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Experimental and numerical study on the emission characteristics of laminar premixed biogas-hydrogen impinging flame

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HIGHLIGHTS

- The total emissions (NO, NO_2 and CO) were measured under the impingement condition.
- A computational model was developed to simulate the impinging jet flames.
- The NO formed via different routes were isolated and calculated in the simulations.
- Effects of impingement on the emission formation process were discussed.

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ABSTRACT

The total emissions (EICO, EINOx, $EINO_2$ and NO_2/NOx ratio) of laminar premixed biogas-hydrogen impinging flame were obtained experimentally while a computational model was developed to calculate the impinging flame. The NO amount produced via different routes (thermal, prompt, NNH and N_2O routes) were isolated and calculated in the simulation. The effects of separated distance and equivalence ratio on the emission formation were discussed quantitatively. The results are summarized as follows. The lower values of EICO at small and large H are caused by the weakened fuel oxidization and improved CO oxidization, respectively, and the EICO is increased with ϕ owing to the increasingly incomplete fuel oxidization. The NO amounts of thermal, prompt, NNH and N_2O routes and their contributions on total NO are affected considerably by the separated distance. The decreased prompt NO with H leads to the initial drop of EINOx at fuel-rich condition. The thermal NO and NNH route dominate the NO formation at $\phi = 0.8$ and 1.0, while the contribution of prompt NO is improved significantly at fuel-rich condition. The rising trend of EINOx with ϕ is primarily predominated by the enhanced prompt NO. As H is enhanced, the rising and dropping trends of $EINO_2$, as well as NO_2/NOx ratio, are caused by more intensive air entrainment, promoting the NO_2 formation, and the extended high temperature region, accelerating the NO formation and the NO_2 destruction, respectively. The enhanced $EINO_2$ with ϕ is primarily caused by the increased H atom in the air mixing region to promote the HO_2 formation.

1. Introduction

Since the flame jet has the enhanced forced convection and high heating temperature, it has been extensively adopted in the domestic and industrial facilities for the impingement heating purpose. However, the chemical reactions occurring in the flame jet make its impingement heat transfer process more complicate than that of the isothermal jet. Thus an increasingly amount of researches are performed to investigate the heat transfer mechanism of the laminar and turbulent impinging flames and the effects of various parameters, such as equivalence ratio, turbulence and heating distance, on its impingement heating performance. These studies can facilitate to establish a comprehensive understanding on the thermal characteristics of the impinging flame jet.

The nozzle to plate distance is a critical parameter affecting the combustion characteristics of flame jets, and it can result in several characteristic flame structures owing to the existence of reaction zone in the flame jet [1–4]. Thus the effects of nozzle-to-plate distance on the heat transfer characteristics of various flame jets have been widely investigated. Rigby and Webb [5] investigated the diffusion flame impingement experimentally, and found that the buoyancy effects can lead to the flame instability and the unsteady impingement zone as the heating distance is increased. Hoogen-

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doorn et al. [6] conducted the experiment to analyze the turbulent heat transfer of the round premixed flame jets. The results show that the radial distribution of heat flux having a bell shape can be observed at large nozzle to plate distance. Hou et al. [7] systematically investigated the effects of heating distance on the combustion characteristics of the flame jet using the Bunsen type burner and suggested a best heating distance qualitatively. Apart from this, a number of studies were performed to study the effects of other significant parameters, such as fuel compositions, equivalence ratio and Reynolds number, on the heat transfer characteristics of laminar and turbulent flame jet using various combustion burners. Wei et al. [8] investigated the effects of heating distance, Reynolds number and equivalence ratio on the heat transfer performance of the laminar premixed Bunsen flame, and proposed a function to predict the optimum heating distance quantitatively. Dong et al. [9] investigated the impinging flame jet at several equivalence ratios, and found that the heat flux is dropped faster at fuel-lean condition due to the excessive air in the flame. Hargrave et al. [10] suggested that the maximum heat flux occurs at the slight fuel-rich condition for the impinging methane/air flame jet. Cremers et al. [11] conducted the numerical model to analyze the heat transfer of the oxy-fuel flames, and reported that the mechanism of thermochemical heat release can account for up to 60% of total heat transfer rate for the oxy-fuel flames. Hindasageri et al. [12] investigated the heat transfer distribution for the premixed methane/air flame experimentally, and reported that the increased Reynolds number can improve the heat flux effectively due to the stronger forced convection process. Besides, several specifically designed burners were used to explore their heat transfer characteristics for the sake of the practical applications [13–15].

With the plenty of works focusing on the impingement heat transfer of flame jets, there are few researches to study the emission characteristics of impinging flame jets, although the pollutant emissions are also significant for the practical utilization of impinging flame jet. Mishra [16] measured the emission data of the impinging premixed LPG flame. It is observed that the emission data are considerably affected by the heating distance, and CO level is increased while NO level is decreased with the increase in equivalence ratio. Saha et al. [17] found that the increased nozzle to plate distance reduces the CO emission but improves the NOx emission of rich methane and ethylene flames. Li et al. [18] performed the experiment to analyze the effects of plate temperature on the emission of the premixed LPG flame and found that the enhanced plate temperature can lower CO emission and increase NOx emission. Zhen et al. [19] observed that the premixed flame has the low CO and NOx emissions than that of the diffusion flame at impingement condition. It can be seen that, for the impinging flame jet, NOx and CO emissions are two significant gaseous emissions. Furthermore, compared to the CO emission, the NOx formation is more complicated since NO can be formed via different routes (thermal NO, prompt NO, N_2O intermediate and NNH route) in the flame. However, rare works are conducted to investigate how impingement affects the NO formation via these routes. In order to obtain a more comprehensive and clear understanding on the emission characteristics of laminar premixed impinging flame, the pollutant emissions (NOx and CO) under the impingement condition will be measured while a computational model will be developed to figure out the NO amounts generated through different routes.

Thanks to the short carbon cycle [20], biogas is considered as a promisingly renewable fuel and has attracted more interest in recent years. It is mainly composed of CH_4 and CO_2, and the methane proportion in the biogas varies from 40% to 80% typically [21–23]. Whereas, CO_2 existing in the biogas can exert several negative influences on the fuel characteristics, which can restrict the practical applications of biogas fuel. In order to better utilized the biogas fuel, blending biogas with hydrogen can be an effective method due to the promotion of hydrogen enrichment on the fuel characteristics, such as the enhanced laminar burning velocity and improved flame stability [24–26]. Therefore, biogas with hydrogen enrichment will be adopted to generate the laminar premixed impinging flame in this study, and the investigation on its emission characteristics can improve the understandings of such a fuel. Based on the experimental and numerical data, the effects of separated distance (H) and equivalence ratio (ϕ) on the emission formation process under the impingement condition will be discussed quantitatively.

2. Experimental apparatus and computational model

2.1. Experimental apparatus

The hood method [27] is adopted so as to measure the overall pollutant emissions of the tested flames. In order to collect the burned gases of the impinging flame, a conical stainless steel hood, whose base-diameter and height are both 300 mm, is placed over the copper plate with a 200 mm diameter. The copper plate is cooled by the water jacket with a constant temperature of 313 K. The sampling was conducted until the respective condition was sustained to 5 min, which can ensure the equilibrium condition of the flue gas in the hood. The gas analyzers used in current study are the California Instruments Corporation Model 400 and Model 300 which can measure the volumetric concentrations of NO/NOx and CO/CO_2, respectively. In addition, the impinging flame temperature was measured with a type-B thermocouple in the experiment, and the radiation and conduction losses were considered for the correction of measured data [28]. More details of experimental apparatus can be found elsewhere [19].

The biogas is emulated by the pure CH_4 and CO_2 according to volumetric ratios of 7.5:2.5, represented by BG75 in the study. The hydrogen is added in the biogas with the volumetric ratio of 10% which is defined as $\alpha H_2 = V_{H2}/(V_{CH4} + V_{CO2})$. The purity of CH_4, CO_2 and H_2 used in the experiment are over 99.99% while the air is supplied by the compressed air. The diameter and length of the burner nozzle are 9 mm and 400 mm respectively. In order to guarantee the laminar flow, the Reynolds number of the unburned gases in the nozzle is less than 2000. With the measured data, the emission indexes were calculated according to the following equation:

$$EI_i = \frac{1000 \cdot n_c x_i M_i}{x_{CO2} M_{fuel}}$$

where x_i and M_i represent the measured concentration and the molecular weight of the pollutant i, and x_{CO2} and M_{fuel} denote the measured concentration of CO_2 and the molecular weight of the fuel, respectively. n_c symbolizes the moles of carbon in a mole fuel. Since the concentrations of other carbon-containing species such as HC and CO were found to be much lower than that of CO_2, only the CO_2 concentration was considered in the equation for the data calculation. Apart from the calculation of EICO and EINOx, since NO_2, which is more toxic than NO, was found to constitute a considerable part of NOx in current study, the $EINO_2$ and NO_2/NOx ratio were also obtained to study its formation process. The uncertainty analysis on experimental data was performed [29]. Using a 95% confidence level, the uncertainties are 0.4% in emission index of CO, 1.5% in emission index of NOx and 1.5% in emission index of NO_2.

2.2. Computational model

STAR-CD software [30] was employed to simulate the laminar premixed impinging flames. With the axi-symmetric flame, 2D