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Outlet geometrical impacts on blowoff effects when using various syngas mixtures in swirling flows ☆

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HIGHLIGHTS

- Syngas mixtures in gas turbines have become extremely important for fuel flexibility.
- The use of special nozzles should be dependent on the type of fuel used.
- Close to blowoff, high H_2 blends suffer negligible effects by swirl phenomena.
- However, low hydrogen mixtures do suffer the effects of structures close to blowoff.
- RANS SST k-ω is a good simulation technique but only for specific hydrogen-CO contents.

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ABSTRACT

Lean premixed swirl stabilized combustion is one of the most successful technologies for NOx reduction in gas turbines. The creation of inherent coherent structures such as recirculation zones is one of the main advantages of these flow-stabilized systems since these zones create regions of low velocity that allow heat transfer improvement between reactants and products while increasing residence time for unburned species. However, these effects can also affect the stability of the flame under lean conditions, with various instabilities that can appear during the combustion stage such as flashback, blowoff, autoignition, etc. These processes are even more complex when new alternative fuels are being used for power generation applications. Synthesis gases (syngas) are some of the most concerning out of the available range of fuels as their heating values, flame speeds, ignition energies, etc. are highly dependent on the combination of species that comprise them. Since new gas turbines need to deal with these new blends for fuel flexibility and current lean premixed swirled stabilized systems seem to be the most cost effective-technical option to keep NOx down, gas turbine designers need more information on how to properly design their equipment to achieve stable flames with low NOx whilst avoiding instabilities.

Therefore, this paper presents a study using numerical and experimental analyses to provide guidance on the use of $CH_4/H_2/CO$ blends in tangential swirl burners. Methane content was decreased from 50% to 10% (volume) with the remaining amount being split equally between carbon monoxide and hydrogen. Ambient temperature conditions were assessed using a swirl number close to 1.0. Particle Image Velocity was used to experimentally validate numerical predictions and determine features of the coherent structures affecting the flame close to the nozzle. Modelling was carried out employing the k-ω SST turbulence model, providing more information about the impact of these structures and the flame turbulent nature close to blowoff limits. The study emphasizes the analysis of various nozzles with different angles and how these geometrical changes at the outlet of the swirl chamber affect the onset of blowoff. Recommendations on the use of RANS CFD modelling are provided on the basis of blend composition.

1. Introduction

Fuel independence has been a major driver for the development of combustion systems during the last few decades, with the aim of finding technologies capable of achieving high fuel flexibility for

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power generation. Swirl combustion has been widely used for this purpose as it provides high flame stability with relatively low emissions consequence of the creation of coherent structures such as the central recirculation zone (CRZ). The CRZ recirculates heat and active chemical species to the root of the flame, allowing flame stabilization in regions of relatively low velocity where the flow and the turbulent flame velocity are matched [1]. These flows can generate other vortical structures capable of producing benefits such as improved mixing, or cause detrimental effects by coupling with natural acoustic modes to give high levels of pressure fluctuation [2–5]. However, it has been recognised over the years that geometrical changes and the nature of the flow regime are critical parameters for the development, evolution and establishment of these structures, with studies and practical applications that demonstrate the changes in these regimes with slight variations of the system augmenting the complexity of the interactions that occur between flame and flow structures [5–9].

As new technologies develop, swirling flows are being deployed for the stabilization of more advanced fuels, amongst them Synthesis gas (syngas) products of gasification processes which contain highly hydrogenated blends with a combination of other species such as CO or CO_2. The use of syngas as a fuel source can potentially reduce CO_2, NOx and other pollutants [10] providing high flexibility in current gas turbines, especially those incorporated in systems known as Integrated Gasification Combined Cycles (IGCC) [11,12]. Therefore, the importance of the study of these fuel blends rests on the development of new gasification systems which employ biomass, waste or coal-based feedstock in order to reduce fossil fuel dependency while producing gaseous streams of enough calorific value to be used for power generation. Analyses of these new blends and their impact during the combustion process are crucial to designers working on this area, as many of these impacts are still unknown. Moreover, there is also a considerable need for validation studies that provide confidence on simulation tools, thus ensuring the most effective and less time-cost consuming methods are used for the design of these systems.

Previous studies [7,13] have demonstrated that high hydrogen concentration considerably alters the combustion characteristics, thus changing the swirl number with its inherent effects on the size, shape and recirculated mass flowrate in the CRZ [7,13]. The addition of CO_2 in the fuel blend can also lead to changes in viscosity, density and radiative heat transfer, thus changing the flow [13]. Experimental studies on emissions performance of syngas using different methods have been previously investigated by several researchers. Ge et al. [14] investigated the combustion performance of non-premixed swirl syngas combustion, in particular the difference in emissions between H_2-lean and H_2-rich syngases with water dilution. Results showed that the level of NOx and CO emissions was constant for the range of syngases tested at low H_2O dilution. Joo et al. [15] investigated H_2-rich combustion with enrichment of CH_4 using swirling partially premixed conditions, showing the reduction of NOx and flame temperature with the increase of CH_4. Zhang et al. [16] conducted a study of syngas flames using a premixed opposed-jet flame. The key finding showed that CO_2 dilution has more profound effects on flame propagation and extinction rate than N_2.

Syngases keep capturing the attention of researchers; not only to achieve fuel flexibility but also to mitigate unwanted emissions. The volume ratio of H_2/CO in most syngas mixtures typically exceeds 0.25, where chemical kinetic and reaction mechanisms of hydrogen play a dominant role in syngas combustion. Hence, syngas generally exhibits large burning rates with small autoignition time [17]. Moreover, CO-rich syngases show different characteristic to H_2-rich blends. Low concentration of H atoms in the former affects fast oxidation pathways of CO, resulting in unstable combustion and high CO emissions that are not well understood [18]. Regarding hydrogen related phenomena, Azimov et al. [19] used biomass/coke derived syngas in a dual-fuel engine. The use of higher H_2 concentrations resulted in reduced CO and HC emissions but an increase in NOx, as temperatures in the combustion chamber augmented. Similar trends of high NOx emissions for H_2-rich syngas were validated by Lee et al. [20] in a 60 kW industrial gas turbine using pure syngas without diluent. NOx emissions increased as the heat input increased. Higher CO was produced with lower combustion efficiency when the gas turbine was operated at low load. Nevertheless, Ouimette et al. [21] found different NOx trends under partially premixed combustion using similar syngases with H_2/CO ratios between 0.8 and 1.3. Watson et al. [22] also demonstrated that NO formation paths for syngases are mainly caused by thermal mechanisms, although N_2O and NNH routes have a considerable influence at lean equivalence ratios.

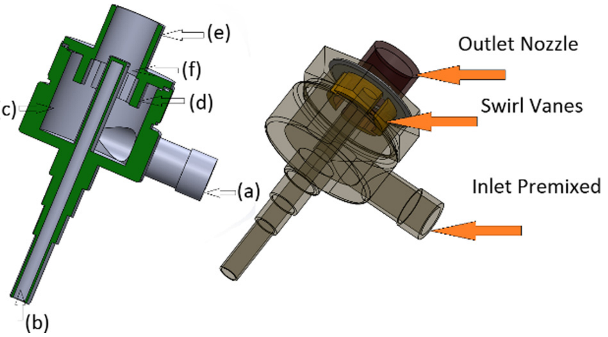

Fig. 1. Schematic of the generic burner.

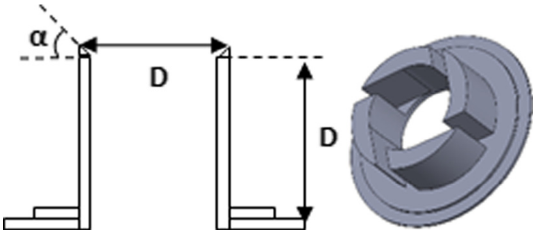

Fig. 2. Angular nozzle and geometrical swirl respectively.

Table 1
Gas compositions.

Gas number	Gas compositions	LHV [MJ/kg]
Syngas 1	10% CH_4 + 45%H_2 + 45%CO	63.53
Syngas 2	20% CH_4 + 40%H_2 + 40%CO	62.08
Syngas 3	30% CH_4 + 35%H_2 + 35%CO	60.52
Syngas 4	50% CH_4 + 25%H_2 + 25%CO	57.51

Table 2
Experimental and CFD conditions, 6.45 kW.

Gas No	$\dot{M}$ fuel [g/s]	$\dot{M}$ Air [g/s]	α°	Total [g/s]	Φ
Syn1	0.101	1.41	30°	1.51	0.425
Syn1	0.101	1.40	45°	1.50	0.428
Syn1	0.101	1.38	60°	1.48	0.453
Syn2	0.104	1.55	30°	1.66	0.485
Syn2	0.104	1.55	45°	1.65	0.486
Syn2	0.104	1.48	60°	1.59	0.508
Syn3	0.107	1.63	30°	1.73	0.563
Syn3	0.107	1.67	45°	1.78	0.548
Syn3	0.107	1.65	60°	1.75	0.557
Syn4	0.113	1.83	30°	1.95	0.689
Syn4	0.113	1.79	45°	1.90	0.707
Syn4	0.113	1.83	60°	1.94	0.692

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