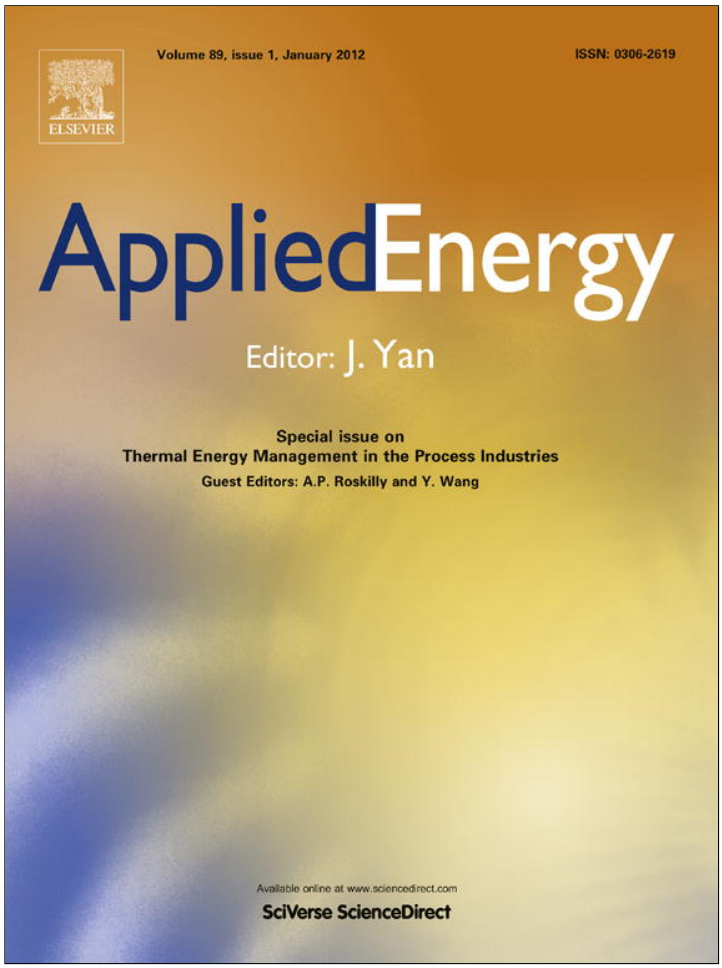
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Applied Energy 89 (2012) 106–110

Contents lists available at ScienceDirect

Applied Energy

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

The effect of hydrogen containing fuel blends upon flashback in swirl burners

Nicholas Syred *, Mohammed Abdulsada, Anthony Griffiths, Tim O'Doherty, Phil Bowen

Gas Turbine Research Centre, Cardiff University, CF24 3AA, United Kingdom

ARTICLE INFO

Article history:
Received 14 July 2010
Received in revised form 21 January 2011
Accepted 25 January 2011
Available online 25 February 2011

Keywords:
Flashback
Swirl burner
Lean premixed
Hydrogen

ABSTRACT

Lean premixed swirl combustion is widely used in gas turbines and many other combustion Processes due to the benefits of good flame stability and blow off limits coupled with low NO_x emissions. Although flashback is not generally a problem with natural gas combustion, there are some reports of flashback damage with existing gas turbines, whilst hydrogen enriched fuel blends, especially those derived from gasification of coal and/or biomass/industrial processes such as steel making, cause concerns in this area. Thus, this paper describes a practical experimental approach to study and reduce the effect of flashback in a compact design of generic swirl burner representative of many systems. A range of different fuel blends are investigated for flashback and blow off limits; these fuel mixes include methane, methane/hydrogen blends, pure hydrogen and coke oven gas. Swirl number effects are investigated by varying the number of inlets or the configuration of the inlets. The well known Lewis and von Elbe critical boundary velocity gradient expression is used to characterise flashback and enable comparison to be made with other available data.

Two flashback phenomena are encountered here. The first one at lower swirl numbers involves flashback through the outer wall boundary layer where the crucial parameter is the critical boundary velocity gradient, G_f. Values of G_f are of similar magnitude to those reported by Lewis and von Elbe for laminar flow conditions, and it is recognised that under the turbulent flow conditions pertaining here actual gradients in the thin swirl flow boundary layer are much higher than occur under laminar flow conditions. At higher swirl numbers the central recirculation zone (CRZ) becomes enlarged and extends backwards over the fuel injector to the burner baseplate and causes flashback to occur earlier at higher velocities. This extension of the CRZ is complex, being governed by swirl number, equivalence ratio and Reynolds Number. Under these conditions flashback occurs when the cylindrical flame front surrounding the CRZ rapidly accelerates outwards to the tangential inlets and beyond, especially with hydrogen containing fuel mixes. Conversely at lower swirl numbers with a modified exhaust geometry, hence restricted CRZ, flashback occurs through the outer thin boundary layer at much lower flow rates when the hydrogen content of the fuel mix does not exceed 30%. The work demonstrates that it is possible to run premixed swirl burners with a wide range of hydrogen fuel blends so as to substantially minimise flashback behaviour, thus permitting wider used of the technology to reduce NOx emissions.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Lean premixed (LP) combustion is a widely used strategy to decrease undesirable emissions in gas turbines. In LP systems, fuel and air are mixed prior to the combustion chamber to promote mixing, combustion efficiency, uniform temperatures and low NO_x. Swirl combustors are almost universally used in some form or other in gas turbine [1–3] and numerous other systems. Especially when operated in a LP mode many problems can be encountered including blow off and flashback [2–4].

Using alternative fuels has become another option to reduce emissions of CO_2. Hydrogen, hydrogen and other fuel blends can cause major issues with many swirl combustors, because of the considerable variation in flame speed with such fuel blends compared to natural gas. Similar comments apply to process gases such as coke oven gas (COG) widely produced in the steel industry. Biomass and coal gasification prototype power plants have performed well, but have not proved to be competitive against conventional boiler technology for power production [5–7], primarily because gas turbine manufacturers have had full order books for conventional units. Demand for systems capable of economically and efficiently producing power and CO_2 for sequestration may well change this. There are many other problems associated with the use of alternative fuels as discussed in [8].

Basically, swirling flows are defined as a flow undergoing simultaneous axial-tangential vortex motion. This flow motion can be generated using swirl vanes or many other methods [9,10]. The

* Corresponding author. Tel.: +44 (0) 2920874318.
E-mail address: syredn@cf.ac.uk (N. Syred).

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.01.057

Author's personal copy

main desirable characteristic of swirl combustors is the formation of unattached reverse flow zones (RFZ) and central recirculation zones (CRZ) capable of recycling hot chemically active reactants to substantially enhance flame stability [4]. The swirl number (S) is one of the main parameters used to characterise swirling flow. It is defined as the ratio of axial flux of swirl momentum divided by axial flux of axial momentum, divided by the equivalent nozzle radius [3]. Commonly owing to flow complexities a geometric swirl number (S_g) is used which depends entirely on the geometry of the burner.

Flashback is a problem which has arisen when using LP combustors especially with hydrogen based fuel mixtures. Flashback occurs when the gas velocity becomes lower than the burning velocity due to flame propagation within boundary layer, core flow or because of combustion instabilities [2, 11–13]. One important manifestation of the flashback phenomenon is that due to flame propagation in the low velocity region of the wall boundary layer. Flame propagation is thus limited by quenching in the very near wall region [13]; for turbulent flow this will be the laminar sub layer. Lewis and von Elbe [14] have suggested use of the critical boundary velocity gradient, based on considerations of the velocity gradient G_f at the wall, the laminar flame speed S_L and the quenching distance d_q.

$$G_f = \left[\frac{\partial u}{\partial r}\right]_{wall} \leqslant \frac{S_L}{d_q} \tag{1}$$

Flashback can also occur because of turbulent flame propagation in the core flow. Combustion instabilities have a very considerable effect on system dynamics and can cause flashback due to non- linear interaction of pressure fluctuations, hence periodic heat release and non linear flame propagation [15]. Finally flashback in swirl burners can be caused by a phenomena termed combustion induced vortex breakdown (CIVB) due to rapid expansion at the burner exit creating a recirculation zone which acts as a flame holder: the breakdown of this structure can occur due to flow perturbations and chemical reaction effects causing the CRZ and hence flame to propagate upstream into the premixing zone [16,17].

2. Experimental setup

The generic swirl burner was used to examine flame stability limits at atmospheric conditions (1 bar, 293 K). The was designed and assembled at Cardiff University's Gas Turbine Research Centre (GTRC). A single tangential inlet feeds an outer plenum chamber which uniformly distributes premixed air/fuel to the inserts, eventually into the burner body. A central fuel injector extended through the whole body of plenum and the insert burner. Principally, the fuel injector is used to produce both non-premixed and partially premixed flames; its position is shown in Figs. 1 and 2. This simulates many industrial applications where liquid fuels are sprayed through a central fuel injector.

Three swirl numbers have been used in the experiments, with the only change in the system being in the exhaust insert with tangential inlets which force flow into the swirl chamber, then exhaust. Three inserts are used with different swirl numbers, achieved by changing the number, length and width of the tangential inlets. The three swirl burners have swirl numbers of: $S_I = 1.47$, $S_{II} = 1.04$, $S_{III} = 0.8$. Based on other work [9,21] an exhaust nozzle extension 0.5De long was added to the exhaust of two of the inserts. The fuel injector was left in the same position Swirl insert III is very similar to II the only differences lying in the width of the tangential inlets, 5 as opposed to 4 mm (nine inlets used). Swirl insert I only has four inlets, but operated at a significantly higher swirl number of 1.47, Fig. 2.

Fig. 1. Exploded view of swirl burner.

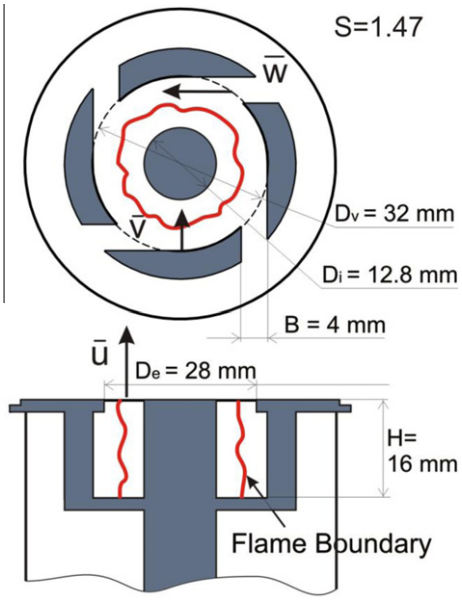


Fig. 2. Schematic diagram of Internals of swirl burner.

Coriolis flow metres have been used simultaneously to measure the mass flow rate of both fuel and air separately.

3. Results and discussion

Three swirl burners plus five different fuels has been used to obtain results, these are summarised in Tables 1 and 2:

Typically the pressure loss coefficient at $S_{II} = 1.04$ is nearly half that at $S_I = 1.47$ and again is about 20% lower again at $S_{III} = 0.8$. Lower pressure drop is a major advantage to designers and operators of gas turbines and other large burners and thus there is a drive to use lower swirl numbers, providing the flame stability advantages of the CRZ are not lost. coke oven gas has been used as a representative process industry fuel gas, which is widely

Table 1
Swirl burners and their specifications.

Swirl Burner name	I	II	III
Geometrical swirl number	1.47	1.04	0.8
Exhaust sleeve 0.5 De long	No	Yes	Yes

Author's personal copy

Table 2
Fuels Blends and their composition.

Fuel name	CH_4 (%)	H_2 (%)	CO (%)	N_2 (%)	LHV (MJ/kg)	$T_{max\ adiabtic}$ (K)
Pure methane	100	0	0	0	50.1	2237
Pure hydrogen	0	100	0	0	126.1	2406
15%H2	85	15	0	0	51.6	2245
30%H2	70	30	0	0	53.7	2253
Coke oven gas	25	65	6	4	54.2	2300

available at steelworks and has the potential to be widely used in power generation in process industry, providing appropriate efficient reliable technology can be developed to utilise it. The system has been tested on a wide range of fuel blends as shown below, Table 2. Up to 15 combinations of swirl burner and fuel gases have been used to investigate their effects on the flashback and blow-off characteristics. Fuel characteristics are interesting as they show similar lower heating values and adiabatic flame temperatures. The exception is pure hydrogen with much higher lower heating value, but adiabatic flame temperature about ~100 K higher than coke oven gas.

Three families of flashback curves are shown in Fig. 3 below, one for a swirl number of $S_I = 1.47$, Fig. 3a, the other at a swirl number $S_{II} = 1.04$, Fig. 3b and 3c for $S_{III} = 0.8$.

Associated flame photographs at conditions just before flashback for pure methane are shown in Fig. 4a ($S_I = 1.46$) and Fig. 4b ($S_{II} = 1.04$).

The comparison is extremely interesting whilst other analysis has revealed two different flashback mechanisms for the different swirl numbers [10,18–21]. With $S_I = 1.47$ the central recirculation zone (CRZ) extends over the central fuel injector to the base plate for all fuels, with an associated flame front on the CRZ boundary. This is illustrated in Fig. 2 (and does not happen with $S_{II} = 1.04$ and $S_{III} = 0.8$). Flashback occurs when the radial velocity in the swirl level drops to such a level that the near radial flame front can flashback to the inlets and often into the plenum chamber [10]. Conversely with $S_{II} = 1.04$ and $S_{II} = 0.8$ flashback occurs by a

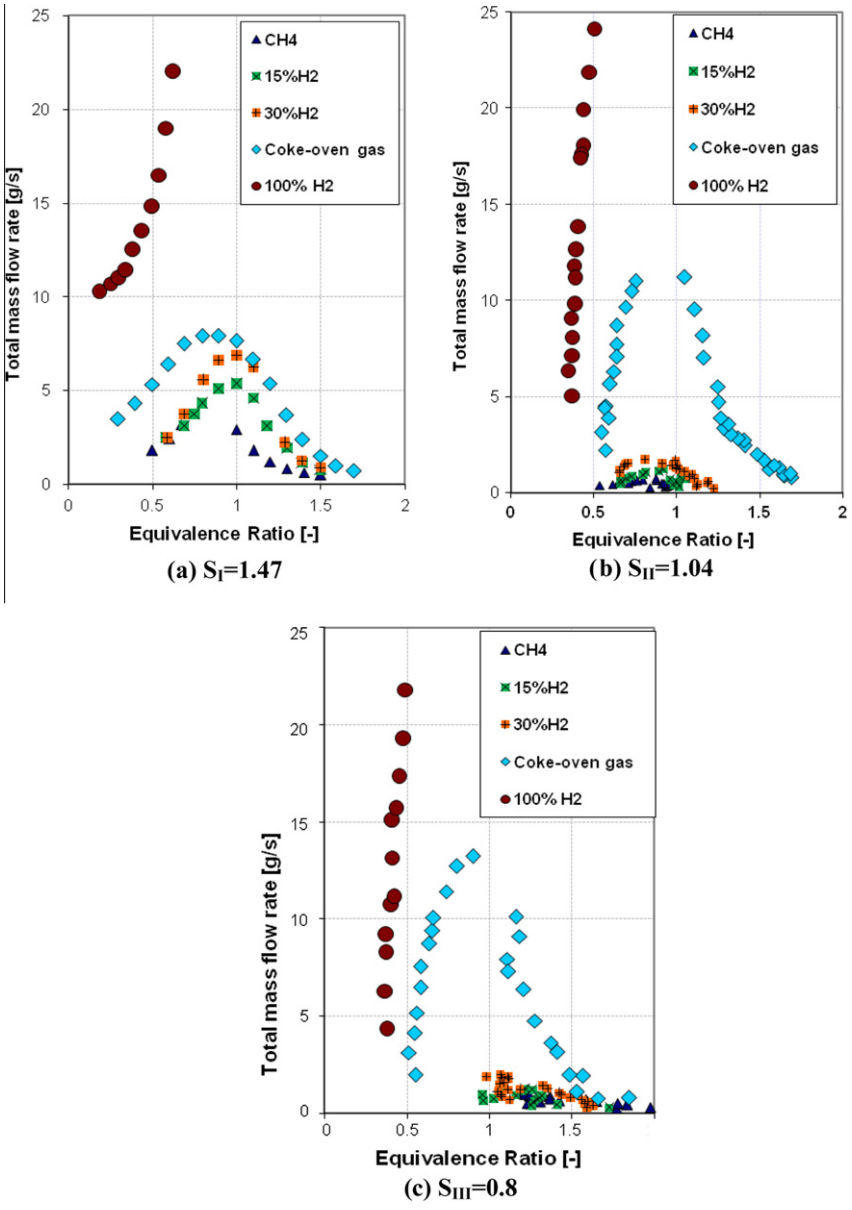


Fig. 3. Flashback limits of the generic swirl burners with three different swirl numbers for five different fuels.

Author's personal copy

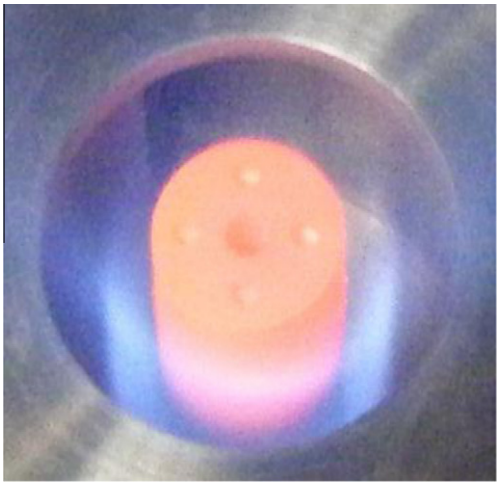


Fig. 4a. Photo of flame surrounding central fuel injector at $S_I = 1.47$, just before radial flashback.

Fig. 4b. Photo of flame just before flashback through outer wall boundary layer, $S_{II} = 1.04$.

different mechanism via flashback in the outer wall boundary layer of the exhaust nozzle, then being controlled by the critical boundary velocity gradient [21] as defined by Lewis and von Elbe [14]. This can be readily derived from geometrical and simple flow considerations and enables comparison with the large quantities of data available in past literature as summarised in [14]. Other work using CFD analysis of the boundary layer region close to flashback has shown that under the turbulent flow conditions of the swirl burner, critical boundary velocity gradients are an order of magnitude higher than those predicted by the Lewis and von Elbe formula [21].

In terms of flashback limits for methane and methane containing up to 30% hydrogen a value of $S_{II} = 1.04$ and $S_{III} = 0.8$ produces flashback which occurs at a mass flow (and hence velocity levels) up to 1/3 of those found for $S_I = 1.47$ for a wide range of equivalence ratios. However with coke oven gas (COG) different effects start to appear as the hydrogen content of the fuel increase beyond 50%. For Swirl Numbers of 0.8 and 1.04 flashback performance is better than $S = 1.47$ for values of equivalence ratio up to 0.6 to 0.65 and mass flows of ~7 g/s. Beyond this point for equivalence ratios > 0.65 and <1.2 a swirl number of 1.47 is better by up to 50%. However for LP combustors the aim is to operate around an equivalence ratio of ~0. 7 or less and thus this is not a disadvantage. Comparison of the three Swirl Number cases, Fig. 3, shows that there is a significant change in flashback behaviour moving between a fuel with 30% hydrogen content to one with 65% hydrogen content as with COG. Moving onto the pure hydrogen results similar trends were evident, although the range of equivalence ratios tested was restricted to being below 0.5 and above 2 due to the very large hydrogen and air flow rates required. Here the higher mass flow, hence velocity levels, associated with hydrogen flashback, produce higher levels of turbulent kinetic energy, thus augmenting the turbulent flame speed and thus worsen the hydrogen flashback limits beyond that expected from considerations of laminar flame speed data [14,21].

More detailed inspection of the results for $S_{II} = 1.04$ and $S_{III} = 0.8$, showed generally both swirlers have very similar characteristics with differences being within experimental limits. $S_{III} = 0.8$ is preferred as it gives lower pressure drop.

Another interesting result was that the peaks of the flashback curves tended to occur at weak equivalence ratios as opposed to the expected just on the rich side of stoichiometric [14]. This effect is thought to be due to changes in the recirculation zone occurring as the equivalence ratio approaches 1. This is also illustrated by Fig. 5 where all the methane data has been plotted as a function of critical boundary layer gradient at flashback, G_f; also included is laminar data on natural gas. The swirl burners at $S_{II} = 1.04$ and $S_{III} = 0.8$ are flashing back at lower values of G_f than the laminar results (albeit at a higher pressure drop), whilst for $S_I = 1.47$ values of G_f are significantly higher.

Overall $S_{III} = 0.8$ gives the best flashback limits for methane based fuels with hydrogen content up to 30% and for hydrogen based fuels with hydrogen content $\geqslant$ 65% for equivalence ratios $\leqslant$ 0.65. However for fuels with hydrogen content in the range 30% $\leqslant H_2$ content $\leqslant$ 65% a more complex picture emerges. The Critical Boundary Velocity Gradient for flashback is higher at lower swirl numbers and equivalence ratios ~1 when compared to $S_I = 1.47$. Separate tests on blow off limits show that the Swirl Number $S = 0.8$ produces the best results.

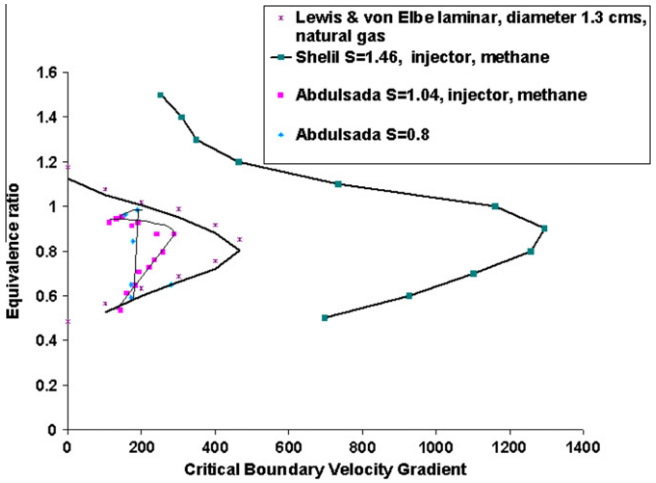


Fig. 5. Lewis and von Elbe Critical boundary velocity gradient comparison for three swirl numbers and laminar data [14].

Author's personal copy

A gas turbine, required to be dual fuelled, with given compressor and turbine system has air mass flow rates at given thermal inputs which vary little as the fuel mass flow is relatively small and the exhaust gas composition, hence enthalpy, is still dominated by the 80% nitrogen content from the air. To produce this thermal input different quantities of fuel and thus equivalence ratio are needed for different fuels such as natural gas, coke oven gas and especially pure hydrogen. When dual fuelling/changeover is needed ideally the operational range of the system between flashback and blow off for two different fuels (such as hydrogen and natural gas) should be such that there is sufficient overlap between the blow off and flashback limits to enable easy fuel change over. Because of the different stoichiometry and heating value, hydrogen containing fuels will always have to be operated at weaker equivalence ratios than natural gas fired systems, typically 78% of the natural gas equivalence ratio for pure hydrogen. This infers that the overlap region between the flashback limit and blow off limit of given fuels is crucial in determining whether or not the system can be dual fuelled. Table 2 indicates that because of similar adiabatic flame temperature and lower heating values fuel gases containing up to 65% hydrogen (as with coke oven gas) with a base fuel of natural gas can be best accommodated in existing or somewhat modified combustion systems.

4. Conclusion

This paper has discussed the flashback limits of three different swirl burners and shown that considerable differences exist. Preference is given to the system with low swirl number as it gives lowest pressure drop. The behaviour of methane based fuels with hydrogen content up to 30% has been shown to follow that of methane as the hydrogen content is increased. However coke oven gas shows distinctly different behavioural patterns, as does pure hydrogen which needs to be investigated further.

Acknowledgments

Mohammed Abdulsada gratefully acknowledges the receipt of a scholarship from the Iraqi Government and for the assistance of Steve Morris, Malcolm Seaborne, Terry Pole during the setup of the experiments. The financial support of the RCUK Energy Programme is gratefully acknowledged. The Energy programme is an RCUK cross-council initiative, led by EPSRC and contributed to by EPSRC, NERC, BBSRC and STFC.

References

[1] Huang Y, Yang V. Effect of swirl on combustion dynamics in a leanpremixed swirl-stabilized combustor. Proc Combust Inst 2005;30(2):1775–82.
[2] Sankaran R, Hawkes ER, Chen JH, Lu T, Law CK. Direct numerical simulations of turbulent lean premixed combustion. J Phys 2006;46:38–42.
[3] Lefebvre AH. Gas Turbine Combustion. LLC, Oxon, UK: Taylor & Francis Group; 1999.
[4] Gupta AK, Lilley DJ, Syred N. Swirl Flows. Tunbridge Wells, United Kingdom: Abacus Press; 1984.
[5] Goy CJ, James SR, Rea S. 2005. Monitoring combustion instabilities: E.ON UK's experience. In: Lieuwen T, Yang V. editors. Combustion instabilities in gas turbine engines: operational experience, fundamental mechanisms, and modeling, Progress in Astronautics and Aeronautics. p. 163–75.
[6] Bagdanavicius A, Bowen P, Syred N, Kay P, Crayford A, Wood J. Burning velocities of alternative gaseous fuels at elevated temperature and pressure. In: 47th AIAA Aerospace Sciences Meeting, Orlando, USA, ref. AIAA-2009-0229; 2009.
[7] Arias B, Fermoso J, Plaza M, Pevida C, Rubiera F, Pis J, Garcia-Pena F, Casero P. Production of H2 by Co-gasification of Coal with biomass and petroleum coke. In: Proceedings of 7th European conference on coal research and its applications. Wales, UK; 2008.
[8] Chiesa P, Lozza G, Mazzocchi L. Using hydrogen as gas turbine fuel. J Eng Gas Turb Power 2005;127:73–80.
[9] Valera-Medina A, Syred N, Griffiths A. Visualisation of isothermal large coherent structures in a swirl burner. Combust Flame 2009;156:1723–34.
[10] Shelil N, Bagdanavicius A, Syred N, Griffiths A, Bowen P. Premixed swirl combustion and flash back analysis with hydrogen/methane mixture. In: 48th AIAA Aerospace Sciences Meeting, Orlando, USA, ref. AIAA-2010-1169; 2010.
[11] Syred N. A review of oscillation mechanisms and the role of the Precessing Vortex Core (PVC) in swirl combustion systems. Progr Energy Combust Syst 2006;32(2):93–161.
[12] Syred N. Generation and alleviation of combustion instabilities in swirling flow. In: Syred N, Khalatov A, editors. Advanced combustion and aerothermal technologies. Springer; 2007. p. 3–20.
[13] Plee SL, Mellor AM. Review of flashback reported in prevaporizing/premixing combustors. Combust Flame 1978;32:193–203.
[14] Lewis B, Elbe G. Combustion, flames and explosions of gases. New York: Academic Press; 1987.
[15] Subramanya M, Choudhuri A. investigation of combustion instability effects on the flame characteristics of fuel blends. In: 5th International Energy Conversion Engineering Conference and Exhibit (IECEC) AIAA, St. Louis, Missouri; 2007.
[16] Fritz J, Kroner M, Sattelmayer T. Flashback in a swirl burner with cylindrical premixing zone. J Eng Gas Turb Power 2004;126(2):276–83.
[17] Kroner M, Fritz J, Sattelmayer T. Flashback limits for combustion induced vortex breakdown in a swirl burner. J Eng Gas Turb Power 2003;125(3):693–700.
[18] Fluent 6.2 Users Guides. ed. F. Incorporated. Lebanon, USA; 2005.
[19] Zimont V et al. An efficient computational model for premixed turbulent combustion at high reynolds numbers based on a turbulent flame speed closure. J Gas Turb Power 1998;120:526–32 (July).
[20] Valera-Medina A, Abdulsada M, Shelil N, Syred N, Griffiths A. Flame stabilization and flashback avoidance using passive nozzle constrictions. In: IFRF International Meeting, Boston, 8th–10th, USA; 2009.
[21] Bagdanavicius A, Shelil N, Syred N, Griffiths A, Premixed swirl combustion and flashback analysis with hydrogen/methane mixtures. In: AIAA 47th Aerospace Sciences Meeting, Orlando, Florida, ref. AIAA-2010-1169; 2010. p. 4–7.