Combustion and Flame 164 (2016) 270–282

Contents lists available at ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Experimental investigation of the stability limits of premixed syngas-air flames at two moderate swirl numbers

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ARTICLE INFO

Article history:
Received 16 April 2015
Revised 12 November 2015
Accepted 22 November 2015
Available online 28 December 2015

Keywords:
Syngas
Gas turbine
Flashback
Lean blowout
Swirl number
OH*-chemiluminescence

ABSTRACT

This article presents an investigation of the swirl number effects on the stability limits of various syngas compositions in an atmospheric premixed variable-swirl burner. Lean blowout (LBO) and flashback (FB) experiments were performed using fuel mixtures containing varying amounts of H_2, CO and CH_4 at two swirl numbers. Reducing the swirl number from 0.66 to 0.53, reduced the flashback propensity of various syngas/air mixtures but it did not affect the LBO limits considerably. The flow-field in the combustor was studied at $S = 0.66$ and 0.53 using high-speed particle image velocimetry (PIV) for a mixture of H_2/CH_4 (50:50) at various equivalence ratios. At both swirl numbers, for the non-reacting flow and low equivalence ratios the flow-field consisted of an inner recirculation zone at the entrance of the combustor, an annular high velocity zone and an outer recirculation zones between the high-velocity zone and the bounding walls. Increasing the equivalence ratio towards the flashback limit, had varying effects on the flow-field, depending on swirl number. At $S = 0.66$, increasing the equivalence ratio did not have a significant effect on the general features of the flow-field. At $S = 0.53$ the flow-field consisted of an inner recirculation zone at low equivalence ratios, but as the equivalence ratio was increased, the high velocity zone extended radially towards the center and the recirculation zone disappeared from the flow-field. The high-speed OH*-chemiluminescence images recorded at the onset of flashback revealed significant differences between $S = 0.66$ and $S = 0.53$ in the flame stabilization mechanism prior to flashback and flame propagation in the premixing tube. Considering the velocity measurements together with the OH*-chemiluminescence images, it was concluded that at $S = 0.66$ flashback was caused by CIVB mechanism whereas at $S = 0.53$ flashback was initiated by the competition between the flame speed and flow velocity in the core flow.

1. Introduction

The ability to replace natural gas with synthesis gas (syngas) in modern gas turbines is important for efficient power production from biomass, using Integrated Gasification Combined Cycles (IGCC). Syngas can be produced from renewable sources such as lignocellulosic biomass, but they can also be produced from fossil fuels such as coal or heavy oil. Due to the variety in the sources and the gasification processes, the composition of syngas fuels can vary widely. Syngas may contain H_2, CO, and CH_4, as well as CO_2, N_2, H_2O, and small amounts of higher hydrocarbons [1]. Modern gas turbines typically use lean combustion approaches to maintain low combustion temperatures in order to limit NO_x formation. This means that fuel and air have to be premixed prior to combustion, which makes gas turbine combustors very sensitive to fuel choices. Changing fuel composition from natural gas to syngas can affect the operability of the gas turbine combustors in several ways: depending on the chemical and physical properties of the fuel mixture, gas turbine combustors can become prone to operability risks such as lean blowout (LBO), flashback (FB) and autoignition. This work is aimed at investigating the stability limits posed by flashback and lean blowout, with particular focus on how these are affected by the fuel composition and swirl number. The following paragraphs provide a short introduction to lean blowout and flashback mechanisms, with a short discussion of how these are affected by fuel composition.

Lean Blowout describes the process of flame extinction under lean conditions, by means of the flame leaving its stable anchored position and being drawn downstream into the combustor where it extinguishes. Lean blowout occurs under conditions where the residence time is not sufficient for the chemical reactions to take place.

Flashback occurs when the flame propagates upstream from the combustor into the premixing section. This can be a result of the turbulent flame speed exceeding the flow velocity along some streamlines in the combustor causing the reaction zone to travel

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http://dx.doi.org/10.1016/j.combustflame.2015.11.026

upstream. Two mechanisms that are driven by the competition between the flame speed and flow velocities are: *flame propagation in the high-velocity core flow* and *flame propagation in the boundary layer*.

In the high velocity core of highly turbulent swirling flows, the local axial flow velocities can be significantly lower than the mean velocity in the combustor due to high turbulent velocity fluctuations. This may increase the risk of upstream flame propagation from the combustor into the premixing section through the core of the flow [2]. This type of flashback has been observed in combustors with turbulent swirling flows operating on H_2 containing fuels [3,4].

Flame propagation in the boundary layer which has been first introduced by Lewis and von Elbe [5] refers to the condition where the flame propagates from the combustor into the premixing section through the low velocity regions close to the wall. The low flow velocities in the boundary layer are associated with low flame speeds due to high heat transfer from the flame to the wall. The chemical reactions cannot sustain closer than a certain distance to the wall, which is referred to as quenching distance. Boundary layer flashback occurs only if the flame speed exceeds the flow velocity at a certain distance within the boundary layer that is greater than the quenching distance. This type of flashback is often more dominant in turbulent low- or non-swirling flows [6–8].

In addition to the competition between the flame speed and the flow velocity, several experimental investigations in the literature have shown that in swirling flows flashback can be triggered as a result of the interaction between the flow-field and the heat release from the flame [9–14]. The heat release from the flame can cause the recirculation zone to move upstream into the premixing section with the flame tip being attached to it. This mechanism for flashback in swirl-stabilized combustors has been referred to as *Combustion Induced Vortex Breakdown* (CIVB) and has been studied by authors in [9–11, 15–17]. The occurrence of CIVB flashback is strongly dependent on the flame stabilization mechanism in the combustor which will be briefly discussed in the following paragraphs.

Flame anchoring in lean premixed combustors is most often achieved aerodynamically by swirl-induced vortex breakdown [18,19]. The sudden expansion of the flow is used to increase the negative azimuthal vorticity in the flow and generate a region of low pressure along the centerline of the combustor. This creates a recirculation zone in the combustor that mixes a portion of the hot combustion products with incoming fresh reactants. This process serves as a continuous source of ignition and acts as a flame stabilization mechanism.

The flow-field in the combustor is influenced by the heat release of the flame. As the reactants are consumed by the flame front, their volume increases and their density decrease in a certain ratio. This contributes to the production of azimuthal vorticity which can alter the position of the recirculation zone and thus causes the flame to propagate from the combustor into the premixing section. The CIVB flashback mechanism has been described by Konle and Sattelmayer [17], considering the azimuthal vorticity transport equation which is presented herein in Eq. (1):

$$\frac{D\omega}{Dt} = \frac{\partial}{\partial t}(\vec{\omega}) + \left(\vec{U}\,.\,\nabla\right)\vec{\omega} = (\vec{\omega}\,.\,\nabla)\vec{U} - \vec{\omega}\left(\nabla.\,\vec{U}\right) + \frac{1}{\rho^2}(\nabla\rho \times \nabla\,\mathrm{p}) \qquad (1)$$

where ω is the azimuthal vorticity, $\vec{U}$ is the velocity vector, ρ is the density and p is the static pressure. It is noted that the contributions of viscous diffusion and dissipation have been neglected in Eq. (1) due to their small influence in the current application.

The last two terms on the right-hand side of Eq. (1) correspond to the combustion-induced terms namely volume expansion and baroclinic torque, respectively. The volume expansion leads to the production of positive azimuthal vorticity and thus to the reduction of the induced axial velocity against the incoming flow. The baroclinic torque produces negative azimuthal vorticity which leads to an induced axial velocity towards the incoming flow, and can push the flame further upstream into the premixing tube. The density ratio across the flame, is thus an important factor in governing the flame position, and its ability to flashback into the premixing section.

In summary, the previous studies have shown that the stability range of swirl-stabilized combustors strongly depends on the interaction of the flame speed and heat release with the flow-field in the combustor. Since flame speed and heat release depend on the fuel composition, using highly reactive fuels such as syngas will change the operability window of premixed combustors. Altering the flow-field may be used as a means of improving the stability limits.

Fuel mixtures comprising H_2 have a particularly narrow operability range in lean premixed combustion as a result of the strong flashback propensity of hydrogen/air mixtures. The high reactivity of H_2, manifests itself in a high flame propagation speed, and increases the risk of flashback at very low equivalence ratios. On the other hand, operating at very lean conditions poses a high risk of combustion instability and lean blowout. In addition, the large differences in the diffusivity of various fuel and oxidizer components of syngas fuels, namely thermo-diffusive effects, may affect the local laminar flame speed and the resistance to strain. The thermo-diffusive effects can become more significant as the H_2 content of the fuel mixtures increases [2].

There have been extensive studies in the literature on the effects of fuel composition on flashback and LBO limits of H_2-containing fuels. Griebel et al. [20], Schefer et al. [21] and Strakey et al. [22] investigated the effect of H_2 enrichment on the lean stability limits of CH_4/air flames showing that the LBO limits of CH_4/air mixtures were greatly enhanced by H_2 addition to the fuel mixture. This was attributed to the higher OH radical concentrations which resulted in higher global reaction rates and higher flame speeds. Griebel et al. [20] further reported that the LBO limit was linearly dependent on the H_2 content of the fuel. Noble et al. [23] studied flashback and lean blowout of H_2/CO/CH_4 mixtures, concluding that the H_2 content of the fuel dominated the mixture lean blowout properties but had less influence on the flashback characteristics which was attributed to the different mechanisms driving flashback in their combustor. In another study, Shaffer et al. [24] investigated the flashback of syngas/air mixtures in a confined jet flame burner. They reported that the FB limit was not only dominated by H_2 content but also by the CO and CH_4 contents of the mixture. Page et al. [25] investigated the operability margins for H_2/natural gas and H_2/CO mixtures showing that adding up to 30% H_2 to the fuel mixture improved the LBO limit without having a significant effect on the FB limit of the fuel/air mixture. They further reported that at higher H_2 contents, the stability range of the H_2/natural gas mixtures was reduced more compared to that of the H_2/CO mixtures.

The current study is aimed at investigating the stability limits of various syngas compositions as the swirl number is altered in an atmospheric variable-swirl burner. In the first part of the study, lean blowout and flashback experiments were carried out for various H_2/CO/CH_4 mixtures at two different swirl numbers. The results showed that when the swirl number was changed from $S = 0.66$ to 0.53 the FB limits of premixed syngas/air mixtures were greatly improved while the LBO limits remained reasonably unaffected. This resulted in a significantly wider stability range.

The second part of the work was focused on providing a description and analysis of how the flashback mechanism was affected as the swirl number was altered. To this end, PIV measurements were performed to analyze the differences in the flow-field between the two swirl numbers for non-reacting as well as combusting flows. The flow-field was obtained at different equivalence ratios ranging from $\phi = 0.0$ (non-reacting) to $\phi = \phi_{FB}$ (flashback equivalence ratio) using a binary mixture of H_2/CH_4 (50:50). In further series of experiments, the flashback event and flame propagation in the premixing