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Research paper

Effect of recess length on the flame parameters and combustion performance of a low swirl burner

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HIGHLIGHTS

- The stability, thermal and environmental performance of LSB is evaluated.
- The effect of burner recess length is exclusively studied.
- The parallel impacts of recess length with swirl number are observed.
- Major influence of recess distance on the flame regime is clarified.
- Lifted flame is better than attached flame in terms of emission and efficiency.

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ABSTRACT

The present experimental study aims to evaluate the stability, thermal and environmental behavior of the natural gas premixed combustion of a 55 kW Low Swirl Burner (LSB). The main focus of this investigation is to clarify the significance of recess length as a controlling factor of combustion performance. The results depicts that by varying the recess length, different flame regimes are distinguished. In terms of heat transfer efficiency and stack losses of the combustion, the lifted stable flame regime has superiority over the attached flames thanks to the more extended flame brush and proper temperature uniformity ratio. The attempt is also made to make an analogy between the effect of recess length and the effect of swirl number on the flame characteristics. The results revealed that the influence of reducing swirl number is proportional to the increase of recess length due to the decaying nature of swirl flow.

1. Introduction

The lean premixed combustion has been introduced as an effective method to comply with the strict emission regulations. For meeting the emission standards applied to the power generation industries, lean premixed combustion became the basis of the current dry low emissions (DLE) gas turbines [1]. When operating on natural gas, CO and NO_x emissions in the DLE combustion system can drop even below 50 and 25 ppm (corrected to 15% O_2), respectively [2–4]. However, lean-premixed combustion technology encounters stability issues due to the limited propagation velocity of the flame in the turbulent premixed reactants [5–7].

Swirl-stabilized premixed combustion is traditionally used as a flame stabilization technique [8,9]. It promotes the flame stability via creating recirculation zones in the flowfield that transport heat and radicals from the products into the reactants which would enhance the flame propagation velocity and sustains the combustion. The mechanism of NO_x production is mainly a function of local flame temperature and residence time of the particles within the reaction zone [2]. The disadvantage of swirl-induced premixed combustion is attributed to the hot spots with high residence time that act as thermal NO_x generators [4].

In order to eliminate the recirculation zones of the traditional stabilization technique, a novel design known as the Low Swirl Burner (LSB) has been developed by Cheng et al. [10–12]. The low swirl intensity in the LSB removes the formation of the inner flow recirculation and instead relies on the divergent flow for flame stabilization in which the flame brush can be settled (Fig. 1).

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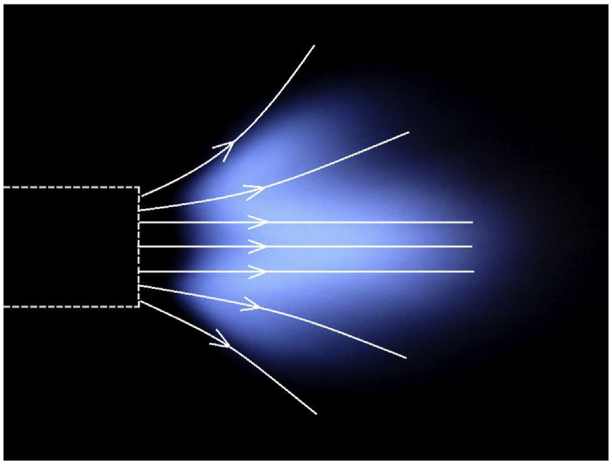

Fig. 1. The LSB flame brush settlement and schematic flow streamlines.

The LSB divergent flow is produced by a state-of-the-art device known as Low Swirl Injector (LSI). The LSI is placed upstream of the burner nozzle exit. The LSI delivers the air-fuel mixture through two passages: an outer annular region with swirling vanes and a central perforated channel that permits a fraction of the flow to remain unswirled. As shown in Fig. 2, the design parameters in the low-swirl injector are inner radius (R_i), core radius (R_c), recess length (L), swirl length (L_s), channel length (L_c) and blade angel (α).

The holes on the perforated central plate control the turbulence intensity developed in the inner channel as well as the flow split between inner and outer regions. Among the main characteristic parameters of the LSB, swirl number (S) and recess length (L) are highly important as they both act in parallel to maintain the divergent downstream flow and stream uniformity. The aerodynamic uniqueness of swirl injector provides a highly turbulent flow with slight swirl that can promote the divergent flow region with decreasing axial velocity downstream of the burner. This velocity ramp is the key to the flame stability. The turbulent flame propagates against the reactant velocity at the speed of S_T. The flame would be settled in a region along the axis where the local flow velocity is equal and opposite of S_T. The stationary flame brush is the result of balance of the opposite velocities.

Due to the simplicity of the LSB aerodynamics, straightforward analytical relation is established by Cheng et al. [13] in order to predict the flame position. Through a series of particle image velocimetry practices it was revealed that in the unconfined swirl flows, the profiles of normalized axial velocity (U/U_0) and the normalized turbulent kinetic energy (q'/U_0) follow their individual same trends. According to this similarity feature of the LSB flowfield, the following general equation is proposed for predicting the flame location with respect to the burner exit:

$$1 - \frac{dU}{dx}\frac{\left(x_f - x_0\right)}{U_0} = \frac{S_L}{U_0} + \frac{Ku'}{U_0} \tag{1}$$

where x_0 and x_f represent the virtual position of the linear velocity origin and the location of the flame front, respectively. Regarding the definition of the former, the axial velocity at the burner exit is known to decline linearly as flow moves along the axis of the burner. The origin position in which the axial velocity is equal with the bulk velocity is named x_0 which virtually occurs inside the burner prior to the exit. Also in Eq. (1) u', U and U_0 are the fluctuating velocity, the axial velocity and the bulk velocity, respectively.

The experimental and numerical investigations on the low swirl combustion mostly concern the stability fundamentals of low-swirl flames [14–17]. Practical study of LSB utilization in industrial applications was first conducted by Cheng et al. [18] in order to determine the operating design limits of LSB in industrial boilers and furnaces. The optimum operating point declared to be at 15 kW thermal capacity and $\Phi = 0.85$ with incredibly low $NO_x = 25$ ppm and $CO = 25$ ppm. The scalability of LSB has been examined by Cheng et al. [10] to derive a scaling law for commercial use of low swirl combustion. It was revealed that the constant velocity principle is valid for scaling the diameter of the burner at higher operating capacities. While the NO_x emission is rather insensitive to the thermal capacity, the CO and unburned hydrocarbons are strongly dependent to enclosure size and are extremely high at low thermal inputs.

In a comprehensive parametric study, Ballachey et al. [14] conducted a series of experiments by using a fully controllable LSB test rig to investigate the flowfield and stability. The examined characteristic parameters were heat release rate, exit radius, swirl angle and fuel composition. The results showed two dominant flame modes. For one common flame mode, a semi-empirical correlation is established which is applicable to a variety of fuels, equivalence ratios and scales.

Typically, the studies characterize the flame topology of the low swirl burners by geometrical parameters of the swirl injector. However, our primary observations showed that the variations of recess length, (L), can provide a new tool for controlling the flame shape. Recess length is mostly recommended to be adjusted between 2 and 3 times of radius upstream of the burner exit [15]. However, the response of the flame to this parameter has not been studied comprehensively. The present study majorly aims to elaborate the effect of recess length on thermal and environmental

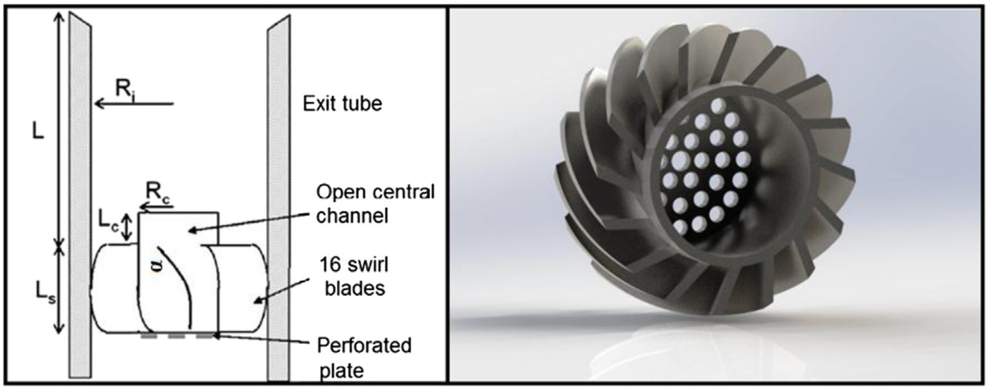

Fig. 2. The design parameters of Low Swirl Injector (*on the left*) and a typical swirler (*on the right*).