Numerical studies of the interaction mechanism between the pilot flame and main flame

Lili Zhang, Yongzhang Cui*, and Pengfei Yin
Department of Thermal Engineering, Shandong Jianzhu University, Jinan, China

Abstract. The interaction mechanism between the rich premixed pilot flame and lean premixed main flame was investigate in this paper. A two-dimensional numerical model was adopted with detailed chemistry and species transport and with no artificial flame anchoring boundary conditions. The transport and reaction characteristics on the both sides of the main flame were analysed with the equivalence ratio via from 0.6 to 0.75. The results show that the radicals diffuse from the pilot flame to the reaction zone of the main flame, which contributing to the change of species concentration and chemical reaction rate. The pilot flame can the increase flame propagation speed, lowered the position of flame base and enhance the flame stability of the main flame.

1 Introduction

Energy efficiency and reduction of the NOx and CO emissions are the key points which restrict the development of the gas water heater[1]. The premixed combustion has the characteristics of lower flame temperature, more complete combustion and lower NOx emission. Whereas, the premixed flame has poor stability and was limited in a narrow equivalence ratio range. The pilot flame[2] is frequently used to stabilize the premixed flame, while the mechanism of the chemistry and mass transport between the flames, and the method to reduce of both NOx and CO are not yet clear.

According to the study of Pires[3], the temperature of the rich premixed flame is higher than the lean premixed flame. The H₂, H, CO radicals are mainly in the rich premixed flames, and the OH, O and O₂ radicals are in the lean premixed flame. The triple flame has a high temperature, where the thermal NO and intermediate N₂O are formed. Duclohier[4] used a complex reaction mechanism to simulate the rich-lean flame. He found that the height of lean premixed flame and triple flame increased with the rich premixed flame equivalence ratio and decreased with lean premixed flame equivalence ratio. And in his research range, the rich premixed flame was very stable, while the lean premixed flame and triple flame are prone to jitter. Ganter[5] found that a high concentration of CO accumulated near the wall due to the diffusion, and a small amount of CO was consumed by chemical reaction. Tomas[6] used OH and CH chemiluminescence method to measure the local equivalence ratio of rich and lean flame. It was found that when the equivalence ratio of main flame was 0.65 and the equivalence ratio of pilot flame was 1.2, the local equivalence

* Corresponding author: cyz@sdjzu.edu.cn
ratio of diffusion zone was close to the theoretical equivalence ratio. When the equivalence ratio is greater than 1.2, the diffusion zone migrates to the lean flame.

In recent years, flame instability caused by the flow and components disturbance\cite{7,8} has attracted great attention. While the stability of flame depends on the flame base. In this paper, the interaction mechanism between the rich premixed pilot flames and lean premixed main flames and wall surfaces is studied by numerical calculation.

2 Numerical model

The schematic diagram of 2-D geometric model adopted in present work is presented in Fig. 1. The diameters of pilot and main flame holes are respectively 1mm and 2 mm. The distance between the holes is 2 mm. To study the effect of pilot flame on main flame, the boundary condition of bottom edge is symmetry free of the effect of pilot flame. The inlet velocity of main flame is 1m/s with the equivalence ratio of 0.6 ~ 0.7, and the inlet velocity of pilot flame is 0.5m/s with the equivalence ratio of 1.25.

![Schematic diagram of computational domain and boundary conditions.](image)

**Fig. 1.** Schematic diagram of computational domain and boundary conditions.

2.1 Governing equations

Considering the low Mach number, the conservation equations of mass, momentum and energy are expressed as:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (1)
\]

\[
\frac{\partial \rho \vec{V}}{\partial t} = -\nabla p - (\vec{V} \cdot \nabla) \rho \vec{V} + \nabla \cdot \vec{\tau} \quad (2)
\]

\[
\rho c_p \left( \frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T \right) = \nabla \cdot (\lambda \nabla T) - \sum_{k=1}^{K} c_{pk} \left( \dot{\omega}_k \right) - \sum_{k=1}^{K} h_k \dot{\omega}_k W_k \quad (3)
\]

where, \( \tau \) is the stress tensor defined as \( \tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \nabla \cdot \vec{V} \right) \). \( \mu \) is the dynamic viscosity, and \( \lambda \) is the thermal conductivity of mixture. \( \dot{J}_k = -\rho \frac{W_k}{W_{av}} D_{km} \nabla X_k \) is the diffusive mass flux of species \( k \). \( W_k \) and \( W_{av} \) are respectively the molar mass of species \( k \) and mixture. \( D_{km} \) is the average diffusion coefficient for species \( k \) with respect to other components. \( X_k \) is the molar fraction of species \( k \), \( \dot{h}_k \) is the enthalpy of species \( k \), \( \dot{\omega}_k \) is the molar production rate of species \( k \).

The species transport equation can be written as:
The ratio of diffusion zone was close to the theoretical equivalence ratio. When the equivalence ratio is greater than 1.2, the diffusion zone migrates to the lean flame. In recent years, flame instability caused by the flow and components disturbance\(^7,8\) has attracted great attention. While the stability of flame depends on the flame base. In this paper, the interaction mechanism between the rich premixed pilot flames and lean premixed main flames and wall surfaces is studied by numerical calculation.

### 2 Numerical model

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### 2.1 Governing equations

Considering the low Mach number, the conservation equations of mass, momentum and energy are expressed as:

\[
\frac{\partial (\rho Y_k)}{\partial t} + \nabla \cdot (\rho \mathbf{v} Y_k) = - (\nabla j_k) + \dot{\omega}_k W_k
\]

\[
\sum_{i=1}^K Y_i = 1
\]

The diffusion velocity of species \(k\) is expressed as:

\[
v_{\text{diff},k} = - \frac{D_{k,m}}{Y_k} (\nabla Y_k + \frac{Y_k}{W_{av}} \nabla W_{av})
\]

The local equivalence ratio is calculated as the Barlow’s equation:

\[
\phi_{\text{local}} = \frac{0.5(H_2 + H_2O) + CO_2 + CO + 2CH_4}{0.5(CO + H_2O) + O_2 + CO_2}
\]

### 2.2 Numerical method

A two-dimensional numerical model is established referring to the Refs.\(^9\) with a mesh size of 0.02 mm. ANSYS Fluent are applied to solve the conservation equations of mass, momentum, energy and species as well as conjugated heat conduction in solid materials. The second-order upwind scheme is used for discretization and the SIMPLE algorithm is employed for pressure velocity coupling. The detailed thermodynamic and transport properties of the gaseous species from the CHEMKIN databases and the detailed DRM-19 chemistry mechanism are adopted in the model. Considering the Soret (second-order) diffusion is generally much weaker than the Fickian (first-order) diffusion for the CH\(_4\)--air mixture, the Soret diffusion is ignored and assume that \(Le\) equals to 1.

### 3 Results and discussion

#### 3.1 Flame structure

The distribution of flame structure (the line of 10% maximum OH concentration) with \(\phi_{\text{main}}\) from 0.6 to 0.75 is shown in Fig. 2. The results show that the main flame heights are within 3.5~6 mm and pilot flame heights are about 1 mm under the research conditions. With the increase of the equivalence ratio of main flame, the flame height gradually decreases and get closer to the pilot flame, the pilot flame height is basically unchanged. This illustrates that the flame propagation speed increasing with the equivalence ratio results in the flame surface moving downstream. At the same time, the heat transfer from the pilot flame to the main flame, consequently the flame propagation speed of main flame on the side of pilot flame increase and the main flame is inclined toward pilot flame.

The Fig. 3 shows the distribution of flame propagation speed on the flame surface at the condition of \(\phi_{\text{main}}=0.7\). Comparing the both sides of the main flame base, the flame propagation speed on the side near the pilot flame is significantly higher than that of the other side. Correspondingly, the distance between the main flame base and wall on the side near pilot flame is smaller than that of the other side, which indicates that the pilot flame enhances the stability of the main flame.
3.2 Mass diffusion

To reveal the interaction mechanism between the pilot and main flame, the diffusion of several main components with mass fraction greater than $10^{-3}$ is analysed under the condition of $\phi_{\text{main}}=0.7$, shown in Figure 4-6. From Fig. 4, comparing both sides of the main flame, the concentration gradient is more significantly on the sides near pilot flame. This illustrates that the pilot flame changes the mass transfer and chemical reaction of the main flame.

The diffusion velocity profiles of different species on the flame base $x=0.0003$ m and main flame hole centre $y=0.002$ m are shown in Fig. 5-6. From Fig. 5, the O$_2$ and CH$_4$ diffuse downstream and the CO$_2$ and H$_2$O diffuse upstream. The H$_2$O, CO$_2$ diffuse away from the main flame and the CH$_4$ and O$_2$ diffuse towards to main flame base on the side near pilot flame. According to the Eq. 7, the CH$_4$ and O$_2$ diffuse from the pilot flame to the main flame increase the local equivalence ratio, which enhances the flame propagation speed and inclines the main flame toward pilot flame.

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**Fig. 2.** Flame structure in different equivalence ratio of main flame.

**Fig. 3.** The distribution of flame propagation speed on flame surface at $\phi_{\text{main}}=0.7$.
3.2 Mass diffusion

To reveal the interaction mechanism between the pilot and main flame, the diffusion of several main components with mass fraction greater than $10^{-3}$ is analysed under the condition of $\phi_{\text{main}} = 0.7$, shown in Figure 4-6. From Fig. 4, comparing both sides of the main flame, the concentration gradient is more significantly on the sides near pilot flame. This illustrates that the pilot flame changes the mass transfer and chemical reaction of the main flame.

The diffusion velocity profiles of different species on the flame base $x=0.0003$ m and main flame hole centre $y=0.002$ m are shown in Fig. 5-6. From Fig. 5, the $O_2$ and $CH_4$ diffuse downstream and the $CO_2$ and $H_2O$ diffuse upstream. The $H_2O$、$CO_2$ diffuse away from the main flame and the $CH_4$ and $O2$ diffuse towards the main flame base on the side near pilot flame. According to the Eq. 7, the $CH_4$ and $O2$ diffuse from the pilot flame to the main flame increase the local equivalence ratio, which enhances the flame propagation speed and inclines the main flame toward pilot flame.

(a) Diffusion velocity in $x$-direction  (b) Diffusion velocity in $y$-direction

Fig. 4. Contours of mass fraction at $\phi_{\text{main}}=0.7$.

Fig. 5. The distribution of diffusion velocity at $x = 0.0003$ m.

(a) Diffusion velocity in $x$-direction  (b) Diffusion velocity in $y$-direction

Fig. 6. The distribution of diffusion velocity at $y = 0.002$ m.
3.3 Chemical reaction

The chemical reactions consist of H2O and CO2 are listed in the Tab. 1 and 2. The profiles of reaction rate of H2O and CO2 at x = 0.0003 m are shown in Fig. 7. The results show that the reaction (1), (6) and (7) mainly generate H2O, and a peak appears on the side near the pilot flame. According to above, the diffusion of H2 from the pilot flame to the main flame promotes the reactions producing the H2O. On the flame base, the CO2 is mainly from the reaction <2>. The maximum reaction rate is on the main flame base, and affected by the pilot flame the reaction rate near the pilot flame is larger than that of the other side.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>number</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH+H2=H2O+H</td>
<td>(1)</td>
</tr>
<tr>
<td>OH+OH=O+H2O</td>
<td>(2)</td>
</tr>
<tr>
<td>H+OH+M=H2O+M</td>
<td>(3)</td>
</tr>
<tr>
<td>HO2+OH=H2O+O2</td>
<td>(4)</td>
</tr>
<tr>
<td>HCO+OH=H2O+CO</td>
<td>(5)</td>
</tr>
<tr>
<td>CH2O+OH=HCO+H2O</td>
<td>(6)</td>
</tr>
<tr>
<td>CH4+OH=CH3+H2O</td>
<td>(7)</td>
</tr>
<tr>
<td>CH3O+OH=CH2O+H2O</td>
<td>(8)</td>
</tr>
</tbody>
</table>

Table 1. The reactions consist of H2O.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>number</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO+OH=CO2+H</td>
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</tr>
<tr>
<td>CO+O+M=CO2+M</td>
<td>&lt;2&gt;</td>
</tr>
</tbody>
</table>

Table 2. The reactions consist of CO2.

Fig. 7. The distribution of flame propagation speed on flame surface at φmain=0.7.

4 Conclusions

In this paper, the interaction mechanism between the lean premixed main flame and rich premixed pilot flame is studied. The main conclusions are as follows:

(1) The pilot flame increases the main flame propagation speed, lower the main flame base and enhances the main flame stability.
3.3 Chemical reaction

The chemical reactions consist of H₂O and CO₂ are listed in the Tab. 1 and 2. The profiles of reaction rate of H₂O and CO₂ at x = 0.0003 m are shown in Fig. 7. The results show that the reaction (1), (6) and (7) mainly generate H₂O, and a peak appears on the side near the pilot flame. According to above, the diffusion of H₂ from the pilot flame to the main flame promotes the reactions producing the H₂O. On the flame base, the CO₂ is mainly from the reaction <2>. The maximum reaction rate is on the main flame base, and affected by the pilot flame the reaction rate near the pilot flame is larger than that of the other side.

Table 1. The reactions consist of H₂O.

<table>
<thead>
<tr>
<th>Reaction number</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>OH+H₂=H₂O+H</td>
</tr>
<tr>
<td>(2)</td>
<td>OH+OH=O+H₂O</td>
</tr>
<tr>
<td>(3)</td>
<td>H+OH+M=H₂O+M</td>
</tr>
<tr>
<td>(4)</td>
<td>HO₂+OH=H₂O+O₂</td>
</tr>
<tr>
<td>(5)</td>
<td>HCO+OH=H₂O+CO</td>
</tr>
<tr>
<td>(6)</td>
<td>CH₂O+OH=HCO+H₂O</td>
</tr>
<tr>
<td>(7)</td>
<td>CH₄+OH=CH₂O+H₂O</td>
</tr>
<tr>
<td>(8)</td>
<td>CH₃O+OH=CH₂O+H₂O</td>
</tr>
</tbody>
</table>

Table 2. The reactions consist of CO₂.

<table>
<thead>
<tr>
<th>Reaction number</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1&gt;</td>
<td>CO+OH=CO₂+H</td>
</tr>
<tr>
<td>&lt;2&gt;</td>
<td>CO+O+M=CO₂+M</td>
</tr>
</tbody>
</table>

4 Conclusions

In this paper, the interaction mechanism between the lean premixed main flame and rich premixed pilot flame is studied. The main conclusions are as follows:

(1) The pilot flame increases the main flame propagation speed, lower the main flame base and enhances the main flame stability.
(2) There are much H₂ and CO in the pilot flame and much OH and O₂ in the main flame. The mass diffusion results in the increasing of the main flame propagation speed on the side near pilot flame and incline the main flame toward pilot flame.
(3) The pilot flame provides radicals for the main flame, which changes the chemical reaction rate on the main flame base resulting in much H₂O and CO₂ formation.

References