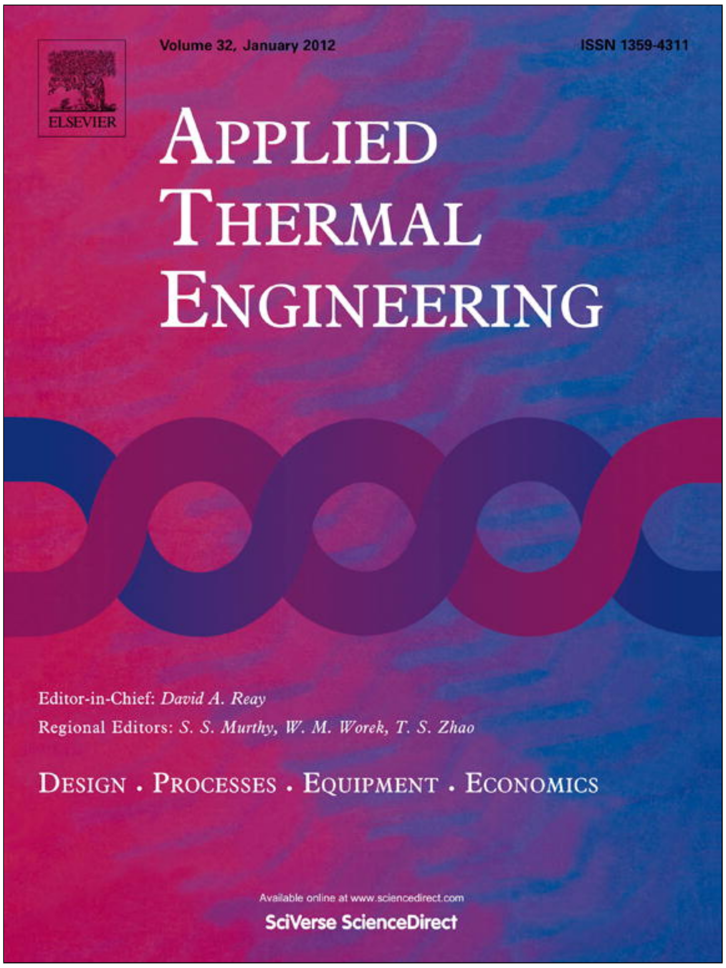

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Applied Thermal Engineering 48 (2012) 426–435

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Effect of exhaust confinement and fuel type upon the blowoff limits and fuel switching ability of swirl combustors

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A R T I C L E I N F O

Article history:
Received 4 December 2011
Accepted 18 April 2012
Available online 9 May 2012

Keywords:
Blowoff
Flashback
Swirl number
Lean premixed
Hydrogen fuel switching

A B S T R A C T

The use of swirl burners with premixed hydrogen–methane fuel blends is a promising technology for low-emission power generation. Utilisation of hydrogen containing fuel mixtures can result in low-emission levels, but it is well known that there are many difficulties, primarily because of the very high laminar and turbulent flame speeds of hydrogen. Problems such as blowoff and flashback limits are extremely important where fuel flexibility is required. In this study, a generic swirl combustor at Cardiff University's GTRC is utilised to investigate blowoff and the ability of the premixed combustor to switch fuels whilst still maintain the same thermal load, for a range of alternative hydrogen based fuel mixtures in configurations where the confinement is representative of gas turbine practice. This complements previous work on the same generic combustor, where the focus was entirely on flashback limits.

Ideally to achieve fuel switching or dual fuelling for nominally similar combustor geometries, the operating points for pure hydrogen and natural gas should lie in an operational regime between the blowoff and flashback limits of both fuels. Normal concepts of equivalence ratio matching need modification to allow for the varying stoichiometric requirements of different fuel mixtures and the associated differences in their heating values. Here heating input from the various fuels as a function of mass flow is used to compare their ability to operate in the same operational, fuel lean regime of the premixed combustor. In practice this is extremely difficult; however, fuel switching/dual fuelling is possible in the swirl burner with certain fuel blends (where the hydrogen content is limited).

The results demonstrate and quantify improvements in blowoff limits for hydrogen-enriched methane flames. Moreover, for all geometrical configurations considerably improved blowoff characteristics were observed for the confined cases in contrast to the unconfined cases. This data offers a significant insight to burner manufacturers aiming to use swirl combustors with hydrogen-containing alternative fuels.

1. Introduction

Lean premixed combustion along with alternative and gasified biomass fuels offer a potential reduction in net CO_2 along with NO_x in the context of gas turbine combustion and power production.

Lean premixed (LP) combustion is a commonly used approach to minimize harmful emissions from gas turbines. By definition within LP combustion systems, lean mixtures of fuel and air are mixed prior to the combustion chamber in order to lower the average combustor temperature and reduce NO_x. To facilitate LP combustion new premixed swirl combustor systems are being developed by manufacturers. Such systems have an increased propensity for flashback and blowoff to occur as operation at lean equivalence ratios is necessary in order to reduce the flame temperature and hence minimize NO_x formation. Flashback and combustion induced instabilities are a particular problem with hydrogen fuel blends [1,2].

Hydrogen/methane fuel blends are thought to offer a promising technology, with recent studies aimed at achieving power generation with limited environmental impact. Hydrogen rich fuels may offer potentially lower, desirable, emission levels, but as is well documented [3–6], there are many difficulties when operating existing combustion technologies on pure hydrogen, primarily because of the relatively high flame speed. Methane blended hydrogen can provide a suitable fuel mixture which can give many advantages in terms of emissions [7,8].

Swirl combustors are almost universally used within gas turbines along with many other combustion processes due to the benefit of

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doi:10.1016/j.applthermaleng.2012.04.042

Nomenclature

CRZ	central recirculation zone [−]
S_L	laminar flame speed [m/s]
h	height of tangential inlets [mm]
S_T	turbulent flame speed [m/s]
m_t	mass flow air and fuel [kg/s]
t	tangential inlet width [mm]
r_o	combustor exhaust radius [mm]
u_o	average axial velocity in combustor exhaust [m/s]
r_i	combustor inlet radius [mm]
U'	RMS fluctuating velocity [m/s]
r_p	fuel injector radius [mm]
φ	equivalence ratio [−]
S	swirl number [−]
ρ_g	gas density in combustor exhaust [kg/m^3]
S_g	geometrical swirl number [−]

increased mixing of the fuel and air along with increased flame stability and improved blowoff limits. The latter is extremely important for gas turbine operation and is affected by many characteristics namely; fuel type, geometrical swirl number and combustion process (diffusion, premixed or partially premixed) [9,10].

The swirl number (S) is the main parameter used to characterize swirling flows, and is defined as the ratio of axial flux of angular momentum divided by the axial flux of axial momentum and the nozzle radius [11,12], as is given below in Equation (1):

$$S = G_\theta / G_x r_o \tag{1}$$

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 which for practical reasons is not common. A practical value of the swirl number is obtained from the geometric swirl number (S_g), which uses geometry and inlet conditions, hence allows pressure variations across the flow to be neglected. For isothermal conditions and constant density, Equation (2) defines the geometric swirl number of the system utilised in this study (which is shown schematically and photographically in Figs. 1 and 2 respectively):

$$S_g = \pi\left(r_o^2 - r_p^2\right)(r_i - t/2)/(4 \cdot t \cdot h) r_o \tag{2}$$

Depending on flame front location the effect of combustion is to increase the axial flux of axial momentum (Equation (1)), whilst scarcely affecting the axial flux of angular momentum. As a result the swirl number reduces and this especially affects the size and extent of the all important central recirculation zone (CRZ); as is discussed later this can eliminate the CRZ for values of $\varphi \rightarrow 1$ [12].

Important Swirl Combustor dimensions are as follows in Table 1:

Flashback is defined as the phenomenon when the flame front retreats back from the combustion chamber into the mixing chamber or even further into the fuel air supply lines. The literature indicates there are several mechanisms, which can result in a flashback including boundary layer flame propagation, core flow velocity propagation, vortex breakdown or combustion instabilities [11,13–16].

Conversely blowoff is defined at the point at which a flame front is unsustainable in the combustion chamber and governs the operational range of the combustor; in this context the blowoff mechanism occurs when the fuel air mixture becomes too lean to support combustion in a predefined flow field [17–19].

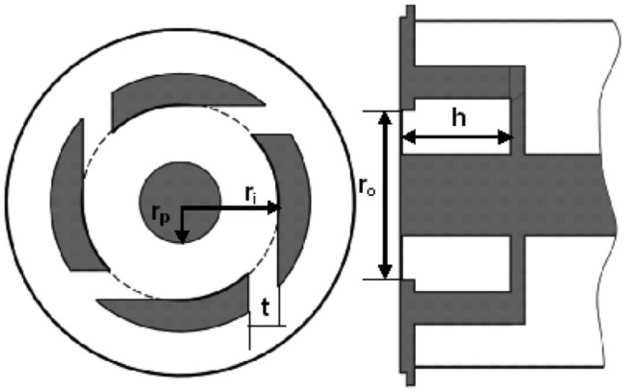


Fig. 1. Radial swirl burner-inlet configuration.

The two aforementioned phenomena are affected by many factors including: the combustion process (premixed, diffusion etc), geometry, the swirl number, ambient pressure, ambient temperature, the Damköhler number and influentially the turbulent flame speed of the particular fuel air mixture being burned [20–22,29,30]. The influence of Damköhler Number changes with increasing hydrogen content for multi-component fuels is recognised, however, its exact effect on blowoff and flashback for premixed combustion and different hydrogen fuel blends is difficult to quantify. Here for analysis we use a correlation for S_T for hydrogen and methane flames, which include Damköhler Number effects in a swirl combustor. This is then coupled with other work which describes the changes in swirl combustor aerodynamic characteristics with equivalence ratio.

In a previous paper the authors discuss flashback limits of a range of fuel blends ranging from 100% hydrogen to 100% methane in a small generic swirl combustor firing freely into the atmosphere at atmospheric pressure [23]. In this paper this work has been extended considerably by considering the effect of combustor exhaust confinements at two lower swirl numbers, deriving blowoff limits and exploring the capability of the system to fuel switch between the same ranges of fuels used in Ref. [23].

New information on blowoff limits for hydrogen containing fuel blends in the 'generic' swirl burner of differing swirl numbers are presented. Several different combustor characteristics are known to be influential, including, turbulent and laminar flame speeds, level of recirculation in the Central recirculation Zone (CRZ), which is strongly influenced by the level of swirl and the combustor equivalence ratio [38].

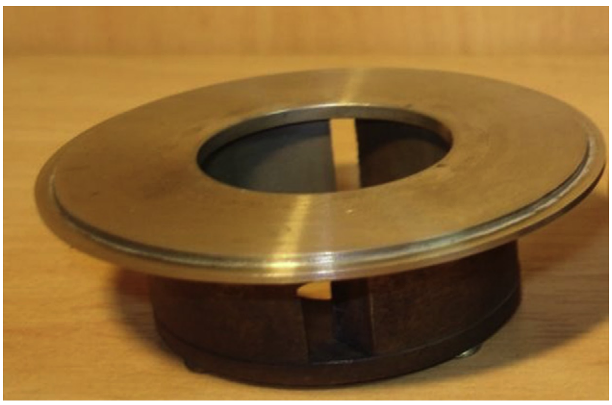


Fig. 2. Swirl insert of $S_A = 1.47$.

Table 1
Swirl burners dimensions.

Swirl type	Swirl number (S_g)	Injector radius (r_p)	Inlet radius (r_i)	Exit radius (r_o)	Tangential inlet width (t)	Height of tangential inlets (h)
A	1.47	6.4 mm	16 mm	14 mm	5 mm	16 mm
B	1.04	6.4 mm	16 mm	14 mm	5 mm	13 mm
C	0.8	6.4 mm	16 mm	14 mm	4 mm	13 mm

All results discussed here are obtained at atmospheric pressure and temperature, with this current data set being combined with previous flashback stability results [23]. By integrating these two datasets, several new curves have been generated to indicate potentially stable operating ranges for different fuel blends. Discussions are presented highlighting the influence of swirl number, exhaust confinements and the influence of other important parameters.

2. Analysis of the results in the context of other data from the literature

Here the work of Cheng is extremely useful [31–33] as it assists considerably in the analysis of the results presented. Cheng developed a low swirl number combustor ($S \sim 0.5$) that achieved flame stability by producing a controlled turbulence central axial flow which just balanced the turbulent flame speed of the fuel blend under investigation. This combustor was developed from an earlier technique used to derive turbulent flame speeds (S_T) for various fuel blends. This combustor was also capable of deriving S_T in the same way by balancing the centre line axial velocity against S_T. Knowing the mean velocity and the turbulence intensity, correlations could be derived for S_T as a function of S_L and U'. Two relationships relevant to this work are:

$$\text{For } H_2: S_T = S_L + 3.15\,U' \quad (3)$$

$$\text{For } CH_4: S_T = S_L + 1.73\,U' \quad (4)$$

A range of syngases was investigated with various hydrogen/methane contents and the values of S_T fell between these curves [32]. For S_L we use Refs. [34,35].

It is evident that the important parameter for the higher velocity operating range of the combustor in determining S_T is U' as average combustor exhaust velocities are commonly >5–7 m/s and extend to 40 m/s. Levels of turbulence intensity are well known to be of order at least 20–30% [12–16]; thus minimum values of U' are ~1–1.5 m/s, often much larger. Clearly the U' term will be very important in the determination of S_T (Equations (3) and (4)) in respect of blowoff for all fuel blends as this will desirably occur at high velocities and mass flows for all fuel blends and thus the U' term in Equation (3) will be dominant. Flashback occurs at much lower velocities and mass flows and thus S_T will be much more influenced by S_L especially for hydrogen rich fuel blends where S_L for hydrogen is much higher than methane.

Coke oven gas (COG) is used as a test fuel in this work (65% H_2, 25% CH_4, 6% CO, 4% N_2) and a correlation for S_T for COG is derived by using mass weightings of the equations for S_T for H_2 and CH_4 from Equation (3), whilst assuming CO performs similarly to CH_4.

Thus,

$$S_T(\text{COG}) = S_L + 1.99\,U' \quad (5)$$

Compared to methane at high velocities we should expect COG blowoff velocities to be about 15% higher than for methane (ratio Equations (3) and (4)) for a similar thermal input providing the system combustion aerodynamics are self similar and the U' term is dominant. Conversely for flashback at much lower velocities and values of U' we should expect S_L to be much more important, especially with hydrogen rich flames.

There are other important factors in analyzing the results and these are concerned with the characteristics of swirling flows and combustors as follows:

i) There are strong Reynolds Number effects as discussed by Sarpkaya [37] and analyzed further by Syred [19] Essentially for isothermal swirling flow (the state normally pertaining in the swirl combustor exhaust around the fuel injector as combustion is normally located downstream of this area), the vortex breakdown and associated CRZ does not reach a steady state position until a Reynolds Number of ~10,000 for $S \sim 1$ (~5000 for $S \sim 1.5$). This corresponds to an average axial velocity in the annulus around the fuel injector of around 6 m/s for $S \sim 1$, 3 m/s for $S \sim 1.5$.

ii) Via reduction in swirl number due to combustion there are strong equivalence ratio effects on the size and shape of the CRZ, especially when the combustor fires into a confinement of the type used here [21,37]. When a natural gas fired swirl combustor of similar configuration to that used here with $S = 0.98$, fired into a free environment the CRZ had virtually disappeared by $\varphi = 0.75$ with partially premixed combustion (76% of fuel premixed). For $\varphi \geq 0.5$ towards richer mixtures normally reduced the mean velocities in the CRZ and reduced the CRZ dimensions, finally leaving a central region of quite low velocity with intermittent forward and reverse flow and reduced potential for flame stabilization. Thus with the work reported here confinement clearly reduced the size, extent and velocity levels in the CRZ especially for values of $\varphi \geq 0.5$.

The adiabatic flame temperatures [35,36] for hydrogen, methane and carbon monoxide are 2097 °C, 1950 °C and 2108 °C respectively. In the authors experience for practical burners, hydrogen flames will not be stable at temperatures below ~900 °C, for natural gas flames this is ~1000 °C and thus this suggests another factor besides flow velocity and S_T which can cause flame blowoff or extinction [39,40]. For a cyclone combustor fired on natural gas it was found that the lowest average temperature at which flames would stabilize was ~1000 °C and this corresponded to a value of $\varphi \sim 0.5$ for a steel combustor operated under similar conditions to those reported here [40].

3. Experimental faculties and method

A bespoke 'generic' swirl burner constructed from stainless steel was used to examine the flame stability limits at atmospheric conditions (1 bar, 293 K) at Cardiff University's Gas Turbine Research Centre (GTRC); a photograph and schematic of the generic burner is presented in Figs. 3 and 4 respectively.

A single tangential inlet (a) feeds the premixed air and fuel to an outer plenum chamber (b) this uniformly distributes the gas to the slot type radial tangential inlets (c) swirling unburned fuel then passes into the burner body (d) then into the burner exhaust (e) where the gases pass around the flame stabilizing central recirculation zone (CRZ). The central diffusion fuel injector (f) (which was not used for fuel during the course of this study) extends centrally through the combustor body to the exhaust.

For a swirl number of $S_A = 1.47$ the exhaust nozzle was a sharp orifice at the exit plane of the fuel injector (as shown above in Fig. 2). However, for lower swirl numbers of $S_B = 1.04$ and $S_C = 0.8$ an extended exhaust nozzle was used (as depicted in Figs. 3 and 4);

Fig. 3. Unconfined assembled swirl burner (open flame).

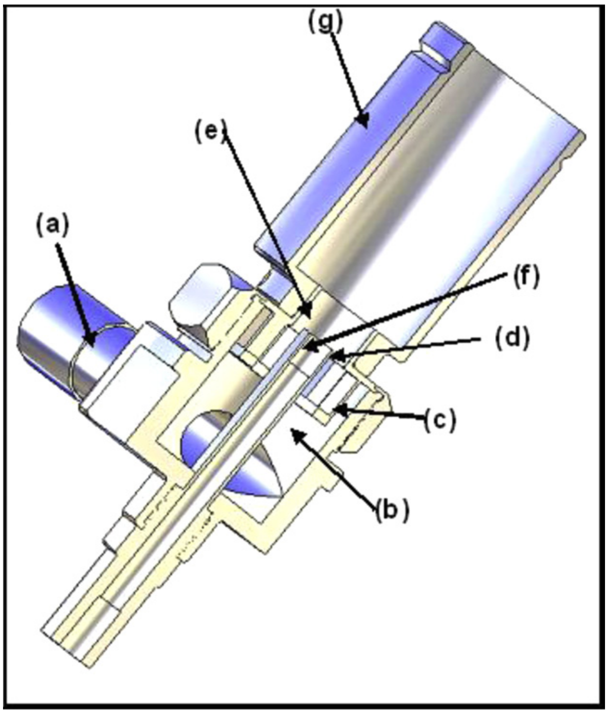


Fig. 4. Schematic diagram section of confined swirl burner for $S_B = 1.04$ and $S_C = 0.8$.

other work has shown considerable benefits from this modification [21].

Fig. 3 shows a complete swirl burner assembly fitted with a swirl insert to provide a swirl number of $S_B = 1.04$. As can be seen the exhaust nozzle is one exit radius long as parallel work suggests that, when used in conjunction with the fuel injector, there is considerable improved stability in terms of both flashback and the blowoff resistance especially for methane and natural gas [23–27]. This particular exhaust geometry is termed unconfined.

However, in this study a cylindrical exhaust confinement (g) (as shown in Fig. 4) was fitted to the original 'unconfined' design to examine its effect on the blowoff behaviour of the swirl burners in conditions more representative of gas turbines. However, these studies were only performed at two swirl numbers ($S_B = 1.04$ and $S_C = 0.8$). A conical cup or contraction could also be fitted to the exhaust of the confinement and this was shown to be beneficial in certain circumstances.

Five fuel blends were examined for each of the swirl burners: The compositions of these fuels (as volumetric concentrations) are similar to those studied elsewhere [23,26,27] and are as follows:

1. 15% H_2 85% CH_4
2. 30%H_2 70% CH_4
3. 65% H_2 25% CH_4 6% CO & 4% N_2 (synthesised coke oven gas (COG))
4. 100% CH_4,

100% H_2 was not studied as a part of this programme but is utilised in complementary studies in the unconfined case [8,23,26,27]. The combustors exhaust was fired into an extraction hood which safely exhausted the waste combustion products.

Mass flowrates of both air and fuel were measured using suitably sized 'Micromotion' coriolis meters, which have an accuracy of ±0.35% FS [28]. Equivalence ratio is calculated in terms of mass flow, giving a combined uncertainty of measurement of ±0.48%.

Blowoff was characterised by the average axial velocity under isothermal conditions formed in the annulus between the fuel injector and the exhaust nozzle. This is defined as follows:

$$u_o = m_t/\pi\left(r_o^2 - r_p^2\right)\rho_g \tag{6}$$

Average axial velocities extended up to nearly 45 m/s.

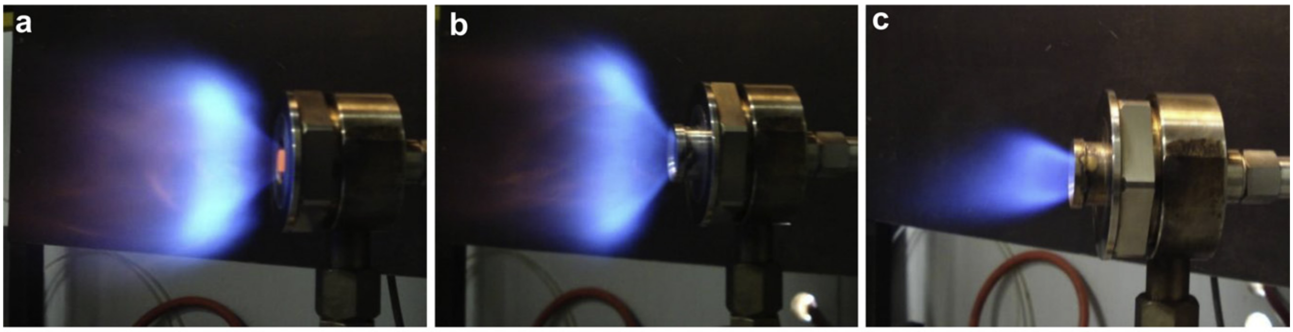
4. Results

4.1. Unconfined swirl burner and blowoff

The experimental investigation highlighted that there are swirl number effects contributing to the mechanism of blowoff. The open flames shown in Fig. 5(a & b), for swirl numbers of $S_A = 1.47$ and $S_B = 1.04$ are typical of those just before blowoff (which occurs very suddenly). Reduction in swirl number to $S_C = 0.8$ results in a slow gradual blowoff process and improved blowoff limits, (Fig. 5c). This increased stability in terms of blowoff can be attributed to reduction in the width of the CRZ and the formation of a much more compact flame which is clearly evident in Fig. 5. This reduces entrainment of external air and reduces flame quenching effects.

As can be seen from the air mass flowrates highlighted in Fig. 5 and from Fig. 6, the 'generic' burner configured to give a swirl number of $S_A = 1.47$ induces the poorest blowoff characteristics which coupled with the fact that the pressure drop is twice that of the $S_B = 1.04$ resulted in only limited experimentation being undertaken for the $S_A = 1.47$ configuration.

Coke oven gas (COG) with 65% hydrogen content gave the best blowoff limits with stable flames being possible at leaner operating



S_A=1.47, $\dot{m}_f = 1.0$g/s, $\dot{m}_a = 7.35$g/s

S_B=1.04 $\dot{m}_f = 1.0$g/s, $\dot{m}_a = 9.0$g/s

S_C=0.8 $\dot{m}_f = 1.0$g/s, $\dot{m}_a = 17.0$g/s

Fig. 5. (a–c): Swirl Number effects on flames with pure methane just before blowoff, (fuel mass flowrate $\dot{m}_f$ constant for each burner geometry with variable air mass flowrate $\dot{m}_a$).

conditions for all swirl numbers; this will be due to the increased hydrogen content which will bring about an increase in turbulent burning velocity along with the possible benefits of the highly diffusive gas. As observed for the pure methane case, the burner configuration with a swirl number of $S_A = 1.47$ gave the worst blowoff and flashback limits for all the fuels tested, with the exception of the pure hydrogen case under very specific conditions [26]. One interesting feature was the differences between blowoff limits for $S_B = 1.04$ and $S_C = 0.8$. The swirl number of $S_C = 0.8$ gave much improved blowoff limits with pure methane and fuel blends containing up to 30% hydrogen. However, both $S_B = 1.04$ and $S_C = 0.8$ gave very similar results for blowoff with higher hydrogen content fuels as shown by the coke oven gas trials.

Starting with pure methane and systematically increasing the hydrogen content of the fuel blend dramatically improves the blowoff limits for specific swirl numbers, confirming as mentioned previously that COG (65% H_2), had the best blowoff limits; rig limitations (in terms of total mass flowrate of air available) precluded obtaining the blowoff limits for pure H_2 flames.

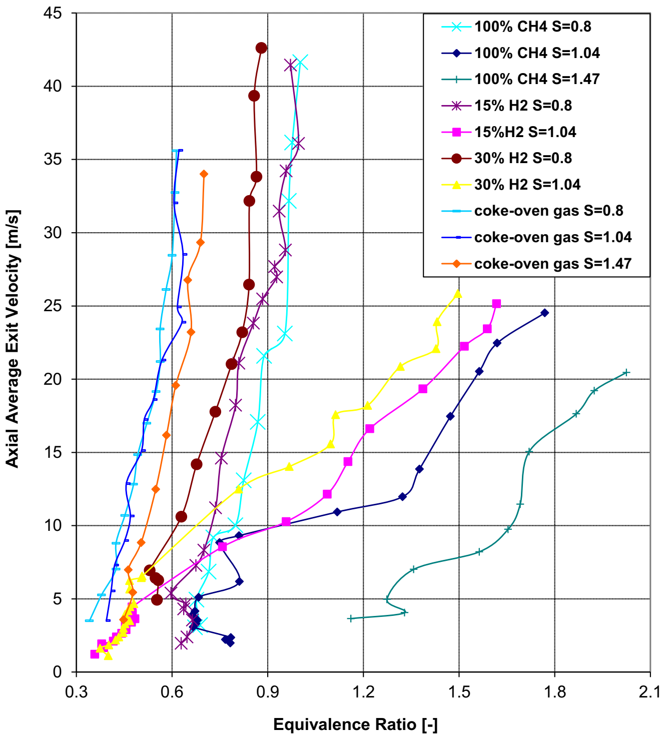


Fig. 6. Blowoff limits for different hydrogen–methane blends for the unconfined swirl burners.

Interestingly COG results produced blowoff curves that had similar slopes and shapes for all swirl numbers. For pure methane and fuel blends up to 30% hydrogen and swirl numbers of $S_A = 1.47$ and $S_B = 1.04$, blowoff was far worse than for $S_C = 0.8$. The far greater spread of the flames for $S_A = 1.47$ and $S_B = 1.04$ is caused by the formation of a much larger CRZ (Fig. 5 a and b), compared to $S_C = 0.8$ where a much narrower flame results with a much smaller CRZ. The flames formed with $S_A = 1.47$ and $S_B = 1.04$ expand considerably more than that formed with $S_C = 0.8$, entrain more cool flow, are more readily quenched and blowoff much more readily.

Confinement will have had complex effects on the Damköhler Number, in both altering the size and shape of the CRZ (a well known effect [12,19]) whilst reducing residence time as velocity decay is reduced. Overall Damköhler numbers probably increase with confinement, whilst turbulence levels decrease, hence turbulent flame speed decreases. However flame quenching effects are eliminated as air entrainment is avoided.

4.2. Effect of exhaust confinements

Confinement conditions as previously discussed and presented (Fig. 4) utilise a cylindrical confinement (with or without a conical cup exhaust) added to the exhaust nozzle of the swirl burner for $S_B = 1.04$ and $S_C = 0.8$. The experiments demonstrated that there was a significant improvement of all the blowoff limits for swirl numbers $S_B = 1.04$ and $S_C = 0.8$ for confined and unconfined exhaust condition. The graphs show similar trends for the two swirl numbers investigated. The significant finding is the improvement of blowoff limits for premixed mixtures moving from the unconfined to the confined combustors. For $S_B = 1.04$, Fig. 7a, blowoff has been moved from $\varphi \sim 0.75$ for $u_o \leq 9$ m/s to $0.35 \leq \varphi \leq 0.6$. For higher values of u_o confinement prevents blowoff at $\varphi \sim 0.65$ for values of u_o up to 45 m/s, whereas open flames can only operate fuel rich in this velocity range. For $S_C = 0.8$ (Fig. 7b) very similar results are obtained with confinement, although the open flame case is superior to that of $S_B = 1.04$. The influence of the confinement appears to arise from the following:

- Confinement eliminates the entrainment of cold air into the flames with the open flames when they leave the burner

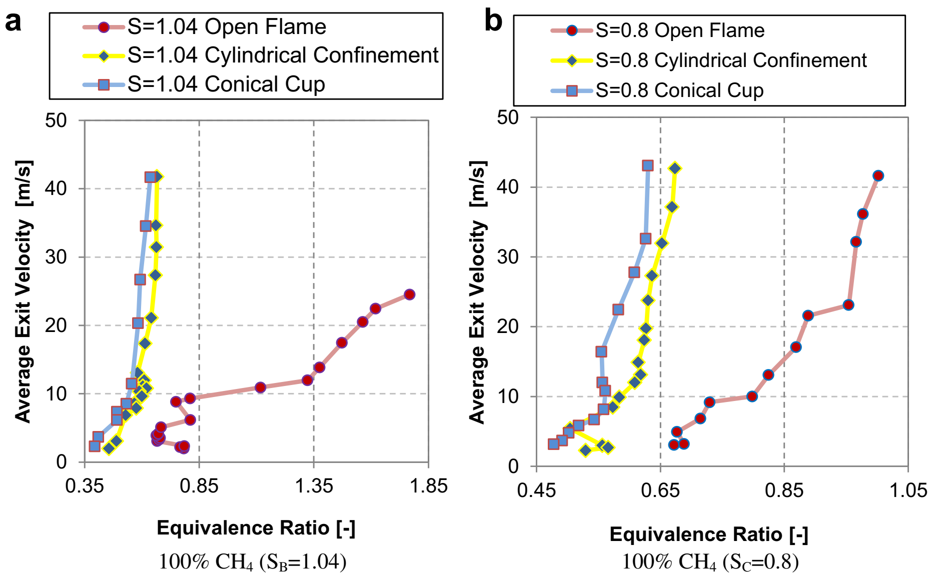


Fig. 7. (a–b): Blowoff limits for two swirl numbers (1.04 & 0.8) with 100% CH_4.

exhaust; this process is also enhanced by the confinement walls heating up and reducing heat loss from the flame stabilization region at the flame base.

- Confinement reduces the size, shape and velocity levels in the CRZ as discussed above and in Refs [21,37] which reduces flame quenching. The CRZs formed with higher swirl numbers possibly recycle too much burnt product and hence flame quenching.

These results follow closely the cyclone combustor results of Ref. [40] in terms of values of φ at blowoff, although the cyclone combustor was fired on natural gas.

Similarly, the fuel blends containing 30% hydrogen behaved in a similar manner to that of pure methane as shown in Fig. 8. Fig. 8(a & b) show the blowoff limit maps for 30% hydrogen/methane fuel blends for the swirl numbers $S_B = 1.04$ and $S_C = 0.8$. As observed previously there is significant improvement in blowoff characteristics compared with unconfined, especially for $S_B = 1.04$. Similar trends were also noted for the 15% hydrogen/methane fuel blend cases. In all cases the conical cup added to the cylindrical confinement exhaust gave the best results.

As discussed in Section 2 there are clear Reynolds number effects, most evident with pure methane and the cylindrical confinements for velocities less than 5–10 m/s.

Typical photos of 30% H_2 70% CH_4 flames can be seen in Fig. 9 for $S_C = 0.8$ with the cylindrical exhaust confinement, over a range of equivalence ratios from fuel rich (a), stoichiometric (b), lean premixed (c) and very close to blowoff (d). Transition to blowoff was very smooth and gradual in contrast to the unconfined flame of Fig. 5c.

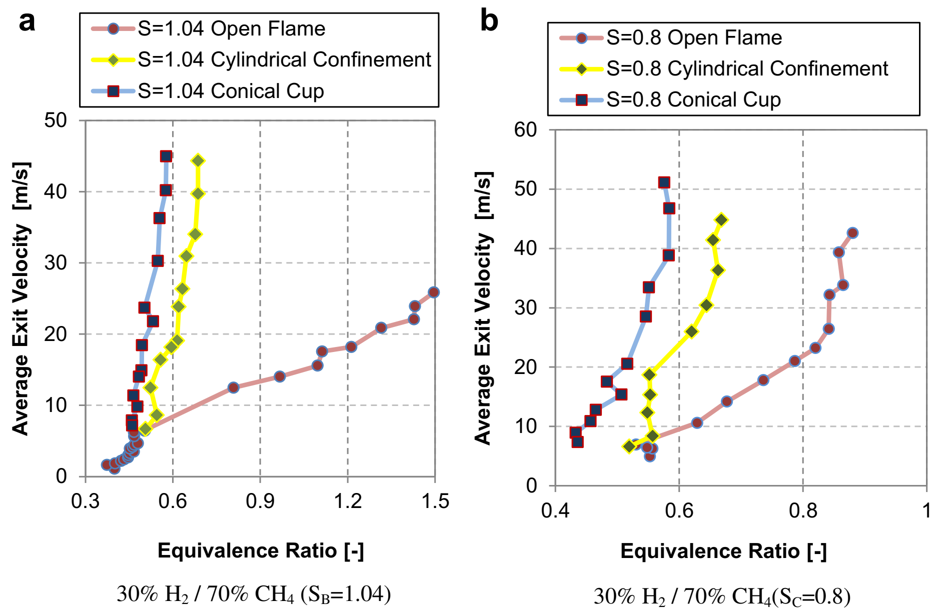


Fig. 8. (a–b): Blowoff limits for swirl numbers (1.04 & 0.8) for 30% H_2/70% CH_4 fuel mixtures.

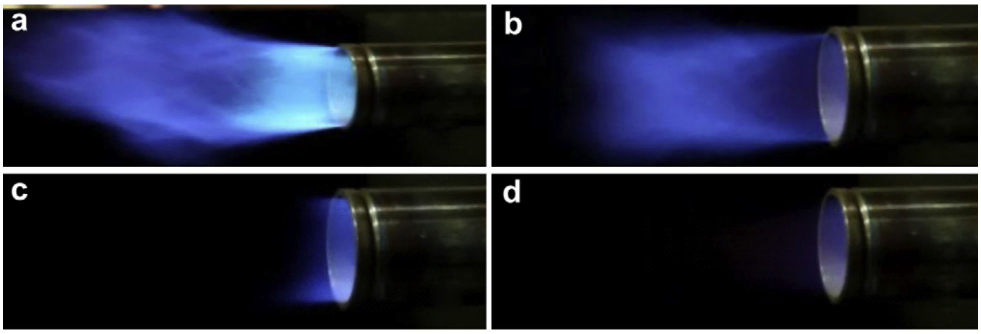


Fig. 9. (a–d): 30% H_2 + 70% CH_4 mixture. Progress to blowoff $S_C = 0.8$ with cylindrical confinement, (a) Fuel rich $\varphi = 1.4$, (b) $\varphi = 1$, (c) $\varphi = 0.7$, (d) Just before blowoff $u_o = 11$ m/s.

Finally, COG has been investigated; however, this was problematic due to the flashback and blowoff limits being close together at low flowrates. Fig. 10(a & b) compare the blowoff limits for open flames and cylindrical confined flames for two swirl numbers $S_B = 1.04$ and $S_C = 0.8$. No results could be obtained with the conical cup exhaust as the blowoff limit appeared to overlap the flashback limit, this needs further investigation.

As discussed earlier the highest hydrogen content fuel (COG – 65% H_2) displays the best blowoff limits for both open and confined flames compared to all the other fuel gas blends tested.

The results for $S_B = 1.04$ are more irregular than those for $S_C = 0.8$, but the trends are very similar to those for $S_C = 0.8$.

For both swirl numbers blowoff limit enhancement – about 20% in term of φ – was observed with the confinement added compared to the open flames at a given exit velocity.

Equations (3)–(5) for S_T provide a sensible explanation for the differences between Figs. 7, 8 and 10 for 100% CH_4, 30% H_2/CH_4 and coke oven gas. Taking the cylindrical confinement values of u_o of 40 m/s at blowoff, the corresponding equivalence ratios are 0.67 (100% CH_4), 0.65 (30% H_2/70% CH_4) and 0.48 (Coke Oven Gas) and are in line with expected changes in mass weighted S_T for a given fuel blend.

A clear conclusion is that blowoff limits generally improve with increasing H_2 levels and with confinement, although at the same time the flashback levels worsen; for coke oven gas these two competing limits are very close at low mass flowrates rendering the range for stable operating condition very small [23–27]. Hence, the design of a versatile swirl burner for hydrogen containing fuels can be problematic because the operational region of a burner will significantly change, as the H_2 content of the fuel blend alters.

5. Blowoff/flashback interaction and the ability to fuel switch

A gas turbine combustor, required to be capable of fuel switching with a given compressor and turbine system, has air mass flowrates at given thermal inputs which vary little for moderately changing fuel flows (for the fuel blends used) whilst the exhaust gas enthalpy is still dominated by the ~79% nitrogen content. To produce this thermal input, different quantities of fuel and thus equivalence ratio are needed for different fuels such as natural gas, COG and pure H_2. When dual fuelling/fuel changeover is required, ideally the operational range of the system between flashback and blowoff for the two different fuels (such as H_2 and methane) considered should be such that there is sufficient overlap between the blowoff and flashback limits to enable ease of fuel change over. Because of the different stoichiometry and heating value, H_2 containing fuels will always have to be operated at weaker equivalence ratios than methane fuel systems, typically 78% of the methane equivalence ratio for pure H_2. This infers that the overlap region between the flashback limit and blowoff limit of given fuels is crucial in determining whether or not the system can be dual fuelled such that fully premixed combustion can be maintained.

To benchmark the new data for confined geometries presented herein, in Fig. 11(a & b), the flashback and blowoff limits [8,25,27]

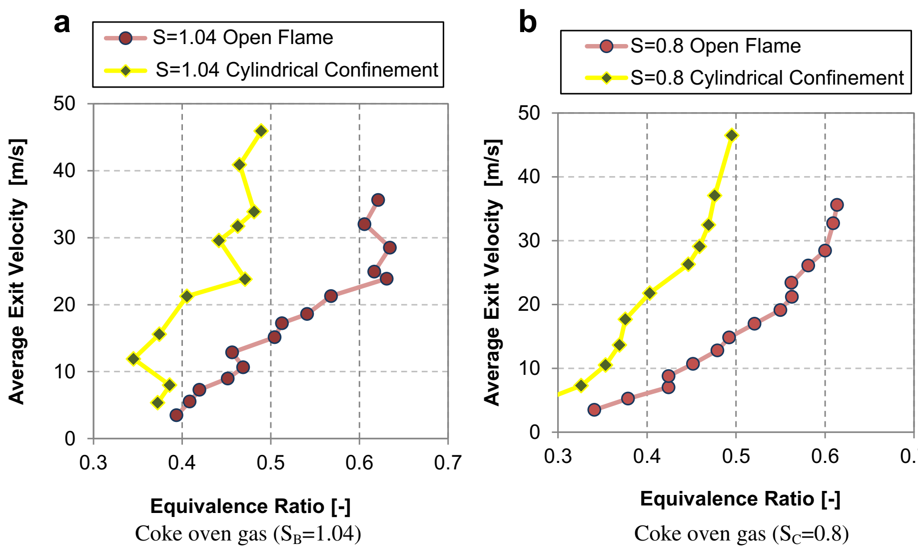


Fig. 10. (a–b): Blowoff comparison for two swirl numbers with coke oven gas.

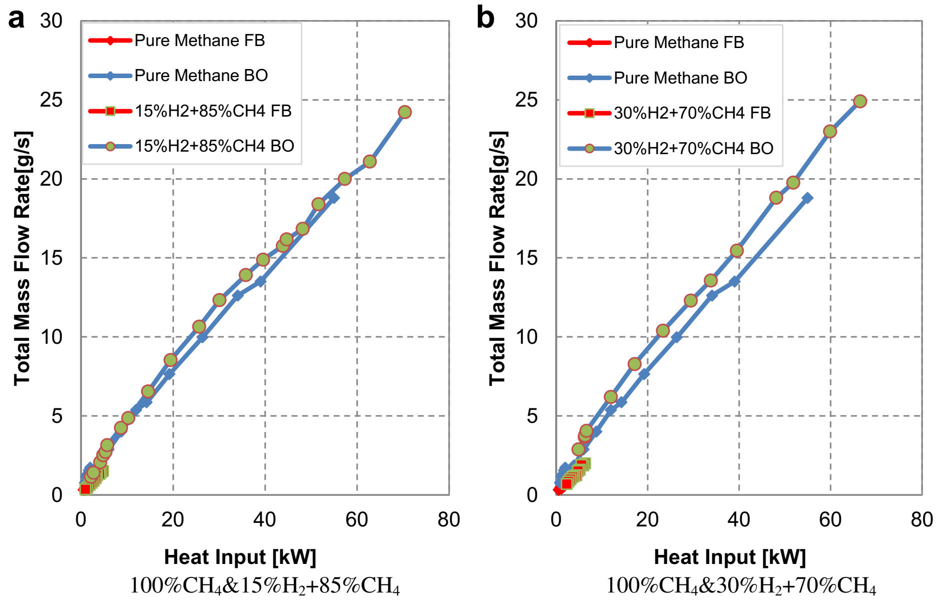


Fig. 11. (a–b): Above blowoff/flashback limits as a function of total mass flow and heat input for methane and hydrogen blends, open flames, swirl number $S_C = 0.8$.

from previous unconfined studies have been re-plotted in terms of heat input, solely for weak combustion up to an equivalence ratio of 1 for a swirl number of $S_C = 0.8$, (open flames). This time total mass flow instead of velocity is used for the '*y*' axis. The two sets of curves compare two different fuel blends against pure methane to see to what extent premixing can be accommodated. The curves show the unconfined burner could be operated with premixed methane up to a blowoff limit of ~22 kW for a total mass flow of air and fuel of ~8 g/s, rising to 27 kW at 12 g/s and 55 kW for ~18 g/s; obviously this is the limit for the other fuel blends. Flashback with methane could be avoided by operating at mass flows >0.8 g/s and thermal inputs >2.5 kW. Fig. 11(a & b) show the possibility to change from pure methane to either 15% H_2 or 30 % H_2 as there is a large common region where no flashback or blowoff will occur with any of the fuel mixtures. Over most of the operational range this is primarily defined by the blowoff limit for methane, being limited at low velocities or mass flows by the flashback limits of the hydrogen containing fuel. Fig. 11 (a & b) shows that this operational region is only slightly larger for the case of 15% compared to the 30% H_2 content fuel blend case, as the difference between the flashback limits for the fuels is small.

Fig. 12(a & b) with the exhaust confinement for a swirl number of $S_C = 0.8$ should be compared to fig. 11. The curves show blowoff improvement arising from the exhaust confinement compared to the results for open flames. For instance, taking a thermal input value of ~22 kW, both H_2 containing fuel blends are limited by the pure methane blowoff limit corresponding to a total mass flow of air and fuel of ~8 g/s for the unconfined case, whereas this rises to ~12 g/s for the confined case, some 50% increase in the mass flow for the same heat input. Flashback with methane can be avoided by

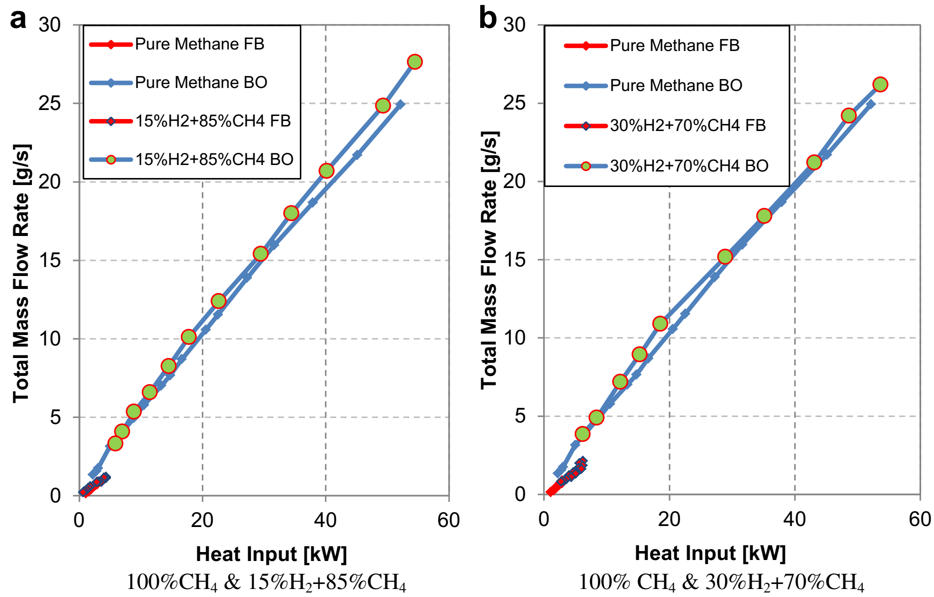


Fig. 12. (a–b): As for fig. 11 (a–b) except for cylindrical confinement on exhaust.

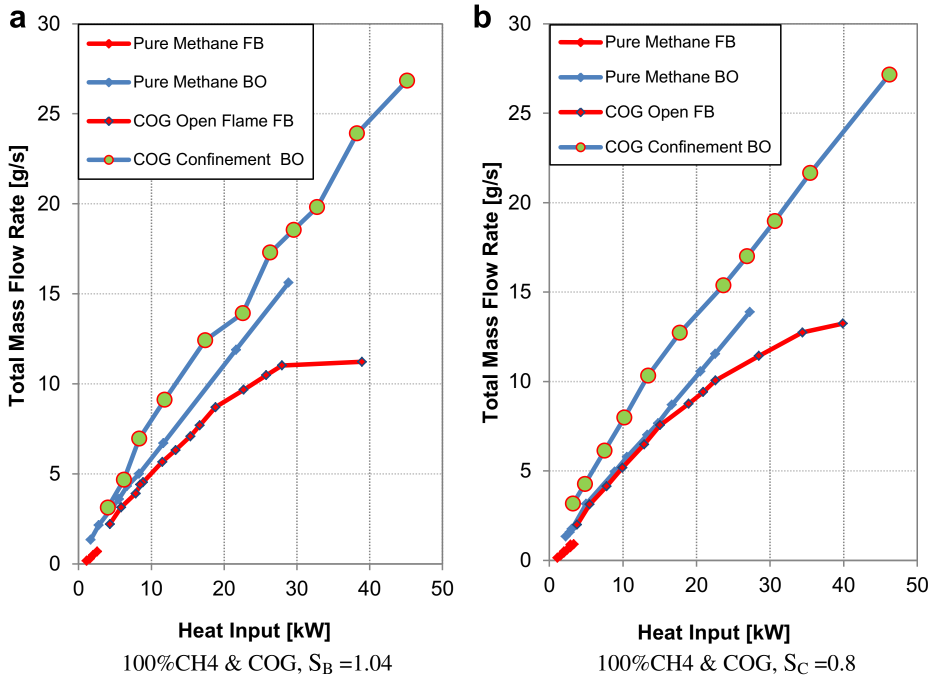


Fig. 13. (a–b) Above blowoff/flashback limits as a function of total mass flow, heat input and swirl number for methane and COG, with confinement except COG FB open flames, swirl number $S_B = 1.04$, $S_C = 0.8$ respectively.

operating at mass flows >0.88 g/s and thermal inputs >2.8 kW with confinement, though this value is very similar to that for the open flames.

For COG and methane (Fig. 13) more complexities were revealed. Again as has been shown earlier the confinement significantly improved the blowoff limits with COG compared to methane, very much in line with the improvement in S_T, predicted (Equation (4)) with the 65% hydrogen in the fuel mix. This improvement was in the order of 15–20% for a given heat input. However, a significant problem was identified with flashback for COG when exhaust confinement present. Particularly at lower mass flowrates the flashback and the blowoff limits virtually coincided, and flashback could not be readily determined. For this reason, Fig. 13 presents the flashback results for COG with open flames.

The methane blowoff curve is narrowly above the COG flashback curve for $S = 1.04$ (Fig. 13a), leaving a narrow region where potential alternate fuelling is possible.

This was not so with $S = 0.8$ (Fig. 13b) where the methane blowoff curve overlapped the COG flashback curve for much of its range.

The problem of changing flashback limits for hydrogen rich fuels such as COG and 100% hydrogen has been discussed in Ref. [23] for the same burner with open flames. These results show dramatic change and acceleration of flashback processes in this swirl burner with COG compared to fuel blends with 30% H_2/70% CH_4 (even more so with 100% H_2). This is most pronounced with $S = 1.04$ and $S = 0.8$ and cannot be readily explained by considerations of S_T as with blowoff.

The reasons appear to lie in the structure of swirling flows, the formation of the CRZ and influencing factors including the effect of the exhaust confinement and the heat release pattern. With natural gas combustion in a similar swirl combustor [21] the fuel injector and exhaust configuration used in this work was found to produce flow patterns and a CRZ which increased the boundary layer velocity gradients compared to the case without the fuel injector. This substantially improved flashback resistance and clearly works with this combustor with fuel blends up to 30% H_2/70% CH_4.

For higher hydrogen content fuels, the higher heat release rate and thus higher flame temperatures for given fuel blends reduce the swirl number further, reduce the strength of the CRZ, allow the outer shear flow to broaden, thus reducing velocity gradients especially in the boundary layers, encouraging flashback.

6. Discussion and conclusions

Blowoff has been examined at three different swirl numbers for up to five different fuel blends including methane, hydrogen, coke oven gas and various blends of H_2/CH_4. Blowoff limits are positively influenced by swirl number, fuel type and exhaust confinement. Fuel blends burnt in a combustor with a low swirl number of $S_C = 0.8$ displayed the best blowoff limits as the flames formed were more compact with less spread and apparently a more compact CRZ. Coke oven gas gave the best blowoff limit and confirmed that increasing the percentage of hydrogen in a fuel blend improves blowoff characteristics, as would be expected from the considerations of S_T, although the flashback limits subsequently deteriorate as discussed a companion paper using the same combustor [23]. The blowoff mechanism appears to be different with $S_C = 0.8$ than for $S_A = 1.47$ and $S_B = 1.04$: the blowoff occurred gradually and smoothly rather than violently as with $S_A = 1.47$ and $S_B = 1.04$. The open flame combustor had a greater susceptibility to blowoff when compared to the comparable burner with exhaust confinement. Thus the exhaust confinement gives rise to a wider operational range. A change in the blowoff behaviour for flames from high hydrogen content fuels is influenced by turbulent flame speed, S_T, and especially U' at high velocities, whilst S_L is more influential at low velocities. Flashback behaviour of hydrogen-rich fuel blends appears to be influenced by changes in swirl number with combustion and associated changes in the structure of the CRZ as equivalence ratio increases beyond 0.5. Increasing the swirl number increases tangential velocities, the size and strength of the CRZ, and also U' [9,12,16] as this acts to increase turbulent flame speed, which in turn influences blowoff limits. This is clearly shown for swirl numbers of 1.47 and 1.04 where better blowoff limits are obtained for hydrogen-enriched fuels compared to 100% methane.

The increase in blowoff velocity for COG compared to methane appears to correlate with the associated predicted increase in S_T between these fuels.

When the data is re-plotted in terms of heat input as a function of total mass flow, the results clearly show that operation of a fuel premixed system was entirely possible for up to 30% hydrogen in methane mixes for open and confined flames. The operational region extends to a much wider range of premixed air for the confined flames, whilst flashback limits are relatively unaffected.

The coalescing of the blowoff and flashback limits for COG at lower mass flowrates with the confinement is of concern as this can seriously limit turndown and ways need to be found to improve this situation for practical combustors, as this trend is likely to continue for higher hydrogen content fuels. Here S_L has a major effect on the flashback limit as velocities are much lower and hence U' term is much less influential in Equations (3) and (4).

It must be noted that there is little information on blowoff for pure hydrogen swirl stabilized flames and how this interacts with flashback limits.

This programme of work has clearly identified that significant further investigation – at a practical as well as fundamental level – is required for fuel blends greater than ∼40–50% hydrogen content.

Acknowledgements

Mohammed Abdulsada gratefully acknowledges the receipt of a scholarship from the Iraqi Government and for the assistance of Malcolm Seaborne, Terry Treherane, Paul Malpas, and Steve Morris during the setup of the experiments. The work is also co-funded by the Welsh European Funding Office, via the Low Carbon Research Institute (LCRI).

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