Propagation Characteristics of Premixed Propane/Hydroegn/air Flame in a Granular Bed

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1. Introduction

Granular bed technology is widely used across the industry, and applications include powder/particle processing, pharmaceuticals, filtration [1], and in burners [2]. After the granular medium has been installed, a granular bed possesses the characteristics of a porous medium. In line with the concept of excess-enthalpy combustion in a porous medium [3], when a premixed flame passes the porous media material the medium will cause heat from the downstream high-temperature zone to propagate back to the upstream low-temperature zone, preheating the upstream premixed mixture. This type of combustion phenomenon tends to enhance both flame transmission speed and stability, and has been studied by many scientists [4-9]. Past experimental research has investigated such aspects as the effect of the material and porosity on thermal conduction, convection, and radiation characteristics in the flame propagation progress, as well as flame propagation stability and the flammability limit. A burner consisting of a granular bed offers the advantages of low NO_x emission and high efficiency of combustion [10, 11], and can burn waste or materials with low heating value, such as biomass and agricultural/forestry residues. These fuels are characterized by high of moisture and many noncombustible components, causing lower heating values and unstable combustion. Takeno and Sato [12] found that combustion of a premixed methane/air mixture in a porous medium enhance combustion efficiency and extend flammability limit. Furthermore, since the flame can be stably transmitted through a ceramic tube, exhaust emissions are far less than for a free-propagated flame. In an investigation of the combustion of methane in a porous medium burner, Evans et al. [13] found that the flame speed in the porous medium was higher than that of a free flame, which increased the flammability limit. Tseng [14] used numerical simulation to investigate the effect of hydrogen addition on the combustion of a methane/air fuel mixture in a porous medium burner, and found that the addition of hydrogen can increase the flame propagation speed and increase the flammability limit, while causing a higher of flame thickness.

These phenomena occurred because of the high mass diffusivity of hydrogen. In the previous researches, study on combustion in a porous medium facilitated understanding of the transmission characteristics of a premixed gas flame in a granular bed burner. The current study used experimental measurements to investigate the flame propagation mechanisms of lean premixed propane/hydrogen/air mixtures in a granular bed under different mixture velocity (U), equivalence ratio (ϕ) , and hydrogen addition ratio (α) conditions.

2. Experimental method

The porous medium burner system used in this study was as shown in Figure 1. The experimental reaction vessel consisted of a steel tube with a length of 100 cm, an outer diameter of 8.5 cm, and an inner diameter of 7.86 cm. The porous medium consisted of a bed of layered ceramic granules. The ceramic granules had an average particle diameter of 4 to 5 mm, and the bed length was 25 cm. Ceramic honeycomb plates were installed at the upstream and downstream ends of the two. The chief

functions of the honeycomb plates consisted of flow regulation and immobilization of the bed medium. The physical characteristics of the ceramic granules were referred to ref. [1], which had a specific heat of approximately 628-700J/kgK and a porosity of 0.33.

The measurement system of granular bed measured the temperature and sampled exhaust gas for analysis. Five K-type thermocouples were installed at intervals of 5 cm upstream of the granular bed, and were used to measure the temperature of the flame in the granular bed. An data acquired system (VR 18) was used to record the temperatures measured by the thermocouples, and the sampling rate was 1 Hz. The fuel supply system provided hydrogen, propane, and air. Different types of flow meters and control valves were employed to adjust the composition and flow rate of the gas entering the mixer, which performed premixing of the fuel gas. The mixing of the fuel gas was described by the following equation:

$$\alpha H_2 + (1 - \alpha) C_3 H_8 + [(5 - 4.5\alpha)/\phi] (O_2 + 3.76 N_2) \rightarrow Products$$
 [1]

Here, α is the percentage of hydrogen in the premixed C₃H₈/air flame, and ϕ is the equivalence ratio. The ceramic honeycomb plates placed at each end of the granular medium increased the fuel gas mixing effect and provided a flow regulation function. The fuel gases consisted of experimental grade 99.99% purity hydrogen and 99.95% purity propane. This study used the granular bed to investigate the effect of different hydrogen addition ratios on the premixed C₃H₈/air flame in the granular bed at different equivalence ratios and different flow rates.



Figure 1 Experimental setup

3. Results and Discussions

To investigate the influence of different premixed propane/hydrogen/air flame equivalence ratios and flow rates on combustion characteristics in a granular bed, this study experimentally measured the temperature distribution in the granular bed, which was used to assess flame propagation characteristics and probe transmission phenomena in the granular bed.

3.1 Flame location measurement

Figure 2 shows the propagation of a premixed $C_3H_8/H_2/air$ flame in a granular bed for pure propane (α =0) and when hydrogen was added (α =10). The axial temperature distribution in the bed is shown at different times (1000~2700 sec) for a flow rate of 30 Liter/min and an equivalence ratio (ϕ) of 0.6. When a premixed flame consisting of pure propane (α =0) propagated from downstream to upstream (dash line), the time when the flame reached the first thermocouple was taken as the initial time. When the time was 1000 sec, the temperature was 1234K at x=2.5 cm, 714K at x=5.0 cm, 319K at x=7.5 cm, 314K at x=10.0 cm, and 312K at x=12.5 cm. Heat released from combustion in the premixed flame propagated upstream through thermal convection, conduction, and radiation, preheating the upstream ceramic granules, and causing upstream propagation of the flame phase. However, due to the emission

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of heat, the thickness of the flame reaction zone widened, causing an increase in thermal radiation, which in turn caused thermal losses from the flame and increased the preheating effect [2]. Due to this preheating effect, the flame continued to propagate upstream with the passage of time. The wave propagation speed (Figure 2) was affected by heat emissions and the equivalence ratio [2]. When hydrogen was added to the premixed C_3H_8/air flame, and when the flow rate was 30 liter/min and ϕ was 0.6, the axial temperature distribution in the granular bed (Figure 2, solid line) showed that the addition of hydrogen (α =0.10) caused the flame temperature to be slightly higher, and the flame reaction to become thinner, than in the case of pure propane (α =0). The chief cause of these phenomena was the mass diffusivity of hydrogen, which facilitated the diffusion of hydrogen into the premixed flame reaction zone, increasing the flame temperature and wave propagation speed.



Figure 2 Temperature distribution of premixed C₃H₈/H₂/air flame in a granular bed

3.2 Effect of hydrogen addition on flammability

Figure 3 show the effect of addition of hydrogen to a premixed C_3H_8/air flame is to increase the flammability of the flame. Under free propagation conditions, the flammability limit of a premixed C_3H_8/air flame is ϕ =0.51. After the flammability limit of a premixed C_3H_8/air flame in a granular bed reaches 0.5, the flammability limit does increase to 0.4 (α =0.15) as the hydrogen addition ratio increases (α increases). This result indicates that the heat retention ability of the ceramic granules in the granular bed can increase flame flammability. When large amounts of hydrogen are added, the flammability limit of the premixed C_3H_8/air flame will approach that of pure hydrogen. Since hydrogen has a higher mass diffusivity compared with that of propane, the addition of hydrogen gives a premixed C_3H_8/air flame wildly flammability.



Figure 3 Hydrogen addition effect of premixed C₃H₈/air flame flammability

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3.3 Flow rate effects

The addition of hydrogen to a premixed C_3H_8/air flame alters fuel characteristics such as unit mass/volume thermal value, mass diffusivity, and thermo diffusivity, and also alters the equivalence ratio and Lewis number of flame front. The firing rate of a granular bed can be expressed as the product of the low heating value and flow rate, as shown in the following equation:

Firing rate=[LHV_{H2}× χ _{H2}+LHV_{C3H8}× χ _{C3H8}]×flow rate [2]

Because of this, for a constant equivalence ratio ($\phi=0.6$), changing the hydrogen ratio and flow rate will change the firing rate of the premixed fuel gas in a granular bed. Figure 4 shows the effect of different hydrogen addition ratios with emissions and flame temperature for $\phi=0.6$. While flame temperature increases with α at low firing rates, the flame temperature distribution becomes $T_{\alpha=0}$ T $a=0.15 > T_{\alpha=0.10}$ after the firing rate increases to approximately 1.35 KJ/sec. As the firing rate increases further, the flame temperature expands. This finding indicates that, while the addition of some hydrogen tends to increase the flame temperature at low flow rates and low thermal emission rates, the flame temperature rapidly decreases as recirculation efficiency increases with the firing rate [2]. The heat transmission mechanism is dominated by thermal conduction at this time. Although thermal radiation is proportional to the flame area and the fourth power of the flame temperature, because the flame temperature is relatively low, the addition of hydrogen causes only a limited increase in the flame temperature, and the flame area is relatively small, flame temperatures are chiefly dependent on fuel characteristics at low flow velocities. However, an increase in firing rate will change the heat transfer mechanism in the granular bed, gradually increasing the importance of thermal radiation and reducing thermal conduction effect. And as the firing rate increases, there will be less preheating due to flame propagation in the granular bed. As a result, although the flame temperature when small quantities of hydrogen (α =0.10) are added will be less than that of a premixed C₃H₈/air flame, the flame characteristics will approach those of pure hydrogen as the addition ratio increases, and both thermal radiation and the preheating effect will increase. As a result, the flame temperature will be slightly less than that of a premixed C3H8/air flame, but still higher than the flame in the case of $T_{\alpha=0.1}$.



Figure 4 Effect of firing rate on flame temperature in a granular bed

3.4 Effect of heat transfer mechanisms on wave propagation

Previous research [2] indicates that, when heat emissions are low, thermal conduction is the dominant form of heat transfer, and has the greatest influence on the flame, in a granular bed. However, as the heat emission rate increases, thermal radiation gradually exerts greater influence over flame propagation characteristics, including flame temperature and wave propagation speed. Figure 5 shows the effect of the Nusselt number of the premixed flame in the granular bed on flame temperature and wave propagation speed. The Nusselt (Nu) number is the ratio of convection to conduction, and is defined as follows:

$$Nu = 2 + 1.1 Re^{0.6} Pr^{1/3}$$
[3]

In this study, for low *Nu* values, because thermal conduction is transferred from the premixed flame to the granular bed, and is transferred through the granular bed, chiefly by conduction, thermal convection in the premixed fuel gas has a relatively limited effect. But as the *Nu* value of the premixed flame increases, heat transfer by thermal convection from the premixed flame to the granular medium increases, which implies greater heat loss from the flame front. But while the Nu value increases with the flow rate, and also increases with the flow velocity, these also increase the firing rate and increase the temperature of the premixed flame. As a result, although the addition of small amounts of hydrogen (α =0.10) increases the firing rate, the high mass diffusivity of hydrogen causes the flame thickness to decrease, reducing thermal radiation. This in turn lessens the effect of preheating of fresh reactant, causing the flame temperature in the granular bed to be lower than for a premixed C3H8/air flame (α =0.10) (figure 5a). But as the hydrogen addition ratio increases, but the preheating effect nevertheless decreases. The wave propagation speed consequently shows the effect of preheating from the premixed flame (figure 5b). This funding is consistent with the results of past research.



Figure 5 Effect of Nusselt number on flame temperature and wave propagation speed of premixed $H_2/C_3H_8/air$ flame in a granular bed

4. Conclusions

The addition of hydrogen to a premixed C_3H_8/air flame will alter the characteristics of the premixed fuel, and also alter the heat transfer mechanism of the premixed flame in a granular bed, changing the heat transmission characters of the premixed gas flame. When a small amount of hydrogen is added, and the firing rate is low, the dominant heat transfer mechanism of the premixed C_3H_8/air flame in a granular bed will consist of thermal conduction, and preheating of the fresh reactant media will not be significant. However, as the firing rate and flame temperature increase, the thermal radiation effect will increase. When hydrogen is added to a premixed C_3H_8/air flame, the premixed gas flame temperature will be $T_{\alpha=0}>T_{\alpha=0.15}>T_{\alpha=0.15}>T_{\alpha=0.10}$. Apart from changing the flame characteristics and heat transmission characteristics, hydrogen also changes wave propagation speed.

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