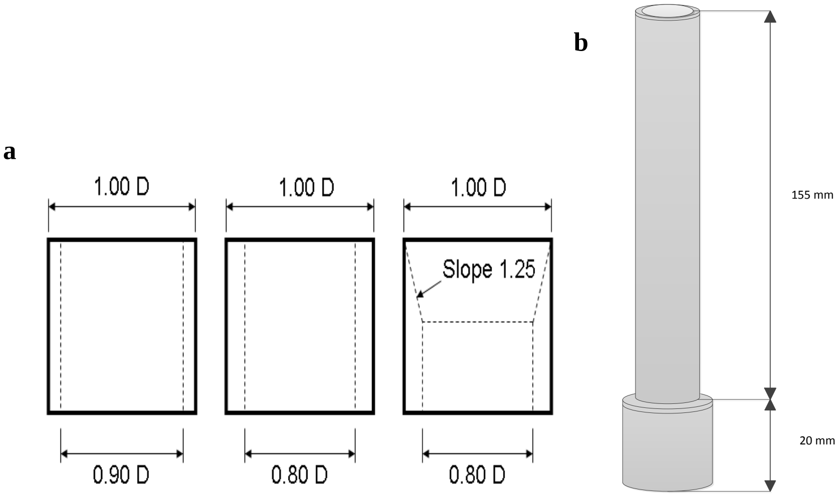

Fig 2. Geometrical changes; a) Nozzle configurations, b) Central injector, variable diameter.

Table 1 swirl numbers for the different nozzles and inserts used

Type of insert	0.8D Nozzle	0.9D Nozzle	Quarl	Swirl number
25%	yes	-	-	0.913
25%	-	yes		1.028
25%	-	-	yes	1.12
50%	yes	-	-	1.59
50%	-	yes		1.8
50%	-	-	yes	1.98
75%	yes	-	-	3.65
75%	-	yes	-	4.1
75%	-	-	yes	4.5

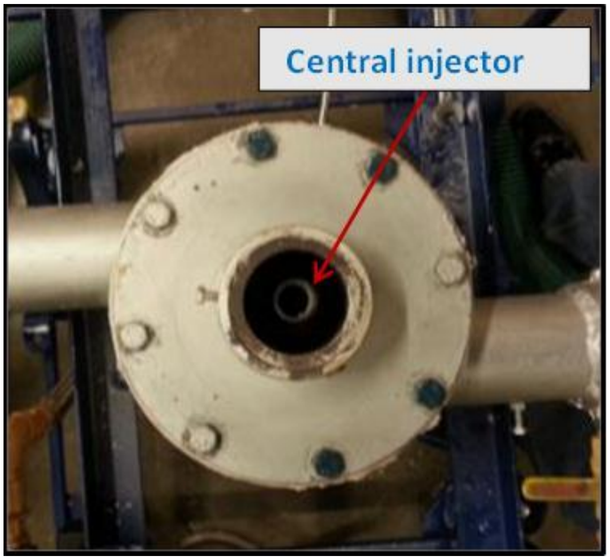

Fig 3. Central diffusive injector inside swirl burner.

III. Results and discussion

A dimensionless number (χ) which represents the ratio of outside injector diameter to the inside nozzle diameter has been used for the analyses. Various χ values are denoted in Table 2. The value used for the flow velocity was the tangential inlet velocity [17] thus allowing a fair comparison between cases without considering the change of Re at the burner mouth caused by the different injectors.

Table 2.Values of fraction χ (Injector OD/Nozzle inside diameter)

Injector type OD in mm	0.8D Nozzle D=60.8 mm	0.9D Nozzle D= 68.4mm	Quarl D=75.0 mm
7.0	0.115	0.102	0.090
12.5	0.205	0.182	0.160
16.0	0.263	0.233	0.213
18.0	0.290	0.260	0.240
19.0	0.312	0.270	0.253
21.0	0.345	0.307	0.280
23.0	0.378	0.336	0.306

Fig. 4a illustrates the flashback curves for different χ using a swirl number of 1.12 (Quarl Nozzle). The use of the tangential velocity provides good correlations. It can also be seen that with the reduction of χ flashback moves to leaner regions in a W_{in} range of 2.0-3.5 m/s over an equivalence ratio (ϕ) ranging from 0.50 to 0.75. Visual observation and correlation with the swirl number for each measurement point clearly show the reason for these changes.

Consider for instance the results for χ =0.09. The results generally follow one curve, visual observation shows a thin burning vortex core region extends over the fuel injector to the baseplate for all tangential inlet velocities. Flashback can be seen to be occuring radial flashback from the outer boundary of the CRZ [20], to the radial aligned tangential inlets. Flashback resistance is poor as the only impedance to this mechanism is the relatively low radial velocity in the flat swirl chamber [20]. There is little interference from the imjector to the development of the CRZ. As the diameter of the fuel injector is increased the flashback limits generally improve somewhat until by χ=0.24 flashback equivalence ratio has improved to ~0.6 over a wide range of tangential inlet velocities.

The CRZ/burning vortex core region still extends right over the fuel injector, not always to the burner baseplate, whilst the mechanism of flashback still appears to be radial flashback in the flat swirl chamber. As χ is increased further to 0.28 and 0.306 flashback resistance desirably increases, indicating significant changes in the location of the flame front and flame stabilization mechanism. At lower tangential velocities the CRZ is unstable, close to vortex breakdown, leading to flame fluctuations and early flashback. Higher tangential velocities stabilize the flow field and now the mechanism of flashback is via the outer boundary layer between the shear layer and the nozzle wall. In fact two flames are formed, one stabilized on the central fuel injector and the other one on the outer lip of the burner, Fig. 4b.

Flashback trends are very similar if the swirl number is reduced to 0.913 (0.8D Nozzle), Fig. 5. It appears that flashback curves are located in Win range of 2.3-4.3 m/s over an equivalence ratio(ϕ) ranging from 0.50 to 0.70. Agin the flashback limits of χ=0.115,0.205 and 0.263 are located in the same equivalence ratio. This infers that similar mechanisms of flashback are occurring for both these swirl numbers.

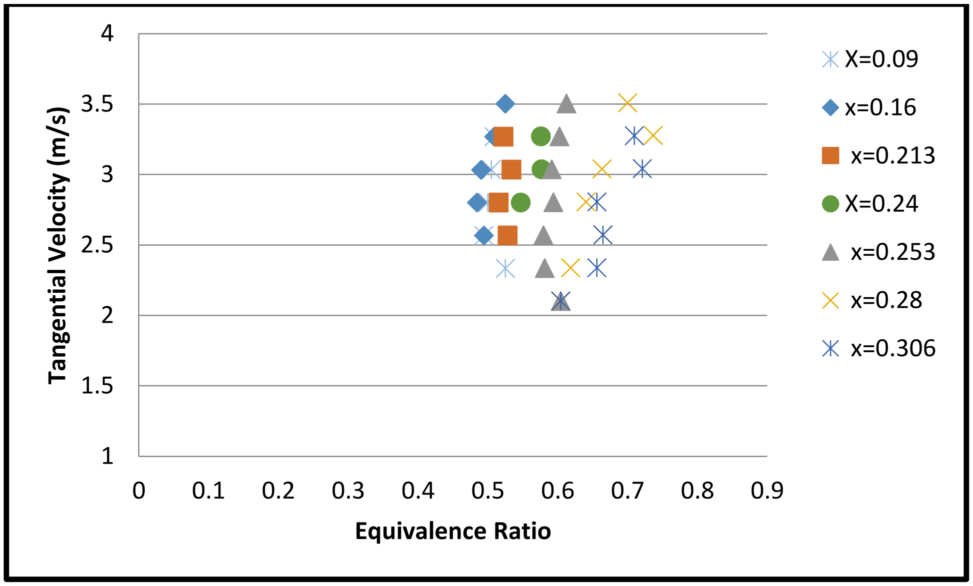

Fig. 4a.Effect of central fuel injector diameter on flashback limits, swirl number 1.12.

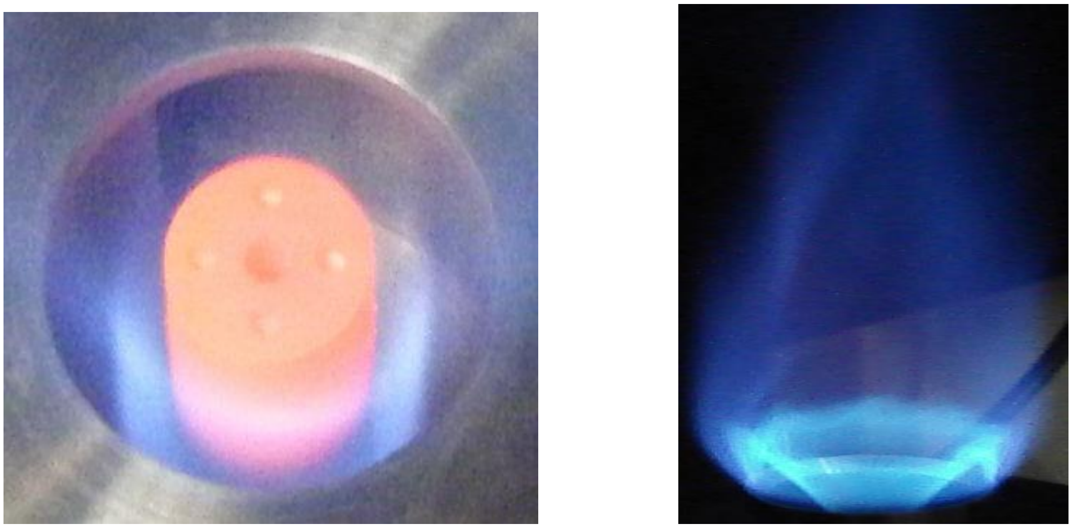

Fig.4b. Flames close to flashback in Premixed Swirl Burners with central fuel Injectors; LHS) flame burns on boundry of CRZ which extends down over the fuel injector to the baseplate; RHS) two flames formed, one stabilized by central fuel injector, the other located on burner lip.

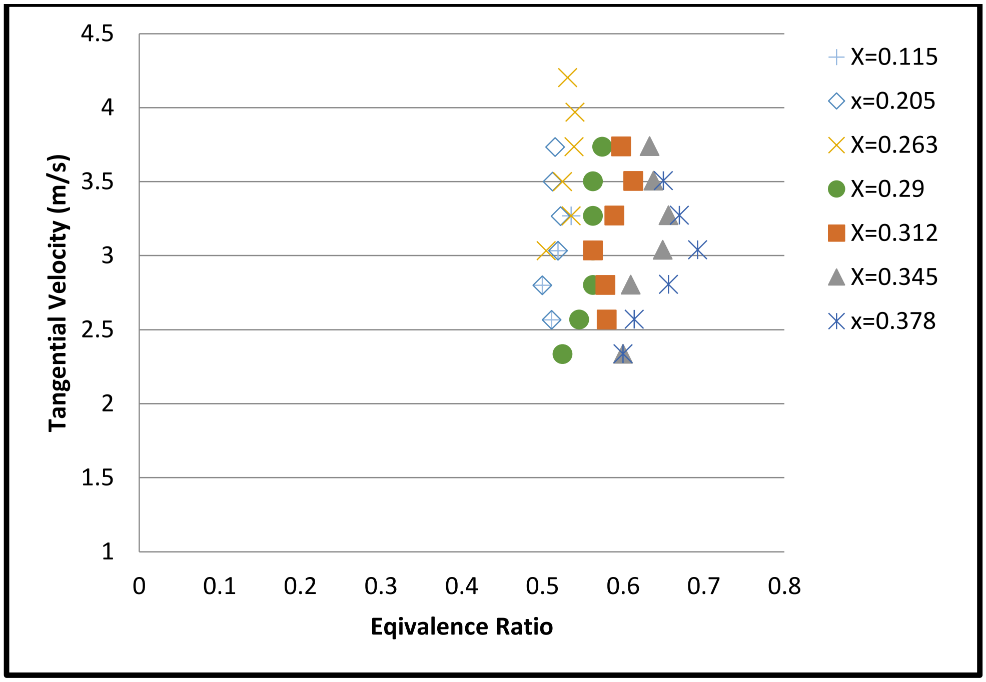

Fig. 5. Effect of central fuel injector diameter on flashback limits, swirl number 0.913.

These results were evident in all the analyses done for all different swirl numbers and geometries. This suggests that the mechanisms of flashback are similar for similar sizes of injector. The crucial value of χ is around 0.28 for S=1.12 and 0.32 for S=0.913. Thus flashback reistance is enhanced with lower swirl numbers: other work has shown this is only until the point of initial vortex breakdown around S~0.7 [11,19].

IV. Conclusions

Results showed that a reduction of the central fuel injector outside diameter can significantly affect the flashback limits, moving the phenomenon to leaner regions. The use of the tangential inlet velocity allows a comparable analysis between cases and revels the effects of outside diffusive injector diameters with different types of swirl burners. The injector diameter can be usefully used to improve flashback resistance in conjunction with optimisation of swirl number at a level beyond initial vortex breakdown (ie S>0.7). This can be used for design purposes in order to have injectors that are big enough to provide enough diffusive fuel for stability purposes but small enough to allow the annhilation of the CIVB/CRZ movement down the sleeve when flashback ocurrs.

V. Future work

Laser Doppler Velocimeter (LDV) will be used to investigate the turbulence and CRZ phenomenology close to the burner mouth during the flashback phenomenon. Furthermore, a dimensionless correlation will be sougth to determine a suitable, general OD_M value at which the flashback mechanism changes from combustion induced vortex breakdown (CIVB) to a wall boundary layer flashback (WBLF) led phenomeon. This will provide more information about why the CIVB remaing stable with small injector diameters. Finally, LDV will help to understand some issues regarding the influence of the injector temperature in flashback phenomena.

VI. Acknowledgments

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