INFLUENCE FACTORS OF METHANE-AIR COUNTERFLOW DIFFUSION FLAME

by

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This paper investigates the influences of pressures, velocities, and temperatures of gases at nozzles on the temperature of flame. Considering that temperature and species mass fractions are functions of axial co-ordinates, a quasi-1-D mathematic model in cylindrical co-ordinates for counterflow diffusion flame is built. The results show that the pressure, velocities, and temperatures of gases can affect the temperature distributions of methane-air counterflow diffusion flame, and that the influence of the variations of velocities at two nozzles on the movement of the starting reaction interface is most significant in these factors.

Key words: counterflow diffusion flame, starting reaction interface, influence factors

Introduction

Counterflow diffusion flame which takes an important role in both theoretic and experimental research has received considerable attention over the past 50 years [1]. The application of counterflow diffusion flame fits the surface ablation of charring materials for reentry of vehicles [2-9]. The physical and mathematical models for counterflow diffusion flame have been studied by many researchers. There are two ways to build the governing equations of counterflow diffusion flame. One combines the potential flow producing at infinitely far position with the boundary layer theory to obtain the governing equations [10]. The other way pointed that the gases come from the two nozzles but not the infinitely far position [11, 12]. However, few researchers pay attention to the starting reaction interface, which is defined as the position where the mole fraction of O_2 shifts to zero. This paper focuses on the influences of the pressure, velocities, and temperatures at two opposed nozzles on the counterflow diffusion flame, especially on the movement of the starting reaction interface.

Model

In fig. 1, we illustrate a schematic of a counterflow diffusion flame stabilized near the stagnation plane of two steady, laminar, axisymmetric, counterflowing, and reactant nozzles. Two opposing axisymmetric nozzles are separated by a distance of L. If we let x and r denote the independent spatial co-ordinates in the axial and the radial directions, respectively, the fuel nozzles are located at x = 0 and the oxidizer at x = L.

The simplifying assumptions are made: (a) the temperature and species mass fractions are functions of x alone; (b) the thermodynamic pressure, P, is constant throughout the

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Figure 1. Schematic of counterflow

diffusion flame

flow field in axial direction, but pressure gradient term appears in the momentum equation in radial direction. Based on the Navier-Stokes equations in cylindrical co--ordinates, the physicochemical processes are expressed by the following conservation equations in the axisymmetric system:

$$G - \frac{\mathrm{d}F}{\mathrm{d}x} = 0 \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\left[\mu\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{G}{\rho}\right)\right] - 2\frac{\mathrm{d}}{\mathrm{d}x}\left(\frac{FG}{\rho}\right) + \frac{3}{\rho}G^2 + H = 0 \qquad (2)$$

$$2Fc_{p}\frac{\mathrm{d}T}{\mathrm{d}x} - \frac{\mathrm{d}}{\mathrm{d}x}\left(\lambda\frac{\mathrm{d}T}{\mathrm{d}x}\right) + \sum_{k}\rho c_{pk}Y_{k}V_{k}\frac{\mathrm{d}T}{\mathrm{d}x} - \sum_{k}h_{k}\dot{\omega}_{k}W_{k} = 0$$
(3)

$$2F\frac{dY_k}{dx} + \frac{d}{dx}(\rho Y_k V_k) - \dot{\omega}_k W_k = 0, \qquad k = 1, 2, \cdots, K$$
(4)

where $G(x) = -\rho v/r$, $F(x) = \rho u/2$, and $H = (1/r)(\partial P/\partial r) \equiv \text{constant}$, the mean molecular weight $\overline{W} = 1/(\sum_{k=1}^{K} Y_k / W_k)$. The parameters ρ , c_p , and λ are, respectively, given:

$$\rho = \frac{P\overline{W}}{RT} \tag{5}$$

$$c_{p} = \sum_{k=1}^{K} c_{pk} Y_{k} = \sum_{k=1}^{K} \frac{C_{pk}}{W_{k}} Y_{k}$$
(6)

$$\lambda = \frac{1}{2} \sum_{k=1}^{K} X_k \lambda_k + \frac{1}{\sum_{k=1}^{K} \frac{X_k}{\lambda_k}}$$
(7)

where the mean molecular weight $\overline{W} = 1/(\sum_{k=1}^{K} Y_k / W_k)$, C_{pk} is the molar heat capacity at constant pressure of k^{th} species, X_k – the mole fraction of the k^{th} species expressing as $X_k = (Y_k \overline{W})/W_k$. The diffusion velocity can be expressed:

$$V_k = -\frac{1}{X_k} D_{km} \frac{\mathrm{d}X_k}{\mathrm{d}x} - \frac{D_k^T}{\rho Y_k} \frac{1}{T} \frac{\mathrm{d}T}{\mathrm{d}x}$$
(8)

where $D_{km} = (1 - Y_k) / \sum_{j \neq k}^{K} X_j / D_{jk}$, and D_{jk} , D_{km} , D_k^T are multicomponent, mixture averaged and thermal diffusion coefficients, respectively.

The chemical reaction rate is a complicated parameter written:

$$\dot{\omega}_{k} = \sum_{i=1}^{I} (v_{ki}'' - v_{ki}') \left\{ k_{f_{i}} \prod_{k=1}^{K} [X_{k}]^{v_{ki}'} - k_{r_{i}} \prod_{k=1}^{K} [X_{k}]^{v_{ki}''} \right\}$$
(9)

The boundary conditions for the fuel (F) and oxidizer (O) streams at the nozzles are:

$$x = 0: F = \frac{\rho_F u_F}{2}, \quad G = 0, \quad T = T_F, \quad \rho u Y_k + \rho Y_k V_k = (\rho u Y_k)_F$$
 (10)

$$x = L: F = \frac{\rho_0 u_0}{2}, \quad G = 0, \quad T = T_0, \quad \rho u Y_k + \rho Y_k V_k = (\rho u Y_k)_0$$
 (11)

The counterflow diffusion flame is seen as a boundary value problem for the dependent variables (*F*, *G*, *T*, Y_k , *H*), which can be solved by the differential eqs. (1)-(5) and the boundary conditions. To obtain the temperatures distributions of counterflow diffusion flame, it is necessary to discretize the differential equations. Here we adopt the central difference format for diffusion term and the upwind scheme for convection term. The final discrete formats of eqs. (1)-(4) can be expressed:

$$-\frac{F_{j} - F_{j-1}}{\Delta x} + G_{j} = 0$$

$$\frac{1}{\Delta x^{2}} \left[\left(\mu_{j} - \mu_{j-1} \right) \left(\frac{G_{j}}{\rho_{j}} - \frac{G_{j-1}}{\rho_{j-1}} \right) + \mu_{j} \left(\frac{G_{j+1}}{\rho_{j+1}} - 2\frac{G_{j}}{\rho_{j}} + \frac{G_{j-1}}{\rho_{j-1}} \right) \right] - \frac{2}{\Delta x} \left(\frac{F_{j}G_{j}}{\rho_{j}} - \frac{F_{j-1}G_{j-1}}{\rho_{j-1}} \right) + \frac{3}{\rho_{j}}G_{j}^{2} + H_{j} = 0$$
(12)
(13)

$$-\frac{1}{\Delta x^{2}} [(\lambda_{j} - \lambda_{j-1})(T_{j} - T_{j-1}) + \lambda_{j}(T_{j+1} - 2T_{j} + T_{j-1})] + \frac{T_{j} - T_{j-1}}{\Delta x} \left(2F_{j}c_{p,j} + \sum_{k} \rho_{j}c_{pk,j}Y_{k,j}V_{k,j} \right) - \sum_{k} h_{k,j}\dot{\omega}_{k,j}W_{k,j} = 0$$
(14)

$$\frac{1}{\Delta x} [2F_j(Y_{k,j} - Y_{k,j-1}) + (\rho_j Y_{k,j} V_{k,j} - \rho_{j-1} Y_{k,j-1} V_{k,j-1})] - \dot{\omega}_{k,j} W_{k,j} = 0, \qquad k = 1, 2, \dots, K$$
(15)

Numerical results

Methane (CH₄) is the main products from decomposition gases for charring ablators in reentry of vehicles. Taking a CH₄-air counterflow diffusion flame as an example, we can get the temperature distributions in the flame by using the program written by us.

Influence of several factors on temperature distributions in the flame is pictured in figs. 2(a)-(d).

From fig. 2(a) we know that the maximum flame temperature moves to the fuel nozzle with an increasing pressure. The width of the reaction zone depends on pressure and the starting reaction interface gets close to the fuel nozzle with a decreasing pressure. Figure 2(b) shows that the maximum flame temperature moves to the air nozzle with an increasing fuel velocity and that the decreasing fuel velocity is a direct ratio to the decreasing the co-ordinate of the starting reaction interface. In fig. 2(c) the maximum flame temperature moves to the fuel nozzle and decreases a bit with an increasing air velocity. From fig. 2(d) it can be seen that the maximum flame temperature moves to the fuel nozzle and increases with an increasing fuel temperature and that the starting reaction interface gets close to the fuel nozzle with an increasing fuel temperature and that the starting reaction interface gets close to the fuel nozzle with an increasing fuel temperature at fuel or air nozzle) on the moving of the starting reaction interface, we compare the co-ordinate variation of the starting reaction interface caused by the percentage changes of influence factors. The influence on this movement is more significant by the variations of velocities at two nozzles than the other factors. It is because of CH₄ decomposing and O₂ ionizing.



Figure 2. Influence of several factors on temperature distributions in the flame; (a) pressure, (b) air velocity, (c) fuel temperature, and (d) air temperature

The maximum mole fraction of CH_4 moves to the air nozzle with an increasing T_o , which can be seen in fig. 3(a). In fig. 3(b) the starting reaction interface gets close to the oxidizer nozzle with an increasing air temperature.



Figure 3. Influence of air temperature on components distributions of flame; (a) mole fraction of CH_4 and (b) mole fraction of O_2

Conclusion

The variations of pressure, velocities, and temperatures of gases at two opposed nozzles can affect the movement of the starting reaction interface and the temperature distributions in the flame. The variation of pressure has the minimum influence while the variations of velocities of gases at two nozzles have the maximum influences. However, under high fuel temperature, the co-ordinate of the starting reaction interface has the most dramatic change because of CH₄ decomposing and O₂ ionizing.

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Nomenclature

- c_p heat capacity, [Jkg⁻¹K⁻¹]
- enthalpy per mass, [Jmol⁻¹] ĥ
- Р - pressure, [Pa]
- temperature, [K] Т
- $u, v velocity, [ms^{-1}]$
- Y mass fraction[-]

Greek symbols

- λ thermal conductivity, [Wm⁻¹K⁻¹]
- μ dynamic viscosity, [Pa·s]

References

- v kinematic viscosity, $[m^2 s^{-1}]$ ρ – density, [kgm⁻³]
- ω chemical reaction rate, [molL⁻¹s⁻¹]

Subscript

- k the k^{th} reactant and product species in the i^{th} reaction

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