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Coherent Structure Impacts on Blowoff using Various Syngases

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Abstract

Swirl stabilized combustion is one of the most successful technologies for flame and nitrogen oxides control in gas turbines. However, complex fluid dynamics and lean conditions pose a problem for stabilization of the flame. The problem is even more acute when alternative fuels are used for flexible operation. Although there is active research on the topic, there are still various gaps in the understanding of how interaction of large coherent structures during the process affect flame stabilization and related phenomena. Thus, this paper approaches the phenomenon of lean premixed swirl combustion of CH_4/H_2/CO blends to understand the impacts of these fuels on flame blowoff. An atmospheric pressure generic swirl burner was operated at ambient inlet conditions. Different exhaust nozzles were used to alter the Central Recirculation Zone and observe the impacts caused by various fuel blends on the structure and the blowoff phenomenon. Methane content in the fuel was decreased from 50% to 10% (by volume) with the remaining amount split equally between carbon monoxide and hydrogen. Experimental trials were performed using Phase Locked PIV. The Central Recirculation Zone and its velocity profiles were measured and correlated providing details of the structure close to blowoff. The results show how the strength and size of the recirculation zone are highly influenced by the fuel blend, changing stability based on the carbon-hydrogen ratios. Nozzle effects on the shear flow and Re numbers were also observed. Modelling was carried out using the k-ω SST CFD model which provided more information about the impact of the CRZ and the flame nature close to blowoff limit. It was observed that the model under-predicts coherent structure interactions at high methane fuel content, with an over-prediction of pressure decay at low methane content when correlated to the experimental results. Thus, complex interactions between structures need to be included for adequate power prediction when using very fast/slow syngas blends under lean conditions.

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Keywords: Blowoff, Central Recirculation Zone, CFD, Syngas.

1. Introduction

Fuel independency has been a major driver for flexible power generation via alternative fuels during the last decades. Swirling flows, a widely spread technology used for combustion stabilization and reduction of emissions, has been employed during all this time for production of power using conventional and

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unconventional blends. However, industrial designers are now pushing the limits of new devices, encountering problems associated with stability issues. A major concern for Dry Low NOx developers is the lower stability limit or blowoff, which causes the flame to detach from the burner and blow out from the system. Blowoff, as some other stability issues found in swirling flows, is related to the complex nature of fluid dynamics and chemical interactions that occur during the combustion process.

Swirl combustion takes advantage of the production of various coherent structures such as the Central Recirculation Zone, a region where hot species are recirculated to provide not only energy to the incoming reacting flow but also to anchor the flame thus increasing operability range [1]. These flows can produce other vortical structures capable of producing benefits such as improving mixing or cause detrimental effects by coupling with natural acoustic modes to give high levels of pressure fluctuation [2-5].

Regarding blowoff, there has been general agreement on the concept that stipulates that it is a process controlled by the competition between chemical kinetics and fluid mechanics well-defined in terms of Damköhler number [6]. Therefore, the phenomenon occurs when the necessary heat required to maintain combustion exceeds the one received from the recirculation zone. However, scarce research has been performed on the impacts of the Precessing Vortex Core (PVC) and its interaction with the CRZ on the blowoff mechanism. Previous experiments [7-8] have shown that turbulence can increase threefold as a consequence of the co-existence of both structures in the region close to the burner mouth, thus leaving a gap of understanding about the effects of this interaction and its propensity to extinguish the flame.

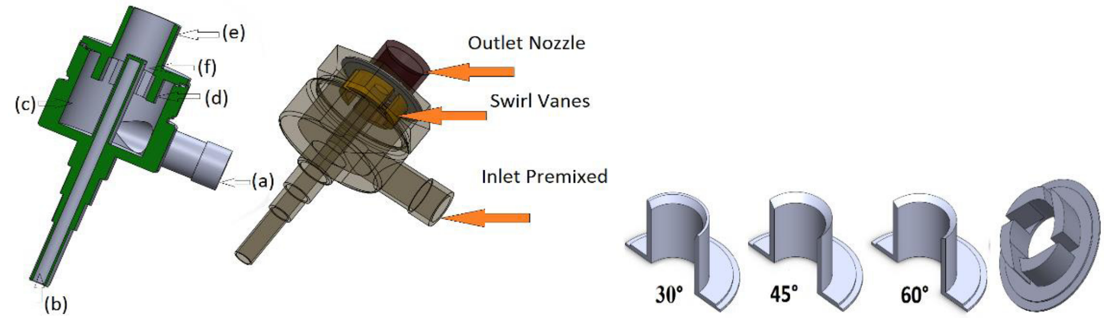
The phenomenon becomes even more complex as the fuel used is changed. Experiments conducted by Lieuwen et al. to investigate impacts of H_2/CH_4 fuels on the operability of lean premixed gas turbine combustors showed that small additions of H_2 substantially enhance the mixture's resistance to extinction or blowoff. Similarly, CO/CH_4 flames showed an alteration in their extinction strain rate [9]. Correlations of the turbulent flame speed were also obtained in the form of $S_T=S_L \cdot f(u')$, {S_T turbulent flame speed, S_L laminar flame speed and $f(u')$ a function of turbulence level}. However, laminar flame speed and turbulence intensity alone do not capture many important characteristics of the turbulent flame speed [9]. Schefer et al. [10] obtained results showing that addition of a moderate amount of hydrogen to methane/air mixtures increased peak OH concentration with a shorter and more robust flame.

However, all these studies have not shown clear correlation between blowoff processes and the strength of the CRZ and its related coherent structures. Therefore, this paper presents experiments and numerical studies to determine correlations between different blends and the appearance of coherent structures towards the onset of blowoff phenomena. Experiments were conducted using a Phase Locked PIV system. Size and behavior of the Central Recirculation Zone were measured and correlated providing details of the structure close to blowoff.

2. Setup

An open stainless steel swirl burner was used to examine methane, hydrogen and carbon monoxide blends under atmospheric conditions. A schematic of the generic burner is presented in Fig. 1a. The system is fed via a tangential inlet (a) whose discharge mixes into a swirl chamber (b). A central fuel injector (c) was used for stability purposes. A swirl generator (d) imposes the required swirling conditions to stabilise the flame. Swirling unburned reactants then pass into the burner body (e) to create the stabilization effect through the creation of a CRZ. Further information can be found elsewhere [11].

A geometrical Swirl number, S_g, of 1.05 was used. The recirculation zone was altered by using 30°, 45°, and 60° chamfers to the exhaust lip nozzles, Fig. 1b [2]. Wall thickness was kept constant to ensure that swirl at the outlet would be the same. The burner nozzles had an internal diameters of D = 0.028 mm. An L/D ratio, being L the nozzle length, was kept at 1.05 for all nozzles.



(a) **(b)**

Fig. 1. a) Sketch of the generic swirl burner; b) nozzles and swirler used.

Experiments were performed to define lean blowoff limits of different fuel blends, Table 1. Experiments were done using Low Power (LP = 3.5 kW), Medium Power (MP = 7.49 kW) and High Power (HP = 11.48 kW) conditions to determine any relation between nozzles, gases and power loads.

Finally, experiments were carried out at the same power output, i.e. 7.49kW, to correlate the impact of blend compositions using numerical and experimental analyses. It is emphasized that the usage of various gases complicates the analysis using defined equivalence ratios for the entire blend. However, the approach was based on assuming complete combustion of all species through the flame front.

Table 1. Syngas compositions

Gas number	Gas compositions
Syngas 1	10% CH_4 + 45%H_2 + 45%CO
Syngas 2	20% CH_4 + 40%H_2 + 40%CO
Syngas 3	30% CH_4 + 35%H_2 + 35%CO
Syngas 4	50% CH_4 + 25%H_2 + 25%CO
Gas 5	100% CH_4
Gas 6	50% CH_4 + 50% CO_2

Velocity measurements were performed using a Dantec PIV system that consists of a dual cavity Nd: YAG Litron Laser of 532 nm capable of operating at 5 Hz. A Hi Sense MkII Camera model C8484-52-05CP of 1.3 MPixel resolution at 8 bits with a 60mm Nikon lense was used. The inlet air was seeded with Al_2O_3. After acquisition, a frame-to-frame adaptive correlation technique was carried out with a minimum interrogation area of 32x32 pixels. 500 pairs of frames were used to create an average velocity map.

Simulations were performed using all syngases under fully premixed conditions with FLUENT 14.5. Different solvers were analyzed and compared to determine which was the most effective to these cases. Based on experimental results carried out at 1.94 g/s, the κ-ω SST model [12] showed the best correlation. ICEM 14.5.7 was used as pre-processor. A mesh dependency analysis showed that a mesh consisting of 425,520 nodes and 237,148 elements provided mesh independent results. A structured grid was created with a higher node density in the burner exit and around the fuel nozzles.

3. Results

It has been demonstrated that the region of interaction between the CRZ and the Precessing Vortex Core (PVC) presents the highest turbulence in the flow [2, 7]. Since their interaction will depend on the strength and shape of the CRZ, thus flow time scales, a greater dependency of Lean BlowOff (LBO) on the geometry was expected. However, at low flow rates just a slight dependency was observed, Fig. 2. Hydrogen content, i.e. chemical time scale, was more important to the phenomenon under these conditions.

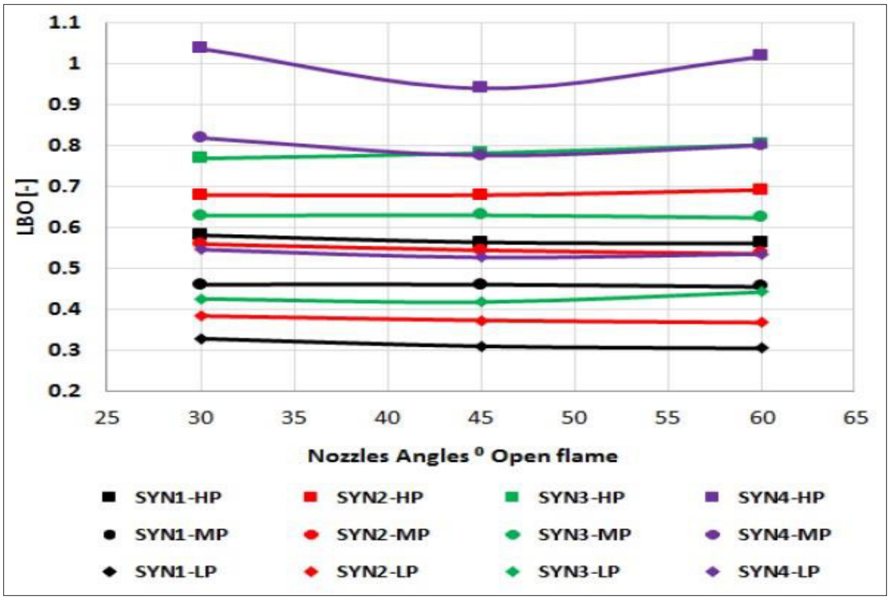


Fig. 2. LBO equivalence ratio for all syngases at LP, MP and LP. Trends are added just to clearly visualize the change.

This is believed to be caused by a weak CRZ-PVC interaction, consequence of the high energy release from hydrogen combustion close to the nozzle. Being a localized phenomenon, this interaction will allow the re-establishment of the flame in other regions [2, 7]. Results show that hydrodynamic interactions between structures play a minor role in LBO for high hydrogen enriched blends at these power outputs. Slight nozzle influence was detected for all cases at low and medium flowrates, Fig. 2. However, there was a considerable shift in LBO equivalence ratios using all nozzles as power was increased and hydrogen decreased, Fig. 2.

PIV velocity contours were obtained to determine the boundaries of the CRZ, Fig. 3. The CRZ boundaries were defined in a velocity range of -1.40 to 0.170 m/s. It is clear the CRZ distortion occurs for all cases, Table 1, using the three nozzles, Fig. 1b.

Therefore, a change in the interaction of the PVC-CRZ would be expected. Use of more hydrogen, i.e. Syngas-1, shows how a faster reactivity shortens the CRZ. The usage of a 30˚ nozzle shows wider structures, as expected. The reduction of hydrogen elongates the CRZ as a consequence of a delayed pressure decay consequence of the lower reactivity of the blend. Simultaneously, stronger CRZ-PVC interactions would be expected consequence of the elongation and widening of the CRZ. Thus, it is believed that for Syngas-4 the interaction is a critical part of the blowoff process due to the flow time scales and lower chemical reaction times.

CFD analyses using the SST-k-ω model were carried out to observe the change in size of the CRZ. Simulations were calibrated by using pure methane, Fig. 4. It is recognized that the CFD slightly under-predicts the location of the shearing flow and size of the CRZ. However, further comparison between experimental results and CFD predictions for the CRZ size demonstrate that very good correlation was achieved between both techniques, Fig. 5 and Tables 2.

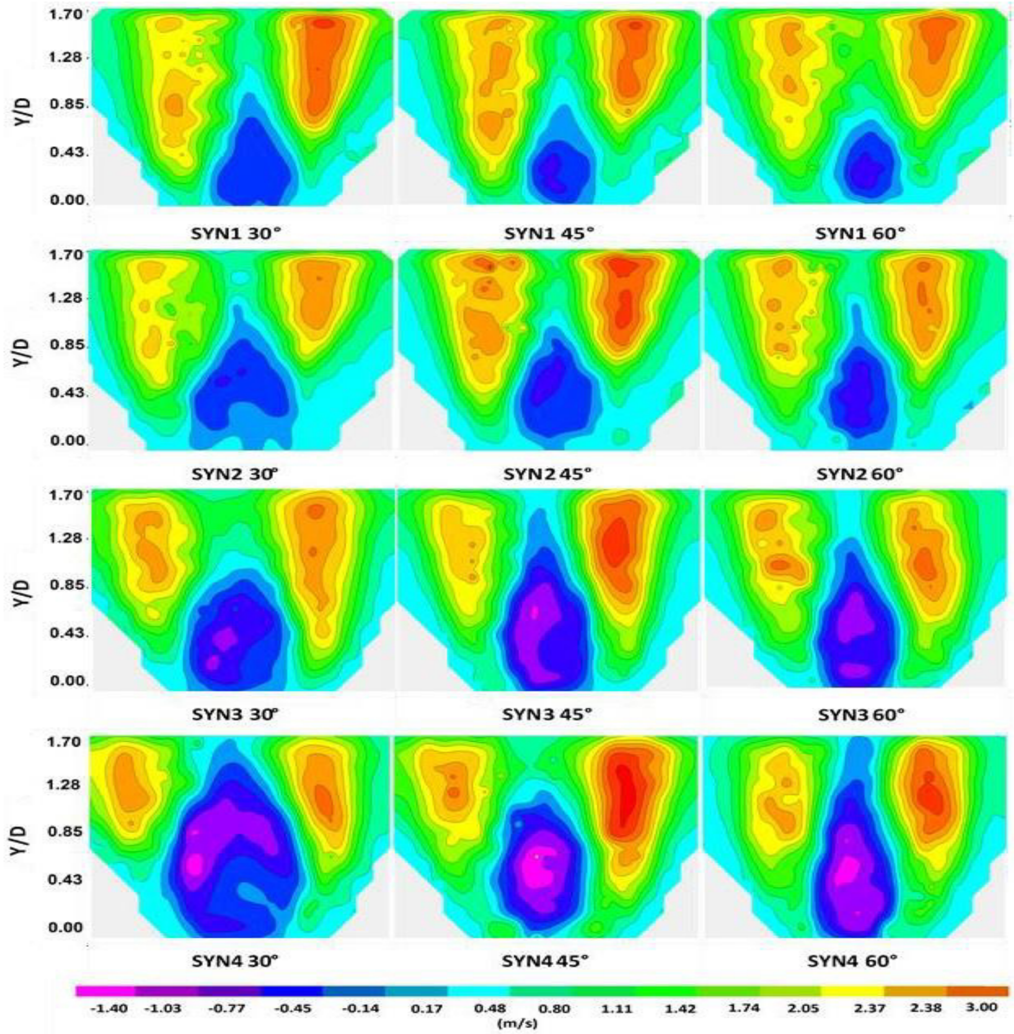


Fig. 3. PIV experimental CRZ boundary contours for each case (scale from -1.40 to 3.00 m/s).

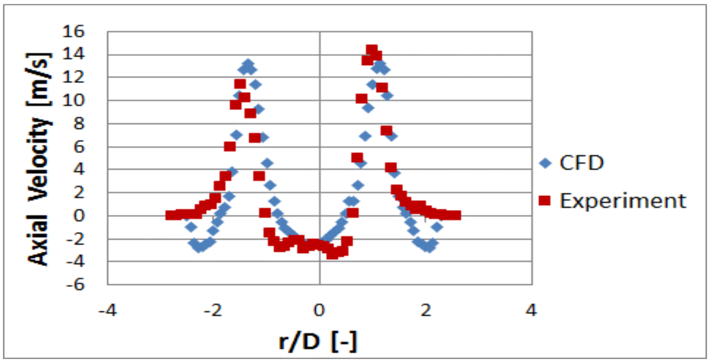


Fig. 4. Correlation between CFD and Experimental simulations using pure methane. 0.107D from nozzle outlet.

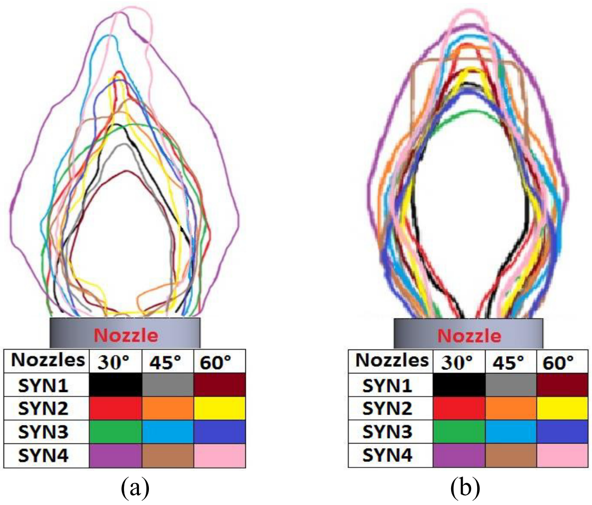


Fig. 5. (a) Experimental and (b) CFD simulations, respectively.

Table 2. Comparison of numerical and experimental results, CRZ size. *W = width, L= length of CRZ.

	30°		45°		60°	
Gas	W [%]	L [%]	W [%]	L [%]	W [%]	L [%]
SYN1	1.48	4.17	7.20	12.1	11.80	25.8
SYN2	2.00	4.09	0.78	0.00	6.19	0.00
SYN3	13.60	10.70	6.90	6.60	8.87	0.00
SYN4	24.00	14.00	6.20	2.20	8.00	16.00

Comparison between experiments and CFD analyses was carried out. Worst predictions were obtained using the 30˚ nozzle and the slowest Syngas-4, and the 60˚ nozzle with the fastest Syngas-1. This lack of accuracy in these 2 points is thought to be a consequence of 3-Dimensional large structures such as the PVC or the coherent shearing flow that are not accurately predicted with this model and lack of resolution during fast reaction phenomena, respectively. This can be a problem that needs to be considered when simulating power conditions close to blowoff (very lean) when using these advanced syngases.

4. Conclusions

The conclusions obtained are as follow,

• It was observed that different CRZs were formed under a variety of conditions at the same power output as a consequence of different decaying pressures and combustion processes.

• Low reactive blends showed the highest impacts to the change in CRZ, thus CRZ-PVC interactions. Therefore, these structures need to be considered when low reactive blends are investigated in Lean BlowOff studies. If higher reactivity blends are analysed, the impact of the structures can be neglected.

• SST-k-ω turbulence models do not depict accurately high reactivity and shearing phenomena of fast blends, whilst they under-predict the impacts produced by coherent structure interactions in slow blends. Thus, complex coupling between structures needs to be considered when using these blends close to very lean power conditions, especially when using low speed blends.

Acknowledgements

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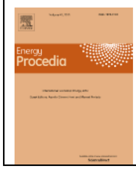

Biography

Dr. Agustin Valera-Medina is a Chartered Engineer, Senior Lecturer at Cardiff University. He works at the Gas Turbine Research Centre on topics such as combustion hydrodynamics, fluid mechanics, alternative fuels and novel power generation cycles.