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Impact of fuel staging on stability and pollutant emissions of premixed syngas flames

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ABSTRACT

Fuel staging is a common alternative for flame stabilization in the vicinity of the lean blowout limit in gas turbine combustors. Whereas this technique has been normally applied to stabilize very lean flames, fuel staging could also have some effect at richer conditions, due to the modification of the spatial distribution of fuel-air ratio, even for a constant global equivalence ratio. This could bring some benefits in syngas flames, where flashback and instabilities may become the main operating issues. However, no previous reference on the effects of fuel staging on those phenomena has been found in published works. The main objective of this work was, therefore, studying the impact and potential benefits of fuel staging with regard to two important syngas combustion issues: widening the stability range of syngas flames and reducing (or, if possible, avoiding) flashback-induced instabilities. At the same time, the effect on pollutant emissions was determined, with a view to minimize their increase or even to attempt to achieve further reduction. In addition, the influence of the injector geometry was also analyzed by comparing the results of different configurations. The results revealed that, if the secondary injector was properly designed, a small quantity of secondary fuel could be enough for avoiding flashback, at the same time that the pressure fluctuations, in case of flashback-induced instabilities, were almost totally removed without significantly increasing pollutant emissions. This finding could be exploited for practical applications, as fuel staging strategies could be useful to alleviate the operational problems due to syngas burning in lean premixed combustors.

1. Introduction

The interest in the use of non-conventional fuels to replace natural gas in gas turbine combustors has increased during the last years. This is the case of some process byproducts (e.g., refinery gas) or, more commonly, the syngases produced from the gasification of a wide number of fuels such as coal, biomass or waste. Since syngases display a broad range of compositions, always very different from those of natural gas, a thorough analysis of their particularities should be made before using syngas in the current combustion systems, which, in general, have been optimized for conventional fuels.

Due to its practical importance, many works [1–13] have been focused on describing the behavior of syngas fuels. In general terms, the most critical operability issues involved in combustion design, which are strongly related to fuel type and stoichiometry, are: blowout, flashback and combustion instabilities. The operating range of premixed flames has been studied in many previous works, showing how some of the components in syngas, especially H_2, had a strong influence on the stability range of practical flames [2,3,5–7,13]. In fact, hydrogen addition has been used for increasing the resistance to blowout in lean premixed burners [9,11,13–15]. However, although working at lean conditions may have some advantages in terms of NOx emissions [3,5–8,13], this type of fuels are more prone to flashback and to combustion instabilities, which may cause serious operational problems.

Furthermore, these problems cannot be independently analyzed since, for example, combustion instabilities can also increase the risk of flame flashback and a feedback mechanism between the two phenomena may appear under certain conditions as it has been previously discussed in [13]. Pressure fluctuations can favor the upstream propagation of the flame since high-amplitude oscillations of injection velocity fluctuations due to large pressure fluctuations can lead to a displacement of the reaction zone into the premixing section [16,17]. The consequence is a modification of flame geometry, in many cases accompanied by significant

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variations in instantaneous heat release rate which is a noise source. These physical phenomena create a closed loop between acoustics and combustion and, under certain conditions, may lead to periodic flashback and strong flame pulsations. Several previous works, such as those by Lieuwen et al. [2,3] or Schefer [10], have analyzed the effect of fuel composition on combustor stability, but most of them are focused on the dynamics of detached flames near the lean blowout limit. Only a few authors, such as Tuncer et al. [17,18] and García-Armingol and Ballester [13], have quantitatively analyzed the existence of a possible coupling between acoustics and flashback with hydrogen enriched fuels, but no solution to this problem has been developed yet.

With the aim of solving these combustion problems, fuel staging has been proposed as an attractive alternative for flame stabilization. Fuel staging belongs to the category of passive instability control techniques which, as opposed to active control methods, seek to attenuate or avoid combustion oscillations by changing the geometry or settings of the combustor or injectors, without adding energy from an external source to modulate the flows (see [19]). In general, passive methods have the advantages of simplicity and lower cost than active techniques. Fuel staging basically consists in dividing the main fuel into different injectors in order to create regions with different equivalence ratios [20], namely: (1) The main combustion zone with low equivalence ratio, which ensures low NOx emissions and reduces flashback appearance, and (2) a zone richer in fuel, capable of sustaining the combustion of the main zone and prevent flame blowout or unstable operation, which otherwise may occur due to the proximity of the lean stability limit.

Although more sophisticated fuel staging configurations can be developed in modern turbines [20], most of the related works published in the open literature deal with the use of pilot flames [21–23], which are the easiest way of implementing fuel staging. This strategy consists in injecting a small amount of pure fuel or of a fuel-rich mixture with the aim of creating a very stable pilot flame that helps to sustain the combustion even if the main flame suffers local extinction episodes due to instabilities or to the vicinity of the blowout. This discrete injection is commonly located along the centerline of the combustor into the recirculation zone [24]. However, this secondary fuel injection has the drawback of generating relatively high amounts of NOx and CO due to the diffusion nature of the flame created.

Although pilot flames have been traditionally applied in gas turbines with stabilization purposes [24], only a few a systematic studies aimed at optimizing the secondary injection have been identified in the open literature [21–23,25]. According to these works, the effectiveness of pilot flames does not depend only on the amount of injected fuel but also on the geometry of the secondary injector [22,23] or on the location of the secondary injection [25]. As a consequence, if the secondary injector is properly designed and located, the use of a small amount of pilot fuel can ensure a good flame anchorage, avoiding blowout and minimizing pressure fluctuations without increasing pollutant emissions [22,23].

Apart from its use for minimizing lean combustion related problems, diverting a percentage of the main fuel makes the primary fuel-air mixture slightly leaner, which could be expected to have some effects on the other limit of the stability range, i.e. on flashback appearance. However, no references about this use of fuel staging have been found in previous works. It should be noted that all the previous works are focused on the analysis of operation strategies for traditional fuels, and no references to specific applications with syngas flames have been found. The objective of this work is to evaluate the possibilities of fuel staging to improve the stability of syngas flames, and more specifically, to delay flashback appearance and to avoid or diminish the thermo-acoustic coupling leading to combustion instabilities. With this purpose, a systematic study was performed including two injector geometries, different fuel staging ratios and a wide range of fuel compositions.

2. Experimental facility

The experimental data shown in this study was collected from swirl-stabilized, turbulent, premixed flames in the combustion rig shown in Fig. 1.

A quartz tube, of 120 mm of internal diameter and 230 mm of length, configured the combustion chamber that allowed optical access to the flame. The fuel-air mixture was injected through an annular duct with 40 and 25 mm of outer and inner diameters, respectively, where an insert was placed into the injection path, surrounding the central gun (see the detail in Fig. 1). This modification enabled reaching flashback conditions for realistic injection velocities and, at the same time, the insert created a restriction in the injection duct which (in most cases) acted as a safety system by avoiding flashback propagation into the volume of inflammable mixture upstream of this element. The results of flame stability tests with different geometries of this insert were reported in a previous article [13]. The configuration with a trailing edge angle $\alpha = 30^\circ$ and the insert retracted at d = 28 mm from the dump plane was selected for the present study. As in [13], the propagation of the flame into the injection duct was detected by means of a 25 μm type S thermocouple installed in the injection duct at 15 mm upstream of the dump plane (see Fig. 1).

Fuel staging was implemented by diverting different amounts of the fuel through a secondary injector installed at the front end of the central gun. All the tests were made by adjusting the total mass flow rate of fuel (Q_t) in order to obtain a total thermal power of 15 kW. Before the injection, the total fuel flow was divided into the two streams, as shown in Fig. 1:

- Fuel P, the main or primary fuel, which was premixed with the combustion air before being injected through choked orifices into a plenum, upstream of the combustion chamber.
- Fuel S, the secondary fuel was directly injected into the combustion chamber through the secondary injector, creating a diffusion flame. The amount of secondary fuel was measured and controlled by using a BRONKHORST thermal mass flow meter. The percentage of secondary fuel ($\%Q_{sec}$) was defined as:

$$\%Q_{sec} = \frac{Q_{sec}}{Q_t} * 100 \tag{1}$$

In order to analyze the influence of the geometry of the secondary fuel injector shown in Fig. 1, the three different configurations of the central injector displayed in Fig. 2 were tested:

- One central hole of 1.7 mm of diameter, denoted as 1.7 C
- One central hole of 2.4 mm of diameter (2.4 C)
- A ring of eight holes of 0.5 mm inclined 45° outwards (R)

The analysis of the effects of fuel staging on flame stability was developed for different fuels compositions at a fixed thermal power of 15 kW. The range of fuels selected for the tests included methane, as a reference fuel, and different blends with H_2 and CO, representative of H_2-enriched fuels and of syngases. For brevity, each fuel was denoted by a capital letter from A to F. As it can be observed in the list below, the effect of hydrogen and CO fractions has been systematically evaluated by analyzing results for fuels A-C and C-F, respectively: