Fuel 222 (2018) 800–809

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Combined effect of equivalence ratio and velocity gradients on flame stability and emission formation

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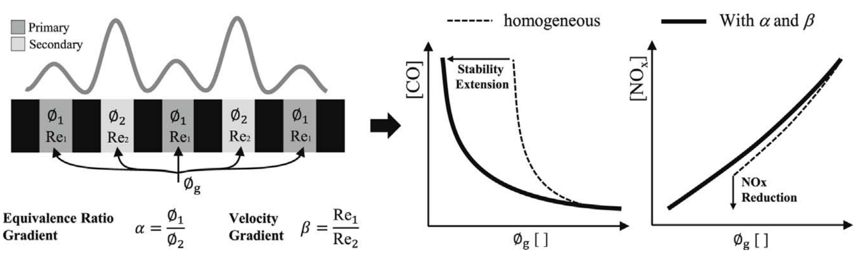
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Equivalence ratio and velocity gradients
Flame stability
NO_x and CO emissions
Tip opening
Stratified burner

ABSTRACT

Premixed flames have shown to behave differently while operating under equivalence ratio or velocity gradients. This distinct behaviour can be used to improve the performance of premixed burners. The present work analysed the effect of both equivalence ratio and velocity gradients on the stability of methane premixed laminar flames. Additionally, the influence of these gradients on CO and NO_x emissions was quantified. Results show that using equivalence ratio and velocity gradients can extend the stability limits of the burner. The lifting phenomenon commonly found on peripheral flames was cancelled by using higher equivalence ratios and lower flow velocities in the primary regime. Consequently, stable flames were achieved in the secondary regime for substantially leaner mixtures. However, flame extinction was eventually reached in the inner region of the burner, due to the tip opening of secondary flames. The minimum global equivalence ratio, ϕ_g, was extended from 0.80 to 0.65, solely by using equivalence ratio gradients. When combined with a velocity gradient, the latter effect was further extended up to $\phi_g = 0.52$. Regarding emissions, results show that different combinations of equivalence ratio and velocity gradients result in distinct NO_x and CO emissions, even for the same ϕ_g. Under this stratified arrangement, a reduction of 43% was achieved in NO_x formation, when compared with the homogeneous case. Overall, results suggest that introducing richer peripheral flames allows a higher extension of the lower stability limits, whereas leaner peripheral flames lead to lower NO_x emissions.

1. Introduction

Currently, assuring flame stabilization for increasingly leaner mixtures is a major challenge for gas-fired burners. For most applications, stability problems usually begin at the peripheral regions of the burner. At this region, air entrainment problems (e.g. dilution, heat loss) lead to a local reduction of the flame propagation speed, resulting on a flame lifting phenomenon [1]. This is responsible for several operational problems, such as the sharp increase in CO emissions and the appearance of thermoacoustic instabilities in the burner. Additionally, progressively stricter emissions standards are forcing burners to operate under leaner mixtures, making these operational problems more severe.

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https://doi.org/10.1016/j.fuel.2018.02.178
Received 15 December 2017; Received in revised form 5 February 2018; Accepted 27 February 2018
0016-2361/

Therefore, finding alternative flame stabilization strategies becomes extremely important to reduce even further the formation of pollutant emissions.

Previous researchers have mainly focused on changing the operating conditions on the regions of the burner most prone to flame stability problems. One example is the introduction of equivalence ratio gradients across the burner [2–5]. By strategically placing back-supporting flames across the burner it is possible to suppress the appearance of local flame stability problems. Regarding peripheral flames, using richer mixtures can minimize air entrainment problems, while providing heat and radicals for the stabilization of the inner neighbouring flames [2]. This allows the latter to operate under substantially leaner conditions, potentially reducing the formation of NO_x. Yasuda et al. [3] have consistently achieved wider stability limits and globally lower flame temperatures, by introducing equivalence ratio gradients across the burner. Shudo et al. [4] experimentally measured the impact of rich-lean combustion on a coaxial burner, for methane and hydrogen. Lower NO_x emissions were obtained on both cases, although the benefits of rich-lean combustion were stronger for hydrogen flames, due to preferential diffusion. Lúcio and Fernandes [5] explored the rich-lean flame interaction in a lamella burner, for methane. The authors successfully extended the stability of the lean regime and were able to characterize the contamination effect from rich to lean flames. However, results have shown that the continuous increase in the rich flame equivalence ratio can only extend the stability limits up to 2%.

A different approach to promote peripheral flame stabilization is changing the flow distribution in this region of the burner. A well-known example is the use of peripheral swirling flows, which allow the central region of the burner to operate under very lean conditions [6]. However, using peripheral swirling flows makes the burner very prone to the occurrence of thermoacoustic instabilities, making them unfit for a wide range of combustion-based systems [7]. Alternatively, a velocity gradient can be imposed across the burner. Chen et al. [8] analysed the effect of velocity gradients on the stability of laminar flames, in a co-centric burner with three independent channels. By using progressively lower velocities from the inner to the outer channel, the authors were able to extend the lower stability limit of the burner. According with the authors, this stability enhancement was obtained as a result of the vorticity induced by the velocity gradient. Nonetheless, the effect of this configuration on emissions was not quantified. Besides this work, little is still known regarding the effect of velocity gradients on the stabilization of premixed laminar flames.

The introduction of either equivalence ratio or velocity gradients has been proven to extend the flammability limits of premixed flames. However, the combined effect of these parameters on laminar flames has not been yet addressed in the literature and the impact of using this strategy on NO_x formation is still unclear. Moreover, CO is frequently overlooked in previous studies, despite being an important operational parameter. For leaner mixtures, the sharp increase in CO usually indicates the presence of incomplete combustion in the burner, dictating its operability limit. The present work aims to quantify the impact of the introduction of both equivalence ratio and velocity gradients on the extension of the burner stability and on NO_x and CO formation. A multi-slit burner with multiple independent channels is used in this work, allowing it to operate under different equivalence ratio and velocity gradients. Direct photography is used to analyse the effect of both variables on the morphology of the different flames and to characterize blowoff conditions. Additionally, exhaust gas measurements were used to analyse the effect of different equivalence ratio or velocity gradients on NO_x and CO formation in the burner.

2. Methodology

To test different equivalence ratio and velocity gradients, distinct flow conditions must be imposed across the burner. For a given power output, P_{in}, and global equivalence ratio, ϕ_g, a specific mass flow rate of air and fuel is required (Fig. 1). With these initial conditions at the burner inlet, the mixture can then be distributed in multiple ways for any given number of regimes. In this work, an alternated two-regime burner arrangement was adopted. Each regime had its own individual equivalence ratio, ϕ, and velocity, Re. The intensity of both equivalence ratio and velocity gradient must be quantified to characterize and compare different combinations of these two variables. Therefore, α and β were defined, expressing the ratio between the equivalence ratio and the flow velocity present on the primary and secondary regimes, respectively ($\alpha = \phi_1/\phi_2$ and $\beta = \mathrm{Re}_1/\mathrm{Re}_2$).

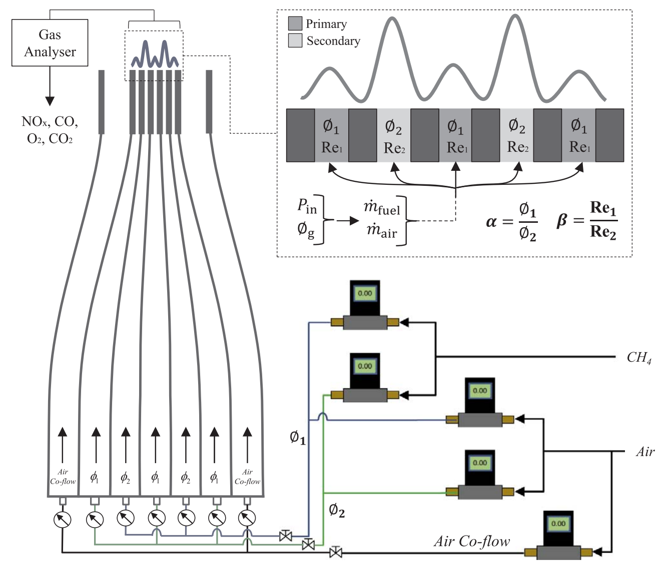

Fig. 1. Representation of the experimental setup and of the alternated two-regime burner arrangement adopted in this work.

As mentioned earlier, peripheral flames are most prone to the occurrence of stability problems. From the literature [5,8], it was possible to conclude that such stability problems can be countered by adopting peripheral flames with higher equivalence ratios and/or lower velocities. Therefore, both $\phi_1 \geqslant \phi_2$ and $\mathrm{Re}_1 \leqslant \mathrm{Re}_2$ conditions were considered for all tested combinations. With these conditions, ϕ_g can be expressed as:

$$\begin{cases} \phi_g = \phi_1 \dfrac{n_1 + n_2\beta^{-1}\left[\dfrac{1+a\phi_1}{\alpha+a\phi_1}\right]}{n_1 + n_2\alpha\beta^{-1}\left[\dfrac{1+a\phi_1}{\alpha+a\phi_1}\right]}\left[\dfrac{\mu_2}{\mu_1}\right] \\ \alpha = \dfrac{\phi_1}{\phi_2} \geqslant 1 \\ \beta = \dfrac{Re_1}{Re_2} \leqslant 1 \end{cases} \tag{1}$$

where a is the stoichiometry fuel/air ratio, n and μ are the number of channels and the mixture viscosity of each regime, respectively. Since only methane and air were used throughout the measurements, $\mu_1/\mu_2 \approx 1$. Consequently, it possible to assume that any differences in Re are mainly related with changes on flow velocity. Eq. (1) was used to determine different operating conditions of each regime, according with the purpose of each experimental test.

A multi-slit burner was developed for the purpose of this work (Fig. 1). The burner consists of five independent 1x40mm channels, separated by 2 mm thick stainless steel slits. The chosen channel dimensions were selected by [5] as the best configuration for the extension of the burner stability, using rich-lean flames. The use of high length/width channels allows the formation of two-dimensional flames, simplifying the visual inspection process. Additionally, the burner follows a $n_1 = n_2 + 1$ configuration, with channels 1, 3 and 5 operating under a primary regime (ϕ_1, Re_1), and channels 2 and 4 operating under a secondary regime (ϕ_2, Re_2). The supply of air and methane to the burner was controlled through independent Alicat digital mass flow