The Use of CO2 to Improve Stability and Emissions of an IGCC Combustor

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THE USE OF CO2 TO IMPROVE STABILTY AND EMISSIONS OF AN IGCC COMBUSTOR

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ABSTRACT

The use of gas for power generation is likely to increase in the medium term. Also, the introduction of new fuels will ensure a higher generation with lower emissions under continuous operation. These scenarios lead to the conclusion that there will be a considerably more diverse range of fuel supply. However, the use of these new fuels contrasts with recent experiences of global operators who report increasing emissions and difficult combustion dynamics with even moderate variations in their fuel characteristics. Clearly there are significant challenges for fuel flexible gas turbines, particularly emission control, combustor dynamics and flame stability.

Trials using a proprietary, power derivative gas turbine combustor and a high hydrogen content fuel produced unusual flash back events, in that flash back was induced by either leaning of the fuel mixture by the increase of combustion air, or by a change in composition through the reduction of methane pilot fuel. The introduction of CO_2 through the combustors pilot injector prevented flash back from occurring under these circumstances. The resulting reduction of temperature in the combustion zone, indicated by lower burner tip temperatures causes a reduction in the emissions of nitrous oxides, whilst there is minimal effect on the effective turbine inlet temperature, only a 2.3% reduction.

Investigations using a ‘generic’, radial swirl burner and stereo PIV demonstrated how the flash back depended on a combination of flow structure augmentation and changes in mixture burning rate. The injection of methane or CO_2 had differing effect on these parameters of the combustion zone, but both produced combinations that facilitated stability.

INTRODUCTION

Rapid depletion of fossil fuels and widespread concern about climate change have prompted researchers, companies and governments around the world to develop new technologies capable of using new fuels that will reduce the final impact towards the environment whilst keeping the energy supply. The number of fuels that can be used for this purpose is vast, ranging from those based on highly enriched hydrogenated blends to those that are produced from bio-materials [1-4]. Therefore, gas turbine technologies are evolving very fast to cope with the use of these new fuels. However, operators are still finding several problems with the usage of fuels that slightly change their characteristics as a consequence of their origin or in-site ambient conditions, posing a new challenge to manufacturers to produce more flexible equipments [5].

However, the design of new equipments is highly linked to their stability and thermo-acoustic patterns, as these issues will impact directly on the propagation of phenomena that can be highly detrimental to the performance and integrity of the system [6]. Thus, a higher understanding of those phenomena that will appear due to fuel changes in the system is needed to control to certain extent the new combustion dynamics. The most important instabilities that can appear are produced by flashback, blow-off and thermo-acoustic oscillations. The crucial feature of new burner technologies using any fuel is the formation of a CRZ, a provider of heat to fresh reactants and anchors the flame. However, unless its size and shape are properly controlled, problems can arise. The CRZ can for instance readily extend back into the burner surrounding the fuel injector and facilitating early flashback (low stability limit) [7-9]. Flashback can be caused by (i) boundary layer flame propagation, (ii) turbulent flame propagation in the core flow, (iii) thermo-acoustics and (iv) upstream flame propagation of coherent vortical structures [8, 10-12]. Two of these mechanisms, i.e. boundary layer flame propagation and upstream propagation of coherent structures, have been studied by several groups using natural gas. However, the use of unconventional fuels can be extremely detrimental to the control of this phenomenon, and very little literature is available on this subject. High turbulence levels, one of the very useful features of swirling flow because of their mixing potential, affects flashback limits detrimentally due to their effects on turbulent flame speed (S_t). It has been found [13, 14] that the current theoretical approximations do not agree with experimental values. Literature on this topic becomes more complex in terms of numerical modeling, but experiments tend to be different from numerical findings especially when complex flows are added to field [14]. For instance, very little has been documented in terms of boundary layer propagation using atmospheric conditions [3, 15, 16], and these findings only show the evolution of 2D structures without swirl and under atmospheric conditions. Thus, the current knowledge on these mechanisms cannot adequately describe the flashback propensity of most practical combustor designs. Therefore, the recognition of the real pattern of this phenomenon is crucial in order to have systems and models capable of utilising new alternative fuels.

Similarly, relatively little literature exists on blow-off (high stability limit) when swirling flows and unconventional fuels are used. The studies that have been conducted consist of a large database on how to improve operability with natural gas, but there is little investigation on the fundamental behaviour underlying combustion stability [17]. As explained by Shanbhogue et al. [18], there are different theories about blow-off. Most of the current theories are based on a flamelet based description upon local extinction by excessive flame stretch [19]. This theory has demonstrated that flame stretching starts blow-off with the initiation of holes in the flame, that are healed by the same flame creating stretching in areas that otherwise would have been unaffected. However, it is also recognised that this mechanism is not the one causing the final blow-off, as it is clear from data that the flame can withstand some extinction. Therefore, it is considered that the “critical extinction level” must be strongly influenced by the entrainment of reactants into the recirculation zone, the cooling of regions of the recirculation zone and the shrinking in size of the CRZ, thus confirming some relation between the phenomenon of flashback and the existence of the CRZ [17]. Unfortunately, this is a theory that has not been corroborated.

Thermo-acoustic instabilities have been studied in these equipments for the last decade, with the recognition of nonlinear responses of the combustion and acoustic oscillations [6, 20]. The combustion dynamics of industrial gas turbines can be influenced by aerodynamic processes, chamber instabilities, and inhomogeneous processes, resulting in a heat release that will cope with the emanating pressure waves in a cycle that will increase the energy in the latter, until the dissipative viscous losses arrest further growth [21-25]. These fluctuations are potentially critical to the structure and efficiency of the system. This phenomenon is of high importance especially to those utility companies that must rely on highly stable cycles.

Some authors [26-31] have observed that the CRZ has a close connection to the stability of the system, with its shape, strength and curvature being of high importance to its resistance to flashback and blow-off [30, 32]. Regular precession occurs in the CRZ, with the appearance of the CRZ dependent on the heat transfer regime. The mode of injection is also important, with an increase in the interaction of the hot products and fresh reactants when confinement is imposed. The recirculation zone behaves as an intermittent structure that will propagate downstream in order to release some internal pressure product of the confinement and intense recirculation at moderate to high swirl numbers [30]. This, on the other hand, can also be detrimental to the phenomenon of flashback as the CRZ will evolve into the Combustion Induced Vortex Breakdown [33], Boundary Layer Propagation [16] or the movement of the CRZ to the system to produce turbulent burning along the voritical axis [34], all damaging to the system. Its interaction with the PVC under combustion and isothermal conditions is also recognised in some works [26, 27], and its influence in the thermo-acoustics of the system is of high impact especially to the wrinkling and stability of the flame [25, 35]. Hence, the understanding of the stability limits and thermo-acoustics represents an important topic of discussion with the use of new, low emission fuels.

In terms of unconventional fuels, the primary goal of introducing CO_2 into the gas turbine combustor is to reduce the emissions of NO_x. This is achieved by cooling the flame, thus the Zeldovich mechanism can be reduced [36]. Previous experimental and numerical studies have investigated the effect of dilution Syngas fuels with various additives, including carbon dioxide, nitrogen and steam [37-41]. In the majority, these studies focus on fundamental characteristics of the combustion process. However, the work by Lee et al [37]and Khalil et al [1] actually investigated the effect of diluting the premix fuel had on the emission of NO_x and CO from a model gas turbine.

Lee et al [37] showed that reduction in ppm NO_x per unit power is logarithmically related to the heat capacity of the total diluent added. Since carbon dioxide has a higher heat capacity than steam or nitrogen, a smaller mass flow rate is required for a comparable reduction in NO_x. Moreover, the use of CO_2 from carbon capture and storage facilities could reduce costs as well as capture equipment further downstream the combustion zone.

Therefore, this study is based on the study of stability of flames that use CO_2 as pilot and in the premixed blend. The system is expected to be stabilized by the high interaction of the CO_2 injected throughout the pilot, whilst creating a highly coherent CRZ that will interact with the fresh reactants. Meanwhile, the CO_2 injected through the premixed blend will reduce the reaction rate, thus reducing the temperature. The high temperature of the CO_2 in the CRZ will ensure a faster chemical reaction of the diluted reactants, thus permitting a stable regime with low NO_x and CO.

Nomenclature

AFT	Adiabatic Flame Temperature
CIVB	Combustion Induced Vortex Breakdown
CRZ	Central Recirculation Zone
GTRC	Gas Turbine Research Centre
HMFR	High Momentum Flow Region
HPOC	High Pressure Optical Casing
IGCC	Integrated Gasification Combined Cycle
PIV	Particle Image Velocimetry
PVC	Precessing Vortex Core
S_g	Geometric Swirl Number

EXPERIMENTAL FACILITIES

HPOC Test Rig

Primary tests were performed using the HPOC rig at Cardiff Universities GTRC. The rig is capable of delivering 5 $kg{\cdot}s^{-1}$ of air at 900K and 16 bara, thus allowing combustors to be operated at conditions applicable to use in a power generation derivative gas turbine engine, a schematic is shown in Figure 1.

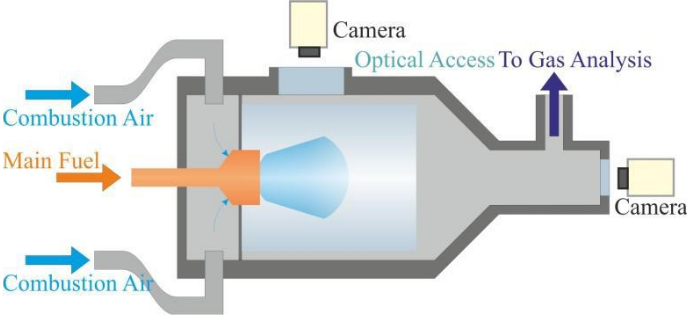


Figure 1: HPOC rig at GTRC

A proprietary gas turbine combustor, designed for use as part of an IGCC configuration, was used during these tests. The volumetric flow rate and temperature of the air passing through the combustor are defined by its designated compressor. There are two available flow paths for combustion air and fuel, the first path is through the combustor pilot. The pilot injector a vane axial swirler that sits on the axis of the combustor, through which pilot fuel and approximately ten percent of the combustion air is fed. The second path is through the main annular axial swirler, which surrounds the pilot swirler. The main swirler is fed by the main fuel supply and the remaining ninety percent of the combustion air. The combination of two swirling flows creates a complex flow structure; however, PIV of the combustor shows that under isothermal conditions the isothermal CRZ resembles that of a combustor with a single geometry imparting swirl on the flow. Figure 2 is a PIV image with air passing through under typical gas turbine operating conditions, it clearly shows how a CRZ has formed and that the reverse flow zone extends to the exit of combustor nozzle.

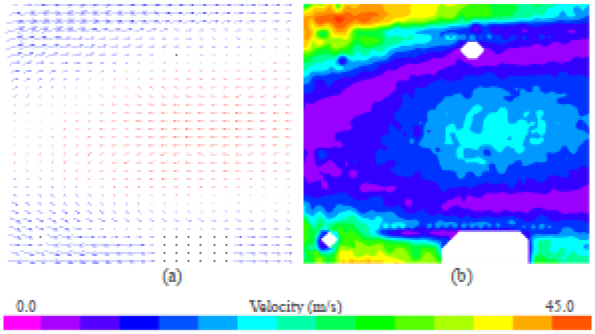


Figure 2: (a) Vector and (b) magnitude plots of combustor under typical gas turbine operating conditions (500 image pairs with approximately 3500 vectors)

Methane was always used as the pilot fuel, however three main fuels were used, pure methane, a 50/50 (by volume) hydrogen and carbon monoxide blend, denoted Syngas A, and an 85/15 (by volume) hydrogen and nitrogen blend, denoted Syngas B. Two configurations of the combustor were also tested with different lengths of nozzle length.

Generic Burner

In order to investigate the fundamental changes in flame structure caused by the introduction of carbon dioxide to the flame, a small-scale burner was used. This burner, with exit diameter of 28mm has been used extensively before to investigate the effect of geometric swirl number, fuel composition and level of confinement on swirl combustion, as has been reported in literature [4, 42-46]. Unlike the axial combustor fitted in the HPOC, the generic burner is of a radial type, as shown in Figure 3, also shown is how the air, fuel and diluent carbon dioxide are introduced.

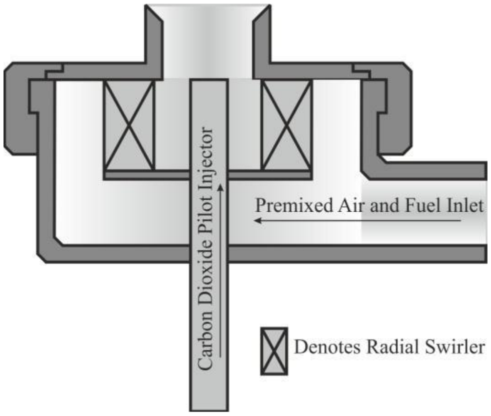


Figure 3: Schematic of the generic burner

The air and fuel, in this case methane, are premixed and pass through the swirl channels before entering the combustion zone, and therefore have both axial and tangential velocity components. The carbon dioxide is introduced through the pilot injector, as such it has only an axial velocity component. Changing the inlet configuration allows the S_g to be altered, however, during these trials the S_g was kept constant.

LEAN FLASH BACK

It has been established that flashback is caused by either one, or a combination, of four reasons [7, 10-12]; flame propagation in either the boundary layer or core flow, CIVB or via violent combustion instabilities. When flashback occurred in the HPOC two different final flame positions were observed, and both were seen as the result of leaning of the global equivalence ratio.

The first position observed was upstream flame propagation in the main fuel and air mixture, one instance of its occurrence was during a test using Syngas A as the main fuel. Prior to flashback, the combustor was operating at its desired power level with a relatively rich pilot mixture (equivalence ratio (Φ) of 0.970), and a lean main mixture ($\Phi = 0.329$). A reduction in the pilot flow saw the flame begin to propagate back to the combustor exit nozzle via the shear boundary layer, as is demonstrated in Figure 4 (a). This propagation in the shear layer has been seen in previous work with methane [4, 42] immediately prior to complete flashback, as seen in Figure 4 (b). In the previous case, the flashback was caused by increasing the equivalence ratio of a fully premixed flame.

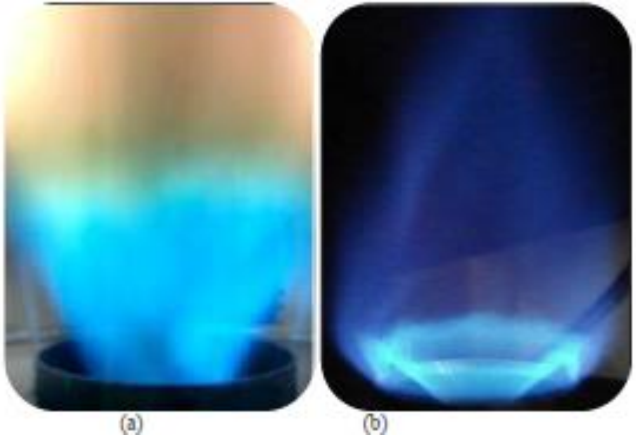

(a) (b)

Figure 4: Still images of flames taken prior to boundary layer flashback (a) demonstration of flame seen during these trials and (b) from Syred et.al. [4]

Strong shear layers develop where the high velocity swirling flow meets the relatively stagnant fluid in the combustion chamber. This shear layer produces regions of low velocity flow, and can allow the flame to propagate back to the combustor nozzle. The further downstream, the greater the fluid velocity is reduced, increasing the thickness of the shear layer; evidence of this is clear the in Figure 4 (a) and (b). The diameter of the low velocity region in the centre of the flow also increases as the distance from the combustor nozzle increases, this can been seen in PIV data taken from the combustor under desired power flow conditions, in Figure 5. The result being that the annular area where overall flow velocity is too great for flame propagation reduces in as downstream distance increases. When flashback occurs in this way the conditions are such that the low velocity flammable regions of the flames main body and shear layer meet up allowing the flame to propagate.

Once propagation through the shear layer has been established, it is possible for flashback to occur via the further propagation through the outer wall boundary layer of the combustor nozzle. This is controlled by critical velocity gradient [47] as defined by Lewis and von Elbe [48].

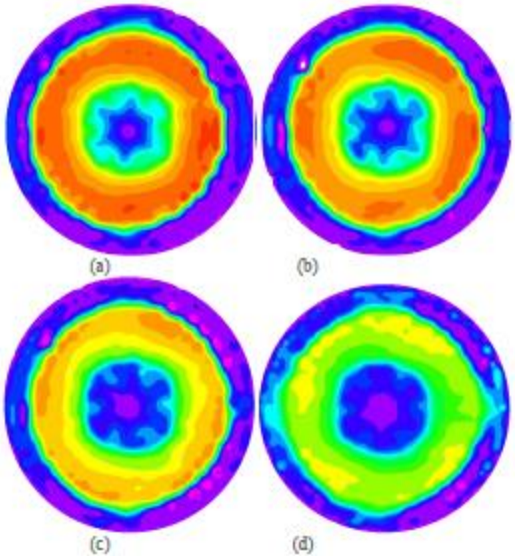


Figure 5: Radial magnitude plots of IGCC combustor on the same scale at (a) 5mm (b) 10mm (c) 25 mm (d) 50 mm from nozzle exit under desired power conditions (500 image pairs each with approximately 2000 vectors)

The mixing layer that exists between the pilot flame and the main fuel mixture [49] ensures that equivalence ratio in the shear layers is not affected by that of the pilot, this suggests that propagation of the flame is initiated by CIVB rather than changes the mixtures burning velocity.

The shape of the CRZ strongly influences the stability of the combustion system, its presence causes the formation of other proceeding structures capable of pushing the flame upstream and increasing propensity for flashback [27]. Previous work by Dam et. al. [13] shows when CIVB occurs the High Momentum Flow Region (HMFR) of the flame contracts and squeezes the CRZ. This results in the flame propagating upstream, the work also demonstrates how the mixing layer approaches combustor nozzle.

Valera-Medina [26] identified a type of flashback that occurred when CIVB, identified as the primary cause of flashback in swirl burners [33], caused the CRZ to propagated upstream, resulting in the flame attaching to an axial fuel injector that protruded into the combustor nozzle, resembling the flashback seen with Syngas B in these trials.

Due to the significantly higher hydrogen content in Syngas B, its burning velocity is greater than Syngas A, this results in its shape being significantly shorter and narrower. The narrow shape of the flame prevents propagation into the shear and boundary layers, allowing vortex breakdown to continue. Eventually the CRZ contacts the body of the pilot injector in the centre of the flow, a process that was demonstrated clearly by Dam et. al. [13].

From standard operating conditions two alterations in flow conditions resulted in flashback of this type. The first saw a reduction in pilot fuel, the result of which was a flame fluctuating between a seemingly stable and flashbacked state before permanently attaching on the pilot injector. The second was to increase airflow steadily, global equivalence ratio decreased from 0.221 to 0.157 before axial flashback occurred.

INITIATION OF CIVB

Work on combustors with co-swirlers provides examples of cases where, under isothermal conditions, the flow patterns resemble those of a single swirler [50], and where flow patterns differ [49]. However the burner used by Dhanuka et. al. [49] which resulted in a different pattern had a significant area between the outlet of the swirlers which acted as bluff body, creating additional recirculation zones.

Isothermal PIV of this combustor shows a CRZ structure resembling that created by a single swirler; largely due to its co-swirl configuration and the dissimilarity between flow rates through the pilot and annular swirlers. The result is a pilot injector that acts in a similar fashion to a bluff body, as seen in the generic burner, and commonly used to stabilise flames in fast flowing fluids [51].

It is believed that the lean flashback observed is the result of CIVB, and after the initiation if CIVB both types of flashback encountered have been adequately explained by previous studies [4, 13, 26]. These studies, however, relate to burners that use a single device to impart swirl on the flow, with both axial and radial flashback being caused by an increase in equivalence ratio. Dam et. al. [13] showed that combustion induced breakdown of vortices is caused by the high velocity zones of a flame squeezing the recirculation zone, causing the CRZ to propagate upstream and vortex breakdown to continue.

Equivalence ratio was increased by increasing the flow of fuel, and as such Adiabatic Flame Temperature (AFT), the expansion and, as a result, volume of hot gas also increased and the intensity in high velocity zones increased.

The increase in the volume of gases, and not the change in equivalence ratio is directly linked to the velocity of the HMFR. This is displayed in the left hand column of Figure 6, which shows stereo PIV plots of 12.5 kW methane flames of different equivalence ratios in the generic burner as detailed in Table 1. All the scalar plots, which represent velocity in the Z direction are on the same scale, the increase in velocity in the flame is readily apparent as the air flow is increased and the flame becomes leaner.

It is important to note the differences, between the proprietary combustor in the HPOC and the generic burner. Whilst both are swirl combustors with similar exit configurations, the generic burner is of a radial type and the proprietary burner is of axial type, they are also using different fuels. The high turbulence generated, along with the large pilot injector in the proprietary burner results in high resistance to blow off, whereas the low turbulence and exit geometry of the generic burner makes it very resistant to flash back.

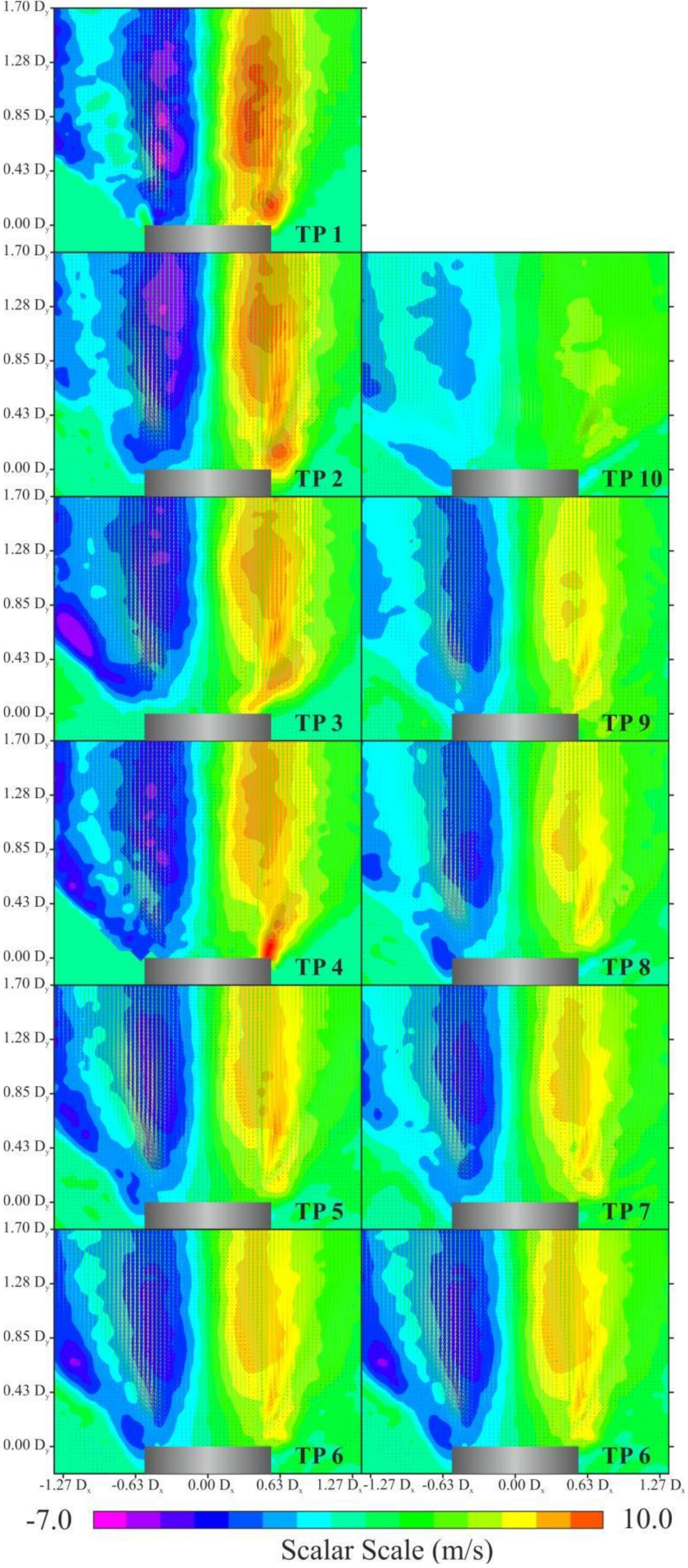


Figure 6: Stereo PIV of 12.5 kW flame in the generic burner with altered (a) premix air flow rate (b) pilot CO2 flow rate (150 image pairs with approximately 5000 vectors)

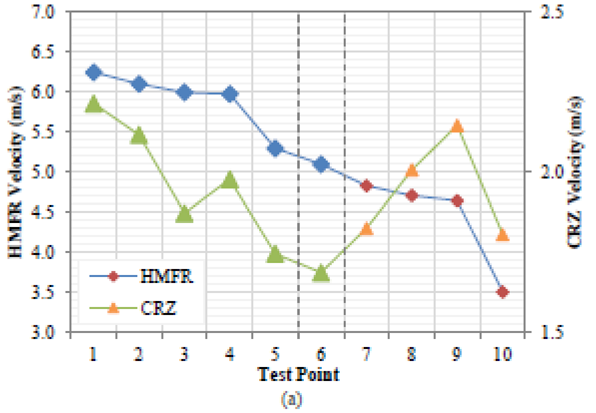
One of the results of these differences is that in terms of equivalence ratio, the operating ranges are very different, the nature of extinction events are also very different. However, within their respective stability ranges, the changes in flow structures caused by changes in air flow rates and introducing carbon dioxide are comparable.

All the tests performed using the generic burner are detailed in Table 1, the minutiae of the HMFR are taken from the numerical PIV data, with areas where velocity exceeds 3 m/s considered to be of a high momentum, the calculated velocities size of these regions are shown in Figure 7 (a) and (b) respectively.

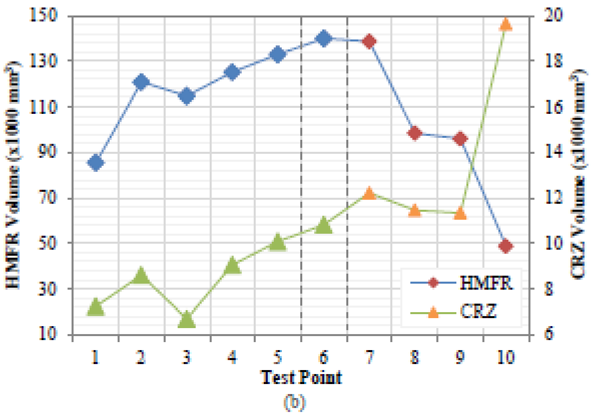
Table 1: Details of generic burner test points

Test Point	Mass Flow Rate (g/s)				Φ	AFT (K)
	CH_4	Air	CO_2	Total		
1	0.25	5.00	0.000	5.25	0.86	2083
2	0.25	4.78	0.000	5.03	0.90	2134
3	0.25	4.30	0.000	4.55	1.00	2226
4	0.25	3.91	0.000	4.16	1.10	2211
5	0.25	3.58	0.000	3.83	1.20	2137
6	0.25	3.31	0.000	3.56	1.30	2057
7	0.25	3.31	0.049	3.61	1.30	2038
8	0.25	3.31	0.103	3.66	1.30	2017
9	0.25	3.31	0.116	3.68	1.30	2012
10	0.25	3.31	0.130	3.69	1.30	2007

Between Test Point (TP) 1 and TP 6, the increase in velocity in the HMFR as total mass flow is increased is obvious; however, instead of this increase in velocity resulting in a larger volume HMFR, the opposite is true. The result being as equivalence ratio reduces in size the HMFR reduces in size but increases in intensity. Figure 7 (a) and (b) also show the velocity and volume of the central recirculation zone for the same conditions, taken from the same PIV data. The data shows that rather than an increasing HMFR volume coinciding with a reduction in CRZ volume, the volumes seem to be closely linked.



(a)



(b)

Figure 7: The effect of air and carbon dioxide flow rates on the (a) velocities and (b) volumes of the HMFR and CRZ

The increased flow rate increased the axial momentum of the flame, which made the flame narrower with higher velocities, indicating an increase in HMFR intensity, rather than size, is linked to contraction of CRZ.

In the generic burner, increasing air flow would ultimately result in blow off, but as it is increased the intensity in the HMFR increases, as seen previously by Dam et. al. [13] during CIVB. If this is also occurring in the HPOC, where the bluff body like pilot injector and high turbulence can inhibit blow off, this would offer an explanation for the lean, axial flash back that occurred.

The reduction in the size of the HMFR, and hence ability for the flame to propagate to the shear layers, as seen in the both this and other work [4] also offers an explanation for the lean, radial flash back that occurred.

STABILISING WITH CARBON DIOXIDE

Stereo PIV images on the right hand column of Figure 6 show how the injection of differing amounts of carbon dioxide through the pilot of the generic burner effected the velocity of the flame, reducing it significantly. TP 6 to TP 10 in Figure 7 also shows how the velocity and volume of the HMFR are affected. Changes in structure and velocity from TP 1 to TP 6 were linked to changes in flow rates, with a 47.5% total change, from the TP 6 to TP 10 the change in premix flow is constant, with change in total flow equal to 3.7%, yet the changes in structure and intensity are significant.

Through TP 6 to 9 the introduction of CO_2 results in a continued decrease in HMFR velocity, however the velocity in the CRZ increases sharply as the CO_2's high specific heat increases the pressure differential that drives recirculation. The CRZ stabilises the flame by recirculating thermal energy and active chemicals whilst allowing turbulent flame speed to match flow velocities [52, 53], all are inhibited by the injection of CO_2, as such, as it is increased the flame tends towards blow off. TP 10 represents a flame in a quasi-stable state, on the verge of blow off. At this point the flame shape has changed significantly, as demonstrated by the difference between Figure

8 (a) and Figure 8 (b), Figure 7 details how there is large expansion and slowing of the CRZ, whilst the HMFR reduces significantly in size and velocity. The results show how the injection of a small flow rate of CO_2 can have significant effects on flame structure; effects which can be utilised to increase the stability range of an IGCC combustor.

Running the IGCC combustor without the injection of pilot fuel is very beneficial to reduce the levels of NO_x produced during the combustion process. It has been established that steadily reducing pilot fuel induces CIVB, and as a result flashback. Suddenly turning off pilot fuel did not instantly cause flashback, however, under many conditions the process of CIVB and propagation of the CRZ will eventually result in flame attachment, the effect of injecting carbon dioxide was investigated on a Syngas B flame. The introduction of CO_2 through the pilot injector, at volumetric flow rate that was equal or greater than that of the pilot fuel prevented lean flashback occurring, whether the fuel was turned off instantly or phased out.

The flow rate of CO_2 was steadily increased to 600 % of that of the initial pilot fuel, not only did the flame remain stable, but also the injection of CO_2 was actually shown to reduce the tip temperature of the combustor, shown in Figure 9. This further reduces the likelihood of flashback as the temperature of gas leaving the pilot injector is reduced, as are burning rates as a consequence. It is also potentially beneficial for the longevity of the combustor as damage caused by overheating is less likely.

Despite the significant drop in burner tip temperature, the temperature of the exhaust was not greatly affected. As the mass flow rate of carbon dioxide injected increased from 0 to 127 % of the Syngas mass flow rate, the burner tip temperature dropped 20.8 %, however the exhaust temperature, effectively the turbine inlet temperature, only dropped by 2.3 %.

According to the extended Zeldovich mechanism [36], as flame temperatures increases so do emissions of nitrous oxides, with reaction rates determined experimentally with reasonable accuracy [54]. Introducing CO_2 into the gas turbine combustor reduces the emissions of NO_x, it does this by cooling the flame in two ways. Stabilising the flame when no pilot fuel is injected, this has a significant effect on the heat of the flame at the pilot injection point, as seen in Figure 9, and absorbing heat from the combustion process, due to its high specific heat.

Previous experimental and numerical studies have investigated the effect of diluting Syngas fuels with various additives, including carbon dioxide, nitrogen and steam [37-41]. In the majority these studies focus on fundamental characteristics of the combustion process, however the work by Lee et. al. [37] actually investigated the effect of diluting the premix fuel had on the emission of NO_x and CO from a model gas turbine. It was shown that reduction in ppm NO_x per unit power is logarithmically related to the heat capacity of the total diluent added. Since carbon dioxide has a higher heat capacity than steam or nitrogen a smaller mass flow rate is required for a comparable reduction in NO_x.

When pilot fuel was used, the combustion process at the desired power condition produced 17.29 parts per million (ppm) of NO_X, when the pilot fuel was switched of and not replaced by a similar amount of CO_2 the NO_X produced dropped to 10.26 ppm, a 40.6 % decrease. The injection of CO_2 saw the NO_X levels drop further, with 8.12 ppm recorded when the amount of CO_2 equalled 127 % of the Syngas by mass, as the results in Figure 10 show.

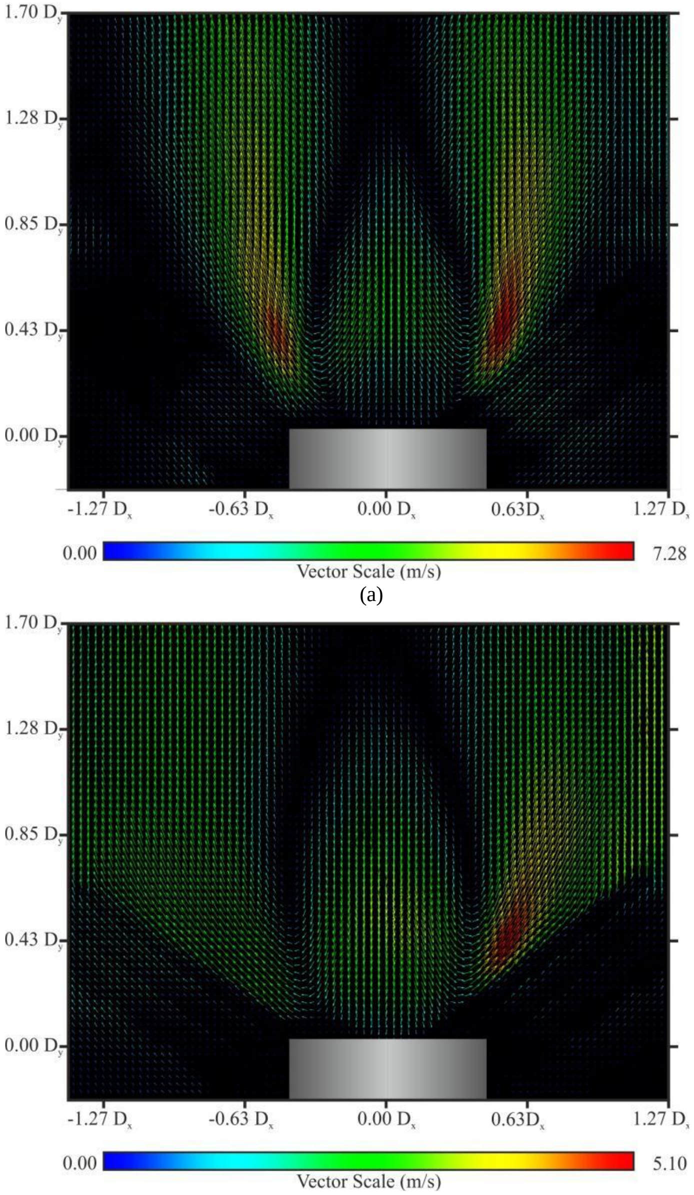


Figure 8: Single camera PIV of (a) test point 9 and (b) test point 10 (150 image pairs with approximately 5000 image pairs)

Ignoring the decrease in NO_X that resulted from turning of the pilot fuel, the drop in ppm NO_X caused by CO_2 addition was 20.9 %. The addition of the CO_2 will increase the mass of the exhaust gases, so this drop is due partly to the dilution effect.

However, when compensating for dilution, the reduction of NOx caused by CO_2 addition is still 17.9 %, total reduction observed was 51.0 %.

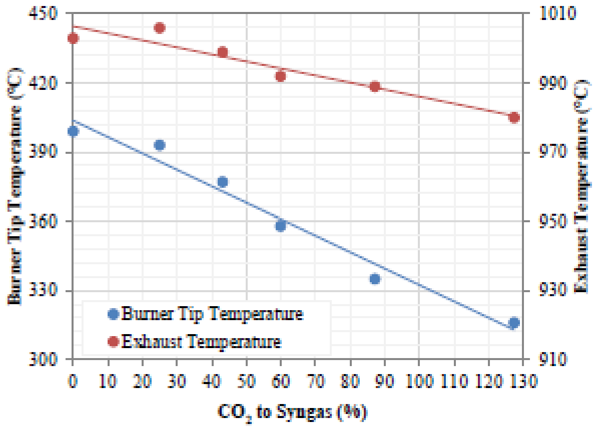


Figure 9: Effect of CO_2 injection on combustor temperatures

During these trials the mass flow rate of both Syngas and air was kept constant (within 1.5 %), as it would be in a gas turbine, therefore the injection of carbon dioxide does not alter the equivalence ratio of the reactant mixture. As such, the percentage of oxygen in the exhaust increases from 12.5 % to 14.5 % when the pilot fuel is switched off, after that it also remains constant within ± 1 %. The amount of unburned hydrocarbons in the exhaust showed a reduction with CO_2 injection, but the results do not produce a trend strong enough to draw any firm conclusions.

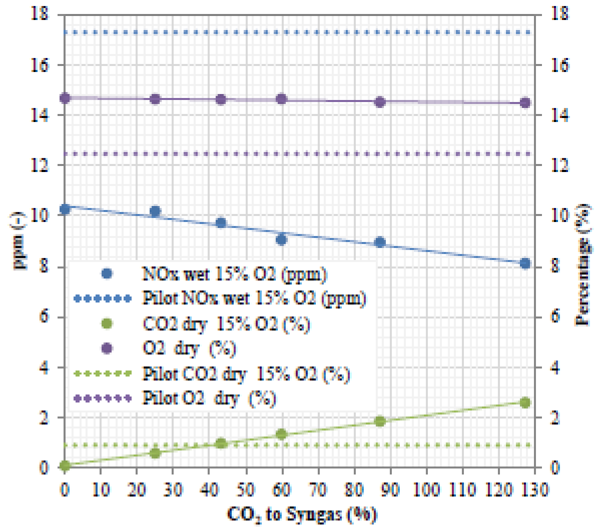


Figure 10: Effect of CO_2 injection on exhaust gases

CONCLUSIONS

Trials using an IGCC gas turbine combustor, fired on different compositions of Syngas, showed a propensity for lean flash back. This was attributed to the high turbulence nature of the combustor, combined with the bluff body like pilot injector and the high burning velocity of the air-fuel mixtures inhibiting blow off, and the decrease in equivalence ratio altering the shape and intensity of the CRZ and HMFR to the extent that CIVB occurred. This augmentation of the CRZ-HMFR pairing by changes in premix air flow was demonstrated by performing PIV analysis on a generic, radial swirl burner, as was the effect of introducing carbon dioxide through the central pilot injector.

The intensity of the HMFR, which was shown in previous work to be integral to the process of CIVB, was shown to increase as air flow reduced the equivalence ratio of the flame, squeezing the CRZ. The introduction of CO_2 increased the intensity of CRZ whilst reducing that of the HMFR, effectively a reversal of the CIVB process.

As well as lean flash back occurring, the IGCC combustor proved to be consistently unstable without a methane pilot, which is undesirable due to a reliance on fossil fuels, and the increased emission of nitrous oxides caused by the increased flame temperature at the centre of the flame. Turning of the methane pilot resulted in a temporarily quasi-stable flame, but NO_x emissions were reduced by 40.6 %. The injection of CO_2 through the pilot of the IGCC combustor continued to reduce the levels of NO_x emitted, and also reduced the temperature at the burner tip, which is beneficial for burner longevity. The maximum amount of CO_2 injected was equivalent to 127 % the mass flow rate of the fuel, defined by the choke point of the delivery line rather than flame stability. At that point total reduction of NO_x and tip temperature were 51.0 % and 20.8 % respectively, modifications to the delivery line would allow further reductions.

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