Research on Gas Mixing Characteristics and Combustion Performance of Micro Burner with Different Channel Angle

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Abstract. In this study, the cold and hot processes at different incident angles of the micro-burner are numerically simulated, and the flow field, concentration field and temperature field in the burner are analysed. The mixing effect of cold H\textsubscript{2} and air streams is the worst when the angle is 15°, and the best while the angle is 75°. When considering the combustion process, the velocity distribution of air and H\textsubscript{2} is similar to the cold state. The combustion temperature rises first, and the average temperature rise rate gradient of the section is the largest while the angle is 15°. The section temperature reaches the maximum in the length of 15mm. When the space of the micro-burner is sufficient, the angle has little effect on the combustion process. In the vicinity of the entrance section, different angles of incidence have a greater impact on the position of the fire in the burner and the violent reaction zone.

1. Introduction

The micro-energy power system can be widely used in electronic devices in various industries such as industry, agriculture, environmental protection, medical and health, aerospace, etc. The micro-energy power system based on combustion can provide power for micro-machines, and has many advantages such as small size and long duration [1]. As the most critical component of the micro-energy power system, the internal flow characteristics and combustion performance of the micro-burner are the focus of research.

The research on micro-burners mainly focuses on the influence of flame propagation state and stability and combustion efficiency with burner structure, environmental factors, inlet parameters, fuel physical properties, etc. Ren et al. [2] conducted an experimental study on the combustion process of micro-burners with different tube diameters, fuels, and inlet speeds, and analysed the changes of the flame state and the influencing factors. Through numerical simulation analysis, Zuo et al. [3] found that adding a stepped pipe expansion structure to a bluff body micro-burner is beneficial to flame stability and propagation, which can improve combustion efficiency, but the inlet velocity increases and the efficiency decreases. Xu et al. [4] used Fluent to numerically simulate three types of micro-ceramic tube burners with different pipe diameters, and discussed the effects of applied voltage, air-fuel ratio, and inner diameter on the burner performance. Zhang et al. [5] conducted numerical and experimental studies on the combustion process of air-associated microtubes, and discussed the effects of tube diameter, inflow velocity, and tube wall material on the maximum temperature and flame extinction limit velocity. Li et al. [6] studied the mixing performance of H\textsubscript{2} and air, flame stability limit and combustion efficiency in a two-dimensional micro burner with a separating plate through numerical simulation.
According to the literature review, it can be determined that the structural heat transfer, inlet height, and inlet velocity all have a significant impact on the mixing process of the fuel and oxidant in the microchannel and the stability of the diffusion combustion flame, thereby determining the flame stability and combustion efficiency. However, for the angle of different incident channels, the mixing characteristics of fuel and oxidant and the combustion characteristics, so far, this aspect has not been thoroughly studied. Therefore, in this work, the effect of different incident channel angles on the mixing performance of hydrogen and air and the combustion characteristics of the planar micro-burner are numerically studied.

2. Numerical Simulation Method

2.1. Physical Model

Figure 1 shows the schematic diagram of the micro-burner. Air and hydrogen enter the burner from the inlet with a diameter \((D_1, D_2)\) of 1 mm, and are discharged from the outlet. The length of the entire burner tube \(L\) is 50 mm, and the length of the air and hydrogen inlet tubes is 2 mm. The default horizontal pipe is a hydrogen pipe, and the angle \(\theta\) with the air pipe can be changed from 15° to 90°. The origin of the coordinate is the center of the inlet of the hydrogen pipeline. A quadrilateral grid was used in the research process. Through the verification of grid independence, a grid with 123,000 grids was finally selected for computational research.

![Figure 1. Schematic diagram of micro burner.](image)

2.2. Mathematical Model

Since the Knudsen magnitude of hydrogen and air is \(10^{-5}\), which is much smaller than the critical magnitude of \(10^{-3}\), hydrogen and air can be regarded as continuous fluid in the burner channel, and can still be described using the Navier-Stokes equation. The control equations mainly include continuity equation, momentum conservation equation, component conservation equation and energy conservation equation [7].

\[
\nabla \cdot (\rho u_i) = 0 \tag{1}
\]

\[
\nabla \cdot (\rho u_i u_i) = -\nabla p + \nabla \cdot (\mu \nabla u_i) + \rho g \tag{2}
\]

\[
\nabla \cdot (\rho u_i T) = \frac{1}{c_p} \nabla \cdot (\lambda \nabla T) - \frac{1}{c_p} \sum_n h_n \omega_n \tag{3}
\]

\[
\nabla \cdot (\rho u_i Y_n) = \nabla \cdot \{ \rho D_n \nabla Y_n + \rho D_n^T \nabla (\ln T) \} + \omega_n \tag{4}
\]

where \(\rho\) is the density, kg/m³; \(u\) is the fluid velocity vector, m/s ; and the subscript \(i\) represents the component in different directions in space; \(p\) is the pressure, Pa ; \(\mu\) is the dynamic viscosity, Pa·s ; \(g\) is the acceleration of gravity, m/ s² ; \(T\) is the temperature, K ; \(c_p\) is the heat capacity at
specific pressure, \( J / (kg \cdot K) \); \( \lambda \) is the thermal conductivity, \( W / (m \cdot K) \); \( h_n \) is the enthalpy, \( J / mol \); \( \omega_n \) is the reaction rate, \( mol / (m^3 \cdot s) \); \( Y_n \) is the mass fraction of the component; the subscript \( n \) represents a certain component; \( D_n \) is the mass diffusivity, \( m^2 / s \); \( D_n^T \) is the thermal diffusivity, \( m^2 / s \).

The chemical reaction occurring in the numerical simulation is a typical exothermic reaction of oxyhydrogen combustion [8]. The inlet velocity of the air flow is 5 m/s, and the Reynolds number is much smaller than 2320, considering that it is a laminar flow. To simplify the calculation, the effect of the burner wall on the gas is not considered, and the effects of volume force, dissipation and radiation are ignored. In the setting of boundary conditions, both the hydrogen and air inlets are set as velocity inlet boundaries, given the flow velocity, temperature and percentage of components of the inlet gas flow; the outlet is set as a free outflow boundary, and the wall surface is a non-slip isothermal wall boundary. The detailed boundary conditions is shown in table 1.

| Case | Wall Temperature (K) | Velocity of H\(_2\) (m/s) | Velocity of air (m/s) | Channel angle \( \theta \) (°) |
|------|----------------------|---------------------------|----------------------|-----------------------------|
| 1    | 300                  | 5                         | 5                    | 15                          |
| 2    | 300                  | 5                         | 5                    | 30                          |
| 3    | 300                  | 5                         | 5                    | 45                          |
| 4    | 300                  | 5                         | 5                    | 60                          |
| 5    | 300                  | 5                         | 5                    | 75                          |
| 6    | 300                  | 5                         | 5                    | 90                          |

3. Results and Discussion

3.1. Effect of Cold Gas Mixing
When only considering the mixing of gas in the burner, and not considering the combustion situation, the cold H\(_2\) and air streams are injected into the burner at the same speed of 5 m/s. Taking case3 as an example, extract the mole fraction of hydrogen in the y direction at different positions along the x direction (figure 2). It can be found that, near the inlet, because the hydrogen is injected horizontally, the mole fraction of hydrogen at the bottom in the vertical direction is much larger than the value at the top. As the gas moves in the x direction, hydrogen and air begin to gradually mix, and the difference of the mole fractions of hydrogen between the top and bottom of the pipe gradually decreases. Figure 3 depicts the hydrogen mole fraction distribution in the y direction at the burner outlet. It can be found that under the six working conditions, at the exit position, hydrogen and air are not completely mixed evenly.

Among them, the mixing effect is the worst when the angle is 15°, and the mixing effect is the best while the angle is 75°. The angle of the incident airflow is small, and the degree of mutual mixing is small, which requires a longer space for uniform mixing. When the angle is greater than 60 degrees, the impact of the bottom airflow is greater, the degree of mutual mixing depends on the speed, and the mixing efficiency is not directly related to the angle.

3.2. Combustion Characteristics
It can be seen from the temperature distribution of case3 (figure 4) that H\(_2\) and air enter the burner, after a short distance of movement and mixing, they start to ignite and burn. The temperature starts to rise sharply, with a maximum temperature of 2500K. As the gas moves toward the outlet, the oxygen in the air is consumed, the heat generated by the combustion is gradually lost by the wall surface, and the final gas temperature is maintained at 329.8K.
Figure 2. Distribution of hydrogen concentration of case 3.

Figure 3. Distribution of hydrogen concentration of x=50 mm.

Figure 4. Temperature distribution of case 3.

Figure 5. Velocity distribution of case 3.

Along the x direction, the average temperature distribution (figure 6) of different sections can be found that when the angle is 15°, the combustion temperature rises first, and the average temperature rise rate gradient of the section is the largest. When the length is 15 mm, the section temperature reaches the maximum.

When the angle changes from 15° to 90°, the smaller the included angle, the greater the temperature gradient. As the degree of reaction weakens, the average temperature of the cross-section gradually decreases. When the angle is 15°, the rate of decline is the fastest, and the range of the high-temperature region is the narrowest, followed by 60° and then 90°. The angles 30°, 45°, and 75° have similar temperature changes, maintaining a long high temperature range.

Figure 7 illustrates the oxygen distribution of different cases. It can be found that the oxygen concentration at the inlet is basically unchanged, and no combustion reaction is performed. As the hydrogen and air are mixed in motion, the two begin to undergo a violent combustion reaction, and oxygen begins to be rapidly consumed. At the case with an angle of 15°, the combustion reaction starts first, and oxygen is consumed first, which is consistent with the temperature in figure 6 that starts to
rise first. When the angle changes from $45^\circ$ to $90^\circ$, the oxygen concentration distribution is very similar. This is because the designed air-fuel ratio is 1:1, so the amount of oxygen is relatively small, oxygen is consumed faster.

![Figure 6. Average temperature distribution along the x direction.](image)

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![Figure 7. Oxygen distribution of different cases.](image)

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Since the length of the burner is 50 times the diameter of the inlet, the molar concentration of $\text{H}_2$ at the outlet remaining nearly the same under 6 cases, which indicates that when the space of the micro-burner is sufficient, the angle has little effect on the combustion process. In the vicinity of the entrance section, different angles of incidence have a greater impact on the position of the fire in the burner and the violent reaction zone.

4. Conclusions
In this study, the cold and hot processes at different incident angles of the micro-burner are numerically simulated, and the flow field, concentration field and temperature field in the burner are analysed. The following conclusions are got:

(1) Cold $\text{H}_2$ and air streams are injected into the burner, the mixing effect is the worst when the angle is $15^\circ$, and the mixing effect is the best while the angle is $75^\circ$. The angle of the incident airflow is small and the degree of mixing with each other is small, which requires a longer space for uniform mixing.

(2) When considering the combustion process, the velocity distribution of air and $\text{H}_2$ is similar to the cold state. The airflow speed of the pipe rises rapidly when the gas is burned; The combustion temperature rises first, and the average temperature rise rate gradient of the section is the largest while the angle is $15^\circ$. The section temperature reaches the maximum in the length of 15 mm.
(3) When the space of the micro-burner is sufficient, the angle has little effect on the combustion process. In the vicinity of the entrance section, different angles of incidence have a greater impact on the position of the fire in the burner and the violent reaction zone.

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