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Experimental Investigation of the Confinement Effect on Flashback in Multi Combustion Modes Tangential Swirl Burner

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ABSTRACT

Given the importance of gas turbines in the process and amount of global energy from fossil fuels, the views were directed toward this study in addition to the availability of the liquefied petroleum gas and because of knowing many details of it is composition and behavior this type of fuel has been proven. The development of the tangential swirl burner geometry also one of the targets of this study by reducing the combustion instability include flashback and the minimizing in the burner size comparing with other classic tangential swirl burner shape include cylindrical confinement with conical cup confinement. The authors take care in previous studies in field of swirling flow either in scope of geometry characteristics or in scope of fuel issues. The geometrical swirl number which play an important factor in swirling flow had been taken in the consideration for the process of the tangential swirl burner manufacturing as well as the heat caloric value of the operating fuel. The experimental results of combustion the liquefied petroleum gas had been proved that the formal additions added in this study to development the burner nozzle mouth will reduce and improve the occurrence of the operational problems represent flashback and an increasing in the working area by increasing the flashback limits for both premixed and partial premixed combustion modes which will be clarified and the mechanism of composition in the following sections of this paper.

1. Introduction

Despite the continuing interest in the details of the designs of the mechanical parts of gas turbines, operational problems remain at the forefront of designers' attention where the requirements and conditions of operation have a clear role in the operational efficiency of the gas turbines and how to connect this operational problem represent by flashback with many issues such as fuel consumption and combustion efficiency and the provision of adequate stability of the flame resulting from the combustion of operating fuel taking into account the heat generated by these reactions to meet the turbine blades taking into account the burner body damage resulting from this operational problem.

This study aims to reduce the occurrence of the combustion instability includes flashback by the development of the burner exhaust shape. This happened by adding the conical cup confinement to the open flame burner mouth as well as use the alternative fuel (LPG) as a working fuel to show the flashback behavior of the two cases and comparing the results for premixed combustion and partially premixed combustion modes.

2. Theoretical approach

Flashback is one of the important operation problems in the lean premixed combustion which occurs when the turbulent propagation flame speed becomes faster than the flow velocity or mixture reactants incoming velocity. This leads to that the flame upstream to the premixed passage either burner tube or pre mixer [1, 2] The high temperature of flame

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Nomenclature

Q	Mixture volume flow rate $[m^3/s]$	Q_f	Fuel volume flow rate$[m^3/s$
A_{ti}	Inlet tangential area $[m^2]$	Q_a	Air volume flow rate $[m^3/s]$
W_{ti}	Inlet tangential velocity $[m^2/s]$	ρ_f	Fuel density $[kg/m^3]$
g_c	Critical velocity gradient $[1/s]$	ρ_a	Air density $[kg/m^3]$
S_f	Laminar flame speed $[m/s]$	$\dot{m}_f$	Fuel mass flow rate $[kg/s]$
∂q	Quenching distance [m]	$\dot{m}_a$	Air mass flow rate $[kg/s]$
CRZ	Central recirculation zone	Ø	Equivalence ratio [-]
CIVB	Combustion induced vortex breakdown	$Ø_t$	Total equivalence ratio [-]
BLF	Boundary layer flashback	FB	Flashback
LPG	Liquefied Petroleum Gas		

cause hardware damage in the pre mixer or burner tube. The fuel content plays an important role in controlling the occurrence of flashback mechanism. Some studies [3-6] refer to that the fuel containing hydrogen with swirl flow has a flame speed of four times greater than of natural gas. Hence the flame speed being more than the inlet tangential velocity of the incoming mixture in tangential swirl burner [7-9], which can be calculated as the following way

$$Q = 2AW \quad \text{(Two tangential inlets)} \tag{1}$$

$$Q_f + Q_a = 2A_{ti}W_{ti\ mixture} \tag{2}$$

$$\left[\frac{\dot{m}_f}{\rho_f} + \frac{\dot{m}_a}{\rho_a}\right] = 2A_{ti}W_{ti\ mixture} \tag{3}$$

$$W_{ti\ mixture} = \frac{\frac{\dot{m}_f}{\rho_f} + \frac{\dot{m}_a}{\rho_a}}{2A_{ti}} \rightarrow W_{ti\ mixture} = \frac{\frac{\dot{m}_f}{\rho_f} + \frac{\dot{m}_a}{\rho_a}}{\frac{2\pi D_{ti}^2}{4}} \tag{4}$$

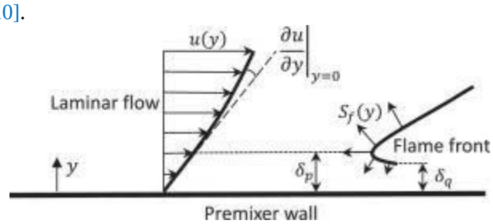
$$W_{ti\ mixture} = \frac{2\left[\frac{\dot{m}_f}{\rho_f} + \frac{\dot{m}_a}{\rho_a}\right]}{\pi D_{ti}^2}\ ,\ \frac{2}{\pi D_{ti}^2} = 270.973 \tag{5}$$

$$\therefore W_{ti\ mixture} = 270.973\left[\frac{\dot{m}_f}{\rho_f} + \frac{\dot{m}_a}{\rho_a}\right] \tag{6}$$

In general, the place of occurrence and the turbulence of the flame speed is the most important factors that determine the type of flashback, which has been classified as follow:-

2.1Boundary Layer Flashback

The velocity profile of the fluid flow as it known is approaching zero towards the wall edge in laminar flow Cartesian coordinates. This low velocity (critical velocity gradient g_c) being lower than the flame speed (S_f) space by a distance call as a quenching distance (∂q) and flashback take place [10].



$$g_c = \frac{S_f}{\partial q}$$

Figure 1. Schematic Diagram of Boundary Layer Flashback

The main drawback of the above expression that it is not taken into account the heat transfer between the burner wall and the flame and that means there is a critical flow velocity gradient for each fuel. Damköhler correlation (experimental data) and flame angle theory are the two methods used by Hoferichter [11] to describe the boundary layer flashback with the turbulent combustion regime for hydrogen fuel. Where the first theory is limited with turbulent combustion regime but the second gives reasonable results for boundary layer flashback.

2.2 Turbulent Core Flashback

A flashback occurs when the turbulent flame speed exceeds the flow velocity along some streamline, allowing the flame to propagate into the premixing section. This fact leads to the very simple design rule that the flow field must not have strong local velocity deficits and that the axial flow velocity must be substantially above the turbulent flame speed [12-14]. The swirl flames have high wrinkled and its high wrinkled mean increasing the surface area of the flame and this leads to that the flame speed being higher than its laminar value.

2.3 Flashback Due to Combustion Instabilities

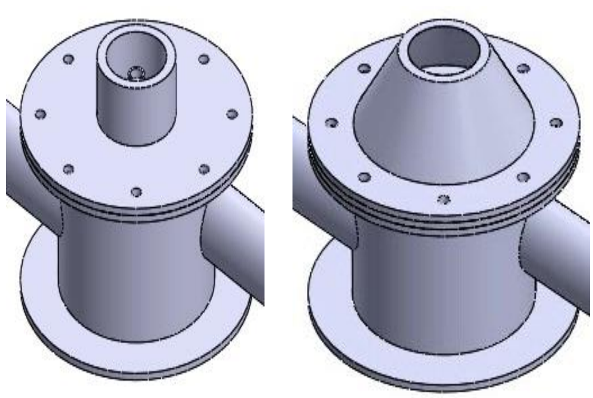
Pulsation in the combustion system may be take place as a result of nonlinear interaction of pressure fluctuation and the periodic heat release. The fluctuation of heat release also flames speed which means the indirectly flame area in addition to the inlet velocity which at a certain level gives a nonlinear of heat release [15-17] represents the three factors play important roles in the fluctuation of heat release hence the combustion instabilities.

2.4 Flashback Due to Combustion Induced Vortex Breakdown (CIVB)

The sudden expansion in the burner exit (mouth) create central recirculation zone, this creation of CRZ can cause by different amount of heat release due to change in swilling or due to different type of fuel which also give different heat release then the CRZ which hold the flame extended to the burner base plate after that the flame re-establishes itself and cause upstream vortex to break down and the upstream flow region will appear due to the negative pressure gradient . The crucial factors in the CIVB are the fuel type (fuel blends) and the burner geometry especially the burner mouth .In the field of fuel many studies investigate the effect of fuel on the CIVB flashback limits .Some studies [5, 18, 19] reached that the behaviour of fuel mixtures different from the separate fuels (individual contents) while other studies [6, 8, 20] referred to the increase of hydrogen content in the fuel decrease the CIBV flashback limits. The increase of equivalence ratio means increase the propagation of upstream flame and this leads to increase the possibility of CIVB take place. The changing from the BLF to CIVB was investigated by Baumgartner and Sattelmayer [21] with increasing equivalence ratio and low swirl flow. Other studies reach the same results but in other words where Sayed [22] reaches the combustion induced vortex breakdown to occur more than boundary layer in high swirl flow .The diffuser position between the burner mixing tube and the combustor also can change CIVB flashback to BLF [23]. The second field in investigations was the entry way of fuel or air which mainly affects the CIVB, the using of axial fuel injection which investigated by Mayer [24] improves the resistance to the CIVB compared with trailing injection . The using of axial air injection [25] in lean premixed swirl-stabilized hydrogen combustion enhances the resistance to CIVB by reducing the axial velocity and hence influence the vortex breakdown position. However, in spite of many studies in this field but the subject remains very difficult to research because of the interaction between heat and chemical reactions with different types of burner as well as the nature of use and different quality of fuel . Micro surfaces of burner nozzle wall with use a properly central air injection are also play an important role in the reduction of boundary layer flashback and combustion induced vortex breakdown [26] .

3. Experimental Setup

The tangential swirl burner consist of two tangential inlets has a circular section with internal and external diameters of 50 and 64 mm respectively to allow the mixture of fuel and air enter to the burner .The burner plenum which is the mixing zone or main swirling chamber has a diameter of 148 mm with a thickness of 7 mm. Upper and lower flanges with asbestos gaskets of 1.5 mm thickness fixed by eight bolts which distributed around the circumference of these flanges. The burner nozzle has an internal diameter of 58 mm with thickness of 7 mm and length of mm to contribute in the swirling flow of the mixture coming from the two tangential inlets, thus the geometrical swirl number of the used burner has a value of 1.02. The burner exhaust geometry was one of the improvements on the burner represented by the addition of the conical cup confinements. The conical cup which is placed at the end of the burner exhaust with external diameter equal to the burner plenum diameter and internal diameter equal to the burner nozzle and length of half the burner plenum length. The use of conical cup confinement to investigate the flashback limits under variable shape conditions of the burner exhaust with several types of combustion modes including premixed combustion mode and partially premixed combustion mode. Set of flow meters used in separate series forms to measure the mass flow rates of the mixture content include fuel and air where all the experiments were under the atmospheric conditions of 1 bar pressure and approximately 300 K temperature.

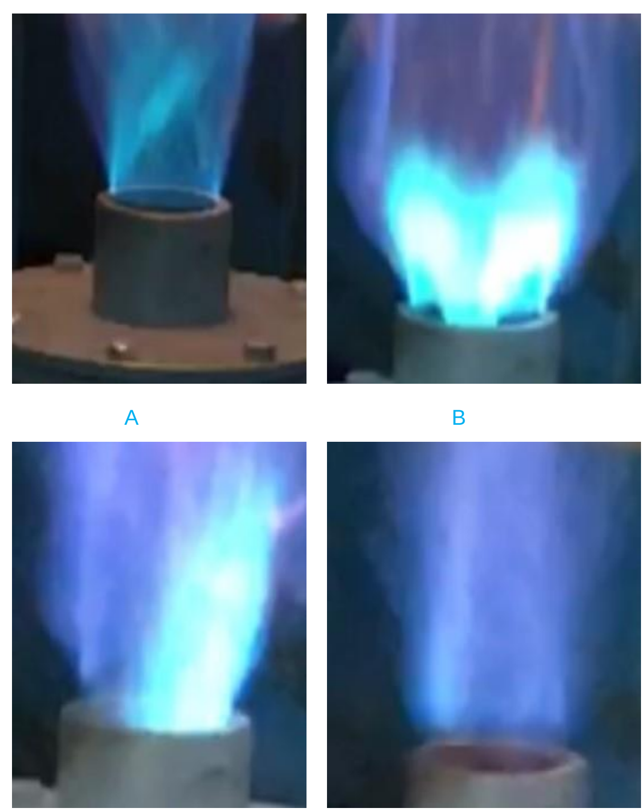


A *B*

Figure 2. (A) Open flame burner. (B) Burner with conical cup confinement.

4. Results and Discussion

In the premixed combustion mode, the combustible mixture of the fuel and air is injected together just from the two tangential inlets. Firstly the fuel injected at a low level in other words low mass or volume flow rate and the oxidizer or air is injected gradually also from the tangential inlets. The operational fuel of this work is the liquefied petroleum gas (LPG) which is flammable mixture of 46 MJ/kg heat caloric value and consist of 65% by volume Butane ($\mathbf{C_4H_{10}}$) and 35% propane ($\mathbf{C_3H_8}$), whereas the density of LPG in the experimental conditions (summer) about 2.3151 kg/m^3 . The flame in starting the combustion being near the nozzle mouth and with increasing the air mass flow rate then it will return to the burner plenum base plate accompanied by a loud voice which is the physical explanation of the flashback. Thus with mixing 0.046 g/s of Liquefied Petroleum Gas with 2.4 g/s mass flow rate for air, the mixture equivalence ratio being about 0.29 (very lean mixture). The Fig. 2. show the photos of the flame stages propagation, hence the flame grow at near the boundary layer of the internal nozzle mouth with a uniform stability and strength as shown in photo labeled A and then the central recirculation zone being clear in appearance taking the butterfly shape having a central location of the burner nozzle as shown in photo labeled B, this is due to the swirling flow effect inside the burner then the flame also the central recirculation zone has a longitudinal extension towards the burner base plate as shown in photos C and D.



A B

C D

Figure 3. Photos of Open Flame Burner in Premixed Mode $\dot{m}_f = 0.046\ g/s$, $\dot{m}_a = 2.4\ g/s$, Ø = 0.29

Fig. 4. shows the results of experimental LPG premixed combustion, approximately linear behaviour in flashback limits with a quick transition from lean mixture to rich mixture, this quick transition due to some experimental difficulties. **Fig. 5.** shows the effect of addition the conical cup confinement to the open flame burner which being not clear in the range of equivalence ratio less than 0.3 to show the flashback limits but it's clear with increasing of the equivalence ratio where the enhancement rate of this addition here about 40% for 3.5 g/s compared with 2.7 g/s total mass flow rate (Ø=0.83) as a 1.5g/s reference point. The figure shows similar behaviour for both cases of open flame burner and burner with conical cup confinement especially in very lean mixture but the working area being clear after 0.6 equivalence ratio, this is due to small amount of the oxidizer that the burner with conical cup confinement need it to reach to the flashback limits.

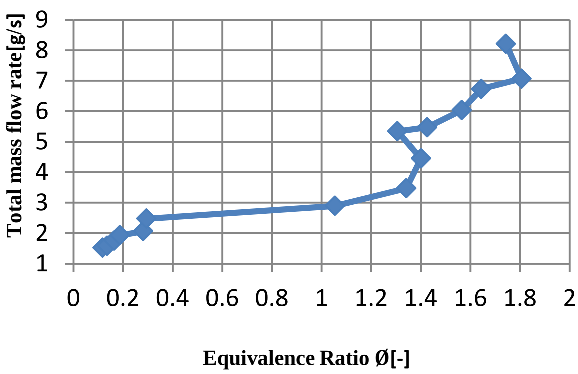


Figure 4. Flashback Limits of Open Flame Burner in Premixed Combustion Mode.

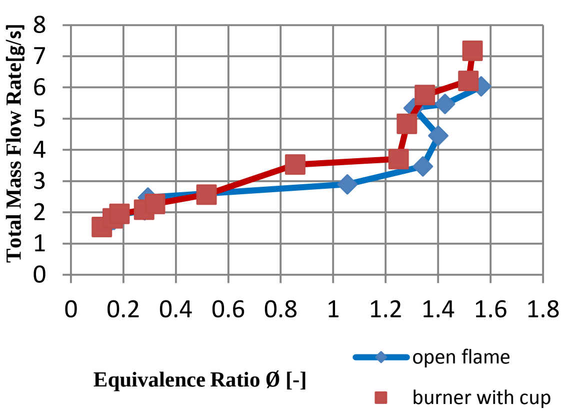


Figure 5. Flashback Limits Comparison of Open Burner and Burner with Cup in Premixed Combustion Mode.

Fig. 6. photo numbered 1 shows the liquefied petroleum gas flame near a boundary layer of the burner nozzle with an initiation of the central recirculation zone, then the central recirculation zone being more appearance with semi helical shape at the middle burner for this geometry of burner as shown in photo number 2. Photo numbered 3 shows the starting of the CRZ backward flow in the direction of burner base plate.

Fig. 7. shows the flashback limits comparison of open flame burner and burner with conical cup confinement in terms of heat input and total mass flow rate with linear performance for both case due to the dependency of heat input on the liquefied petroleum gas heat caloric value and fuel mass flow rate.

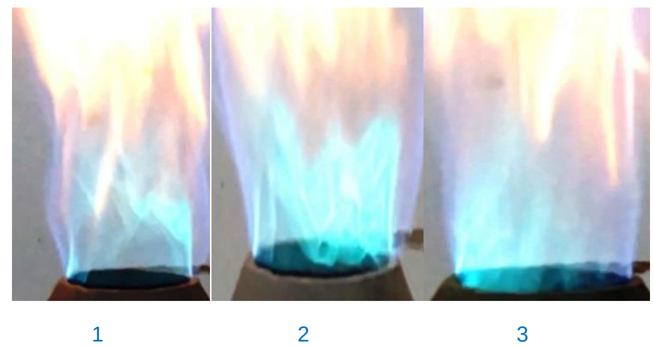


Figure 6. Photos of Burner with Conical Cup Confinement flame in premixed Combustion mode $\dot{m}_f = 0.185\ g/s$, $\dot{m}_a = 3.3\ g/s$, Ø = 0.85

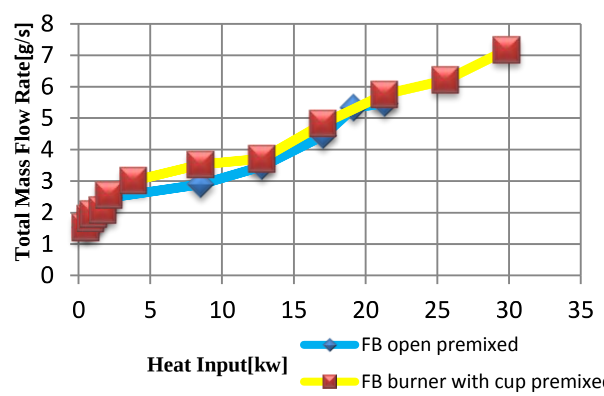


Figure 7. Flashback Limits Comparison of Open Flame Burner and Burner with Conical Cup Confinement in Premixed Combustion Mode as a Function of Heat Input and Total Mass Flow Rate.

Partial premixed combustion elements are introduced through the use of the technique of combining the other combustion modes. This method involves the introduction of a very small amount of fuel through direct input volumetric flow rate through the fuel separate flow meter to measurement the diffusive mass flow rate and thus the diffusive stoichiometric ratio. The other way of entering the fuel is the two tangential inlets also through a set of valves and flow meters then air is injected from the only port of the air here which is from the two tangential inlets passing through the turbine flow meter and share with fuel to generate the premixed mode which also has a premixed stoichiometric ratio .The result of partial premixed combustion can be represented by a combination of premixed equivalence ratios for premixed and diffusive equivalence ratio for non-premixed to create the total equivalence ratio and compare it with the total mass flow rates of fuel and air. **Fig. 8**. shows the experimental results of the flashback limits map for open flame tangential swirl burner in partial premixed combustion mode for both ranges of weak and rich equivelance ratios passing by the stoichiometric ratio.

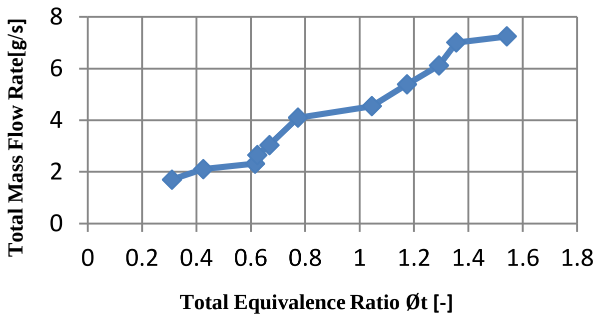


Figure 8. Flashback Limits of Open Flame Burner in Partial Premixed Combustion Mode.

Once again, this mode of combustion sequence was used to show the percentage of improvement that the conical cup confinement adds to the limits of the flashback where the experimental results showed that adding of the cup directly to the burner improves the limits of flashback by 36% when comparing 5.3 g/s total mass flow rate with 4.25 g/s (i.e. Øt = 0.87) as a 2.4 g/s reference point as shown in **Fig.9.**

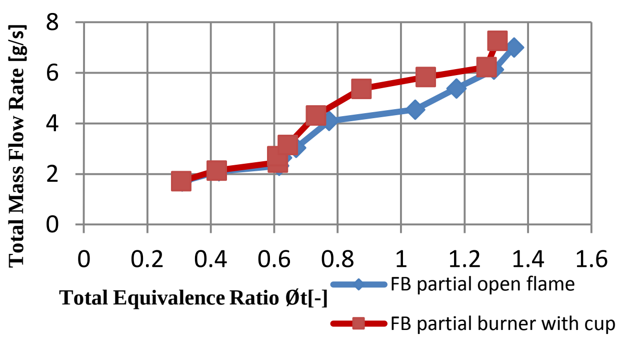


Figure 9. Flashback Limits Comparison of Open Flame Burner and Burner with Conical Cup Confinement in Partial Premixed Combustion Mode.

5. Conclusions

The flashback limits maps of the liquefied petroleum gas combustion has been proved that the addition of the conical cup confinement to the open flame tangential swirl burner improving these limits by maximizing the operational areas with different combustion modes by certain values especially in range of more than 0.3 equivalence ratios .It is clear from the enhancement rates and fuel consumption of the two combustion modes that the premixed combustion mode is better than the partial premixed combustion mode, this is due to the effect of the nonpremixed fuel which reduces the flashback resistance. It was also observed that the behavior of open flame burner and burner with conical cup confinement is almost similar, this is due to the proximity of the swirling zone from the combustion zone for the two burner geometries.

REFERENCES

[1] G. Baumgartner, L.R. Boeck, T. Sattelmayer, Experimental investigation of the transition mechanism from stable flame to flashback in a generic premixed combustion system with high-speed micro-particle image velocimetry and Micro-PLIF combined with chemiluminescence imaging, Journal of Engineering for Gas Turbines and Power, 138(2) (2016) 021501.

[2] A. Kalantari, V. McDonell, S. Samuelsen, S. Farhangi, D. Ayers, Towards Improved Boundary Layer Flashback Resistance of a 65 kW Gas Turbine With a Retrofittable Injector Concept, in: ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition, American Society of Mechanical Engineers, 2018, pp. V04AT04A060-V004AT004A060.

[3] A.C. Benim, K.J. Syed, Flashback mechanisms in lean premixed gas turbine combustion, Academic press, 2014.

[4] M. Abdulsada, N. Syred, A. Griffiths, P. Bowen, Effect of swirl number and fuel type upon the flashback in swirl combustors, in: 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2011, pp. 62.

[5] B. Shaffer, Z. Duan, V. McDonell, Study of fuel composition effects on flashback using a confined jet flame burner, Journal of Engineering for Gas turbines and Power, 135(1) (2013) 011502.

[6] N. Syred, M. Abdulsada, A. Griffiths, T. O'Doherty, P. Bowen, The effect of hydrogen containing fuel blends upon flashback in swirl burners, Applied Energy, 89(1) (2012) 106-110.

[7] V.-Z.M. Osvaldo, S. Nicholas, V.-M. Agustín, D.l.R.-U. Daniel, Flashback avoidance in swirling flow burners, Ingeniería, Investigación y Tecnología, 15(4) (2014) 603-614.

[8] M. Abdulsada, N. Syred, A. Giles, P. Bowen, Tangential Velocity Effects and Correlations for Blow-Off and Flashback in a Generic Swirl Burner and the Effect of a Hydrogen containing Fuel, in: 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, pp. 736.

[9] M. Abdulsada, N. Syred, P. Bowen, T. O'Doherty, A. Griffiths, R. Marsh, A. Crayford, Effect of exhaust confinement and fuel type upon the blowoff limits and fuel switching ability of swirl combustors, Applied Thermal Engineering, 48 (2012) 426-435.

[10] C. Eichler, T. Sattelmayer, Experiments on flame flashback in a quasi-2D turbulent wall boundary layer for premixed methane-hydrogen-air mixtures, Journal of Engineering for Gas Turbines and Power, 133(1) (2011) 011503.

[11] V. Hoferichter, C. Hirsch, T. Sattelmayer, A. Kalantari, E. Sullivan-Lewis, V. McDonell, Comparison of two methods to predict boundary layer flashback limits of turbulent hydrogen-air jet flames, Flow, Turbulence and Combustion, 100(3) (2018) 849-873.

[12] F. Hatem, Flashback analysis and avoidance in swirl burners, Cardiff University, 2017.

[13] R. Szasz, A. Subash, A. Lantz, R. Collin, L. Fuchs, E. Gutmark, Hysteretic Dynamics of Flashback in a Low-Swirl Stabilized Combustor, Combustion Science and Technology, 189(2) (2017) 266-289.

[14] Y.-C. Lin, S. Daniele, P. Jansohn, K. Boulouchos, Turbulent flame speed as an indicator for flashback propensity of hydrogen-rich fuel gases, Journal of Engineering for Gas Turbines and Power, 135(11) (2013) 111503.

[15] J.H. Cho, T. Lieuwen, Laminar premixed flame response to equivalence ratio oscillations, Combustion and flame, 140(1-2) (2005) 116-129.

[16] R. Balachandran, A. Dowling, E. Mastorakos, Dynamics of bluff-body stabilised flames subjected to equivalence ratio oscillations, in: Proceeding of the European Combustion Meeting, 2011.

[17] R. Balachandran, B. Ayoola, C. Kaminski, A. Dowling, E. Mastorakos,

Experimental investigation of the nonlinear response of turbulent premixed flames to imposed inlet velocity oscillations, Combustion and Flame, 143(1-2) (2005) 37-55.

[18] T. Lieuwen, V. McDonell, E. Petersen, D. Santavicca, Fuel flexibility influences on premixed combustor blowout, flashback, autoignition, and stability, Journal of engineering for gas turbines and power, 130(1) (2008) 011506.

[19] B. Dam, G. Corona, M. Hayder, A. Choudhuri, Effects of syngas composition on combustion induced vortex breakdown (CIVB) flashback in a swirl stabilized combustor, Fuel, 90(11) (2011) 3274-3284.

[20] B. Dam, N. Love, A. Choudhuri, Flashback propensity of syngas fuels, Fuel, 90(2) (2011) 618-625.

[21] G. Baumgartner, T. Sattelmayer, Experimental investigation of the flashback limits and flame propagation mechanisms for premixed hydrogen-air flames in non-swirling and swirling flow, in: ASME Turbo Expo 2013: Turbine Technical Conference and Exposition, American Society of Mechanical Engineers, 2013, pp. V01AT04A010-V001AT004A010.

[22] P. Sayad, A. Schönborn, M. Li, J. Klingmann, Visualization of different flashback mechanisms for H2/CH4 mixtures in a variable-swirl burner, Journal of Engineering for Gas Turbines and Power, 137(3) (2015) 031507.

[23] T. Sattelmayer, C. Mayer, J. Sangl, Interaction of flame flashback mechanisms in premixed hydrogen–air swirl flames, Journal of Engineering for Gas Turbines and Power, 138(1) (2016) 011503.

[24] C. Mayer, J. Sangl, T. Sattelmayer, T. Lachaux, S. Bernero, Study on the operational window of a swirl stabilized syngas burner under atmospheric and high pressure conditions, in: ASME 2011 Turbo Expo: Turbine Technical Conference and Exposition, American Society of Mechanical Engineers, 2011, pp. 141-152.

[25] T.G. Reichel, S. Terhaar, O. Paschereit, Increasing flashback resistance in lean premixed swirl-stabilized hydrogen combustion by axial air injection, Journal of Engineering for Gas Turbines and Power, 137(7) (2015) 071503.

[26] F. Hatem, A. Alsaegh, M. Al-Faham, A. Valera-Medina, C. Chong, S. Hassoni, Enhancing flame flashback resistance against Combustion Induced Vortex Breakdown and Boundary Layer Flashback in swirl burners, Applied energy, 230 (2018) 946-959.