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# EFFECT OF SWIRL NUMBER AND FUEL TYPE UPON THE COMBUSTION LIMITS IN SWIRL COMBUSTORS

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## Abstract

Increasing interest in lean fuel premixed swirl combustors has arisen because of reduced NOx emissions. Alternative fuels, including hydrogen-enriched natural gas and by products of process industries such as coke oven gas are now receiving increasing attention.

This gives rise to areas of concern including, flashback, temperature levels, blow-off and combustion instability. Flashback with hydrogen containing fuels is of special concern, owing to the high flame speed of hydrogen, to such an extent that diffusion combustion is commonly employed resulting in high NOx emissions.

This paper examines the effect of hydrogen containing fuels upon flashback and blow-off in a generic, compact, premixed swirl burner in swirl number regimes representative of those found in practical systems. All results are obtained at atmospheric pressure without air preheat as a precursor to pressurised tests, the burner firing freely into atmosphere for most tests. The swirler has radial tangential inlets firing into a swirl chamber, which then feed into the exhaust. A central fuel injector just extends into the exhaust and is ~40% of the exhaust diameter, a common industrial size. Four tangential inlets are used for S=1.47, while nine has been used for S= 1.04 and S=0.8.

Flashback and blow-off are sensitive to the level of swirl, the exhaust configuration and the type of fuel. High swirl numbers, S=1.47, gave flashback limits with methane considerably worse than those produced at S=1.04 and S=0.8, although there were differences in exhaust nozzle configuration. At equivalence ratios ~1 total mass flow at which flashback occurred (hence velocities) was reduced by a factor of two. Changes in flashback behaviour were especially noticeable when the hydrogen content in fuel blends was > 60% by volume. Blow-off was very much a function of hydrogen content of the fuel and Swirl Number. Best blow-off limits for all fuel blends are obtained at S=0.8, the worst for S=1.47. Coke Oven gas (COG) with 65% hydrogen content gave best blow-off limits of the fuels tested, although data was not available for pure hydrogen due to rig limitations.

## Nomenclature

| | | |
|---|---|---|
| CRZ | Central Recirculation Zone | |
| Gx | Axial Flux of Axial Momentum | [J] |
| $G_\theta$ | Axial Flux of Angular Momentum | [J] |
| Q | Volume Flow Rate | [$m^3$/s] |
| PVC | Precessing Vortex Core | |
| $\dot{m}$ | mass flow rate | [kg/s] |
| S | Swirl Number | [-] |
| Sg | Geometrical swirl number | [J/kg] |
| $S_L$ | laminar flame speed | [m/s] |
| $S_T$ | turbulent flame speed | [m/s] |
| $d_q$ | quenching distance | [m] |
| $g\nu$ | velocity gradient | [m/$s^2$] |
| U | premixed flow velocity | [m/s] |
| RFZ | Reverse Flow Zone | |
| $r_{eff}$ | Effective Radius at the middle of pipe | [m] |
| $\varnothing$ | Equivalence Ratio | [-] |
| i | inlet condition | |
| o | exit condition | |

## I. Introduction

Lean premixed (LP) combustion is a widely used strategy to decrease NOx emissions in gas turbines. In LP systems, fuel and air mixed prior to combustion chamber to promote mixing and combustion efficiency. Swirl combustors are commonly used in the LP mode and can be optimised to produce emissions commensurate with the latest regulations[1-2]. However, the combination of swirl combustion and LP technology can produce problems such as instabilities, blow-off and flashback, especially when fuel blends include hydrogen[3-5].

Hydrogen and hydrogen fuel blends are major issues in the new and existing designs of gas turbine combustor. Hydrogen-Methane blends have significantly received more attention as an alternative fuel for gas turbines. These considerations obviously arise because of the propensity to reduce $CO_2$ emissions, the technology often being associated with biomass and coal gasification pilot and prototype power plants[6-8]. However, there are many technical and cost difficulties with the use of hydrogen or any hydrogen fuel blend; these include the high capital cost of the plant, high running costs, the high flame speed of hydrogen and hydrogen fuel blends, flashback, blow-off and instabilities [9].

As will be seen later for a given swirl number, there is far greater differences between the flashback limits for hydrogen and methane than would be expected from simple considerations of laminar and turbulent flame speeds. This appears to arise from enhancement of turbulent flame speed with hydrogen fuel blends as well as changes in flashback mechanisms.

Swirl combustors are a well known technology,[10] their main attribute being the generation of aerodynamically stabilised central recirculation and reverse flow zones, which recycles hot chemically active reactants to the flame root producing excellent flame stability and wide blow-off limits[11]. The swirl number (S) is one of the main parameters used to characterize swirl flows: it is defined as the ratio of axial flux of swirl momentum divided by the axial flux of axial momentum, and the nozzle radius[4]:

$$S = \frac{G_\theta}{G_x \cdot D_o/2} \qquad (1)$$

However, as the flow patterns are highly complex, it is difficult to specify the exact experimental swirl number unless very detailed 3D velocity measurements are available (a rare occurrence). A practical value of swirl number is obtained from the geometric swirl number ($S_g$), which uses inlet conditions and hence can ignore pressure variations across the flow. For isothermal conditions and constant density it has to be assumed that,

- The axial velocity u can be obtained as the overall flow rate Q divided by the exit area, $A_o$.
- The angular momentum term is taken as the inlet velocity ($Q/A_i$) multiplied by an effective radius $r_{eff}$, located at the middle section of the tangential inlets.
- The radius is the exit radius, here half the exit diameter $D_o$.

The above allows a simple derivations of a geometric swirl number to be made for the burner shown in figures 1 to 3 below [4, 11].

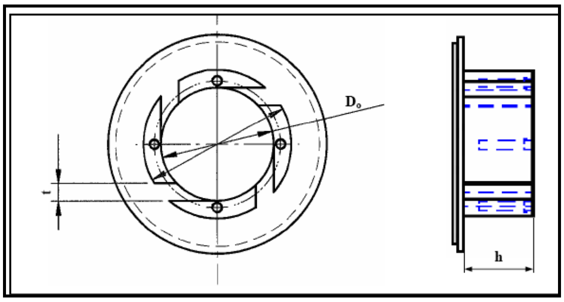



**Figure 1: Radial Swirl Burner-Inlet Configuration**

Flashback with LP combustion is an especial problem with hydrogen, hydrogen fuel blends, as increases by a factor of 20 are common (in mass flow, hence velocity) inferring that new or substantially modified combustors are needed, whilst dual fuelling is difficult (with say natural gas or fuel blends with hydrogen content > 60%) due to the very different requirements of the two fuels. Flashback can occur via a number of mechanisms including flame propagation within boundary layers, core flow, and other regions of low velocity or due to combustion instabilities[3, 12, 13].

In more detail flashback can be caused by:

I. Flame propagation in the boundary layer: This type of flashback is well known due to low flow velocities in the inner laminar sub layer of the boundary layer; this allows upstream flame propagation limited by quenching in the wall mixing zone[14]. Lewis and von Elbe [15] have suggested a relationship between laminar flame speed, $S_L$ and the velocity gradient ***gv*** at the wall divided by the quenching distance $\boldsymbol{d_q}$,

$$g_v = \left[\frac{\partial u}{\partial r}\right]_{wall} \leq \frac{S_L}{d_q} \qquad (2)$$

Equation (2) indicates that when the flow velocity at distance $d_q$ from the wall is lower than the flame velocity flashback will take place leading to upstream flame propagation next to the wall.

II. Turbulent flame propagation in the core flow: Flashback at the core can occur when turbulent flame velocity $S_T$ becomes greater than the local flow velocity in the core flow. The turbulent burning velocity depends on the chemical kinetics and the turbulence structure, the length scales and the local velocity fluctuations[14].

III. Combustion instabilities, Combustion instabilities due to non-linear interaction of pressure fluctuations and periodic heat release cause pulsations in combustion systems, which can intermittently create low velocity regions, allowing flashback. Boundary layer and core flow upstream flame propagation often comes from combustion instabilities[16].

IV. Combustion induced vortex breakdown (CIVB), the rapid expansion at the burner exit plane creates a recirculation zone (CRZ) which acts as a flame holder. Different heat release patterns due to swirl number variation, different fuels or combustion instability can cause the CRZ to expand into a tulip shaped structure extending to the burner base plate [17], the flame then re-establishes itself on the new, extended CRZ boundary.

Blow-off is an equally important phenomena and again can occur by a number of mechanisms, commonly when the flow velocity exceeds the turbulent flame speed across all the flow section; this is made obviously more complex in swirl burners by the presence of a Central recirculation Zone (CRZ) [3, 10, 15].

This paper studies flashback and blow-off in the generic swirl burner previously described for three different swirl numbers and fuel mixes ranging from pure methane to coke oven gas with some limited pure hydrogen tests.

## II. Experimental Setup

Experiments were all carried out under atmospheric conditions for the generic swirl burner. Premixed air fuel mixtures have been used entirely without any diffusive fuel to provide a base case of data for configurations likely to give lowest NOx. It is accepted that some diffusive fuel will usually be used as a pilot flame; partial premixing for a similar burner has been discussed elsewhere[21].

The generic swirl burner was used to examine flame stability limits at atmospheric conditions (1bar, 293K) at Cardiff University's Gas Turbine Research Centre (GTRC) A single tangential inlet feeds an outer plenum chamber which uniformly distributes premixed air/fuel to the inserts, eventually into the burner body. The central fuel injector (not used for fuel injection here) extended through the whole body of the plenum and swirl burner body to the exhaust, figures 2 and 3. For the swirl number of 1.47 the exhaust nozzle was a sharp orifice where the fuel injector exhausted. For the swirl numbers of 1.04 and 0.8 an extended exhaust nozzle was used, one exit radius long as parallel work showed this, when used with the fuel injector, considerably improved flashback resistance [18].

**Figure 2: Actual Swirl Burner All Parts**

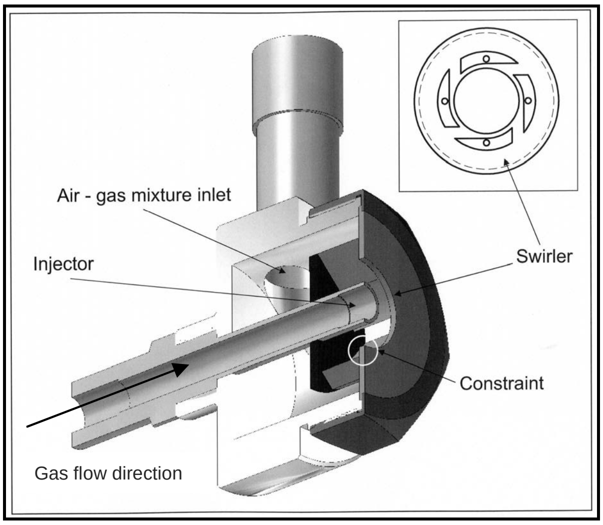



**Figure 3a: Generic Swirl Burner Diagram**

Three different swirl numbers have been used in the experiments: this was achieved by changing the insert count the tangential inlets, 4 in the case of S=1.47, 9 for S=1.04 and 0.83, , figures 1 and 3b.

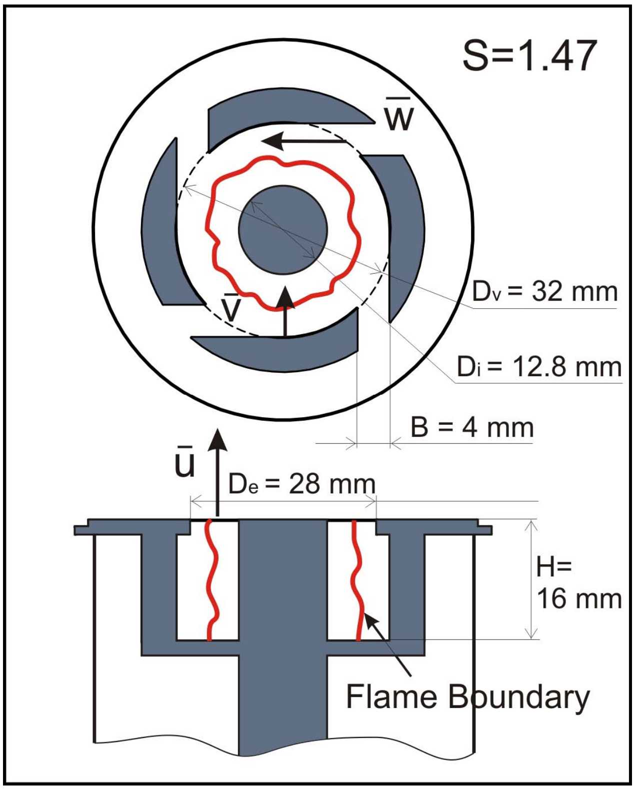



**Figure 3b: Schematic Diagram of Generic Swirl Burner with Location of Flame Front**

The configurations investigated are as follows:

A. Swirl burner, four tangential inlets no exhaust nozzle and geometrical swirl number 1.47, figure 3b.
B. Swirl burner, nine tangential inlets with exhaust nozle and geometrical swirl number 1.04.

C. Swirl burner, nine tangential inlets with exhaust nozzle and geometrical swirl number 0.8.

Swirl insert C is similar to B, the difference is the wider tangential inlets. The complete assembled swirl burners A and B can be shown in figure 4. Different exhaust nozzles are illustrated in figure 5.

**Figure 4: Swirl Burner Assembly-Left Hand, 4 Inlets $S_A$=1.47 Right Hand, 9 Inlets, $S_B$=1.04.**

**Figure 5. Swirl Burner Inserts-Left hand, 4 inlets $S_A$=1.47 Right hand, 9 inlets, $S_B$=1.04.**

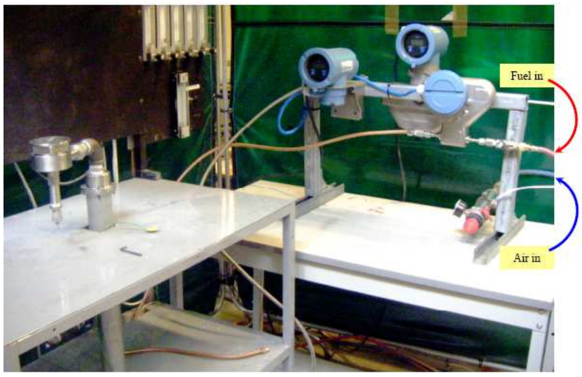



**Figure 6: Experimental Setup**

The reason for the different exhaust nozzle configurations for $S_B$=1.04 and $S_C$=0.8 was that blow off limits with the nozzle extension, figure 5 (right hand side), were much improved, although flashback limits were hardly affected. These swirl burners normally produce a central recirculation zone (CRZ) responsible for flame stabilization. They can be readily adjusted to give, non-premixed, premixed or partially premixed combustion, whilst the central fuel injector is used for liquid fuels or partial premixing. Coriolis flow meters were used to measure mass flow rate of both fuel and air separately, figure 6.

## III. Results and Discussion

Three swirl numbers plus seven different fuels blends (volume basis mixtures) have been used to establish flashback results as summarized in table 1 and 2. All tests were carried out with the burners firing freely into air, typically the pressure loss coefficient at $S_B$=1.04 is nearly half that at $S_A$=1.47 and again is about 20% lower again at $S_C$=0.8. Where possible and within the flow limits of the rig in terms of air and fuel gas supply flashback limits have been derived for the three different swirl numbers and up to eight different fuels shown in table 2.

| **Swirl Burner name** | **A** | **B** | **C** |
|---|---|---|---|
| **Geometrical swirl number** | 1.47 | 1.04 | 0.8 |
| **Exhaust nozzle 1 exit radius long** | NO | Yes | Yes |

**Table 1: Swirl Burners and Their Specifications**

| **Fuel Name** | **%$CH_4$** | **%$H_2$** | **%CO** | **%$N_2$** | **%$CO_2$** |
|---|---|---|---|---|---|
| **Pure Methane** | 100 | 0 | 0 | 0 | 0 |
| **Pure Hydrogen** | 0 | 100 | 0 | 0 | 0 |
| **15%$H_2$/85%$CH_4$** | 85 | 15 | 0 | 0 | 0 |
| **30%$H_2$/70%$CH_4$** | 70 | 30 | 0 | 0 | 0 |
| **Coke Oven Gas** | 25 | 65 | 6 | 4 | 0 |
| **15%$CO_2$/$CH_4$** | 85 | 0 | 0 | 0 | 15 |
| **30%$CO_2$/$CH_4$** | 70 | 0 | 0 | 0 | 30 |

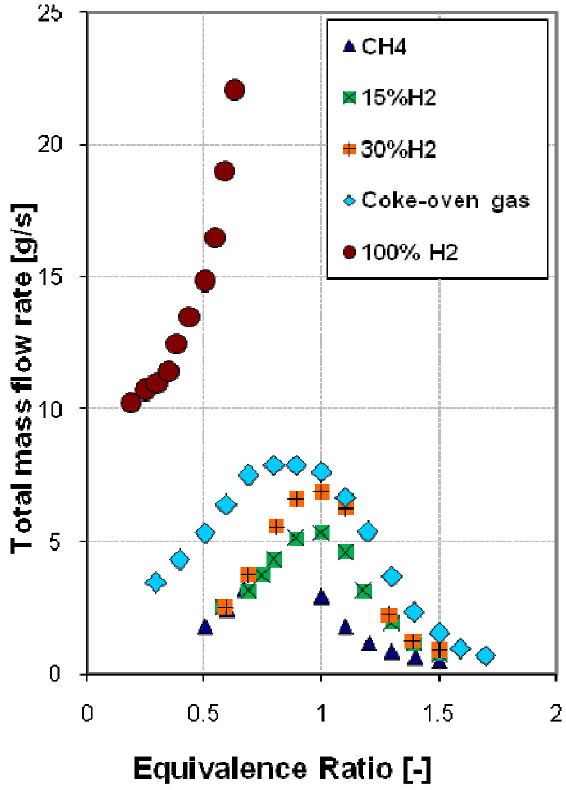
**Table 2: Fuels Blends Tested and Compositions, % by Volume**

Because of the high turbulent flame speed of hydrogen it was not possible to obtain complete flashback or blow-off loops, this being beyond the capability of the rig. Experiments with $CH_{4}/CO_2$ blends were restricted as flashback limits were so good at lower swirl numbers that they were difficult to measure.

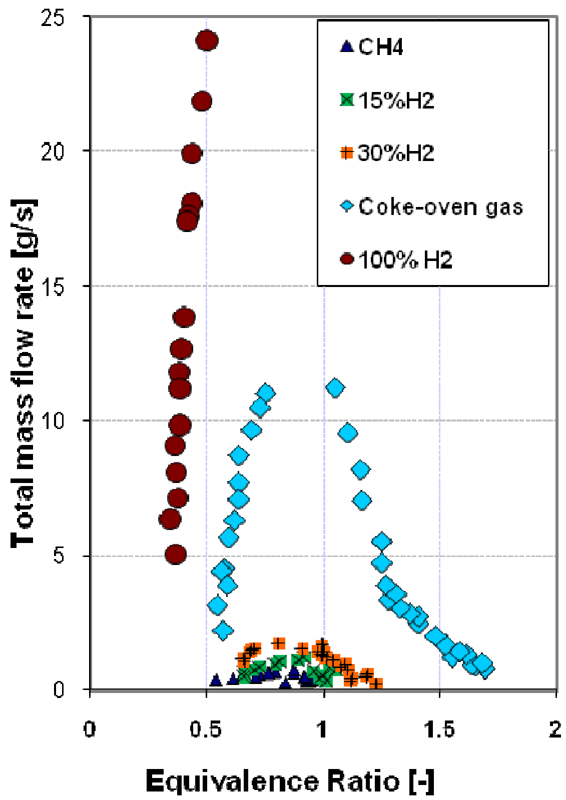
Three families of flashback curves are shown in figure 7 below, for swirl numbers of $S_A$=1.47, figure 7a, $S_B$=1.04, figure 7b and figure 7c for $S_C$=0.8. Fuel blends use range from pure methane, methane with 15%, 30% hydrogen, coke oven gas with 65% hydrogen, 25% methane, 6% CO, and pure hydrogen.

Associated flame photographs at conditions just before flashback for pure methane are shown in figures 8a ($S_A$=1.47) and 8b ($S_B$=1.04).

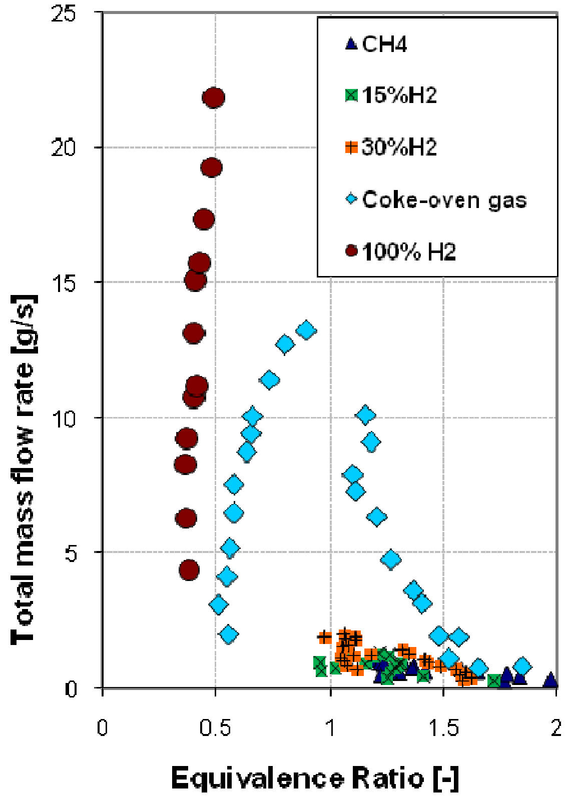
The comparison is extremely interesting and reveals different flashback mechanisms for the three different swirl numbers. With $S_A$=1.47 the central recirculation zone (CRZ) extends over the central fuel injector to the base plate for all fuels, with an associated flame front on the CRZ boundary, as illustrated in figure 3b.




**a) $S_A$=1.47**




**b) $S_B$=1.04**




**c) $S_C$=0.8**

**Figure 7: The flashback stability limit of the three burners with different swirl numbers for five different fuels.**

At S=1.47 flashback occurs when the radial velocity in the swirl chamber around the area of the CRZ ( surrounding the fuel injector, figures 3b and 8a) drops to such a level that the near radial flame front can flashback to the inlets and often into the plenum chamber. Conversely with $S_B$=1.04 and $S_C$=0.8 flashback occurs by a different mechanism via flashback in the outer wall boundary layer of the exhaust nozzle, then being controlled by the critical boundary velocity gradient as initially defined by Lewis and von Elbe[21]. A comparison of different flame shapes at $S_A$=1.47 and $S_B$=1.04 is shown in figure 8a and 8b.

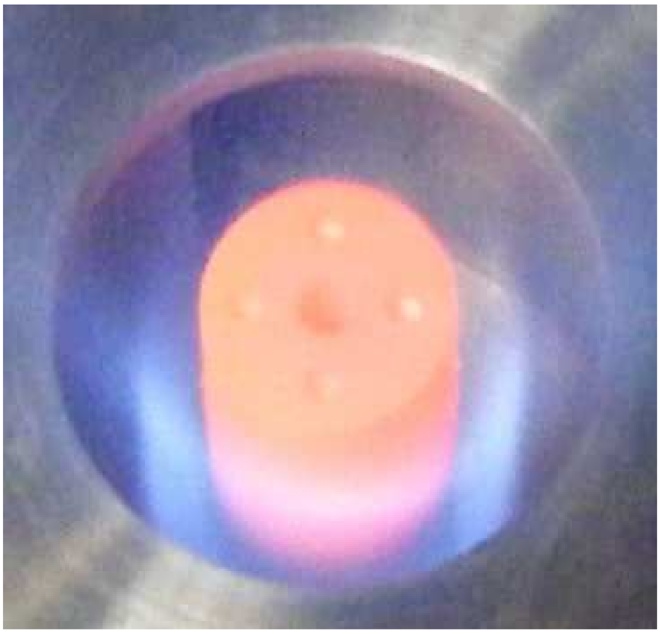


**Figure 8a: Photo of flame surrounding central fuel injector at $S_A$=1.47, just before radial flashback**

**Figure 8b: Photo of flame just before flashback through outer wall boundary layer, $S_B$=1.04**

In terms of flashback limits for methane and methane containing up to 30% hydrogen a value of $S_B$=1.04 and $S_C$=0.8 produces flashback which occurs at mass flow (and hence velocity levels) between ½ to 1/3 of those found for $S_A$=1.47. However with coke oven gas more complex behaviour occurs. The swirl number $S_A$=1.47 gives much better flashback resistance at values of equivalence ratio~1 (~50% improvement). However the respective flashback curves cross at an equivalence ratio ~ 0.55, where after the flashback limits are better for the swirl number $S_B$=1.04 and $S_C$=0.8. Indeed flashback could scarcely be detected for equivalence ratios less than 0.5. Pure hydrogen gave similar trends to coke oven gas. The effect of swirl number for pure hydrogen reflected that for coke oven gas with the characteristics for S=1.47 being better for equivalence rat5ios >0.45. The range of equivalence ratios tested was restricted to being below 0.6 and above 2 due to the very large hydrogen and air flow rates required compared to those for methane.

More detailed inspection of the results with pure hydrogen for $S_B$=1.04 and $S_C$=0.8, figure 7b and 7c indicated that the flashback limit for $S_C$=0.8 was slightly better than $S_B$=1.04: at $S_C$=0.8 swirl number produces less pressure drop: it is clearly favoured. No significant differences between the flashback trends with methane, methane/hydrogen blends and coke oven gas could be found for these two swirl numbers. .

The effect on flashback of $CO_2$ addition to methane were also studied, experiments being carried out with 15%, 30% of CO2 blends with CH4 to check the flashback effect at atmosphere conditions. During these experiments flashback was often eliminated and thus only a few points were determined. A comparison of flashback has been made between the two swirl numbers $S_A$=1.47 and $S_B$=1.04; flashback points for 15% and 30% CO2/$CH_4$ blends are shown in figure (9-a) and (9-b) for the both swirl numbers. These curves show that $S_B$=1.04 virtually eliminates flashback. This confirms the differences in flashback mechanisms between the two swirl numbers

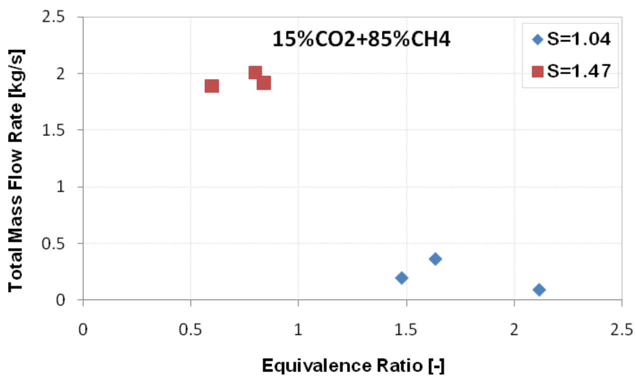



**Figure 9-a: Flashback comparison between swirl numbers $S_A$=1.47 and $S_B$=1.04 for 15%CO2**

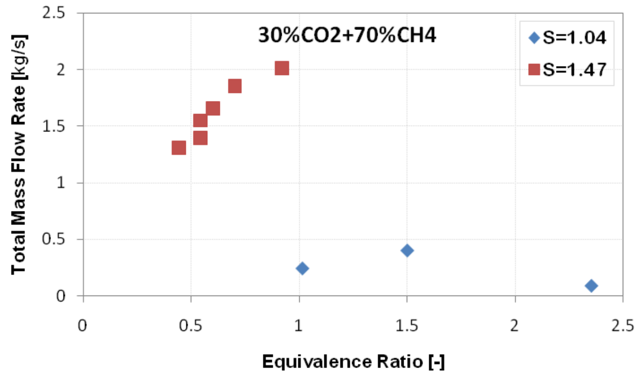



**Figure 9-b: Flashback comparison between swirl numbers $S_A$=1.47 and $S_B$=1.04 for 15%CO2**

Generally, CO2 addition decreases the turbulent burning velocity, thus making flashback more difficult. Unfortunately, CO2 addition worsens the blow-off limits and thus is normally undesirable.

Another interesting result was that the peaks of the flashback curves all occurred at weak equivalence ratios as opposed to the expected values around the stoichiometric ratio. This effect is thought to be due to changes in the recirculation zone occurring as the equivalence ratio approaches 1. This is also illustrated by figure 10 where all the methane data has been plotted as a function of critical boundary layer gradient at flashback, ($G_f$), also included is laminar data on natural gas. The swirl burners at $S_B$ =1.04 and 0.8 are flashing back at lower values of $G_f$ than the laminar results (albeit at a higher system pressure drop), whilst for $S_A$=1.46 values of $G_f$ are significantly higher. Overall $S_C$=0.8 gives the best flashback limits for methane based fuels.

However the opposite occurs for fuels with hydrogen content in the range 30%≤ $H_2$ content ≤ 65% with the Critical Boundary velocity gradient being higher at lower swirl numbers, reflecting the previously discussed results.

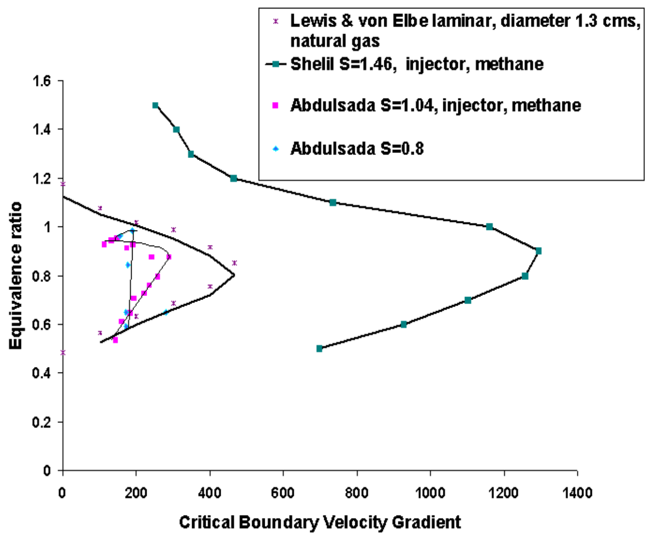



**Figure 10: Lewis and von Elbe Critical Boundary velocity gradient Comparison for 3 swirl numbers (natural gas and methane) and laminar data**

Blow-off data for the fuel range is shown in figure 11 below. Significant data for pure hydrogen blow-off could not be obtained due to rig limitations Swirl numbers, $S_A$=1.47, gave worst blow-off limits for all fuels, although coke oven gas with 65% hydrogen content gave a dramatic improvement. The most interesting feature was the differences between blow-off limits for $S_B$=1.04 and $S_C$=0.8. $S_C$=0.8 gave much improved blow-off limits with pure methane and fuel blends containing up to 30% hydrogen. Both swirl numbers gave very similar results for blow-off with coke oven gas.

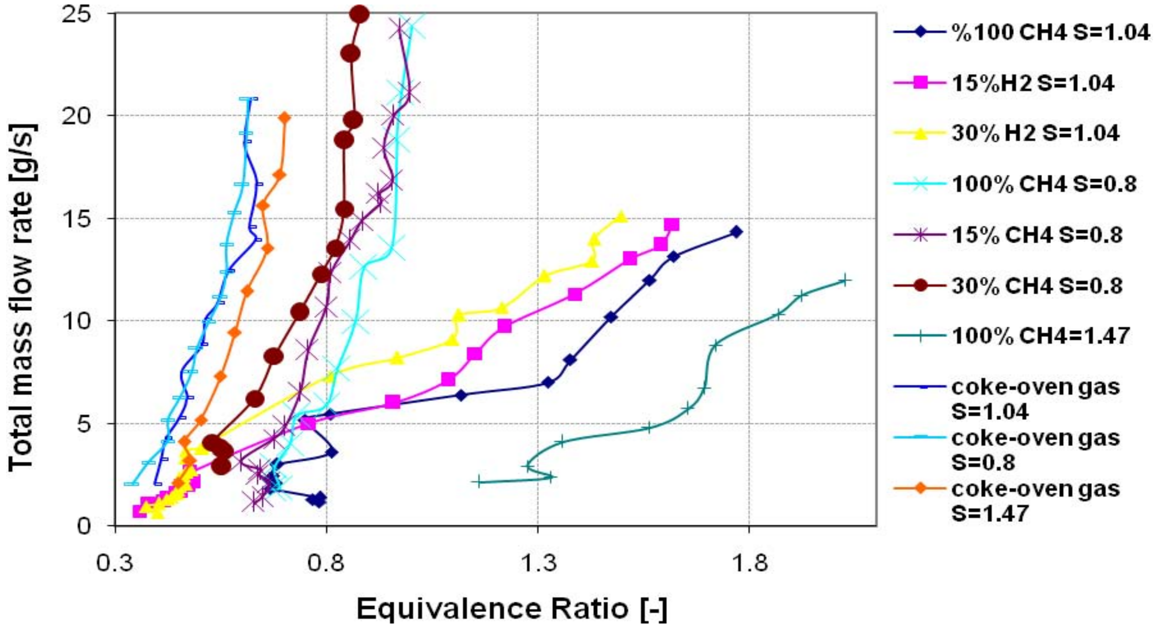



**Figure 11: Blow-off Limits for Different Hydrogen Based Fuel Blends**

## IV. Conclusion

Flashback and blow-off has been investigated at three different swirl numbers and with up to seven different fuel blends including methane, hydrogen, coke oven gas and various blends of $H_2/CH_4$ and $CO_2/CH_4$.

Flashback and blow-off limits are decisively influenced by swirl number, exhaust configuration, fuel type and especially those containing significant quantities of hydrogen with methane and up to 30% hydrogen blends with methane the lowest swirl number of 0.8 gave the best flashback limits, when the low pressure drop is taken into account. Similar results were found with up to 30% $CO_2/CH_4$fuel blends.

The mechanism of flashback appeared to be different with $S_A$=1.47 as the CRZ extended back over the fuel injector to the base plate and flashback occurred by radial movement of the flame front from the CRZ boundary to the tangential inlets. Conversely at lower swirl numbers (and with a different exhaust nozzle) the mechanism of flashback appeared to be via the outer wall boundary layer and the critical boundary velocity gradients. Comparison of the various critical boundary velocity gradients using the analysis of Lewis and von Elbe showed that the swirl burner $S_C$=0.8 produced values even lower than that from laminar flames, whilst the swirl burner with $S_A$=1.47 was substantially worse.

Coke oven gas and pure hydrogen produced more complex behaviour with $S_A$=1.47 having lowest flashback levels at values of equivalence ratio~1: conversely $S_B$=1.07 and $S_C$=0.8 gave better flashback limits for very lean combustion conditions.

Blow-off limits were equally interesting showing complex behaviour with unexpectedly worst limits with $S_A$=1.47 and hydrogen content <60%. Blow-off limits converged with coke oven gas for all three swirl numbers, although $S_C$=0.8 was just the best.

Recent results have shown that not unexpectedly the addition of an exhaust confinement, akin to a gas turbine combustor significantly improves the blow-off limits.

The effect of the levels of air preheat typically found in gas turbines are likely to improve blow off, but also increase flashback. Pressure effects are likely to alter flashback limits as well; some work indicates that flashback effects will also increase. Further experiments are obviously needed. The unit has been designed for testing under simulated gas turbine conditions with air preheat and pressures up to 12 bar; this work should commence soon.

## V. Acknowledgments

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