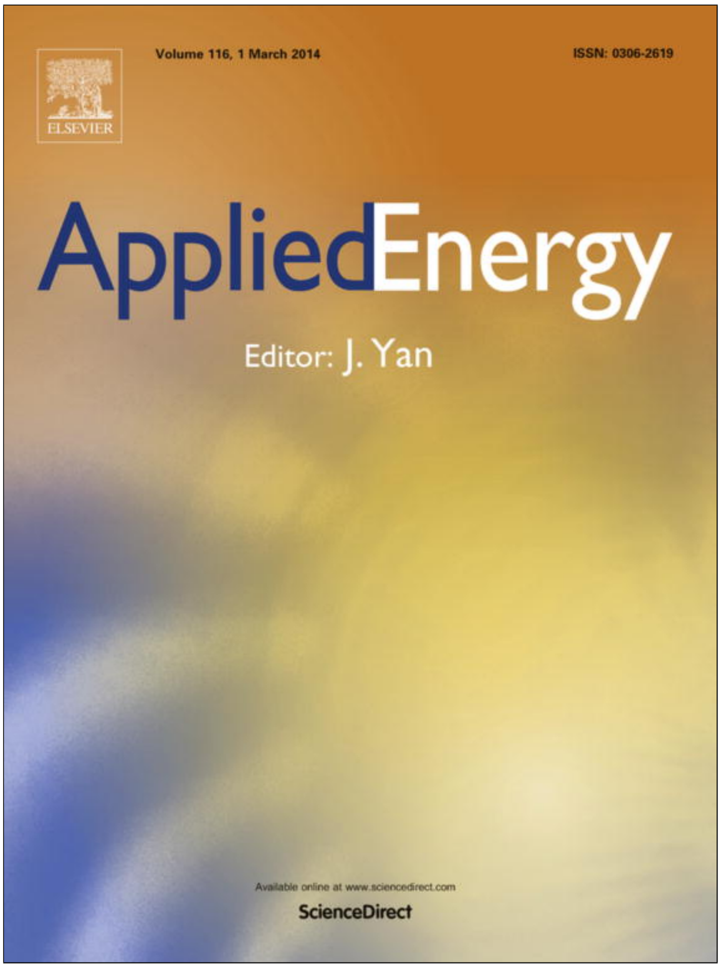
Volume 116, 1 March 2014
ISSN: 0306-2619
ELSEVIER
AppliedEnergy
Editor: J. Yan
Available online at www.sciencedirect.com
ScienceDirect

Applied Energy 116 (2014) 288–296

Contents lists available at ScienceDirect

Applied Energy

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

Effect of inlet and outlet configurations on blow-off and flashback with premixed combustion for methane and a high hydrogen content fuel in a generic swirl burner

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HIGHLIGHTS

- Correlation of blowoff and flashback using the tangential inlet velocity.
- The correlation appears to arise from the exhaust shear flow.
- Reynolds Number effects can be important with methane and flashback.
- For flashback the correlation was effective for 0.8 ⩽ swirl number ⩽ 2.2.
- For blowoff the correlation was effective for 0.8 ⩽ swirl number ⩽ 4.

ARTICLE INFO

Article history:
Received 12 September 2013
Received in revised form 17 November 2013
Accepted 28 November 2013
Available online 20 December 2013

Keywords:
Blowoff
Flashback
Hydrogen
Premixed combustion

ABSTRACT

The paper analyses new data for three fuels, natural gas, methane and Coke Oven Gas (COG) in two swirl burners. Flashback and blowoff can be correlated with the inlet tangential velocity, not the inlet mass flow, over a range of swirl numbers from 0.8 to more than 4. Geometry and fuel type are important. The correlation gives best fit for a particular outlet geometry and with higher hydrogen content fuels. The correlation still holds with methane and natural gas, especially with confinement.

Analysis of the correlation infers that both blowoff and flashback occurrences are governed by the shear layer surrounding the Central Recirculation Zone (CRZ). The CRZ acts to control the width and strength of the shear flow region. Blowoff was found to occur when the CRZ was extensive and well develop and could be modeled by a well stirred reactor system. Two modes of flashback were found, both of which could be characterized by the same correlation of inlet tangential velocity. The first flashback case occurred at lower swirl numbers when the flame attached to the burner rim and flashed back through the outer boundary layer. At higher swirl numbers the CRZ and associated flame located next to its boundary extended back over the fuel nozzle inside the swirl chamber. Flashback occurred when the flame suddenly moved radially outwards towards the inlets. A clear trend was established for COG; as the swirl number was increased from 0.8 to 1.5 blowoff slightly worsened, whilst flashback improved. Thus higher swirl numbers are tentatively favored for flashback protection for higher hydrogen content fuels.

1. Introduction

Characterizing the limits of a gas turbine combustion system is crucial. This involves determining laws and relationships which enable predictions to be made normally based on extrapolations of existing data. Although enormous progress has been made in the utilization of CFD codes [1–5] there is still a lack of basic relationships describing combustion limits and the effect of parametric variations [1–10]. Derivation of such relationships is complicated by the move towards dry low emission premixed combustors where limits are influenced by fuel composition variation. Premixing itself brings in the subject of flashback [2–4,7–10] which is commonly avoided by partial premixing which in itself leads to compromises in NOx and other emissions, especially when hydrogen or hydrogen rich fuels are considered [11–16]. Stabilization of gas turbine combustors is almost universally carried out by some form of swirl combustor [6,8,10]. Although blow off limits are especially important for all combustors, limited experimental work is available characterizing and correlating the phenomena

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http://dx.doi.org/10.1016/j.apenergy.2013.11.071

Nomenclature

CRZ	Central Recirculation Zone	S_t	turbulent flame speed
h	height of tangential inlets (mm)	t	tangential inlet width
m_t	mass flow air and fuel (kg/s)	Uex	average axial velocity in combustor chamber
De	combustor nozzle diameter (mm)	U'	RMS total fluctuating velocity
W_{in}	average inlet tangential velocity (m/s)	ϕ	equivalence ratio
CIVB	Combustion Induced Vortex Breakdown	ρ_g	gas density in combustor chamber
S	swirl number based on geometry		
S_L	laminar flame speed		

in terms of inlet velocities and equivalence ratios. The work that is available is normally carried out on specific combustors, often commercial in nature, which precludes full publishable analysis [17].

Similarly knowledge of the effects of geometry, swirl number, method of swirl generation, type of confinement and outlet nozzle are sparse especially for premixed situations, despite the trend towards premixing [15,16]. Moves towards higher hydrogen content fuels raise many problems including those of operational range overlap with different fuels, i.e. although a combustor may operate stably within the blowoff and flashback limits with natural gas and with a fuel blend such as Coke Oven Gas (COG, 65% H_2, 25% CH_4, 6% CO, 4% N_2) the two operational regimes do not overlap [16]. Other problems include the closeness of the flashback and blow off limits with H_2/CH_4 fuel blends where the hydrogen content exceeds 50% [16,17].

Instabilities are another problem not covered here [18], whilst the general problems of integration of premixed systems in gas turbine combustors are complex [9,19].

Combustion Induced Vortex Breakdown (CIVB) is a form of flashback, prevalent with high hydrogen content fuels which arises primarily when no or only a small fuel injector is present [20–22] and a significant upstream forward axial velocity exists on the centerline, in contrast to most swirl burners. As a large central fuel injector is used in all the work reported here, to retain capability for piloted flames as well as the use of liquid fuels, CIVB is not considered.

This paper analyses data on two combustors developed at Cardiff as well as other data available in the literature and shows that burner correlations can be developed for both blowoff and flashback for premixed swirl combustion and for fuels ranging from methane to Coke Oven Gas (COG) containing 65% hydrogen.

2. Experimental setup

The two swirl burners used in this work are shown in Figs. 1 and 2. They have been extensively described elsewhere together with the associated rigs and measurement equipment [10,15,16,23,24]. Different Swirl numbers were used with different gases (Natural Gas, CH4 and COG). Open and confined flames was both investigated to observe the impact of confinement on flashback and blowoff.

The unit of Fig. 1 is a small 28 mm nozzle diameter generic swirl burner with radial tangential inlets and capable of giving geometric swirl number variation from 0.6 to more than 2.0. During this work a 9 inlet version was used giving swirl numbers of 0.8 and 1.04. Blocking off three inlets symmetrically also gave swirl numbers of 1.2 and 1.5. An earlier version with four inlets and a much shorter exhaust gave a swirl number of 1.46. The swirl burner may fire into a circular confinement chamber with an expansion diameter ratio of 2, Fig. 1b, representative of industrial practice.

Conical contraction exhausts were sometimes added. This unit has been extensively tested on a wide range of fuel blends at Cardiff University's GTRC facility. Its thermal Input is up to 25 kW.

The swirl burner of Fig. 2 has a much larger thermal capacity, up to 150 kW and here uses natural gas as fuel with an exhaust diameter of 76 mm.

The geometric swirl number, S, of this burner was varied by adding 'D' shaped inserts to the inner face of the two 67 mm diameter tangential inlets. These 'D' shaped inserts ranged from 0% of the inlet width ($S = 0.74$), 25% ($S = 1.04$), 50% ($S = 2.02$) and 70% ($S = 4.46$).

The system was designed for efficiently combusting poor quality gaseous fuels such as produced by process plant. Large area circular tangential inlets are used so tars and deposits do not seriously degrade its performance under premixed conditions. Circular exhaust confinement chambers similar to the design shown in Fig. 1b were also used [6,10]. Extensive data on blowoff and flashback has been obtained for both burners, whilst extensive PIV, LDA and other detailed velocity data (including phase locked time dependant data) is also available [20,21]. The exhaust nozzle for both units is to the same design and uses a recessed central fuel injector. This configuration has been shown to give best results in terms of overall limits whilst restricting flame impingement on the fuel injector or indeed recirculation causing the flame to extend to the rear baseplate around the fuel injector. All results shown are at atmospheric pressure for fully premixed swirl combustion, with no air preheat. The geometric swirl number, S, was used for characterization as extensively discussed in Refs. [6,10,23,24]. Flow velocity data was obtained using a Phase Locked PIV system, as discussed somewhere else [6].

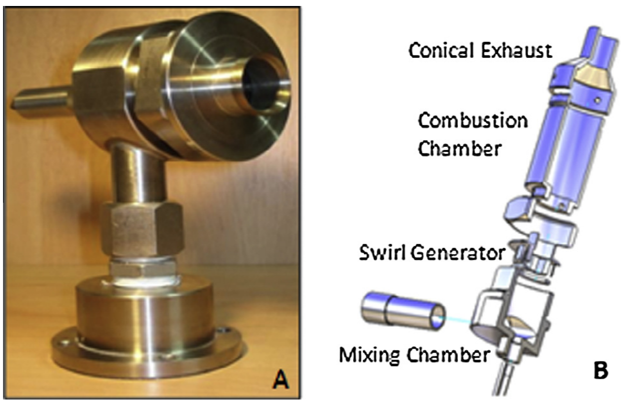

Fig. 1. (A) Unconfined swirl burner 1. (B) Schematic diagram of swirl burner 1 with combustion chamber and conical cup exhaust.

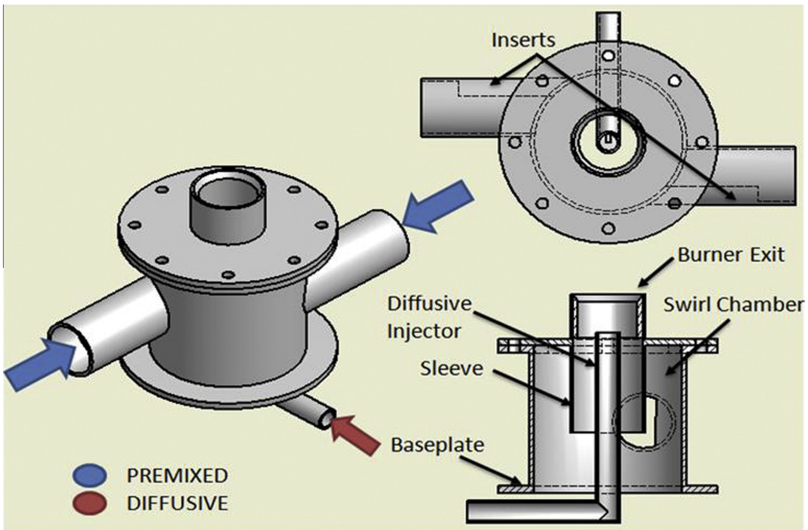

Fig. 2. Burner 2 for efficient combustion of poor quality fuels. Variable swirl number.

3. Results and discussion

Fig. 3 shows flashback and blowoff data for Coke Oven Gas (COG) for 3 different swirl numbers as a function of tangential inlet velocity and equivalence ratio for burner 1. Plotting the data against tangential velocity allows almost all of the data to fall onto one curve.

This was not so when the data was plotted in terms of total inlet mass flow or average exhaust velocity. The dropping of most of the data for blowoff and flashback onto singular curves was surprising as the unit with $S = 1.46$ had an earlier exhaust nozzle (just a sudden expansion past the fuel injector, Fig. 1) and the only region where this had a major effect was for flashback for weak conditions with equivalence ration, $\phi < 0.8$. This caused further investigation into this behavior with other fuels. Similar trends were found but generally not quite as strong. Further discussion on the COG and methane flashback behavior is made later.

Fig. 4A and B shows blowoff and flashback data for methane (burner 1) and some flashback data for natural gas (burner 2), both without exhaust confinement. Data for $S = 1.2$ and 1.5 nearly coincide (6 inlets), that for $S = 0.8$ (9 inlets) only matches the other two curves at $W_{in} > 35$ m/s, Fig. 4a. For W_{in} 10 m/s the curves significantly differ. This may be due to the variation in the number of inlets used as all other geometrical details were identical. The abnormal $S = 1.46$ blowoff result is ascribed to the different exhaust geometry. Increasing hydrogen fuel content incrementally improved blowoff with $S = 1.46$ [15,16], compare Figs. 3A and 4A. Moving onto flashback, Fig. 4B, results from both burners 1 and 2 are shown, for unconfined flames. The results for burner 2 all fit onto one curve and lie in the W_{in} range of 1.8–3 m/s over an equivalence ratio range of 0.6–1.1. Conversely for the smaller burner 1 W_{in} flashback velocities are beneficially much lower in the range typically from 0.6 to 1.4 m/s over a very wide range of equivalence ratios from very weak to very rich. This may be due to Reynolds Number effects as the exhaust Reynolds Number (isothermal), based on average axial velocities is only ~2000 for burner 1, whilst being ~10,000 for burner 2. Also the configuration and number of tangential inlets may be important as indicated by Fig. 4A.

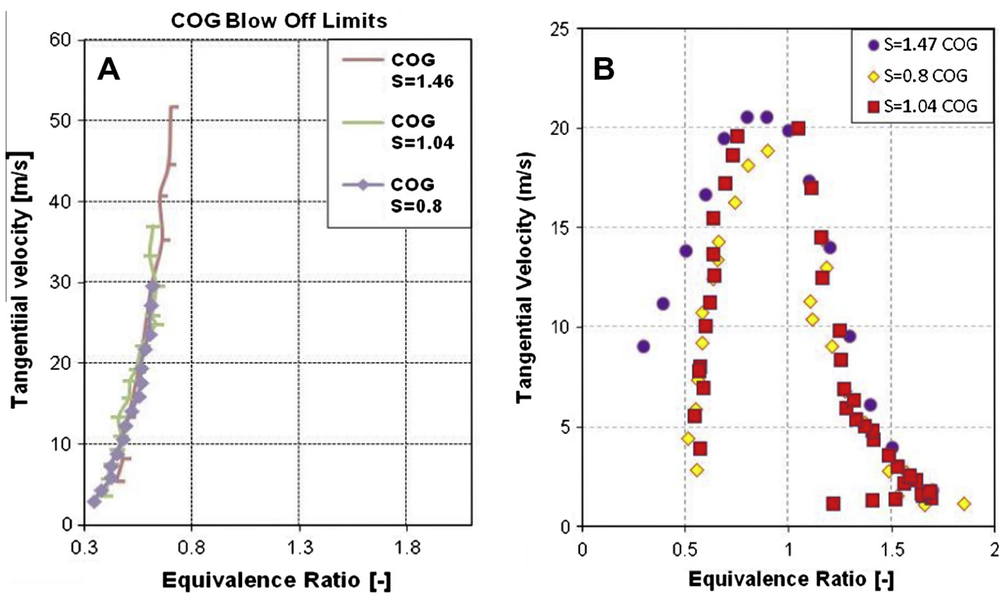

Fig. 3. (A and B). Blowoff and flashback data for Coke Oven Gas (COG 65% H2/25%CH4) for 3 different swirl numbers for burner 1-open flames.

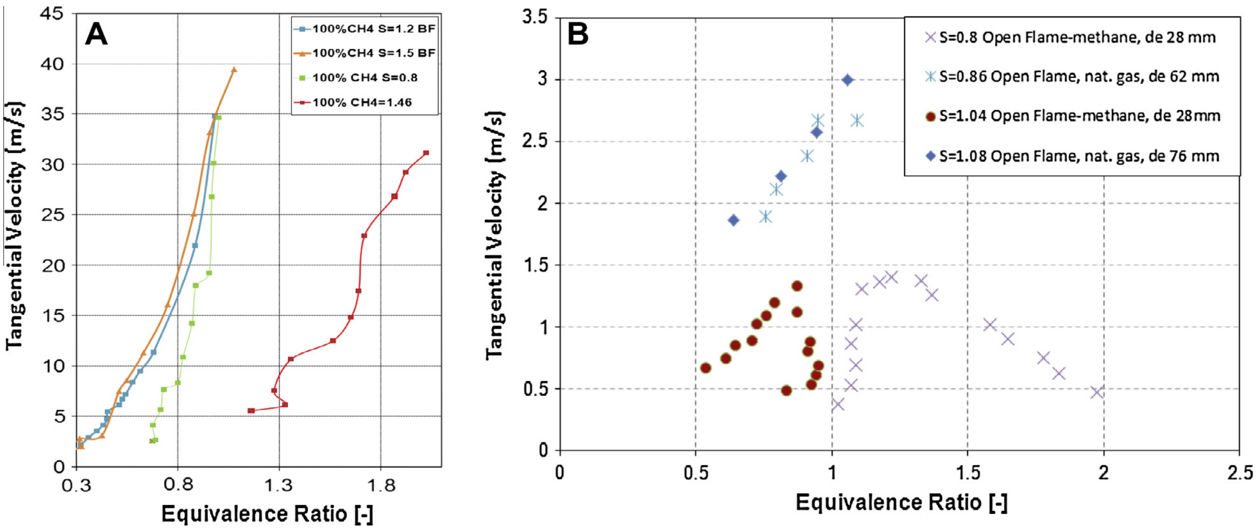

Fig. 4. (A) Blowoff for methane, burner as Fig. 1; (B) Flashback with natural gas in burner 2; Flashback with methane in burner 1. All results for open flames.

Reynolds Numbers effects are not considered in detail as they only appear to be particularly significant for methane flashback with burner 1 and all other results were taken at high Reynolds Numbers.

Fig. 5 shows the results from burner 2 fired on natural gas with exhaust confinement chambers as shown in Fig. 1b, except that two conical exhaust contraction were added: type A (45° Contraction to 76 mm diameter exhaust) and type B (as type A except 30° Contraction). Most results were obtained with confinement A.

For blowoff most results, apart from $S = 0.74$, fall on very similar curves. The result is not quite as good as Fig. 3A for Coke Oven Gas but still evident. For flashback apart from $S = 0.74$ and $S = 4.46$ the results are very close together for $S = 1.08$ and $S = 2.02$ and tangential velocities ranging from 2 to 6 m/s, considerably higher than for unconfined flames with the same burner, Fig. 4b. At equivalence ratios, $\phi \sim 0.6$ both confined and unconfined flames flashback at similar tangential inlet velocities of ~2 m/s, the range of ϕ of interest. Two modes were found with this configuration as discussed later.

The high swirl number flashback results for $S = 4.46$ are associated with a clearly visible strong CRZ which surrounds the fuel injector and alters the flashback mode. The result at $S = 0.74$ shows that the burner is close to vortex breakdown with a very weak or non-existent CRZ [6,8,10]. The intermediate form of flashback for $1 < S < 2.2$ is discussed later. Results have been obtained for burner 1 for blowoff with a type A confinement. Similar ranges of ϕ were covered. The main difference was that the blowoff limits at high values of W_{in} were slightly worsened with blowoff values of ϕ being 0.65 for burner 1 and 0.5 for burner 2 for W_{in} of 35 m/s.

3.1. Further analysis

The dependence of flashback and blowoff on the tangential inlet velocity clearly needs further analysis. To facilitate this Table 1 shows calculated adiabatic flame temperatures for a range of fuels and blends under investigation for 20 °C inlet temperature and atmospheric pressure. In the authors experience of practical industrial premixed gas combustors, it is not practical to run a unit with mean gas temperatures significantly below the following temperatures even when the unit is very well insulated, whilst the internal flow corresponds approximately to a well stirred reactor [25,26],

$$\text{Natural gas/methane} : 1000\,^{\circ}\text{C}/1273\ \text{K}$$

$$\text{Hydrogen content}(>60\%)\ \ \text{fuel blends} : 900\,^{\circ}\text{C}/1173\ \text{K}$$

Table 1 indicates that for natural gas/methane with lean blowoff, we cannot expect our combustors to operate below values of ϕ of ~0.36 for methane/natural gas, ~0.3 for COG and ~0.28 for hydrogen. These figures will alter with air preheat and/or pressurized combustion. Examination of Fig. 3a shows that at low inlet velocities ~2 m/s the combustor is operating at $\phi \sim 0.32$ with COG and 0.32 for methane (burner 1). This infers that the premixer is not working properly at low velocities in the inlets, especially for burner 1 with methane. This problem appears to be rectified by about 5 m/s inlet velocity. For the burner of Fig. 2: Fig. 5 shows with natural gas the lowest value of $\phi \sim 0.42$, inferring that the premixing system (multiple radial small jets firing just upstream of the inlets) is working well.

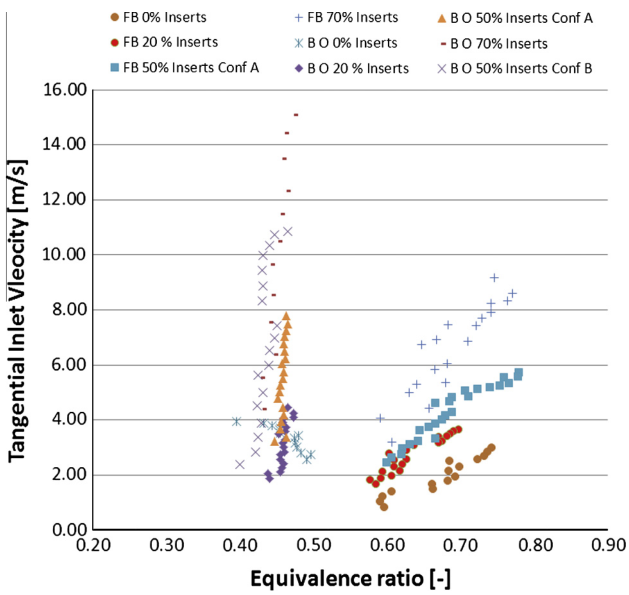

Fig. 5. Effect of swirl number and confinement on flashback and blowoff limits for swirl burner 2, natural gas as fuel. Differences between confinements A and B lie in configuration of a conical cup (similar to that of fig. 1B) added to confinement exhaust ($S = 0.74$ 0% inserts, $S = 1.04$ 20% inserts, $S = 2.02$ 50% inserts, $S = 4.46$ 70% inserts).

We now utilize Figs. 6–8 to illustrate the effects of the combustion process and equivalence ratio upon the combustion aerodynamics, especially the CRZ and exhaust shear flow, the data all having been obtained from burner 2 [20,21,24,25]. We then discuss how these combustion aerodynamics together with the tangential inlet velocity W_{in} influence blowoff and flashback. To facilitate reliable data gathering and stable flames partial premixing was primarily used with 76% of the fuel premixed, the rest injected axially through the fuel nozzle. Some results with diffusive combustion are also used to illustrate trends in CRZ behavior with equivalence ratio (confined flames} and Fig. 4 (open flames) (burner 2) shows that for swirl numbers of interest $0.8 < S < 2.5$ the operational range of equivalence ratios for blowoff is between 0.45 and 0.5, for flashback between 0.58 and 0.8 with corresponding values of W_{in} between 2 and 8 m/s. For an W_{in} of 5 m/s the operational equivalence ratio range is $0.45 < \phi < 0.6$. For $W_{in} \sim 8$ m/s the operational equivalence ratio range has substantially moved above the measured flashback limit, just being limited by $\phi \sim 0.45$, the blowoff limit. Between these limits there is substantial change of combustion aerodynamic conditions which will critically alter the mechanism of blowoff and flashback.

Fig. 6 shows axial radial PIV data in the central exit plane of burner 2 [24,25], operating at overall equivalence ratios of (a) 0.99, (b) 0.623, (c) 0.453. Red to green indicates positive axial velocities, light blue, velocities around zero and dark blue negative axial velocities. At $\phi = 0.453$, Fig. 6c, the flow is of well known form [6,8,10] with a large CRZ surrounded by an annular shear flow, (this condition is close to lean blowoff). These are phase locked velocities in the 0–180° phase plane [27,28]. With $\phi = 0.623$, Fig. 6b, the higher flame temperatures have reduced the swirl number such that the CRZ has weakened [6,8,10], whilst the shear flow still shows the same asymmetry as with $\phi = 0.453$. By $\phi = 0.99$ the CRZ has virtually disappeared, Fig. 6a, with a much thinner central region with just small, localized areas of reverse flow and recirculation. The outer annular shear flow surrounding this region is still evident, whilst it has broadened, and shows asymmetry as before [27,28]. This change in flow structure with ϕ is well known and arises because combustion increases the axial flux of axial momentum, but not the axial flux of angular momentum significantly [6,8,10], thus reducing the actual flow swirl number.

Fig. 7 shows results for averaged mean axial velocity in the CRZ for burner 2 (open flames) as a function of φ, with natural gas [24]. Various modes of fuel injection/premixing are shown and it is clear that for all modes the reversed axial velocity rapidly decreases, becoming positive as $\phi \rightarrow 0.8$ under partially premixed conditions. The resulting flow form is as Fig. 6a; there is still a central low velocity region (with some intermittent recirculation) surrounded by an annular shear flow.

However the stabilizing influence of a strongly recirculating flow has gone and the main function of the central region appears to form an area where the local turbulent flame speed S_t can match the flow velocity. Conversely at weak blowoff the CRZ will be of similar form to that of Fig. 6c; it will be quite strong and can be expected to have a strong influence on flame stability.

Here conventional models of blow off using well stirred reactor models based on the flow in the CRZ and inner section of the shear flow are relevant as discussed later.

Fig. 8 shows a tangential radial PIV velocity image close to the burner exhaust. It highlights the fact that much of the flow is concentrated in a red/orange high velocity crescent shaped region in the annular shear layer. Velocities diametrically opposite are much reduced. This is in accord with the PIV images of Fig. 6 where strong asymmetry across the shear layer is shown [20,21,24,25].

It is now pertinent to consider the influence of W_{in} on the blowoff and flashback limits. Considering the variation of swirl number from 0.8 to 1.5 with burner 1 and 1.08 to 2.02 for burner 2 there are well known variations of the CRZ in terms of length, diameter, shape, mass recirculated, reverse flow velocities and changes due to equivalence ratio variations [19].

The flow feature which is common to both flashback and blowoff as illustrated in Figs. 6–8 is the shear layer which surrounds the CRZ and strongly interacts with it via pressure fields and flow recirculation. Here it is entirely possible and probable for the inlet tangential velocity to substantially influence turbulent flame speed, S_t, through the generation of high levels of velocity fluctuation in the shear layer as indeed has been recorded in the literature [6,8,10].

The results shown in Figs. 7 and 8 pertain to the burner 2; they are however not unique. Kim et al. [11,12]carried out extensive measurements on a 5 KW vaned, premixed, swirl burner with swirlers of 30°, 45°, 60°, vane angle corresponding to low, medium and high swirl conditions. PIV images and integrated recirculated mass flowrates were used to illustrate the results obtained at different swirl levels and the effects of different H_2/CH_4 fuel mixes ranging $100\%CH_4$, to $9\%H_2/91\%CH4$ by weight. Equivalence ratio was very similar for the three cases investigated (~0.7) with similar average adiabatic flame temperatures. Stronger swirl increased the size of the CRZ and the recirculated mass flow, as to be expected. However the different H_2/CH_4 ratios produced different temperature distributions which reduced the recirculated mass flows as hydrogen content was increased, clearly due to earlier heat release and its effect on the local swirl number.

It is now useful to consider a number of other studies concerning turbulent flame speed [26–30], the effect of centrifugal force fields and vortex flows on flame speed [31–39] as well as the effect of hydrogen based fuels in other designs of swirl burners [11–13,40,41].

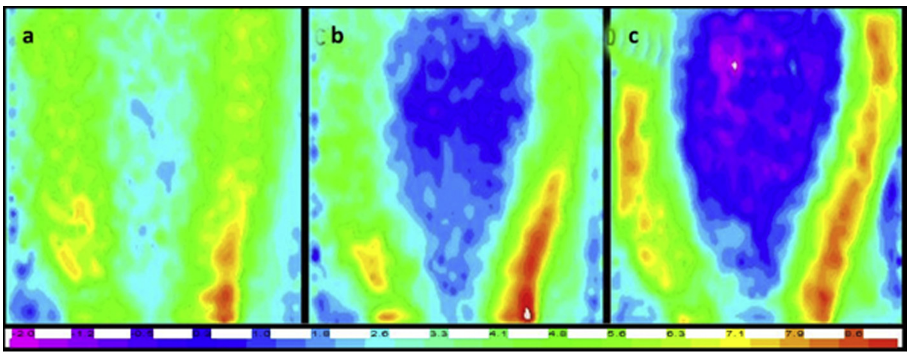

Fig. 6. Phase locked PIV images in the 0–180° phase plane of axial radial velocities for burner 2, open flames (a) $\phi = 0.99$, $W_{in} = 2.94$ m/s, (b) $\phi = 0.623$, $W_{in} = 4.7$ m/s and (c) $\phi = 0.453$, $W_{in} = 6.46$ m/s. All cases 25 l/min diffusive and 80 l/min premixed injection.

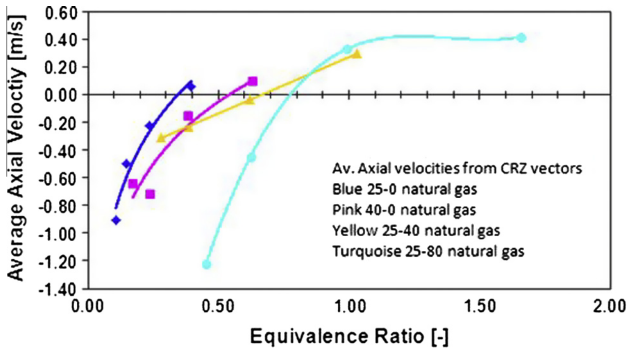

Fig. 7. Effect of equivalence ratio on averaged reversed axial velocity in CRZ, $S = 1.08$. Fuel natural gas. Nomenclature, 25–80 refers to 25 l/min diffusive and to 80 l/min premixed.

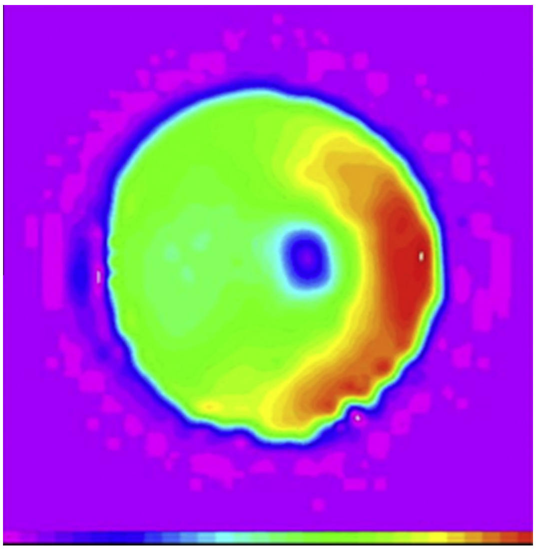

Fig. 8. Tangential Radial PIV velocity Image just above burner exhaust-open flame, $S = 1.08$. The velocity scale is from 0.00 to 12.00 m/s in increments of 0.81 m/s.

The well known equation for turbulent flame speed, S_t, as derived in [26,27] is:

$$S_t = S_L + KU' \quad (1)$$

K is a constant dependant on fuel, 3.15 for H_2, 1.73 for CH_4 [29,30]. For COG we derive an interpolated value of K, of 2.73, from the volume/molecular concentration of hydrogen to methane. At low Reynolds Numbers (influence of U' low) the effect is accentuated by the contrast between the high value of S_L for hydrogen and the low value for methane [31] and the corresponding effects on methane/hydrogen fuel blends such as COG. Eq. (1) is especially important as it shows a multiplier effect of hydrogen based fuels due to the high value of K (clearly due to kinetic effects) compared to methane. This is in contrast to earlier theories (i.e. Lewis and von Elbe [3]) where S_t was postulated to be ≈ $S_L + U'$.

Lewis [32,33] showed via experiments of flame propagation in a vertical rotating tube and showed considerable enhancement of S_t with centrifugal force field. Claypole et al. [34] showed that the precessing vortex core (PVC) could produce similar effects. Several studies [35–40] have shown the enhancing effect of vortex tubes, cores or rings on turbulent flame propagation. Thus the correlation found in this work between flashback, blowoff and tangential inlet velocity is not unexpected, as the strength of the central vortex flow (where flames are stabilized) and associated centrifugal force fields are clearly related to the inlet tangential velocity for a given swirl burner geometry [6].

The results shown in Fig. 5 for burner 2 show that when confined the blowoff limit is approaching the equivalence ratio limit indicated by the 1000 °C limit for practical swirl stabilized premixed natural gas combustion, Table 1, and is giving results close to those found with distributed combustion [13,41,42]. Centrifugal force field and vortex flow field effects are clearly important here in increasing St as shown by the dependence of the blowoff and flashback results on the inlet tangential velocity. Clearly further work is needed to produce more fundamental explanations for this phenomena.

3.2. Analysis of fuel effects

3.2.1. Methane and natural gas

We assume here that the properties of methane and natural gas are identical. Fig. 9A and B shows photographs of the open flames formed from burner 1, just before blowoff and flashback, $S = 1.04$: those from burner 2 look very similar. With flashback, Fig. 9B there is an annular flame front located on the outer burner with a secondary internal flame stabilized on the boundaries of the wake formed by the fuel injector. Flashback appears to occur through or near to the boundary of the outer nozzle wall boundary layer. Changes in inlet tangential velocity appear to be crucial in determining the thickness of the boundary layer and the important critical boundary velocity gradient. Comparison of Figs. 4b and 5 shows the following conditions for $\phi = 0.6$, where the values of W_{in} for the confined and unconfined flames of burner 2 are similar:

Burner 1 S = 1.04 Open flame

Flashback at $W_{in} = 0.7$ m/s : Uex = 0.921 m/s.

Average Reynolds No burner exhaust. = 1720

Burner 2 S = 1.08 Open flame/Confined flame

Flashback $W_{in} = 1.8$ m/s : Uex = 2.37 m/s;

Average Reynolds No.burner exhaust = 12,000

For burner 1 and $S = 0.8$ values of Reynolds Number are even lower than 1720 due to the larger area tangential inlets. Fig. 4b shows that with burner 1 and $S = 0.8$ and 1.04 the Reynolds Numbers based on Uex are laminar and this is reflected in the two mirror imaged curves which cover the same W_{in} velocity range but are of different equivalence ratios. However because of 3D flow effects we expect parts of the flows to be turbulent. Thus with burner 1 it is expected for flashback the influence of U' on S_t will be low for methane.

Fig. 5 shows that for burner 2 flashback values of W_{in} are some 1.1–1.3 m/s higher than burner 1. Taking Eq. (1) and values of $K = 1.73$ this indicates a value of fluctuating velocity U' of at least 0.65–0.75 m/s. This is consistent with the calculated values of Uex of 2.37 m/s (actual maximum values of axial velocity in the exhaust shear layer will be at least twice these values, see Figs. 6 and 8 [6,8,10,21,24,25]. Thus burner 1 may give different flashback results with methane as it is scaled up in size. The results with COG illustrate this as the flashback region is moved into the turbulent regime with enormous effects on S_t and deleterious effects on flashback. However there are also clear effects of the tangential inlet configuration. With burner 1 and methane there are differences in blowoff values of ϕ with $W_{in} < 20$ m/s for values of S of 0.8, 1.2 and 1.5. These may be Reynolds Number effects or those of changing the number of inlets from 9 to 6 (achieved by blocking off every other third inlet). Similarly the differences in flashback limits between burners 1 and 2 may be due to the very different inlet configurations (9 symmetrical inlets as opposed to two circular ones). Flashback studies in the swirl chamber of burner 2 have revealed

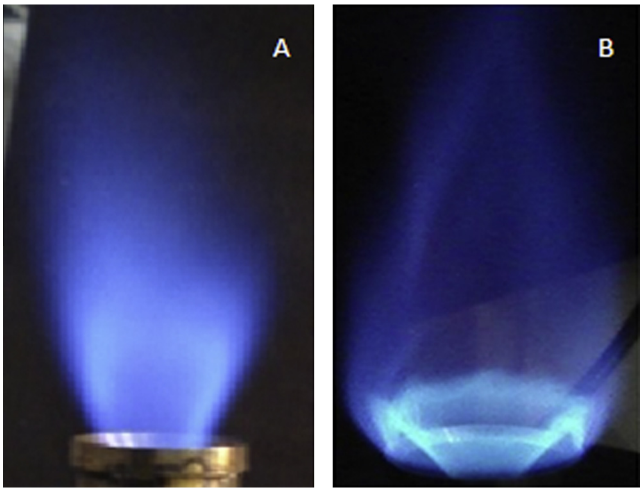

Fig. 9. (A and B). Burner 1, open flames, methane (A) Just before flashback and (B) Flame just before blowoff, $S = 1.04$.

quite high levels of turbulence generation in the outer part of the swirl chamber which may contribute to the differences in flashback velocities.

Blowoff results from Figs. 4a and 5 for burners 1 and 2 again should be compared, a typical flame just before blowoff for burner 1 is shown in Fig. 9A. Fig. 4a for burner 1 shows some effects of swirl number and the number of inlets and exhaust configuration. Results for $S = 0.8$, 1.2 and 1.5 converge at high values of $W_{in} = 35$ m/s and Reynolds Number > 50,000. With burner 2, Fig. 5, the blowoff curves are different as the flames are confined.

They are consistent with Table 1 being all around values of $\phi \sim 0.45$ to 0.5 (doubtless due to some heat losses from the confinement). Here for open flames near blowoff the flame seems to retreat into the CRZ region and a small distance into the shear flow region, but not completely across the shear layer to the wall, Fig. 9A. The flame also does not extend completely to the end of the CRZ, Fig. 9A, and blowoff limits are significantly worse than for flames firing into a confinement.

Fig. 5 shows blowoff values of W_{in} ranging from 2 to 35 m/s (corresponding to values of Uex between 1.6 and 28 m/s) and φ from 0.45 to 0.5. Again shear flow axial velocities will be at least twice those of Uex, see Figs. 6 and 8, with velocities of 3.2–56 m/s. Here, S_t will be dominated by turbulence effects. The high forward flow axial velocity will be balanced by the high value of S_t, in the shear layer as the system moves closer to blowoff. High values of U' are to be expected here [6,8,10,21,24,25].

3.2.2. Coke Oven Gas COG (65% H_2, 25%CH_4, 6% CO, 4% N_2)

Results are only available for burner 1. These strongly show the tangential inlet velocity correlation. Data for flashback and blowoff are close together and could not be obtained for confined flows as the two limits overlapped as observed by others [17]. The crucial factor appears to be the factor K in Eq. (1) of 2.73 which brings the flashback limits close to the blowoff limit. For blowoff maximum values of Uex are ~29 m/s, despite the high values of W_{in} (because of the value of S of 1.46). In the shear flow maximum axial velocities will be up to 58 m/s and thus values of U' may be up to 21 m/s giving high values of S_t due to high vales of S_L [28] and K in Eq. (1). This is consistent with the forward axial velocity balancing S_t in the shear flow layer.

For flashback and in comparison with methane COG Reynolds Numbers are of order 10 times higher and well into the turbulent flow regime. As discussed later it is interesting how the flashback curves for three different swirl numbers quite closely coincide, Fig. 3b as the CRZs formed and flashback mechanisms appear to be different. For $S = 1.47$ the CRZ surrounds the central fuel injector, for $S = 0.8$ and 1.04 the flames just before flashback are similar to Fig. 9B

3.2.3. Vaned swirlers. Comparison

Vaned swirlers are widely used in gas turbine combustors. There is little literature data on premixed combustion and vaned swirlers apart from that of Beltagui and Maccallum [43,44] who undertook a substantive programme with hubless straight vaned swirlers of vane angle varying from 15° to 70° for natural and town gas (49% H_2, 25% CH_4), for open flames. As for burner 2 anomalous behavior occurred for the lowest and highest swirl vane angles (i.e. swirl numbers). No CRZ was found with the 15° vanes giving poor blow off limits, whilst 70° vanes produced different flames which undesirably stuck to the vanes. The data has been re-analyzed and an average tangential velocity for the flow leaving the swirl vanes derived using the swirl vane angle for the 30°, 45°, and 60° vanes. An inlet tangential velocity has thus been defined.

W_{in} = axial velocity leaving swirler* tan (swirl vane angle).

This enables the data to be recast into a similar format to Figs. 4 and 5 of inlet tangential velocity against equivalence ratio. The natural gas results produce a curve upon which the majority of the data fits well, Fig. 10. A similar trend is found for town gas although there is more scatter in the data. Fig. 10 indicates that the hubless vaned swirler is following a similar pattern of blowoff behavior to burners 1 and 2. A blowoff model [43,44] was derived using the total average velocity leaving the swirl vanes and a modified equivalence ratio to allow for air entrainment into the CRZ. The experimental measurements were used to develop a well stirred reactor model whose volume was formed from the outer part of the CRZ and part of the shear layer which recycled flow to the CRZ. Blowoff was assumed to occur at the peak of the heat release rate for a given equivalence ratio. A reasonable fit for Town Gas was also obtained, similar to Fig. 10. The model has also been successfully applied to the data from the swirl burner of Figs. 1 and 2

Table 1
Mean adiabatic temperatures in °C. Inlet gases at 20 °C-ambient pressure.

ϕ	Pure CH_4	COG	Pure H_2
1	1964	2027	2133
0.9	1963	2021	2109
0.8	1894	1901	2015
0.7	1721	1762	1850
0.6	1523	1573	1657
0.5	1259	1359	1464
0.4	1095	1112	1257
0.3	NA	NA	956
ϕ limit for methane and natural gas (1000 °C): COG & Hydrogen (900 °C)	0.359 (1000 °C)	0.307 (900 °C)	0.278 (900 °C)

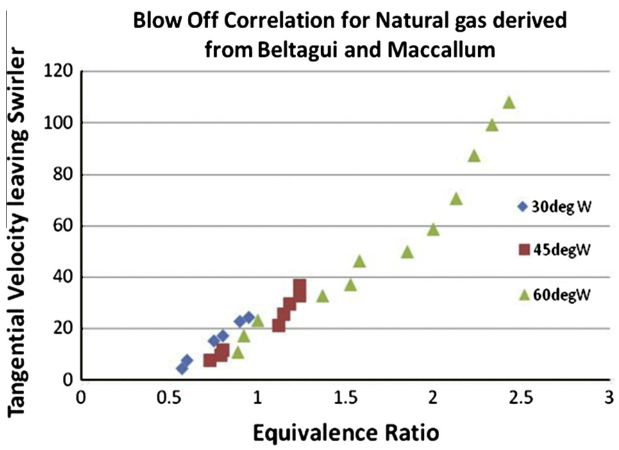

Fig. 10. Tangential velocity blowoff correlation for vaned swirlers.

4. Discussion

One of the most interesting results is the influence of tangential inlet velocity both on blowoff and flashback for a range of swirl numbers. It has been demonstrated [43,44] that blowoff can be represented by a well stirred reactor model encompassing part of the CRZ and shear flow region and dependant on inlet velocity.

With flashback in the work reported here there are two known modes [15,45]:

(a) For this mode flashback occurs as an annular flame becomes attached to the burner rim and then apparently flashes back through the outer wall boundary layer as in Fig. 10B. This is the sort of behavior shown by burner 2, Fig. 5 for $1 \geqslant S > 2.2$ and natural gas, also for burner 1 up to $S \sim 1$. Probably the boundary layer thickness, velocity gradients and turbulence are controlled by the tangential inlet velocity levels. There are also Reynolds Number effects which merit further experimentation especially for methane.

(b) For burner 1 and $S \sim 1.5$ [15,34] the CRZ extends back over the fuel injector through the swirl generator to the backplate and is surrounded by an annular flame on its boundary. Experiments and analysis of this behavior shows that flashback occurs when the flame on the CRZ suddenly moves radially outwards to the inlets, being a function of the radial velocity which is a function of the tangential inlet velocity. Burner 2 also produced this mode of flashback at $S = 4.46$

5. Conclusions

- Detailed measurements of blowoff and flashback limits have been used to develop a new correlation for both blowoff and flashback, based on the tangential inlet velocity, not the inlet mass flow, for a range of swirl numbers and the two different burners. This was not expected as the two phenomena occur via different mechanisms. It is attributed to the influence of the annular shear flow leaving the burner which interacts strongly with a strong CRZ close to blowoff and for one mode of flashback by strongly influencing conditions in the outer boundary layer.
- The correlation has been found to be applicable to COG, methane and natural gas combustion.
- Two different modes of flashback have been found, occurring at different places in the operational fields of the two burners, but following the same tangential velocity correlation.
- Reynolds Number effects can be important, especially for the smaller burner 1 and methane, where flashback is apparently affected by the laminar flame speed as exhaust Reynolds Numbers are often less than or 2000.
- There are clear effects of the inlet configuration.
- Burner 2 of larger size and thermal capacity indicated that there were upper and lower limits of the correlation in terms of swirl number. Best results were obtained in the swirl number range 0.8 to just above 2 for flashback; this extended to swirl numbers > 4 for blowoff. Results obtained by other workers for vaned swirlers showed similar trends.

Acknowledgements

The authors gratefully acknowledge the support of the Welsh Assembly Government Low Carbon Research Initiative Programme, EPSRC (Grant no EP/G060053) and the European Union via various grants.

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