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Effect of hydrogen addition on overall pollutant emissions of inverse diffusion flame

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ABSTRACT

In this paper, the effect of hydrogen (H_2) addition on the pollutant emissions of an IDF (inverse diffusion flame) burning LPG (liquefied petroleum gas) has been studied. Pollutant emission behavior was intensively investigated at fuel lean condition, and CO_2, CO, HC, and NO_x emitted from the flame were measured with their emission indices reported. HC and CO emissions are highly dependent on overall equivalence ratio, and both HC and CO are very high at fuel lean condition while reduce to nearly zero at equivalence ratio larger than 0.8 in LPG-H_2 IDF. NO_x emission follows the trend of HC due to N_2O-intermediate and Fenimore mechanisms at fuel lean condition while NO_x emission increases with equivalence ratio at fuel rich condition due to thermal NO_x mechanism. Hydrogen addition is found to promote the conversion of CO and HC into CO_2, and there exists a threshold fraction of hydrogen over which a significant reduction of CO and HC occurs. High air jet Reynolds number tends to induce poor combustion and thus increasing HC, CO and NO_x emissions. Compared to LPG IDF, LPG-H_2 IDF starts to generate noticeably CO and HC emissions earlier, and both CO and HC emissions are heavier.

1. Introduction

With high flexibility in flame adjustment and wide range of stable operation, IDF (inverse diffusion flame) is a kind of flame, which has great potential in domestic and industrial application. Although IDF has separately supplied air jet and fuel jet(s), IDF is different from NDF (normal diffusion flame) that the central air jet of IDF is surrounded by the fuel jet(s). Typically in an IDF, the velocity of the central air jet (v_{air}) is much higher than that of the surrounding fuel jet(s), and thus the velocities difference entrains the fuel jet(s) into the air jet, resulting in strong air-fuel mixing and thus better flame stability. Many research efforts have been conducted to investigate the structure of IDF [1–5]. The results show that almost all the important characteristics of a flame, such as flame length, pollutant emission, temperature, and stability, can be changed by adjusting the air jet and fuel jet(s) velocities.

Studies on IDF during the past decade were primarily focused on pure hydrocarbon fuels, mainly including LPG (liquefied petroleum gas) [4,6–21]. These LPG IDFs have inevitable emissions of CO/CO_2/HC. Also, the CO and HC emissions are significantly high when the equivalence ratio ($\varnothing$) is less than one [12], which inevitably limits the use of LPG IDFs.

An alternative option is to mix LPG and hydrogen as a fuel mixture to decrease the C/H ratio and reduce the toxic CO/HC emissions as well as CO_2 emission. However, hydrogen has very distinct properties from LPG, so the effect of hydrogen addition to LPG on reducing CO/HC/CO_2 emissions would not be straightforward. Although the increased amount of H and OH radicals caused by hydrogen addition may accelerate the pyrolysis of LPG, the promoting effect may be not significant for butane and propane, which, as the major components of LPG, already contain many H atoms. Also, there are some contradicting results reported in the literature. Some researchers found that hydrogen addition reduced CO/CO_2 emissions for hydrocarbon flames [22,23] and engines [24,25], while some researchers found a slight increase in CO/CO_2 emissions [26,27]. So it can be expected that the effect of hydrogen addition to LPG on CO/CO_2 and HC emissions is a complicated phenomenon. Further, adoption of inverse diffusion flame in this project also adds uncertainties to flame emissions. Although the overall gaseous emissions of IDF have been studied

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Nomenclature

d_{air}	Diameter of air jet nozzle, m
$\varnothing$	Overall equivalence ratio
$H_2\%$	Volumetric percentage of hydrogen in the fuel mixture of LPG-H_2, %
ρ_{air}	Density of air, kg/m^3
μ_{air}	Dynamic viscosity of air, kg/(m s)
MW_i	Molecular weight of species *i*, g/mol
MW_{LPG}	Molecular weight of LPG, g/mol
MW_{Fuel}	Molecular weight of fuel mixture, g/mol
$\mathrm{Re}_{\mathrm{air}}$	Reynolds number of air jet
v_{air}	Air jet velocity, m/s
V_{air}	Volumetric flow rate of air jet, Liter/min
V_{fuel}	Volumetric flow rate of fuel jets, Liter/min
V_{H_2}	Volumetric flow rate of H_2 addition, Liter/min
V_{LPG}	Volumetric flow rate of LPG, Liter/min
x_{fuel}	Moles of carbon per mole of fuel
x_{LPG}	Moles of carbon per mole of fuel
χ_i	Mole fraction of emission
$\mathrm{EI}_{\mathrm{fuel}}$	Fuel-based emission indices, kg/kg for CO, CO_2, and HC, g/kg for NO_x
$\mathrm{EI}_{\mathrm{LPG}}$	LPG-based emission indices, kg/kg for CO, CO_2, and HC, g/kg for NO_x

before, for example, Sze et al. [4] investigated NO_x emission of an IDF and Zhen et al. [2,28,29] worked on effect of swirl on IDFs, there is still a lack of comprehensive study on the CO, CO_2, HC, and NO_x emissions of IDF burning a mixture of LPG and H_2 fuels. Therefore in this study, experiments were carried out under various equivalence ratios and air jet Reynolds numbers to identify the effect of hydrogen addition on the CO, CO_2, HC, and NO_x emissions for a LPG-H_2 IDF. The fundamental information, such as flame structure and flame stability, of the LPG-H_2 IDF can be found in Ref. [30].

2. Experimental setup

Fig. 1 illustrates the experimental system. The IDF burner used in this study has similar design with that in Ref. [30]. The burner consists of a central air jet surrounded by 12 fuel jets arranged circumferentially. The diameters of the central air nozzle (d_{air}) and fuel nozzles are 5.5 mm and 2 mm, respectively. The center-to-center distance between the air nozzle and each fuel nozzle is 12 mm. Compressed air was used for the central air jet. The main fuel used is commercial standard LPG available in Hong Kong, which contains 30% propane and 70% butane by volume. Hydrogen of 99.9% purity was added to LPG as an additive. LPG and H_2 were mixed inside the mixing chamber of the burner, which is full of wire net to enhance mixing of the two gaseous fuels. Detailed properties of the fuel mixtures are given in Table 1.

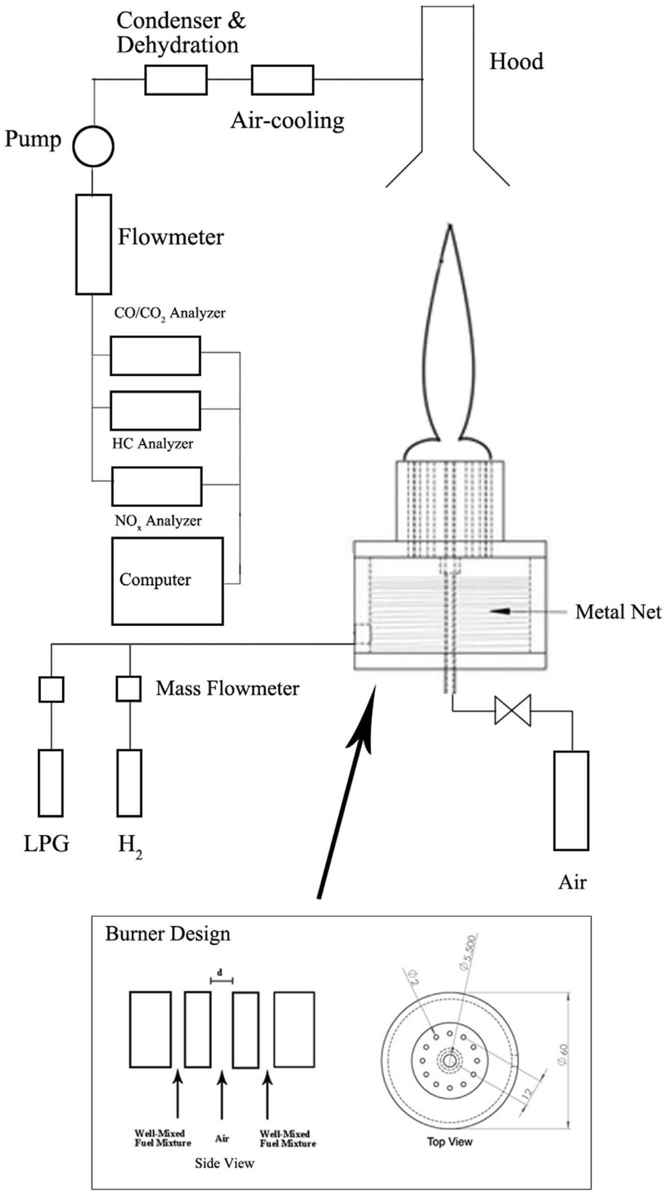

Fig. 1. Experiment setup.

The pollutant emissions of the IDF were measured by the 'hood' method. A copper hood was placed over the flame tip to channel the flue gas. The flue gas was sampled and cooled down through a long stainless-steel tube inserted into the hood, and dehydrated before being delivered to the gas analyzers, (Non-dispersed Infrared Sensor for CO/CO_2, HFID (Heated Flame Ionization Detector) for HC, and HCLA (Heated Chemiluminiscence Analyzer) for NO_x). For each experimental condition, 100 emission data were collected, and the averaged values were reported in this paper. The method reported by Kline and McClintock [31] was used in uncertainty analysis. With 95% confidence level, the maximum uncertainties in emission measurements were 8.5%, 8.4%, 8.3%, and 9.6% for CO_2, CO, HC, and NO_x respectively.

3. Experimental method

The main experimental parameters include the air jet Reynolds number ($\mathrm{Re}_{\mathrm{air}}$), the overall equivalence ratio ($\varnothing$) of the supplied air and fuels, and the volumetric fraction of hydrogen in the LPG-H_2 mixture ($H_2\%$). In an IDF, the air jet velocity (v_{air}) plays an important role in anchoring the flame and enhancing air/fuel mixing. The air jet Reynolds number, $\mathrm{Re}_{\mathrm{air}}$, is used to indicate the magnitude of v_{air}. $\mathrm{Re}_{\mathrm{air}}$ and $\varnothing$ were calculated as:

$$Re_{air} = \frac{\rho_{air} v_{air} d_{air}}{\mu_{air}} \tag{1}$$