Using Hydrogen Blends as Fuel in a Swirl Burner

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Abstract: Lean premixed combustion using hydrogen fuel blends is important for reducing carbon emissions to the environment in the forthcoming technology of gas turbine combustors. In relative terms, pure hydrogen shows promise as a likely upcoming fuel for use in power generation. This is achieved by new burner designs that use a low fuel equivalence ratio (having a great calorific value of hydrogen) and burn to release relatively low NOx emissions. This article explains extensively the experimental results of the swirl burner model using pure hydrogen and hydrogen-enriched methane blends. In addition, the paper discusses the problems of flashback and blowoff and the ability to switch fuels. However, fuel blends that use a high hydrogen percentage give significantly less working operational area between flashback and blowoff when compared to CH4. Safety problems are one of the challenges in using hydrogen blends, and there is a potential for serious danger because of the high rates of burning of the fuel mixture, the propensity for flashback, and the high degree of combustion instability sometimes caused in quenching the flame. Coke oven gas (COG) has a high hydrogen percentage and provides less operational area. Blowoff limits were found to improve as the outlet velocity increased and can be further mitigated with flame confinement.

Keywords: Hydrogen, Swirl, Flashback, Blowoff

1. Introduction
Hydrogen shows promise as a future energy carrier. Recently, hydrogen has been produced by many different means, and companies will be able to make these production methods cost-effective in the near future [1-3]. Pure hydrogen and hydrogen blends provide a high energy density, low emissions, and a high flame temperature and speed, and the different flashback and blowoff performance characteristics need to be extensively investigated [4-7].

Coke oven gas is formed by heating coal to 1100°C in the absence of air. The typical composition of coke gas is 51% hydrogen (H2), 34% methane (CH4), 10% carbon monoxide (CO), and 5% ethylene (C2H4). The composition may also include benzene (C6H6), ammonia (NH3), hydrogen sulphide (H2S) and other components [8]. In this piece of work, the COG used contained 65% hydrogen, 25% methane, 6% carbon monoxide and 4% nitrogen. As it has high percentage of hydrogen, COG burns violently under particular conditions, with a behaviour close to that of pure hydrogen, and it is difficult to control the combustion. Flashback, a very complex phenomenon, arises when the speed of gas flow becomes smaller than the flame burning speed, causing the flame to reach the mixing chamber [9, 10]. There are many different manifestations of flashback; it may occur in the free stream (central flashback) or, due to low gas velocity, in the boundary layer near the walls of the burner opening. Pure hydrogen or its blends significantly increase the propensity for flashback, as the turbulent flame speed is higher [11, 12]. The other crucial phenomenon is blowoff, which takes place in many different ways.
depending on the fuel mixture, type of fuel (lean or rich mixture), burner design geometry, and swirl number. Flame instability can increase the tendency for blowoff. However, the central recirculation zone (CRZ) extends the blowoff limits by recycling heat and active chemical species to the flame in the burner exit. The blowoff problem becomes more serious when the swirl burner is employed with a lean premixed mixture [13-17].

Swirl burners are largely used in gas turbine combustors because of the advantages of a fine fuel/air mixture and improved flame stability. The main parameter used to measure the excitation of flow inside the swirl zone is the swirl number ($S$), which is usually defined using the fluxes of angular and linear momentum ($G_\theta$ and $G_x$, respectively). The swirl number is used for characterising the intensity of swirl in enclosed and fully separated flows [10, 13, 18, 19]:

$$S = \frac{G_\theta}{G_x} \left( \frac{D_o}{2} \right).$$

However, an approximate value for the swirl number, known as the geometrical swirl number ($S_g$) [13, 20], can be found from the burner geometry. The formula used to calculate the geometrical swirl number is:

$$S_g = \pi \left( D_o^2 - \frac{1}{4} t \right) \frac{D_\theta}{(D_t - t) \cdot h} D_o,$$

where:

- $D_o$ is the diameter of the combustor outlet,
- $D_t$ is the inlet diameter of the combustor,
- $D_\theta$ is the diameter of the injector,
- $t$ is the gap between the blades, and
- $h$ is the vertical length of the mixing zone (see figure 1).

### 2. Experimental Setup

A prototype swirl combustor was used to observe the blaze stability limits at standard conditions of pressure and temperature in the laboratory of the Gas Turbine Research Centre (GTRC) at Cardiff University. The burner consists of the main mixing chamber (plenum), which is fed by a single tangential inlet and exports a uniform fuel/air mixture to the insert, which produces a swirling flow that moves into the burner body (figure 2).
It is possible to change the swirl insert of this burner to change the swirl number. In this research, three inserts were used to give three swirl numbers (1.5, 1.0, and 0.8). These three different swirl numbers were achieved by using an insert having a number of tangential inlets with specific dimensions. The central fuel injector penetrates the entire frame of the burner (figure 2). This design can be easily modified to provide all combustion modes. The device used for flow measurement of air and fuel was a Coriolis mass flow meter, as shown in figure 3.

3. Results and Discussion

Starting with pure hydrogen, the flashback curves were plotted for the three swirl inserts, as shown in figure 4. The curves illustrate the flashback boundaries over a range of equivalence ratios observed for both lean and rich areas for two swirl numbers (S=0.8 and 1.0) and only the lean region for S=1.5. The flashback chart is roughly the same for both S=0.8 and 1.0; for S=1.5, the flashback is somewhat improved for equivalence ratios greater than 0.5 when compared to lower values. For the lower two swirl numbers (S=0.8 and 1.0), the combustion still continued even when the mass flow value reached around 5g/s for equivalence ratios less than 0.4; for a swirl of 1.5, this number was about 10 g/s, this indicates that low swirl numbers increase the area of gas turbine operation for H₂.

![Figure 4](image1.png)

**Figure 4.** Hydrogen flashback boundaries for the unconfined swirl combustor

The flashback/blowoff curve limits of unconfined (open flame) coke oven gas for S=0.8, 1.0, and 1.5 are shown in figure 5.

![Figure 5](image2.png)

**Figure 5.** Coke oven gas flashback/blowoff design map
Blowoff was almost the same for all swirl numbers. Flashback curves were similar for the burners with the lower two swirl numbers, but for the highest swirl number, 1.5, the peak of the curve reduced, and the width of the flashback area in the fuel-weak region increased. Importantly, on the lean side of all curves it can be seen that the flashback and blowoff lines are close to each other and in some case intersect. Throughout the experiments, this meant it was difficult to distinguish between them, as behaviour was unstable and aggressive. Figure 6 shows the blowoff limits range for CH₄/H₂ blends with 30% and 15% hydrogen content. It can be seen from the curves that, in general, the blowoff improved with a decrease in swirl number as the swirl becomes weaker.

![Figure 6](image)

**Figure 6.** Blowoff boundaries for unconfined burner (CH₄ and H₂ blends) for different swirl numbers

A strong swirl gives more instability, which helps the flame to burn out. Furthermore, the blowoff limits worsen as the percentage of hydrogen is increased in the fuel. This is clearly illustrated by the right-hand graph. The 15% hydrogen mixture behaves better than the 30% mixture, and the effect increasing the swirl was more significant than changing the percentage of hydrogen.

![Figure 7](image)

**Figure 7.** Blowoff for unconfined and confined shapes and two fuels (100% CH₄ and 30% H₂+70% CH₄) at S=1.0
Figure 7 illustrates the effect of confined (cylindrical and conical cup) and unconfined burners for $S=1.0$ and fuels with 100% CH$_4$ and 70% CH$_4$ with 30% H$_2$ separately. The results suggest that the recirculated flow, and hence blowoff, is affected by the swirl design geometry, especially for gas mixtures with a low burning speed and those dominated by CH$_4$ performance. The shape of the CRZ becomes less important with fuels with a higher percentage of hydrogen because of increased burning velocity. In general, confinement improves the blowoff limit and mitigates the effect of adding H$_2$.

4. Conclusion

Swirling flow is widely used in gas turbine combustors. The flashback and blowoff limits are significantly affected by swirl number, geometry, exhaust outlet configuration shape, and kind of fuel. For higher-percentage hydrogen blends with methane, lower swirl numbers gave the best flashback boundaries at lower pressure drop. Increasing the percentage of hydrogen, either pure or in coke oven gas, increases the tendency for flashback because turbulence increases as a result of the low total density of the fuel. The flashback mechanism seemed to be dissimilar with higher swirl numbers, as the CRZ moves down into the body of the fuel injector pipe towards the mixing zone, and flashback occurs via circular movement of the blaze front from the boundary of the CRZ to the mixing zone. Conversely, flashback seemed to lie on the outer wall of the boundary at the critical velocity gradient of the boundary layer. The flame extinct (blowoff) limits improve with a decrease in swirl number, as turbulence reduces the time required for blowoff. The hydrogen blends also minimise the chemical reaction time for fuel burning and improve the blowoff limits. Confinement further enhances the blowoff limit, as this also reduces the chemical reaction time.

The next generation of gas turbine burners will have ability to switch fuels according to energy demand and fuel availability. Using fuel enriched by hydrogen is an aim for many companies, as it gives great energy value. However, concerns regarding instability and safety are barriers to this aim. This is the crucial point in this piece of work.

5. References

[1]. Liu, Y., et al., Recent developments of hydrogen production from sewage sludge by biological and thermochemical process. International Journal of Hydrogen Energy, 2019. 44(36): p. 19676-19697.
[2]. Martínez-Salazar, A.L., et al., Technoeconomic analysis of hydrogen production via hydrogen sulfide methane reformation. International Journal of Hydrogen Energy, 2019. 44(24): p. 12296-12302.
[3]. Minet, R.G. and K. Desai, Cost-effective methods for hydrogen production. International Journal of Hydrogen Energy, 1983. 8(4): p. 285-290.
[4]. Schefer, R. and J. Oefelein, Reduced Turbine Emissions Using Hydrogen- Enriched Fuels. 2003, Sandia National Laboratories, Livermore CA.
[5]. Ravi, S. and E.L. Petersen, Laminar flame speed correlations for pure-hydrogen and high-hydrogen content syngas blends with various diluents. International Journal of Hydrogen Energy, 2012. 37(24): p. 19177-19189.
[6]. Syred, N., et al., The effect of hydrogen containing fuel blends upon flashback in swirl burners. Applied Energy, 2012. 89(1): p. 106-110.
[7]. Shelil, N., et al., Premixed Swirl Combustion and Flashback Analysis with Hydrogen/Methane Mixture in 48th AIAA Aerospace Sciences Meeting. Orlando, USA, ref. AIAA-2010-1169, 2010.
[8]. Yu, P., et al., Prediction of hot coke oven gas reforming by LES coupled with the extended flamelet/progress variable approach. Fuel, 2018. 231: p. 234-243.
[9]. Fritz, J., M. Kroner, and T. Sattelmayer, Flashback in a Swirl Burner with Cylindrical Premixing Zone. Journal of Engineering for Gas Turbines and Power, 2004. 126(2): p. 276-283.
[10]. Liu, Y., et al., Review of modern low emissions combustion technologies for aero gas turbine engines. Progress in Aerospace Sciences, 2017. 94: p. 12-45.
[11]. Nauert, A., et al., Experimental analysis of flashback in lean premixed swirling flames: conditions close to flashback. Experiments in Fluids, 2007. 43(1): p. 89-100.
[12]. Marco Osvaldo, V.-Z., et al., Flashback Avoidance in Swirling Flow Burners. Ingeniería, Investigación y Tecnología, 2014. 15(4): p. 603-614.
[13]. Abdulsada, M., et al., Effect of exhaust confinement and fuel type upon the blowoff limits and fuel switching ability of swirl combustors. Applied Thermal Engineering, 2012. 48: p. 426-435.
[14]. Chaparro, A.A. and B.M. Cetegen, Blowoff characteristics of bluff-body stabilized conical premixed flames under upstream velocity modulation. Combustion and Flame, 2006. 144(1-2): p. 318-335.
[15]. Plee, S.L. and A.M. Mellor, Characteristic time correlation for lean blowoff of bluff-body-stabilized flames. Combustion and Flame, 1979. 35(0): p. 61-80.
[16]. Shanbhogue, S.J., S. Husain, and T. Lieuwen, Lean blowoff of bluff body stabilized flames: Scaling and dynamics. Progress in Energy and Combustion Science, 2009. 35(1): p. 98-120.
[17]. Syred, N., et al., 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. Applied Energy, 2014. 116: p. 288-296.
[18]. Syred, N., A review of oscillation mechanisms and the role of the precessing vortex core (PVC) in swirl combustion systems. Progress in Energy and Combustion Science, 2006. 32(2): p. 93-161.
[19]. Beer, J. and N.A. Chigier, Combustion Aerodynamics. 1972, London: Applied Science, LTD.
[20]. Valera-Medina, A., N. Syred, and A. Griffiths, Visualisation of isothermal large coherent structures in a swirl burner. Combustion and Flame, 2009. 156(9): p. 1723-1734.