Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 7, Issue, 06, pp.16815-16827, June, 2015

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

ISSN: 0975-833X

RESEARCH ARTICLE

BURNER FLAME STABILISATION OF ALTERNATIVE FUELS USING NOZZLE CONSTRICTIONS

***Dr. Mohammed Hamza Abdulsada AL-Hashimi**

Department of Mechanical Engineering, College of Engineering, Al-Qadisiya University, Iraq

ARTICLE INFO

Article History:
Received 20th March, 2015
Received in revised form
28th April, 2015
Accepted 10th May, 2015
Published online 27th June, 2015

Key words:
Combustion,
Burner,
Swirl.

ABSTRACT

Swirl flame stabilisation of lean premixed fuels has been studied and applied to gas turbines for a number of years, giving considerable benefits in terms of reduced pollutant emission, especially of NOx. However, there are still problems that can occur during the combustion process including those related to flashback (especially with hydrogen enriched fuels) and combustion induced instabilities. Swirl of the primary system is optimised to minimize pressure drop, flame contact with the injectors and swirl system, whilst avoiding flashback. Pure hydrogen or hydrogen enriched fuels give rise to especial problems owing to the high flame speed of hydrogen, potential for flashback in conventional or simply modified combustors and often requirement for multi fuel operation. Solutions adopted commercially are normally compromised, leaving considerable room for improvement. This paper describes a combined practical and modelling approach to study and reduce the effect of flashback in practical swirl burners using both a flexible experimental combustor, coupled with extensive Computational Fluid Dynamics modelling to guide experimental progress. The results proved that by adding CO_2 the flashback limits can be improved, whilst H_2 enriched flames are more difficult to control. Several varied CRZs developed in the field as a consequence of the nozzle configuration, showing high dependence not on the Swirl number, but the type of flow expansion. It was confirmed that the flame can be manipulated to avoid physical contact with the burner solid surfaces, the Swirl number being a particularly important parameter. The size and shape of the CRZ can be readily manipulated to satisfy particular requirements.

Citation: Dr. Mohammed Hamza Abdulsada AL-Hashimi, 2015. "Burner flame Stabilisation of alternative fuels using nozzle constrictions", *International Journal of Current Research*, 7, (6), 16815-16827.

INTRODUCTION

Amongst the most promising technologies used to reduce the impact and production of NOx, lean premixing and swirl stabilized combustion are regarded as very good options. However, premixing is not perfect because usually fuel and air are mixed shortly before entering the combustion chamber leading to a significant degree of unmixedness (Sadanandan *et al*., 2008). This generates a complex process that creates thermoacoustic instabilities which would feedback into the mixing-reaction process of combustion (Lieuwen and Yang, 2005; Meier *et al*., 2007). Swirl flow technologies have shown to give high flame stability taking advantage of coherent structures such as Corner and Central Recirculation Zones (CoRZ, CRZ) which anchor the flame, recirculating hot products and active chemical species whilst also increasing their residence time, allowing the use of low equivalence ratios thus giving lower flame temperatures and NOx emissions (Syred and Beer, 1974; Syred, 2006; Valera-Medina *et al*., 2008; Brundish *et al*., 2007).

****Corresponding author: Dr. Mohammed Hamza Abdulsada AL-Hashimi,***
Department of Mechanical Engineering, College of Engineering, Al-Qadisiya University, Iraq.

However, there are still many gaps in the understanding of these flames. According to Sadanandan *et al*. (2008) little reaction occurs in the internal region of the CRZ. In contrast, the shear layer between the inflow and the recirculation zone is a region of intense combustion. Phase Locked Planar Laser Induced Fluorescence (PLIF) OH analysis, related to the temperature and lifetime of the radical in different reaction zones, have shown regions of super-equilibrium where the reaction zone can be established and high temperature zones of chemical equilibrium co-exist. However, these are highly asymmetric and dependent on the position of the trigger used for phase locking (Meier *et al*., 2007). New coherent structures have been observed as part of the entire flow that may contribute to the complex mechanism of swirl (Valera-Medina *et al*., 2008), denoting regions of high asymmetry and three-dimensionality. Complex vortical structures with slightly curved helicity have been observed, with cases denoting three-dimensional vortex dipoles with little literature on the subject apart from (Cala *et al*., 2006). Other problems are related to the injection system (Meier *et al*., 2007; Brundish *et al*., 2007; Paschereit and Gutmark, 2008). High momentum injection within the swirler shows less sensitivity to pressure variations than those observed in air. Fluctuations in air supply can thus produce significant variation of equivalence ratio, creating gas pockets of varying equivalence ratio inside of the system. This represents the first step of a feedback loop known as oscillating fuel supply combined with a convective time delay (Meier *et al*., 2007; Dhanuka *et al*., 2009). The use of a pilot flame cannot be generally avoided, as it augments the stability of the system, especially for lean swirling combustion (Dhanuka *et al*., 2009; Valera-Medina *et al*., 2009).

Another problem is the flashback produced by swirl stabilized combustion systems. Here we define two different mechanisms. Type 1 flashback occurs when the CRZ extends back over the CRZ, often to the rear backplate (Cala *et al*., 2006; Kroner *et al*., 2003; Umemura and Tomita, 2001). This allows flame propagation into this region, often causing equipment damage. Type 2 flashback occurs when the flame propagates into the tangential inlets or swirler, often back to the premixing system. This occurs when the turbulent flame speed exceeds the flow velocity along some streamline, often occurring in the boundary layers, which usually are the point of lowest flow velocity (Lieuwen *et al*., 2008). Visualisation of Type 2 flashback shows it is not a continuous upstream propagation but is composed of numerous movements or jumps of the flame from one region to another. Resistance to these effects have also been linked to preheating temperature, laminar flame speed and fuel composition (Kroner *et al*., 2003).

Combustor reliability to hold the flame in a quiet, safe mode has always concerned the manufacturers (Lieuwen *et al*., 2008). Industrial companies and research groups are focusing their efforts in the analysis of new fuels consistent of biofuel blends or those with high hydrogen contents in order to reduce the emission of CO_2. Whilst the aviation sector is focusing its efforts on biofuels whose heat value content are similar to kerosene (http://www.omega.mmu.ac.uk/international-conference-on-alternative-fuels.htm), stationary turbines are being investigated with high hydrogen fuel mixes in efforts to develop technologies for syngas fuels. Unfortunately, the study of the latter has proved to be difficult, with first forced flashback tests under industrial conditions causing burner damage at high air velocities in tests by Siemens and Alstom (Lenze and Carroni, 2007). Flashback is an important issue in lean premixed combustion systems that use hydrogen as an additive fuel due to the widely varying flame speeds of the mixtures considered. As such, the effect of fuel composition variation upon flashback depends upon the corresponding change in local flame speed, both laminar and turbulent (Barmina *et al*., 2007).

Different transport properties and laminar/turbulent flame velocities also obviously occur with different fuels, diluents and hence flames (Lieuwen *et al*., 2008). Many different diluents such as N_2, CO_2, H_2O, have been studied (http://www.omega.mmu.ac.uk/international-conference-on-alternative-fuels.htm). Even when large N_2 dilution levels are used to reduce NO_x, they tend to promote flashback, contrary to the intuitive assumption that higher levels are safer (Lenze and Carroni, 2007). CO_2 can lower flame temperature and laminar flame speed, whilst fuels with similar laminar flame speed may have different turbulent flame speeds (Lieuwen *et al*., 2008). Air temperature is also a concern, since it has been found that the onset of flashback shifts to higher air temperatures with higher velocities and small injector diameters (Markides and Mastorakos, 2008). Clearly flashback depends on factors such as pilot fuelling rate and geometry (Dhanuka *et al*., 2009). Other researchers (Lamnaouer *et al*., 2008) have studied the effects of flashback using the Wobbe number (Wo) (MJ/m^3), which gives the energetic characteristics of the gas used. The Damkohler number (Da), a parameter that relates residence and chemical times, has also been used for the study of the phenomenon.

Mixtures with lower Wo tend to flashback easier than those with higher values (Lamnaouer *et al*., 2008), the result for any nozzle was only valid for a limited Wo range. When Wo is varied greatly from the original fuel specification, system modifications are necessary to avoid failure. Moreover, recent experiments show that fuels with similar Wo but with diverse mixes of heavy hydrocarbons may respond differently during the combustion process, producing more or less NO_x (Nag *et al*., 2007). High Low Heat Value fuel blends tend to have less resistance to flashback. Turbulent flame speed is not especially dependent on pressure, and only heat transfer produced by wrinkled flames was linked to Da dependence (Lamnaouer *et al*., 2008), Da having an inverse dependency with increasing pressure. Thus, it is a combination of parameters, Wo Number, Da number, heating value, Turbulent and Laminar Flame Speed, autoignition temperature, that define the resistance to flashback in a system. While a significant amount of fundamental understanding of flame propagation has been gained in natural gas systems, little is known about alternate gaseous fuels such as hydrogen enriched blends (Lieuwen *et al*., 2008; Kroner *et al*., 2003).

It has been recognised that the shape of the CRZ can influence the final stability of the system (Kroner *et al*., 2003; Paschereit and Gutmark, 2006). However, vortical structures can be modified by geometrical factors and flow conditions (Paschereit and Gutmark, 2006), as well as by the interaction of unburnt gases and the reaction zone (Kroner *et al*., 2003), complicating even more their part especially in Type 1 flashback occurrence and avoidance. Another problem related to Type 1 flashback (especially with liquid fuels) is the amount of deposit produced by the high concentration of carbon radicals generated in the CRZ. If the CRZ extends back to the injector, this can leave thick deposits on the injector surfaces, causing damage increasing maintenance requirements (Barmina *et al*., 2007).

Swirling flows have been studied for decades, with detailed descriptions in the work of Syred (1974) and Gupta *et al*. (Gupta *et al*., 1984). Other authors like Vanoverberghe (2004) and Coghe *et al*. (2004) have demonstrated the reduction of emissions by increasing the swirl, producing flames stabilized by the surrounding structures, such as inner and outer recirculation zones, formed as a consequence of the dynamics of the swirling mechanism. However, the structures that drive these systems are only inferred in these studies or studied partially, without fundamental knowledge of their interaction and co-existence. The parameter used for comparison was the well known Swirl number, S, specified elsewhere (Syred and

Beer, 1974; Valera-Medina *et al*., 2008), but it is recognised that it has its limitations as the phenomena occurring are a strong function also of detailed geometry, flowrates, modes of fuel injection and equivalence ratio.

Biomass and coal gasification pilot and prototype plants have been operating for many years. They, in association with other plant, can be operated to produce hydrogen rich fuel gases for testing as gas turbine fuels (Lenze and Carroni, 2007; Bagdanavicius *et al*., 2009; Arias *et al*., 2008). Many of the current models of swirl combustion leave much to be desired when considering hydrogen rich fuels due to the variety of parameters to be considered in highly turbulent flows, especially the high turbulent flame speed (Jakirlic *et al*., 2002) and the larger mass diffusion coefficients for hydrogen (Kroner *et al*., 2007). Other simulations mention the independence of the behaviour of the CRZ on inflow conditions (Baba-Ahmady and Tabor, 2008) due to nature of the structure, a fact that has been challenged by experimental results using tangential burners (Valera-Medina *et al*., 2008; Valera-Medina *et al*., 2008).

This paper is thus aimed at analysing the mechanisms of Type 1 and 2 flashbacks which occur in practical swirl burners so as to understand the physical processes which occur and how they can be alleviated. Different nozzle geometries are used with the possibility of both premixed and diffusive fuel injection. High-Speed Photography (HSP) and Phase Locked Particle Image Velocimetry (PIV) are used to define the flames and CRZs formed as well as to observe the flashback processes. As flashback occurred in parts of the flow field where time dependence was not significant complimentary time averaged simulations using FLUENT were carried to investigate the occurrence of flashback as well enabling the extrapolation of the results to high pressure, air preheat and different fuel blends.

SETUP

Experimental Approach

Experiments were performed in a 100 kW Steel versions of a 2 MW Swirl burner under combustion conditions. Two tangential inlets were used together with 25% width inserts in order to obtain a swirl number of 0.98. This configuration has been proved to be highly stable (Syred and Beer, 1974; Valera-Medina *et al*., 2008; Valera-Medina *et al*., 2009). 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. Figure 1 depicts the burner.

Two different modes of natural gas injection were utilized for the prototype; a diffusive mode with fuel injected along the central axis from the burner bottom and a premixed mode with entry in one or both tangential inlets, located before the inserts used for varying the swirl number, partial premixing was also extensively studied. Premixed gas injectors, extending across the inlet ducts, were located just before the inlets.

Various diffusive fuel injectors were used as follows,

1. Wide injector, 23.4 mm diameter. Positioned 47.5 mm upstream of the burner nozzle.
2. Perforated injector of 27.5 mm diameter, with 8 perforated holes of 1.7 mm diameter. Positioned 11.6 mm downstream of the burner nozzle.
3. Narrow injector, 9.9 mm diameter. Positioned 0.9 mm upstream of the burner nozzle.

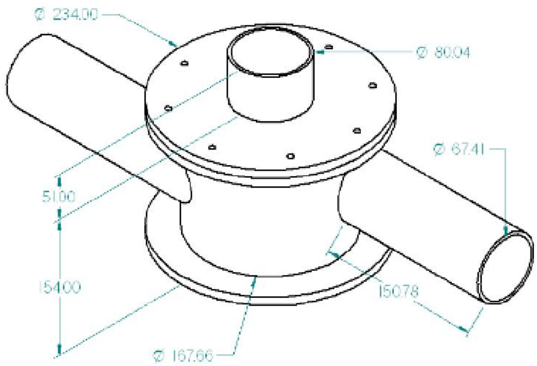

Figure 1. Swirl Burner geometry in Unconfined mode (mm)

Overall equivalence ratio φ was reported as well as the fuel proportion injected diffusively and that premixed in the tangential inlets. The format (25-80) here refers to 25 l/min diffusive natural gas injection, the 80 l/min to that injected as premixed. Due to the high temperature variation, the Re is defined from the nozzle diameter and isothermal conditions. The S number has defined from isothermal conditions (Syred and Beer, 1974; Syred, 2006). Pressure fluctuation measurement was made with an EM-1 Yoga Electret Condenser Microphone, with a frequency response of 20 Hz-16 kHz and sensitivity of -64±3 dB. Its resolution allowed the determination of high pressure peaks attributed to the existence of a crescent shaped high momentum region linked to the well known PVC phenomena in these burners (Syred and Beer, 1974; Syred, 2006; Valera-Medina *et al*., 2008; Valera-Medina *et al*., 2009). Even thought the signal was obtained successfully, combustion processes created a more unstable signal and filtering was needed. The signal was analyzed using a Tektronic DS2024B Oscilloscope at 2 Gsamples/s, 200 MHz and four channels.

Experiments at atmospheric conditions were made using a Phase Locked PIV system. This technique has proved to be consistent with the results of different experiments under a variety of approaches (Valera-Medina *et al*., 2009).

The use of condenser microphones has been used by others for acoustic measurements (Baba-Ahmady and Tabor, 2008). Its signal was conditioned to obtained low-frequency parameters related to large scale structures. This signal was redirected to a BNC Model 500 Pulse Generator, whose TTL signal was sent to a Dantec PIV system. The latter consists of a Nd: YAG Litron Laser of 532 nm at 5 Hz and a Hi Sense MkII Camera model C8484-52-05CP, with 1.3 MPixel resolution at 8 bits. A 60mm Nikon lens was used for resolution purposes, with a depth of view of 1.5 mm. The inlet air was seeded with aluminium oxide (Al_2O_3) by a Venturi system positioned 2.0 m upstream of the burner inlets. 250 l/min of air was used to fluidize the seeding material; this was accounted for the determination of the final flowrate. The entire system was triggered at 90% of the highest peak observed after 5 minutes of free run. It is recognised that this empirical value was arbitrary, yet consistent with all the measurements and previous experiments (Valera-Medina *et al*., 2009), enabling a quantitative comparison between cases. The entire system is depicted in Figure 2.

mass fraction that originated from the fuel stream. In other words, it is the local mass fraction of burnt and unburnt fuel stream elements (C, H, etc.) in all the species (CO_2, H_2O, O_2, etc.). The approach is elegant because atomic elements are conserved in chemical reactions. In turn, the mixture fraction is a conserved scalar quantity, and therefore its governing transport equation does not have a source term. Combustion is simplified to a mixing problem, and the difficulties associated with closing non-linear mean reaction rates are avoided.

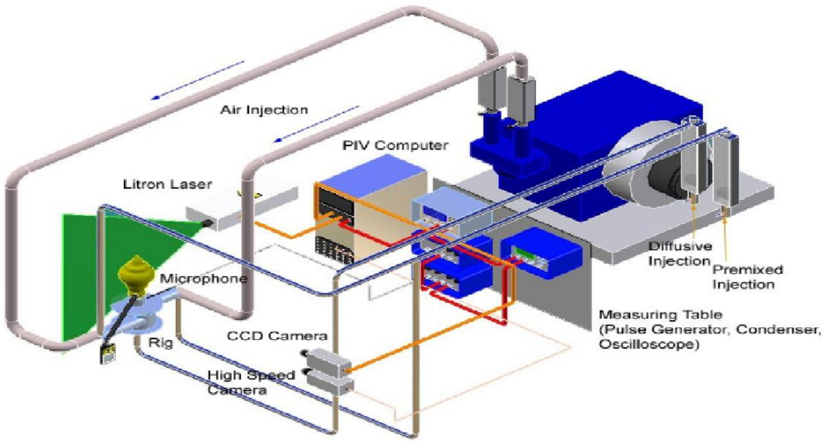

Figure 2. Setup of the Entire System, including HSP and PIV, Fuel is injected via 2rotameters (yellow arrows) whilst air is tangentially introduced at different flow rates

Being at the same voltage level throughout the experiment, large structures of the system were framed every time that the high momentum structure crossed the same position. This allowed a spatial representation of the same phenomenon every cycle. Four radial constrictions with no axial enlargement were used at the burner outlet with the aim of characterizing the flame and its behaviour under a variety of geometrical cases. Tubular constrictions of 0%, e.g. no constriction, 10% and 20% (both square section) of the outlet diameter were utilized. Thus, nozzle geometries of 1.00 D, 0.90 D and 0.80 D were characterized. A last case was used with a quarl modification initially 0.80 D expanding to 1.00 D, with a geometrical slope of 1.25. An entire diagram of the inserts and configuration used is shown in Figure 3.

A Kodak M753 digital camera in speed mode was used to capture colour images of the lifted flames in order to find the position of initial flame stabilisation and the characteristic of the inner recirculation zone and surrounding flame envelope. Acquisitions were performed at same flow rates for comparison purposes.

Numerical Simulation

Tangential Swirl Burner

In non-premixed combustion, fuel and oxidizer enter the reaction zone in distinct streams. This is in contrast to premixed systems, in which reactants are mixed at the molecular level before burning. Under certain assumptions, the thermo chemistry can be reduced to a single parameter: the mixture fraction. The mixture fraction, denoted by f, is the

Once mixed, the chemistry can be modelled as being in chemical equilibrium with the Equilibrium model, being near chemical equilibrium with the steady laminar flamelet model, or significantly departing from chemical equilibrium with the unsteady laminar flamelet model.

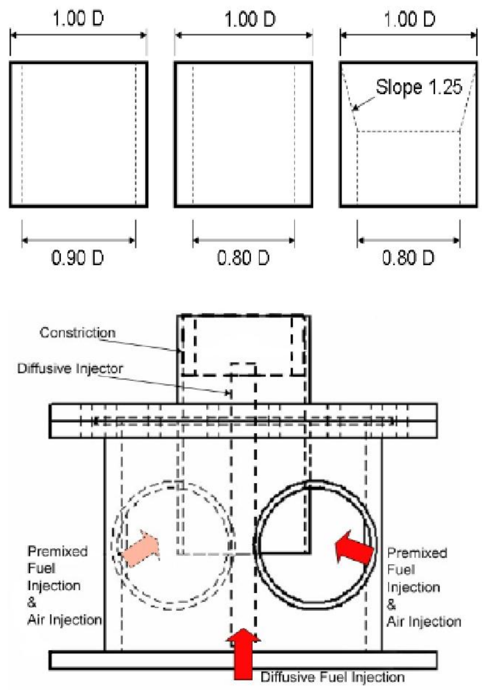

Figure 3. Diagram of Constrictions and Rig for experimental purposes

In premixed combustion, fuel and oxidizer are mixed at the molecular level prior to ignition. Combustion occurs as a flame front propagating into the unburnt reactants. Premixed combustion is much more difficult to model than non-premixed combustion. The reason for this is that premixed combustion usually occurs as a thin, propagating flame that is stretched and contorted by turbulence. For subsonic flows, the overall rate of propagation of the flame is determined by both the laminar flame speed and the turbulent eddies. The essence of premixed combustion modelling lies in capturing the turbulent flame speed, which is influenced by both parameters.

Partially premixed flames exhibit the properties of both premixed and diffusion flames. They occur when an additional oxidizer or fuel stream enters a premixed system, or when a diffusion flame becomes lifted off the burner so that some premixing takes place prior to combustion.

Turbulence Modelling

The turbulence model used was the standard k-ωmodel, a method based on the Wilcox k-ω model (Wilcox, 1998; Zimont *et al*., 1998), whichincorporates modifications for low-Reynolds-number effects, compressibility, and shear flow spreading. The Wilcox modelpredicts free shear flow spreading rates that are in close agreement with measurements for far wakes, mixing layers, andplane, round, and radial jets, and is thus applicable to wall-bounded flows and free shear flows. The standard k-ωmodel isan empirical model based on model transport equations for the turbulence kinetic energy (k) and the specific dissipation rate(ω). As the k-ωmodel has been modified over the years, production terms have been added to both the k and ωequations, which have improved the accuracy of the model for predicting free shear flows.

The transport equations for the model can be defined by,

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right)+G_k - Y_k + S_k \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right)+G_\omega - Y_\omega + S_\omega \qquad (2)$$

Physical System and Model Setup

The Fluent model used simulates that used during the experiments. Two different modes of natural gas injection were utilized for the prototype; a diffusive mode (non-premixed) with fuel injected along the central axis from the burner bottom and a premixed mode with entry in one or both tangential inlets, located before the inserts used for varying the swirl number. Apart from methane, which was used to validate the model with the experimental results, mixtures of methane, hydrogen and carbon dioxide at different concentrations were used to recognise the points of stability and flashback with different nozzle constrictions. The numerical analysis was expanded to the use of confinement and nozzle quarl exhaust constrictions, which showed during the experimental analysis to be the most advantageous in terms of flame stability. Methane, hydrogen and carbon dioxide blends were also analyzed under these conditions.

The simulation was performed utilizing FLUENT. A three dimensional model was used for the analysis, which can be seen in Figure 4. The constriction used is presented in Figure 5, which posses the same dimensions as its experimental counterpart.

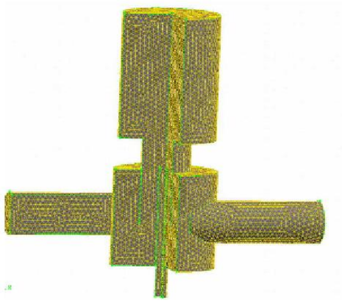

Figure 4. Tangential Swirl Burner Model

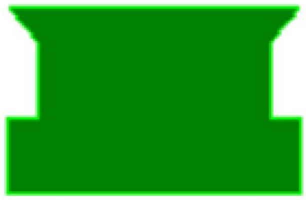

Figure 5. The modification has been carried out on the swirl burner exhaust to reduce the occurrence of flashback

RESULTS AND DISCUSSION

Experimental

First experiments were performed with no burner exhaust nozzle constriction. The aim was to characterize the CRZ and the effects produced by the change in equivalence ratio and fuel injection in the former. Equivalence ratio plays a decisive role in the shape of the CRZ, figure 9. First experiments were carried out using entirely diffusive fuel injection, which showed a coherent structure whose strength was dependant on the Re number. Higher equivalence ratios showed trends of more stable and stronger CRZs, probably due to the higher velocities and general stability of the flow.

Experiments using entirely premixed injection showed stability over a very narrow range of flow rates, thus experiments were continued with diffusive-premixed fuel entry. A small amount of diffusive fuel proved sufficient to allow the stable anchoring of the flame, increasing considerably the stability of the system. It was found that these systems developed strong recirculation zones past the Vortex Breakdown faster than their entirely diffusive counterparts. This is visible in the case at 1600 l/min air and 25-120 l/min gas, which is still wobbling and unstable since it has only passed the Vortex Breakdown threshold (remember combustion reduces the swirl number, see figure 9, φ=0.99, 1000 l/min, 25-80 l/min of gas where the CRZ has disappeared).

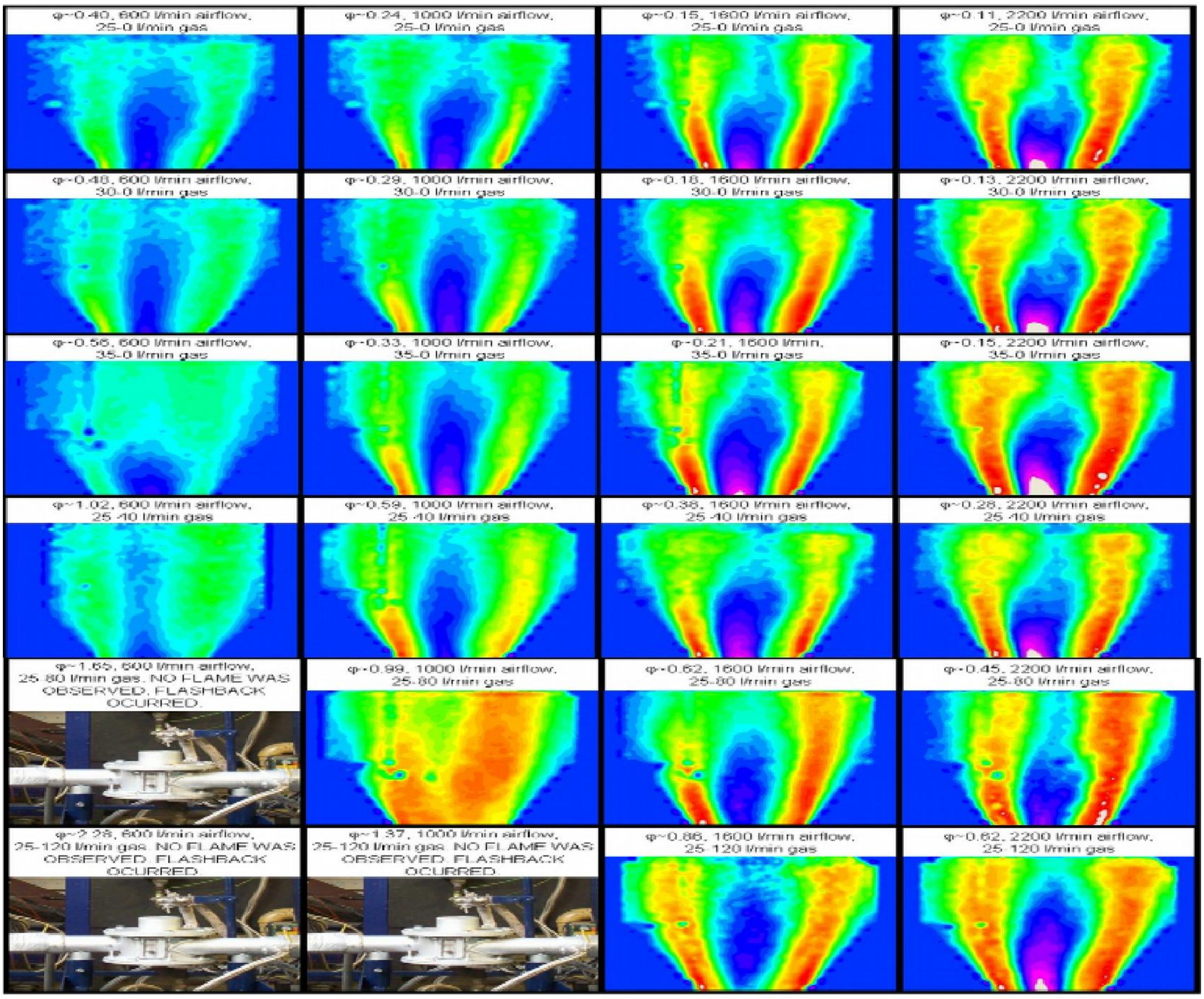

Figure 9. Fixed air flow rates, different modes of gas injection and gas rates. Wide Injector Used. Colour bar in (m/s). InitialCRZ formation after Vortex breakdown occurs as a wobbling unattached weak (blue) region, very difficult to visualize. TheCRZ is completely attached to the fuel injector, very coherent and strong (purple), being very easy to follow for visualizationpurposes

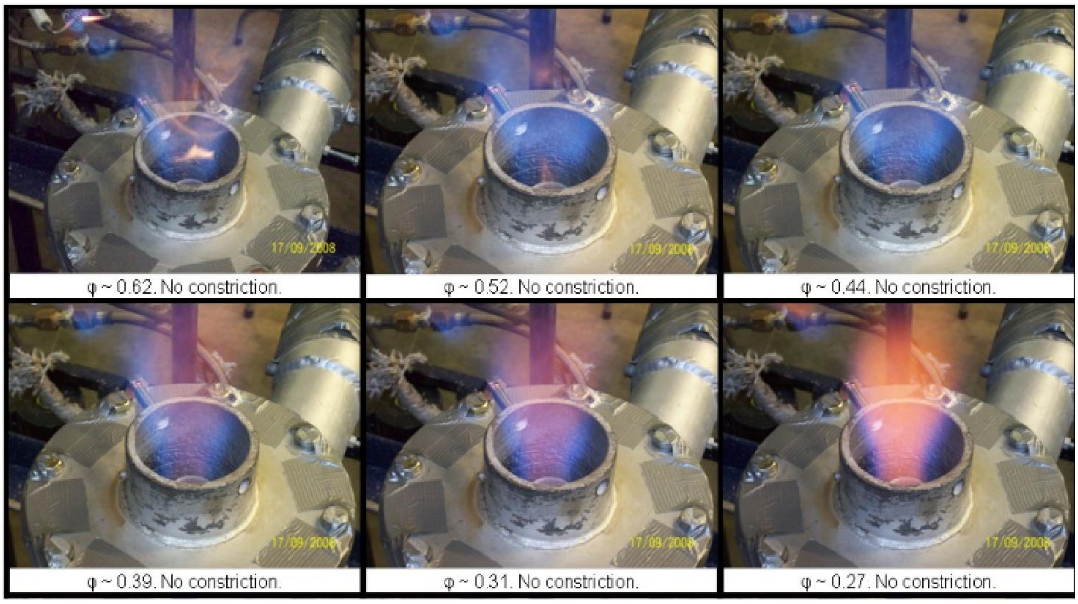

Figure 10. Non-constricted exhaust case at different equivalence ratios. Gas Injection of 25 l/min diffusive (Wide Injector), 40 l/min premixed

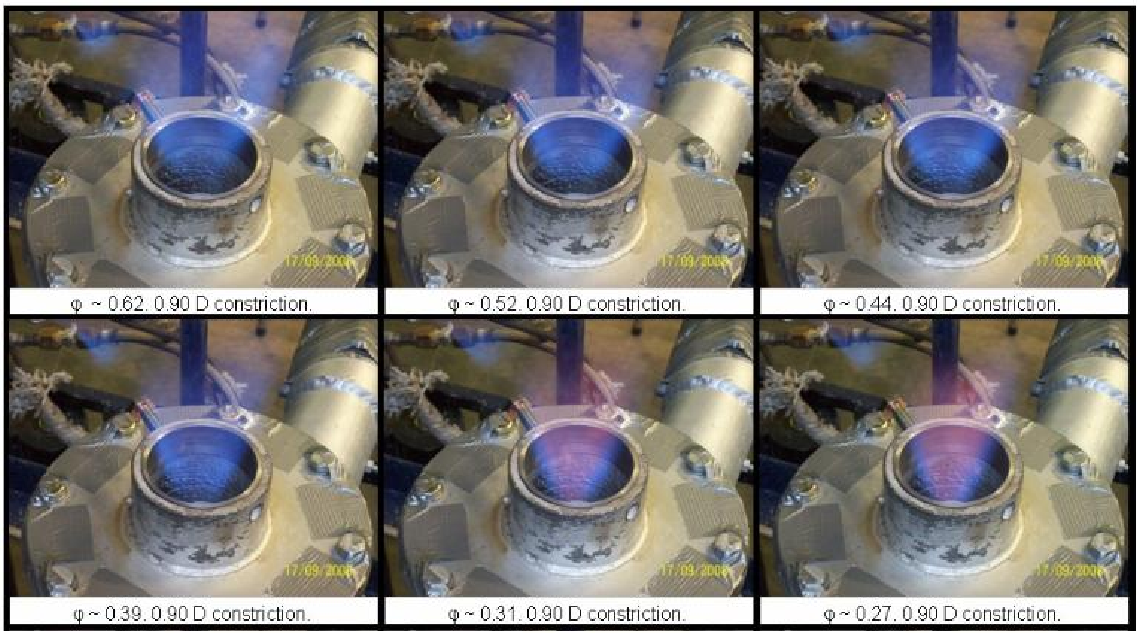

Figure 11. 0.90 D Tubular exhaust nozzle at various equivalence ratios. Gas Injection of 25 l/min diffusive (Wide Injector), 40 l/min premixed

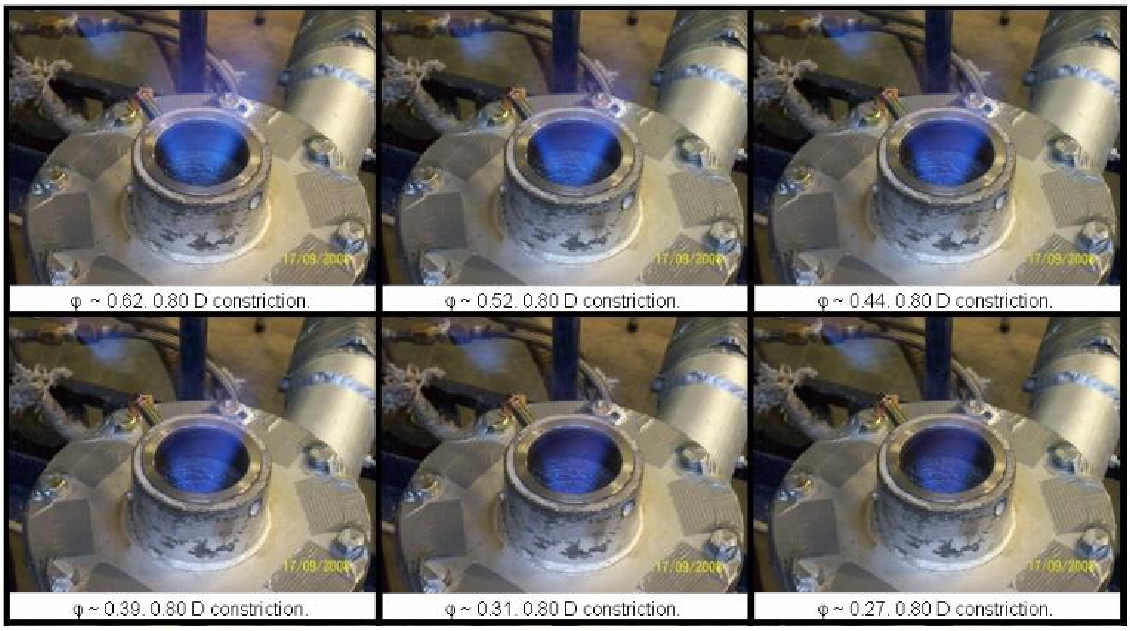

Figure 12. 0.80 D square constricted case at different equivalence ratios. Gas Injection of 25 l/min diffusive (Wide Injector), 40 l/min premixed

The following case at 2200 l/min air and 25-120 l/min gas depicts very strong recirculation, whose length surpasses those of its predecessors. Comparison with the entirely diffusive flames is difficult as the equivalence ratios are very different. Visual observation and figure 9 shows that the diffusive-premixed flames are spread over a larger area at the swirl nozzle and hence show lower axial velocities, despite the higher equivalence ratios (which normally should give higher axial velocities for the same flame shape), compare φ=0.15, 35-0 l/min (pure diffusive) to φ=0.62, 25-120 l/min (diffusive-premixed). This also appears to be the reason for the poor stability of the entirely premixed flame as the outer flame boundary is located well away from the CRZ; the CRZ appears to thus need the input of active chemical species from the initial flame reactions, not just recirculated hot burnt products. Injection of small amounts of diffusive fuel into this region achieves this aim.

Both types of flashback (Type 1 and Type 2) were observed with this configuration, flame propagation around the fuel injector to the baseplate followed by radial flashback to the tangential inlets, obviously depending on equivalence ratio and flowrate.

To reduce and eliminate Type 1 flashback, different burner exhaust geometries were used to push the flame upwards and avoid contact with the injector. With no confinement or combustion can to fire into, the open flames proved to be dirty at low airflow rates, with a very thin envelope and very rich inner core. Figure 10 shows the flames obtained for a fixed fuel flowrate of 25-40 l/min and varying airflow hence φ. The flame can be seen to strengthen and become more stable as the airflow is increased and φ reduces. Again this is due to the reducing value of φ, higher swirl number and stronger CRZ. The initial dirty flames at low air flowrates and highest vales of φ are thus due to the flow being located around the point of Vortex Breakdown with a very weak CRZ.

Changing to a burner exhaust nozzle constriction of 0.90 D, figure 11, the flame showed considerable improvement, for a constant fuel flowrate of 25-40 l/min. Initially, the flame was pushed up enough to avoid touching the injector at low flowrates. This flame was cleaner and of more stable shape than the previous case. Contrary to the entirely open case where the flame touched the injector at 1000 l/min (φ ~ 0.62 with a depth of ~30 mm) of air, this was delayed until 1600 l/min at φ ~ 0.39. Higher air flowrates, hence lower values of φ, allowed the CRZ to increase in size and length and extend back undesirably over the fuel injector. This again is a swirl number effect. This exhaust constriction alters the swirl number to 0.88 (Syred and Beer, 1974; Syred, 2006) and this work thus shows the importance of nozzle geometry.

The burner exhaust nozzle constriction of 0.80 D, Figure 3, gave a cleaner flame at low flowrates, figure 12. This flame never touches the injector and remains always blue, showing a higher degree of mixing and reaction, despite the slightly lower value of S at 0.78. Possibly this is due to the higher Re. As the air flowrate is increased φ overall decreases from 0.62 (1000 l/min) to 0.27 (2200 l/min) when the flame is now only a few millimeters long (being just stabilized by the diffusive fuel) and the CRZ has enlarged in size as the swirl number is not reduced so much by the effects of combustion.

Finally, a short quarl constriction was used, with a constricted tubular bottom of 0.80 D expanding to 1.00 D at the burner exit, Figure 13. This configuration proved to be the most effective in terms of flame stabilization. The flame never touched the injector and the expansion caused by the radial movement of the shearing flow allowed a wider stronger flame at high Re. Finally, a short quarl constriction was used, Figure 6.1, with a cylindrical base of 0.80D expanding to 1.00D at the nozzle in an 8 mm length, flames are shown in Figure 13. This configuration proved to be the most effective in terms of flame stabilization.

This configuration increases the stability of the flames with a more defined and stable envelope while maintaining the flame out of contact with any surface or part of the burner, despite the large variation in φ from 0.62 to 0.28. Reynolds number effects are felt to be quite small here. Since the velocity of the flow has increased considerably, Type 2 flashback is reduced (Type 1 does not exist) and the flame remains located at a couple of centimeters from the injector outlet, reducing the risk of damage and soot nucleation with particle growth on cooler surfaces. It must be noted here that high levels of confinement can alter this characteristic with quarls (Syred and Dahmen 1978). This is usually taken to occur when the ratio of the confinement diameter to the burner throat diameter is less than ~3.

A Phase Locked PIV analysis was then carried out to determine the size, shape and contribution of the CRZ at high flow rates more representative of gas turbine combustion. These were at φ ~ 0.62 and 25-125 l/min gas, using only the Wide Injector, Figure 14. The length of CRZ has decreased in comparison to the case with no exhaust constriction, whilst the strength appears to have increased somewhat, especially with Figures 6.8C and 6.8D with the 80% square and quarl nozzles. The CRZ has become wider allowing more extensive mixing, matching the premixed flame front with that of the CRZ better, producing better combustion with colour white being out of the range (extremely strong negative velocity for these cases).

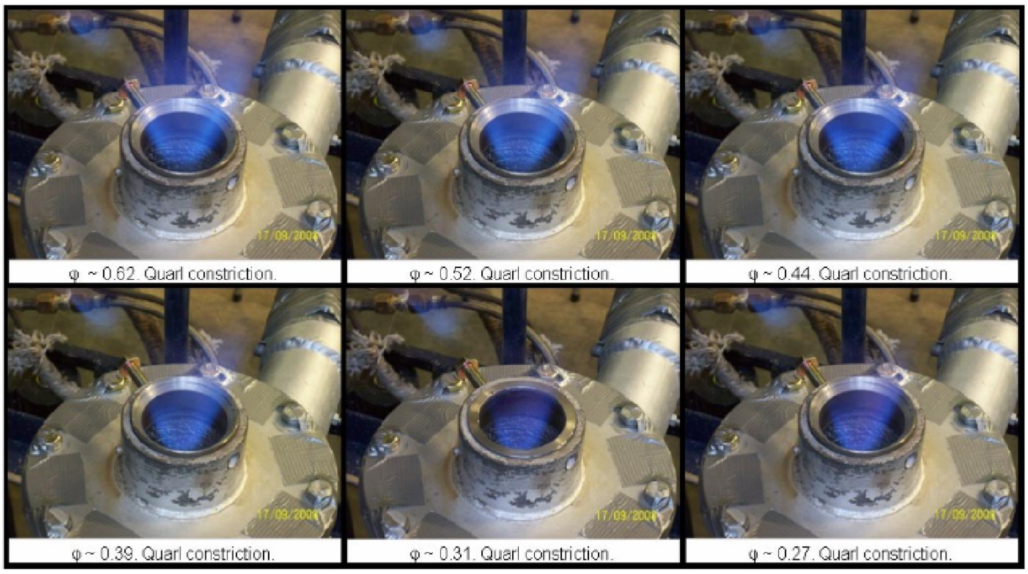

Figure 13. Quarl constricted case at different equivalence ratios. Gas Injection of 25 l/min diffusive (Wide Injector), 40l/min premixed

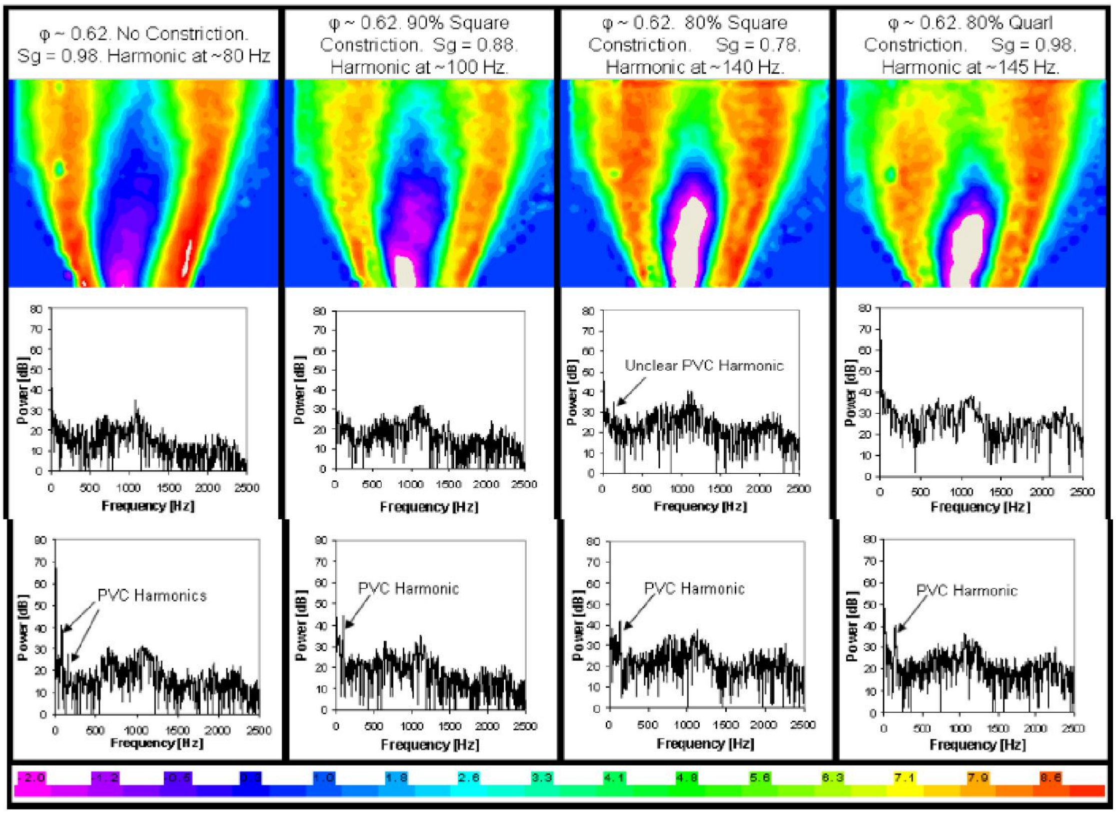

Figure 14. Combustion at φ ~ 0.62 and 25-125 l/min gas injection, in comparison with Isothermal case. Firstrow of FFT signals refers to combustion condition. Second row is the Isothermal condition. A) Non-confined. B)0.90D square confinement. C) 0.80D Square confinement. D) Quarl Confinement. The colour bar represents theflow velocity (m/s), with colour white being out of the range (extremely strong negative velocity for thesecasess)

Isothermal and Combustion conditions were also characterized using FFT Analyses, to depict the harmonics of the Precessing Vortex Core (PVC) (Valera-Medina 2006; Syred, 2006). This structure is highly attenuated when using higher thermal input conditions such as these. Although the structure has been observed under combustion with high coherence and interaction with the CRZ in other experiments, (Valera-Medina *et al*., 2008; Valera-Medina *et al*., 2008; Valera-Medina *et al*., 2009), the FFT analysis did not show as high a level of coherence as in the isothermal and lower thermal input cases, possibly as combustion generated noise starts to overwhelm the signal–Thus although the structure has been observed under other combustion conditions the FFT analysis did not clearly show its existence here under high power conditions as in the isothermal and lower power cases.

Finally, comparison between cases was performed using the average radial velocity of the flow (passing from the outer swirl chamber through the gap between the baseplate and the backwards facing nozzle extension, Figure 15) and the equivalence ratio to recognise regions of Type 2 flashback for both premixed and diffusive-premixed conditions. Type 1 flashback, arising from extension of the CRZ around the central fuel nozzle, has been generally eliminated by changes to the burner exhaust constriction. Figure 16 shows the results. Flashback, region C, is clearly a function of equivalence ratio, as expected, with radial velocities in the range to 1-2 m/s (based on isothermal gas flowrates), slightly higher than most measurements of turbulent flame speed.

Possibly the flame is propagating through the backwards facing exhaust extension boundary layer (lower velocities).

The two flashback curves for fully premixed and diffusion-premixed combustion can be made to match almost exactly if the equivalence ratio solely based on the premixed equivalence ratio is used. Thus flashback limits can be readily altered by using partially premixed combustion. Configurations at high equivalence ratios showed very long and emissive flames before flashback up to φ~1.2. After this, flames have an unstable elongated shape that pulsates before flashing back. Experiments were expanded to the use of configurations with constrictions. Since the Quarl proved to be the most efficient geometry, this was evaluated for flashback analysis. It was found that the system using diffusive injection never flashbacked under the conditions analyzed, as to be expected. The flame only retouched the quarl and created an elongated emissive pattern whose length depended on the injector used. Higher equivalence ratios and Re could not be tested due to equipment limitations.

Experiments in the premixed case without diffusive injection showed flashback. Without the fuel injector, no diffusive gas and quarl constriction, the flashback limit peaked at φ~0.875 and ~2.1 m/s, figure 17. The case without constriction, figure 16, peaked at φ~1.03 and ~1.7 m/s, showing a considerable reduction in the flashback limit using the quarl. The velocities were always derived at the throat of the exhaust nozzle.

The flashback curve peaks faster than the case, of Figure 16. When the fuel injector was replaced and not operated leaving an entirely premixed condition, the resistance to flashback increased considerably, peaking φ~1.09 and ~1.17 m/s, Figure 18. This is a velocity reduction of almost twice that observed without the injector. The nozzle suffers a constriction of ~50% of its diameter due to the injector, increasing the Re number in this area, and pushing the flame out of the nozzle.

Figure 18 also shows different flame regions, with the position of the lifted flame and regions where the flame touches the quarl at high equivalence ratios, probably due to the low flow velocities. A summary of the experimental results is presented in Table 1. This contains some of the cases studied experimentally, with their implications and type of flame. Only the peak values -highest Re and lowest Flashback resistance- for each configuration are mentioned, since the number of experiments exceeds 220 single trials for the recognition of the flashback phenomenon. The position of the flame at high Re is also presented, with its depth of penetration for each exhaust nozzle constriction. Best flames were obtained using the quarl exhaust nozzle constriction.

Numerical Simulation

Tangential Swirl Burner

During the simulation, various types of solvers and turbulence models used. Based on 1400 l/min air flow rate, the k-□model gave results closest to experiments. Figure 19 shows the predicted CRZ formed at the centre of the system, with thesurrounding shear flow. The should be compared to the experimental results, figure 10 (φ ~ 0.38 25-40 l/min), where thecoherence of the structure, its position and relation with the surrounding flow are very similar.

This modelling was found to confirm the experimental results that the use of the Quarl exhaust nozzle constriction increased the resistance of the unit to flashback. Bagdanavicious *et al.* (2009), has shown that the use of hydrogen and CO_2 can drastically alter the flame characteristics, hydrogen increasing the turbulent flame speed whilst the addition of CO_2 is a way of retarding the combustion process, observing various combinations of Methane, Hydrogen and CO_2. The case of the Quarl figures says no exhaust nozzle constriction burner exhaust constriction was then modelled with the fuel blends of Bagdanavicious (2009) in order to characterise the flashback occurrence for this geometry with an exhaust confinement, other cases being simply used for model validation.

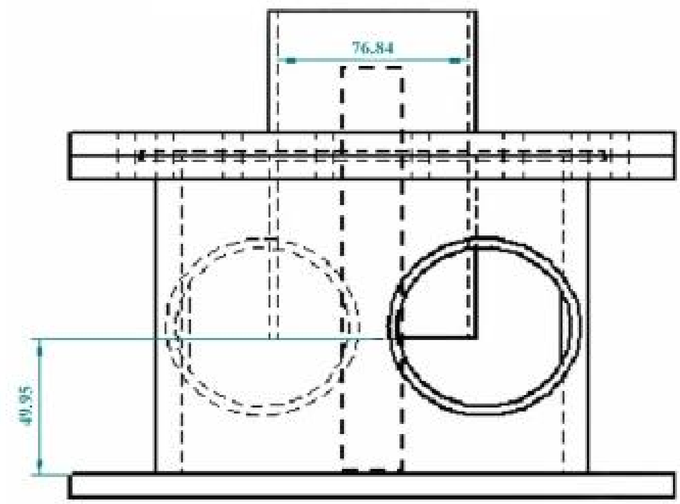

Figure 15. Gap of ~50.00 mm between baseplate and nozzleextension used to define the flashback of the system

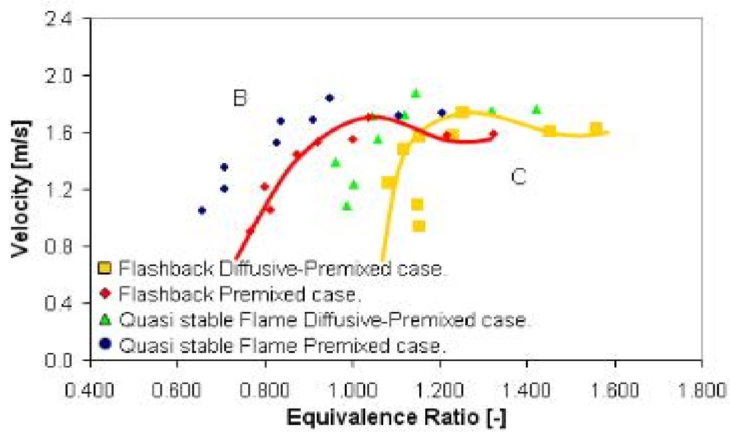

Figure 16. Different regions recognised in the flashback mapat atmospheric conditions. B) Region of quasistability for the flame, with different flame shapes. C)Flashback region. Region A) Blowout occurs at muchlower φ and is not visible herre

Table 1. Results Summary. At high Re (~39,000) strong stable flames were observed. At lower Re, Flasback iscited at the highesrt values for each case. The position of the flame is measured from the tip of the injectoor

Configuration	Injector [-]	Re [-]	φ [-]	Diffusive Inj. [l/min]	Premixed Inj. [l/min]	Flame Colour/Flash back [-]	Flame Strenght and Emissivity [-]	Length [mm], CRZ Shape [-]	Position upstream tip injector [mm]
Open Case	Wide	~39,000	0.27	25	40	Orange	High	130, Long	~30
0.90 D Constriction	Wide	~39,000	0.27	25	40	Purple	High	100, Long	~22
0.80 D Constriction	Wide	~39,000	0.27	25	40	Blue	Weak	80, Long	-
Quarl Constriction	Wide	~39,000	0.27	25	40	Blue	Medium	65, Top Spinning	-
Open Case	Wide	~21,000	1.03	0	120	Flashback	Medium	Totally inside	Inside Rig
Open Case	Wide	~21,000	1.25	25	120	Flashback	Medium	Totally inside	Inside Rig
Quarl Constriction	None	~25,500	0.87	0	130	Flashback	Medium	Totally inside	Inside Rig
Quarl Constriction	None	~16,000	1.94	25	140	Reattached	Low	Variable	Tip of Burner
Quarl Constriction	Wide	~15,000	1.09	0	90	Flashback	High	Totally inside	Inside Rig
Quarl Constriction	Wide	~8,000	1.77	25	50	Reattached	Low	Variable	Tip of Burner

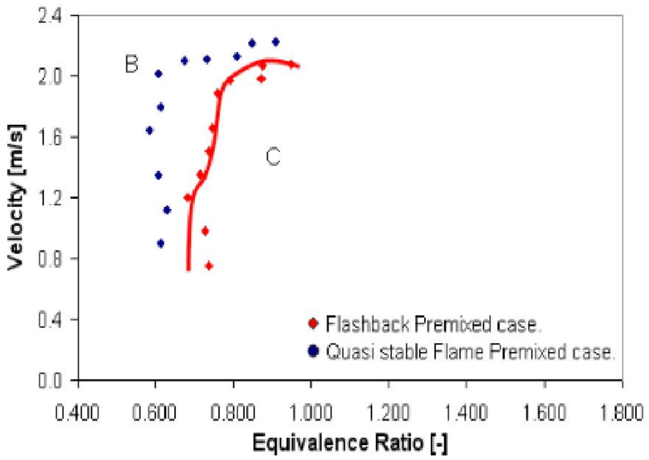

Figure 17. Different regions in the flashback map atatmospheric conditions using the Quarl Nozzlewithout fuel injector. B) Region of quasi stability forthe flame, with various flame shapes. C) Flashbackregion

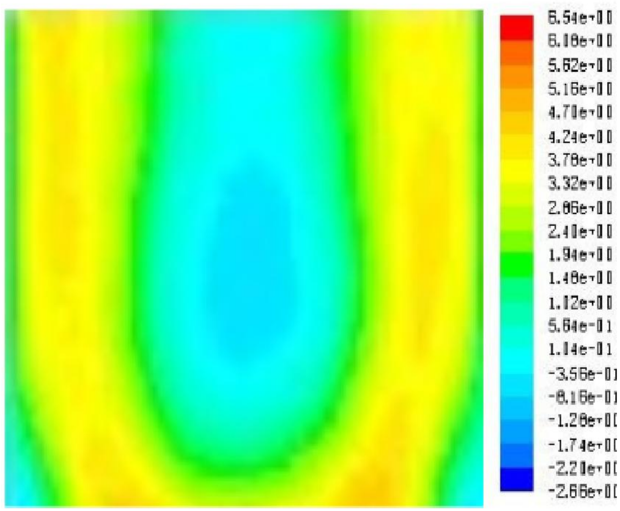

Figure 19. Modelled velocities showing the CRZ surrounded by the outgoing shear flow. Scale in m/s

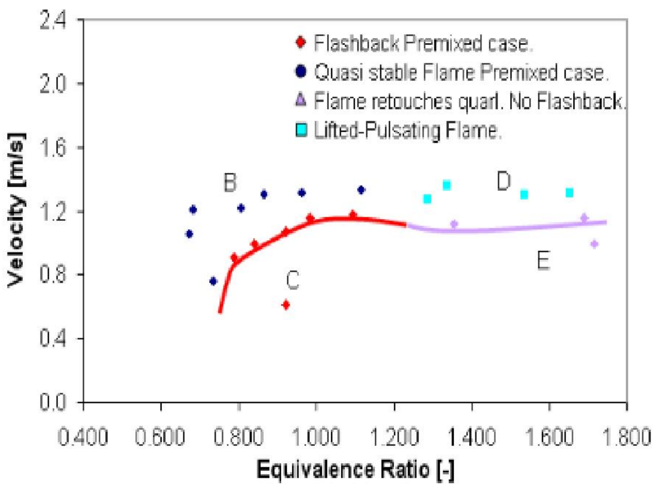

Figure 18. Different regions in the flashback map atatmospheric conditions using the Quarl Nozzle withinjector. B) region of quasi stability for the flame,various shapes. C) Flashback region. D) Lifted flame.E) The flame retouches the qua

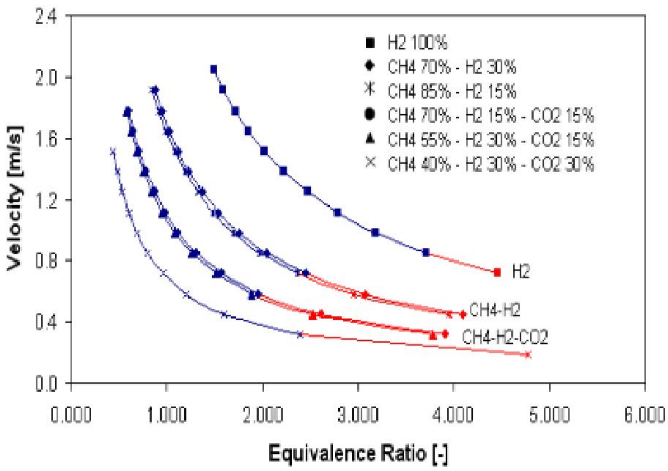

Figure 20. Flashback analysis for different blends at 1400l/min air flow using No Exhaust Nozzle Constrictionat 25-40 l/min gas injection. Flashback (red) and nonflashback conditions (blue). CH4-H2 blends havealmost the same trend, as well as CH4-H2-CO2 at15% CO2

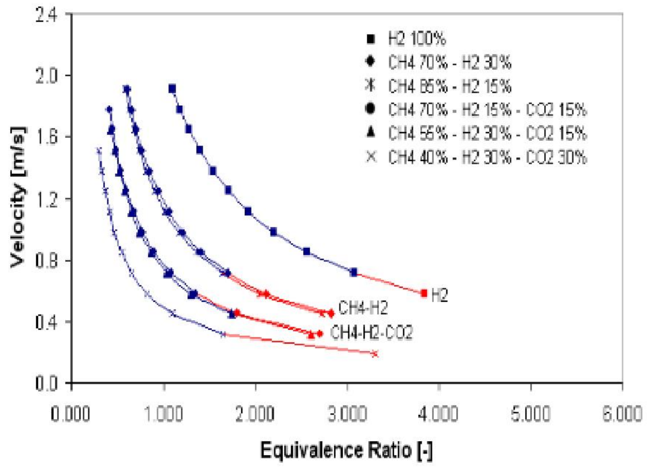

Figure 21. Flashback analysis for different blends at 1400l/min air flow using No Exhaust Nozzle Constrictionat 5-40 l/min gas injection. Flashback (red) and nonflashback conditions (blue). CH4-H2 blends havealmost the same trend, as well as CH4-H2-CO2 at15% CO2

Partially premixed cases were analyzed, with 40-25 l/min, Figure 20 since experimental results have demonstrated that some diffusive fuel injection increases the stability of the flame. Blow-off occurred at velocities above 1.2 m/s, a topic not cover in this paper. The results show how the least resistance to flashback occurs with pure hydrogen. Increasing quantities of methane in the blend show greater resistance to flashback , although there is significant difference between 85% and 70% methane. However, when CO_2 is added to the blend, the resistance to flashback increases considerably, up to twice that observed with pure hydrogen. Interesting is the fact that 15% increase in hydrogen did not change flashback significantly, possibly due to chemical kinetic effects and the relatively small mass ratios of hydrogen involved. When the diffusive fuel injection was reduced to 5 l/min, figure 21, flashback limits improved especially for values of $\varphi<1$ blow off the flame was observed above 1.2 m/s as well.

Even thought the velocity at which the flashback takes place is practically the same as at 25 l/min, the equivalence ratio has decreased considerably by means of reduced diffusive injection. Therefore, the diffusive injection seems to play an important role in flame stabilization but a minor role when related to flashback resistance. However, when using pure hydrogen there is a slight increase in resistance caused by less fuel in the system. Clearly the reduced quantities of hydrogen improves the flashback limit. For other fuels, a very beneficial attribute of less diffusive injection has been a reduced equivalence ratio at which flashback occurs, possibly improving the burner stability and operational limits. It thus appears that most benefit accrues when very small quantities of diffusive fuel injection are used.

Conclusion

This paper has examined experimentally the flames produced by and the stability of a small swirl burner. Work is focussed on producing flames that do not impinge onto nozzle surfaces or extend back to and around the central fuel injector. Partial premixing of fuel and air is shown to have significant advantages, as is well known industrially. Type 1 flashback, arising from flame propagation around CRZs which extend back around the fuel injectors, has been eliminated by geometrical changes to the burner exhaust nozzle. Velocities at which Type 2 flashback occurs are characterised and certain nozzle configurations are shown to have advantages in reducing this, typical flashback velocities range from ~1.6 to ~1.2 m/s.

The work has been successfully compared to a Fluent CFD model of the system, which was then extended to other fuel mixtures containing methane, hydrogen and carbon dioxide. As expected pure hydrogen made enormous changes to the Type 2 flashback limit, although this was readily ameliorated by carbon dioxide dilution or the use of significant quantities of methane.

REFERENCES

Arias B., Fermoso J., Plaza M., Pevida C., Rubiera F., Pis J., Garcia-Pena F., Casero P., 2008, "Production of H2 by Co-gasification of Coal with biomass and petroleum coke", Proceedings of 7th European Conference on Coal Research and Its Applications, Wales, UK.

Baba-Ahmady H., Tabor G., 2008, Inlet "Conditions for Large Eddy Simulation of Gas-Turbine Swirl Injectors", *AIAA Journal*, vol. 46, no. 7, pp. 1782-1790.

Bagdanavicius A., Bowen P., Syred N., Kay P., Crayford A., Wood J., 2009, "Burning Velocities of Alternative Gaseous Fuels at Elevated Temperature and Pressure", 47th AIAA Aerospace Sciences Meeting, Orlando, USA, ref. AIAA-2009-0229.

Barmina I., Desnickis A., Meijere A., Zake M., 2007, "Active Electric Control of Emissions from Swirling Combustion", Advanced Combustion and Aerothermal Technologies, NATO Science for Peace and Security Series, *Springer*, pp. 405-412.

Brundish K., Miller M., Morgan L., Wheatley A., 2007, "Variable Fuel Placement Injector Development", Advanced Combustion and Aerothermal Technologies, NATO Science for Peace and Security Series, *Springer*, pp. 425-444.

Cala E., Fernandes C., Heitor M., Shtork S., 2006, "Coherent Structures in unsteady swirling jet flow", Experiments in Fluids, vol. 40, pp. 267-276.

Coghe A., Solero G., Scribano G., 2004, "Recirculation phenomena in a natural gas swirl combustor", *Experiments in Thermal Fluid Science*, Vol. 28, pp. 709–714.

Dhanuka S., Temme J., Driscoll J., Mongia H., 2009, "Vortex-Sheeding and mixing layer effects on periodic flashback in a lean premixed prevaporized gas turbine combustor", Proceedings of the Combustion Institute, Vol. 32, Issue 2, Pages 2901-2908.

Fluent Incorporated, 2005, Fluent 6.2 Users Guides, Lebanon, USA.

Gupta A.K., Lilley D.J., Syred N., 1984, "Swirl Flows", Abacus Press, Tunbridge Wells, United Kingdom.

Jakirlic S., Hanjalic K., Tropea C., 2002, "Modelling Rotating and Swirling Turbulent Flows", A Perpetual Challenge, *AIAA Journal*, vol. 40, no. 10, pp. 1984-1997.

Krebs W., Hoffmann S., Prade B., Lohrmann M., Buchner H., 2002, "Thermoacoustic Flame Response of Swirl Flames", Proceedings of the ASME Turbo Expo 2002, GT-2002-30065, pp. 333-344.

Kroner M., Fritz J., Sattelmayer T., 2003, "Flashback Limits for Combustion Induced Vortex Breakdown in a Swirl Burner", *Journal of Engineering for Gas Turbines and Power*, vol. 125, pp. 693-700.

Kroner M., Sattelmayer T., Fritz J., Kiesewetter F., Hirsch C., 2007, Flame Propagation in Swirling Flows –Effects of Local Extinction on the Combustion Induced Vortex Breakdown, *Combustion Science and Technology*, vol. 179, pp. 1385-1416.

Lamnaouer M., Petersen E., Laster R., "Flashback Analysis for ULN Hydrogen Enriched Natural Gas Mixtures", Department of Mechanical Engineering, University of Central Orlando, report (online).

Lenze M., Carroni R., 2007, "Public Summary Report of ENCAP deliverable D.23.3 Report on limits of current burner using H_2-rich fuel mixtures" (online). www.encapco2.org (Accessed 10 February 2009)

Lieuwen T., McDonell V., Petersern E., Santavicca D., 2008, "Fuel Flexibility Influences on Premixed Combustor Blowout Flashback, Autoignition and Stability", *Journal of Engineering for Gas Turbines and Power*, vol. 130, ref. 011506.

Lieuwen T., Yang V., 2005, "Combustion Instabilities in Gas Turbine Engines", AIAA, Progress in Astronautics and Aeronautics, vol. 210, U.S.A.

Markides C., Mastorakos E., 2008, "Flame Propagation following the Autoignition of Axisymmetric Hydrogen, Acetylene and Normal Heptane Plumes in Turbulent Coflows of Hot Air", *Journal of Engineering of Gas Turbine and Power*, vol. 130, ref. 011502.

Meier W., Weigand P., Duan X.R., Giezendanner-Thoben R., 2007, "Detailed characterization of the dynamics of thermoacoustic pulsations in a lean premixed swirl flame", Combustion and Flame, vol. 150, pp. 2-26.

Moore J., 2009, "Hydrogen- a central player in tomorrow's energy mix", Energy World, Energy Institute London, February, no. 368.

Nag P., Wu J., Abou-Jaoude K., LaGrow M., Rising B., Mumford S., Engel J., 2007, "LNG Interchangeability in Land Based Gas Turbines: The Siemens Approach, Proceedings of Power 2007", ref. POWER2007-22094.

OMEGA Aviation in a sustainable World, 2008, International Conference on Alternative Fuels, 24-26 November, http://www.omega.mmu.ac.uk/international-conference-on-alternative-fuels.htm (Accessed 01 December 2008)

Paschereit C., Gutmark E., 2008, "Enhanced Stability and Reduced Emissions in an Elliptic Swirl-Stabilized Burner", *AIAA Journal*, Vol. 46, issue 5, pp. 1063-1071.

Paschereit C., Gutmark E., Control of high-frequency thermo-acoustic pulsations by distributed vortex generators, *AIAA Journal*, vol. 44, no. 3, 2006, pp. 550-557.

Sadanandan R., Stohr M., Meier W., 2008, "Simultaneous OH-PLIF and PIV measurements in a gas Turbine model Combustor", Applied Physics B, vol. 90, pp. 609-618.

Syred N., 2006, "A Review of Oscillation Mechanisms and the role of the Precessing Vortex Core (PVC) in Swirl Combustion Systems", Progress in Energy and Combustion Systems, Vol. 32, issue 2, pp. 93-161.

Syred N., Beer J., 1974, "Combustion in Swirling Flows: a Review", Combustion and Flame, Vol. 23, pp. 143-201.

Umemura A., Tomita K., 2001, "Rapid Flame Propagation in a Vortex Tube in Perspective of Vortex Breakdown Phenomenon", Combustion and Flame, vol. 125, issue 1-2, pp. 820-838

Valera-Medina A., Syred N., Griffiths A., 2008, "Characterization of Large Coherent Structures in a Swirl Burner", AIAA International Meeting 2008, ref. AIAA 2008-1019.

Valera-Medina A., Syred N., Griffiths A., 2008, "Large Coherent Structures Visualization in a Swirl Burner", Proceedings 14th International Symposium on Applications of Laser Techniques to Fluid Mechanics 2008, Lisbon, Portugal.

Valera-Medina A., Syred N., Griffiths A., 2009, "Characterization of Large Coherent Structures in a Swirl Burner under Combustion Conditions", AIAA International Meeting 2009, ref. AIAA 2009-646

Vanoverberghe K., 2004, "Flow, Turbulence and Combustion of Premixed Swirling Jet Flame", PhD Thesis, Faculty of Engineering, Katholieke Universiteit Leuven, Belgium.

Wilcox, D.C. Turbulence Modeling for CFD. DCW Industries, Inc., La Canada, California, 1998. www.clemson.edu/scies/UTSR/FellowLamnaouerSUM.pdf (Accessed 29 October 2008)

Zimont V., Polifke W., Bettelini M., and Weisenstein W., 1998. "An Efficient Computational Model for Premixed Turbulent Combustion at High Reynolds Numbers Based on a Turbulent Flame Speed Closure". *Journal of Gas Turbines Power*, Vol. 120, pp. 526- 532.

****