Abstract

This study investigates the characteristics of a lean premixed hydrogen/air flame in a ceramic granular bed (CGB) by conducting experimental measurements and numerical simulations. The experimental results show that the operating range (equivalence ratio, $\phi = 0.2 - 0.4$) of CGBs for flame propagation is smaller than that of free flame due to the laminar flame speed ($S_L$), reactivity, and firing rate ($I$) of H$_2$. In addition, flame temperature ($T_f$) increases with increasing $I$, but decreases with increasing $\phi$. Furthermore, $S_{ab}/S_L$ decreases with increasing $u_H/S_L$ by the fuel characteristic of Hydrogen (H$_2$) and heat recirculation in the CGB. The numerical simulation results show that the flame reaction zone in the CGB (porosity, $\varepsilon = 0.33$) is greater than that of free flame ($\varepsilon = 1$) because H$_2$ reacts early and changes the flame propagation characteristics.

1. Introduction

H$_2$ is characterized by high flame speed, low minimum ignition energy, and wide flammability [1–2], thus being advantageous for use as a fuel. However, the high reactivity of H$_2$ limits its storage and combustion applications. The applied research has mostly focused on H$_2$ co-fired with hydrocarbon in internal engines [3-4]. The fundamental research of hydrocarbon-hydrogen-air mixtures have been extensively studied [5-6]. The process of H$_2$ diffusion is influenced by flame stretch [7], which causes instability [8-9]. Premixed flames propagate in porous medium. The heat accumulation and porosity characteristics of porous media allow premixed flames to transfer heat in these media. A porous medium preheats reactants, altering the heat transfer characteristics between the products and reactants in premixed flames, the mass diffusivity and thermal diffusivity of premixed flame front. Therefore, the propagation of premixed flames in a porous medium is characterized by a higher burning rate and a more stable flame than that occurring in free flame propagation. These characteristics vary with the properties and porosity of...
the porous medium, causing changes in thermal conduction, convection and radiation during the flame propagation process, thereby influencing flame stability, propagation speed and flammability [9-13]. Numerical simulation methods were used by Mishra et al.,[14] to explore the flame characteristics of different material stacks and also by Al-Hamamrre et al.,[15] who investigated porous-medium burners with various porosity levels. Their results indicated that the porosity and characteristics of porous media have some influence on the burning rate and flame temperature, depressing the temperature to below adiabatic flame temperature, \( T_{ad} \).

The present study involves measuring the flame propagation characteristics of a CGB containing premixed \( \text{H}_2/\text{air} \) flames. A numerical simulation method was used to investigate the changes in the flame structure and heat transfer mechanism when the premixed flame is influenced by the properties of the CGB [12,16]. The results show that at low firing rates (\( I \)), \( T_f \) is substantially lower than \( T_{ad} \), and a broad flame distribution exhibits a flameless phenomenon. In addition, Yang and Wu [16] found that the propagation of premixed \( \text{H}_2/\text{C}_3\text{H}_8/\text{air} \) flames in CGBs produces a higher \( S_{ab} \) and lower \( T_f \) than premixed propane/air flames. In addition, \( T_f \) was low because of the mass and thermal diffusivity changes that occurred when the concentration of \( \text{H}_2 \) was increased. This indicated that \( \text{H}_2 \) has a relatively high level of diffusivity in preheated CGB. These previous studies have revealed that, because \( \text{H}_2 \) is limited by its own fuel characteristics, it is typically used in co-firing with hydrocarbon fuel. \( \text{H}_2 \) is a gas featuring low molecular weight and high reactivity. Therefore, we measured the absolute propagation speed and flame temperature of premixed \( \text{H}_2/\text{air} \) flame in CGB and calculated the thickness of flame and the effects of chemical mechanism in an effort to understand the influences of premixed \( \text{H}_2 \) flame on CGB.

2. Experimental method

Figure 1 shows the CGB and the measurement system used in the experiments. The CGB comprised ceramic balls (average diameter 5 mm) placed in a steel pipe (diameter = 8.5 cm; length = 100 cm). The physical properties of the ceramic balls are shown in Ref. [12]. The specific heat was 628–700 J/kgK, and a porosity (\( \varepsilon \)) of 0.33 was obtained after the ceramic balls were stacked. The composition of the premixed \( \text{H}_2/\text{air} \) flame is represented as \( \text{H}_2 + \frac{1}{28} [\text{O}_2 + 3.76\text{N}_2] \rightarrow \text{Products} \), where \( \phi \) is the equivalence ratio. The mixture velocity (\( u \)) and porosity velocity (\( u_\varepsilon \)) are defined as \( u_\varepsilon = \varepsilon u \), where \( \varepsilon \) is the porosity of the CGB. Temperatures were measured by five K-type thermocouples located 2.5 cm apart in the CGB, and the data was extracted using a VR18 data extraction system at 1 Hz. To consider the effect of thermal radiation, the measured temperature was defined as the measured gas temperature in the CGB [12]. Previous studies have shown that flame characteristics are related to the \( u_\varepsilon \), \( \phi \) and \( I \) [12]. The firing rate \( I \) is equal to the heating value of hydrogen by the mass flow rate of hydrogen. To calculate the firing rate of the input fuels, the following formula was used as firing rate, \( \Gamma (\text{kJ/s}) = \dot{m}_{\text{H}_2} \times \text{HHV}(\text{H}_2) \).

3. Experimental Results

\( \text{H}_2 \) is characterized by a wide flammability because of its fuel characteristics, and hydrocarbon fuel extends it flammability in CGB. However, in this study, premixed \( \text{H}_2/\text{air} \) flame in CGB did not extend its flammability. When within the operating range (\( u<110 \text{ cm/sec} \)), the premixed \( \text{H}_2/\text{air} \) flame can be categorized into blow-off, submerged, and flash-back flames according to its heat transfer phenomenon. The operating condition of the submerged flame is \( \phi = 0.2–0.4 \) (Figure 2). According to a previous study [12], at low\( \phi \), the heat transfer mechanism influencing the flame propagation characteristics in CGB is dominated by thermal conduction. Therefore, flames with low \( \phi \) tend to transform into surface flames and even blow off. These flames do not easily develop into submerged flames. As \( \phi \) increases, \( S_L \) rapidly increases, causing the surface flame to transform gradually into a submerged flame. At this point, the heat
transfer mechanism of premixed flame changes with changing gas velocity. At low $u$, the dominant effect of heat transfer mechanism is thermal conduction; as $u$ increases, the effect of thermal conduction gradually weakens, increasing the thermal radiation effect. When $\phi>0.4$, $S_L$ increases drastically, weakening the heat recirculation effect in CGB and consequently causing the premixed flame to flash back.

4. Numerical Simulation Approach

To investigate the propagation characteristics of premixed H$_2$/air flames in the CGB, commercial software ANSYS FLUENT v14, H$_2$ oxidation mechanisms[17], thermochemical[18] and transfer[19] properties were employed to determine the two-dimensional structure of the premixed H$_2$/air flame at $\phi = 0.35$ in pipes with and without porous medium. The calculation domain incorporated the flame
structure in a geometrically shaped CGB, in which the premixed H$_2$/air was at an initial temperature of 300 K. Energy equations for solid and gas phase of the CGB as the follows:

$$\frac{\partial}{\partial t}(\varepsilon \rho_g E_g + (1 - \varepsilon) \rho_s E_s) + \nabla \cdot (\varepsilon \rho_g \overrightarrow{E}_g + \rho_s \overrightarrow{E}_s) = \frac{S^h_g}{\tau} + \nabla \cdot \left( k_{\text{eff}} \nabla T - (\sum \Delta h f_i) + (\bar{\tau} \cdot \vec{v}) \right)$$  \hspace{1cm} (1)

$$k_{\text{eff}} = (\varepsilon k_g + (1 - \varepsilon) k_s)$$  \hspace{1cm} (2)

5. Numerical Simulation Results and Discussion

Figure 3 is a distribution diagram of flame temperature and major chemical species at $\varepsilon = 1$ and $\varepsilon = 0.33$ for the premixed H$_2$/air flame where $\phi = 0.3$, $u = 26.69$ cm/s, and $\Gamma = 0.65$ kJ/s. When $\varepsilon = 1$, $T_f$ increased rapidly at $x = 5$ cm. H$_2$ and O$_2$ also started to react at this point. The flame reaction regime was small, and $T_f$ reached approximately 1100 K (Figure 3a). When the flame propagated in the CGB at $\varepsilon = 0.33$, the flame temperature slowly increased at $x = 5$ cm. H$_2$ reacted earlier than O$_2$ because H$_2$ was influenced by the temperature, enhancing mass diffusion that caused the early reaction. The heat transfer between the flame and the CGB generated a broader flame reaction zone and reduction of $T_f$.

6. Conclusion

Experiments and numerical simulations were conducted to explore the combustion characteristics of premixed H$_2$/air flame generated by heat recirculation in the CGB. The combustion phenomena and resulting factors of lean premixed H$_2$/air flame in the CGB were investigated. The premixed H$_2$/air flame in the CGB did not extend its flammability. This was because the H$_2$ flame exhibited a higher SL and lower $\Gamma$ than that of the hydrocarbon flame. Consequently, heat recirculation between the flame and the CGB decreased, thus reducing the operating range. The numerical simulation results showed that the H$_2$ flame reaction zone in the CGB was larger than that of the free flame, which caused greater flame heat loss and heat recirculation. Consequently, $T_f$ decreased, generating a flameless phenomenon. Moreover, because the intensity of the reaction step was influenced by changes both in temperature and concentration caused by heat recirculation, the flame regime and reaction intensity were lower than those of the free flame.
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References


