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Experimental study of bluff-body stabilized LPG–H_2 jet diffusion flame with preheated reactant

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ABSTRACT

The effects of hydrogen, H_2 addition and preheated reactants on bluff-body stabilized LPG–H_2 diffusion flame for two cases namely, (I) preheated air and (II) preheated air and fuel are reported in the present paper. Results confirm that the H_2 addition leads to a reduction in flame length. Besides this, the flame length is also observed to be reduced with increasing reactant temperature and lip thickness of the bluff-body. The soot free length fraction (SFLF) for both cases is observed to be increased with H_2 addition to fuel stream, which might have caused due to decrease in the C/H ratio in the flame. Interestingly, the SFLF is observed to be reduced with increasing lip thickness and reactants temperature, which can be attributed to the attenuation in induction period of soot formation and enhanced soot volume fraction, respectively. The NO_x emission level is found to be decreased in coaxial burner with hydrogen addition for both case I and II. In contrast, it is observed to be enhanced in bluff-body stabilized flame. The former can be ascribed to the reduction in residence time of gas mixture, whereas the latter can be explained on the basis of enhanced flame temperature. Besides this, emission index of NO_x ($EINO_x$) is also found to be enhanced with increase in lip thickness and reactant temperature which may be caused due to both enhanced residence time and thermal effect, respectively.

1. Introduction

Recently, the hydrocarbon–H_2 hybrid fuel is emerging as a viable technique of reducing emission level while enhancing performance of combustor [1]. In order to enhance the blow-off limit and flame stability, the bluff-body is employed as flame holder in combustors [2]. In flame stabilization, the central to annulus mass flux ratio is one of the controlling parameter in turbulent jet diffusion flames [3]. Tankin et al. [4] studied the bluff-body effect on the bluff-body stabilized flame combustor and concluded that central jet having higher momentum than air jet, penetrated through recirculation zone and affected its size. Later on, a numerical investigation of the blockage ratio effect on the jet mixing was carried out by Ma and Harn [5]. It was argued that intensity of the recirculation increased with its cone angle.

Soot formation not only depends upon the fuel type [6,7], but it also depends on the mixing characteristics within a flame [8]. Kent and Bastin [9] studied the effect of mixing on soot formation in turbulent diffusion flame and demonstrated that the local soot concentration gets reduced with increase in strain rate. Later on, Dally et al. [10,11] investigated the effect of Damkohler number on the NO formation and the structure of recirculation zone in bluff-body stabilized turbulent non-premixed flame for several composite fuels. It was found that NO concentration gets affected by the consumption mechanism such as NO to N_2.

The effect of H_2 addition on flame structure in the ethylene, propane and butane jet diffusion flame was investigated experimentally by Gulder et al. [7]. It was observed that in all these flames, the visible flame length exhibited insignificant variation upto 20% H_2 addition. However, Choudhary and Gollahalli [12] studied the characteristics of coaxial diffusion flame of hydrogen–hydrocarbon fuel and reported that an increase of propane level in the hydrogen–hydrocarbon mixture enhances the flame length. Later on, in lean non-premixed natural gas swirl-stabilized flame, Cozzi and Coghe [13] demonstrated the effects of hydrogen addition on flame structure and revealed that hydrogen addition produces a shorter visible flame length without providing any plausible explanation. Kumar and Mishra [14] also investigated the effects of hydrogen addition on LPG–H_2 coaxial diffusion flame and observed that the flame length gets reduced with hydrogen addition to the fuel stream.

Gulder et al. [7] showed the influence of H_2 addition on soot yield. For ethylene, the H_2 addition suppressed maximum soot volume fraction by 15% but for propane and butane, no effect on soot formation was noted. This was attributed to the amount of H_2 and H

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concentrations, produced during pyrolysis of ethylene and propane. In the hydrogen–hydrocarbon mixture, propane addition enhanced soot concentration and hence radiative heat losses due to higher C/H ratio [12]. Mustafa [15] investigated the effect of thermal radiation in hydrocarbon–H_2 hybrid fuel combustion and concluded that thermal radiation affects the combustion characteristics of hybrid fuels. Additionally, the effects of residence time and Damkohler number on NO_x production in hydrogen and methane jet diffusion flames were studied by Chen and Driscoll [16]. It was argued that, additive (He) to the fuel stream reduced global residence time due to reduction in flame length. Subsequently, Meunier et al. [17] investigated the NO_x emission characteristics in propane diffusion flame and found that the $EINO_x$ was proportional to the residence time of the reaction products implying that residence time had also significant effect on NO_x emission level.

Based on the above discussion, it can be concluded that the study of preheated reactants on the bluff-body stabilized LPG–H_2 jet diffusion flame has not been explored to the best of our knowledge which finds industrial application. Hence in view of the aforesaid issues, the present study is intended to investigate experimentally the effects of H_2 addition and preheated reactants on combustion characteristics of bluff-body stabilized LPG–H_2 diffusion flame. It is expected that these data can be useful for validation of computational studies.

2. Experimental method

The details of the experimental setup and procedure can be found in Kumar and Mishra [14], however, for completeness, it is discussed briefly in the current section. For the present experimental studies, two types of burners are used, (a) coaxial burner and (b) coaxial burner with bluff-body, as shown in Fig 1. In order to study the influence of lip thickness on combustion characteristics of LPG–H_2 hybrid fuel jet diffusion flame, a tulip shaped bluff-body is attached to the simple coaxial burner. The details of the geometry of two bluff bodies employed in present study are given in Table 1. Commercially available liquefied petroleum gas (LPG) containing 69% (Vol %) C_3H_8 and 30% (Vol %) C_4H_{10} and other trace of gases are used as fuel. The flame shape and size were measured using images from SONY DCR-PC350E video camera which has the option of taking 21 images at 0.5 s intervals (see Fig. 2). The image is analyzed using ImageJ software through smoothing, sharpening and edge detection techniques.

The soot free length fraction (SFLF), defined as the ratio of apparent blue portion of flame to total flame length is determined from these photographs. A water-cooled radiometer (Medtherm Model 64P-1-22) is used to measure the radiant heat flux. The radiant fraction, defined as the ratio of the total radiative heat loss to the heat of the combustion, from a single heat-flux measurement as [14]:

Table 1
Details of bluff-body geometry.

Lip thickness (δ) (mm)	Diameter (D_b) (mm)	Blockage ratio (D_b/D_a)	Lip thickness ratio (δ/D_f)
0.75	6.5	0.114	0.15
3.25	12.8	0.224	0.65
6.50	18.1	0.317	1.3

$$\chi_r = \left[\frac{4\pi r^2 \times \dot{q}_{rad}}{\dot{m}_f \times \Delta H_c}\right]$$

where $\dot{q}_{rad}$ is the measured radiant heat flux (W/m^2), $\dot{m}_f$ is the fuel mass flow rate (kg/s), r is the radial distance of the radiometer from the flame axis and ΔH_c is the heat of combustion (kJ/kg). Exhaust gas samples are withdrawn through a stainless-steel, water-cooled sample probe for emission measurement [14].

3. Results and discussion

The effects of H_2 addition to the LPG fuel jet stream on flame length, soot free length fraction (SFLF), radiant fraction, gas temperature and NO_x emission level are investigated for two different cases as shown in Table 2. For both cases, the total mass flow rate for fuel stream is kept constant while adding H_2 to the LPG. The low velocities are chosen to neglect the effect of flow turbulence caused due to high jet velocity and thus enabling us to investigate the effect of bluff-body generated vortex on the flame characteristics.

3.1. Flame length

The variation of non-dimensionlized flame length is shown in Fig. 3a and b with change in H_2 mole fraction in the LPG–H_2 hybrid fuel with three different bluff-body burner configurations for cases (I) and (II), respectively.

3.1.1. Preheated air

For $\delta/D_f = 0.15$ [14], the flame length is observed to be reduced with hydrogen addition. The change in flame length is around 10% when hydrogen addition is varied from 0% to 40%. Similar trends for $\delta/D_f = 0.65$ and 1.3 are observed in Fig. 3a. However, the

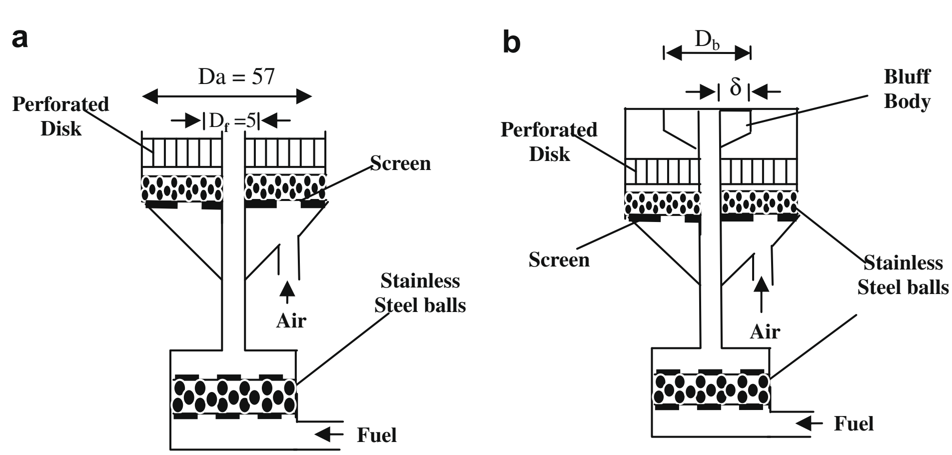

Fig. 1. Schematic diagram of (a) coaxial burner and (b) coaxial burner with Bluff-Body.