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Novel analytical model for predicting the combustion characteristics of premixed flame propagation in lycopodium dust particles †

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Abstract

This paper presents the effects of the temperature difference between gas and particle, different Lewis numbers, and heat loss from the walls in the structure of premixed flames propagation in a combustible system containing uniformly distributed volatile fuel particles in an oxidizing gas mixture. It is assumed that the fuel particles vaporize first to yield a gaseous fuel, which is oxidized in a gas phase. The analysis is performed in the asymptotic limit, where the value of the characteristic Zeldovich number is large. The structure of the flame is composed of a preheat zone, reaction zone, and convection zone. The governing equations and required boundary conditions are applied in each zone, and an analytical method is used for solving these equations. The obtained results illustrate the effects of the above parameters on the variations of the dimensionless temperature, particle mass friction, flame temperature, and burning velocity for gas and particle.

Keywords: Analytical model; Different Lewis numbers; Heat loss effect; Flame temperature; Burning velocity

1. Introduction

Dust explosions are the phenomena wherein flame propagates through dust clouds in air with the increasing degree of partition of any combustible solids. They have been recognized as threat to humans and property for the last 150 years [1]. Several experimental studies on the flame propagation properties of lycopodium dust particles in a vertical duct determining the burning velocity have been reported [2-5]. Seshadri, Berlad, and Tangirala [6] analytically studied the inherent structure of laminar dust flames. In addition, several studies have been conducted on the structure of flame propagation through starch particles [8,9]. Recently, Han et al. [10] conducted an experimental study to elucidate the structure of flame propagation through lycopodium dust clouds in a vertical duct. Moreover, Proust [11, 12] measured the laminar burning velocities and flame temperatures for starch and lycopodium dust particles.

It is essential to consider the effect of the Lewis number in the combustion phenomenon, for instance, in the propagation of premixed laminar flames in narrow open ducts [13]. Chakraborty et al. [14] presented a thermo-diffusive model to investigate the interaction of a non-unity Lewis number and heat loss for laminar premixed flames propagating in a channel. Recently, Chen et al. [15] theoretically and experimentally studied the trajectories of outwardly propagating spherical flames with emphasis on the different Lewis numbers.

In the present study, a novel mathematical approach is developed to describe the steady and one-dimensional flame propagation in a combustible system containing uniformly distributed fuel particles in air. Moreover, the aspects of flame propagation and the structure of the combustion zone are obtained in order to clarify the effects of the temperature differ-

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ence between gas and particle, different Lewis numbers, and the heat loss phenomena on the combustion characteristics of lycopodium dust particles.

2. Theory

In this research, after following [6], it is assumed that the flame structure is composed of three zones as follows:

A preheat-vaporization zone $(-\infty < x < 0^-)$ where particles are heated until they reach the ignition temperature. In this zone, Z_e is considered large; thus, the chemical reaction between the gaseous fuel and the oxidizer is negligible, and due to the temperature difference between gas and particle, the heat exchanged between them is considered.

A reaction zone $(0^- < x < 0^+)$ where the particles are oxidized and burnt. In this region, the convective terms and vaporization terms in the conservation equations are assumed small in comparison with the diffusive terms and reactive terms.

A convection zone $(0^+ < x < \infty)$ where the diffusive terms in the conservation equations are assumed small in comparison with the other parameters.

2.1 Governing equations

In this research, it is assumed that the fuel particles vaporize to form a known gaseous compound, which is then oxidized. The kinetics of vaporization is assumed to be represented by the following expression:

$$w_v = A n_s 4\pi r^2 T^n \, , \tag{1}$$

where A and n are constants assumed to be known, and T is the gas temperature. The combustion process is modeled as a one-step overall reaction, $\nu_F[F] + \nu_{O_2}[O_2] \rightarrow \nu_{\mathrm{Prod}}[P]$, where the symbols F, O_2, P denote the fuel, oxygen, and product, respectively, and the quantities $\nu_F, \nu_{O_2}, \nu_{\mathrm{Prod}}$ denote their respective stoichiometric coefficients. The constant rate of the overall reaction is written in the Arrhenius form $k = B\exp(-E/RT)$, where B represents the frequency factor; E is the activation energy of the reaction; and R is the gas constant. The characteristic Zeldovich number, Z_e, which is assumed large, is defined as

$$Z_e = \frac{E(T_f - T_u)}{RT_f^{\,2}} \, . \tag{2}$$

The subscripts f and u denote the flame and the ambient reactant stream conditions, respectively.

Mass conservation is expressed as

$$\rho v = const \, . \tag{3}$$

Energy conservation is given as

$$\rho v C \frac{dT}{dx} = \lambda_u \frac{d^2T}{dx^2} + w_F \frac{\rho_u}{\rho} Q - w_v \frac{\rho_u}{\rho} Q_v - \frac{\rho_u}{\rho} Q_L \tag{4}$$

where Q, Q_v, Q_L are the heat release per unit mass of the burnt fuel, the heat associated with the vaporizing unit mass of the fuel, and the effect of heat loss per unit mass, respectively. The heat loss effect is formulated as follows:

$$Q_L = \frac{b'\lambda}{d^2} \, . \tag{5}$$

Gaseous fuel conservation is expressed as

$$\rho v \frac{dY_F}{dx} = \rho_u D_u \frac{d^2 Y_F}{dx^2} - w_F \frac{\rho_u}{\rho} + w_\upsilon \frac{\rho_u}{\rho} \, . \tag{6}$$

The mass fraction equation of the particles neglecting the diffusion term is written as follows:

$$\rho v \frac{dY_s}{dx} = -w_\upsilon \frac{\rho_u}{\rho} \, . \tag{7}$$

The equation of state is given as

$$\rho T = const \, . \tag{8}$$

The heat capacity appearing in equation (4) is the combined heat capacity of the gas and particles that can be evaluated from the following expression:

$$C = C_p + \frac{4\pi r^3 C_s \rho_s n_s}{3\rho} \, . \tag{9}$$

The boundary conditions for equations (4), (6), and (7) are given as follows:

$$\begin{aligned} &\text{At } x \rightarrow -\infty \\ &Y_F = 0, Y_s = Y_{Fu}, T = T_u \\ &\text{At } x \rightarrow \infty \\ &Y_F = finite, T = T_b < T_b', T = T_f < T_f' \end{aligned} \tag{10}$$

At adiabatic condition $T_b = T_b', T_f = T_f'$

Furthermore, the effect of the temperature difference between gas and particle is determined using the energy conservation equation for particles as

$$\left(\frac{4}{3}\pi r^3 \rho_s C_s\right)\upsilon_u \frac{dT_s}{dx} = \left(4\pi r^2\right)\frac{\lambda_u}{r}(T - T_s) \,. \tag{11}$$

2.2 Nondimensionalization of the governing equations

The nondimensional parameters are as follows:

$$\theta = \frac{T - T_u}{T_f - T_u}, \theta_s = \frac{T_s - T_u}{T_f - T_u}$$
$$y_f = \frac{Y_F}{Y_{FC}}, m = \frac{\rho\upsilon}{\rho_u \upsilon_u} \tag{12}$$
$$z = \frac{\rho_u \upsilon_u C}{\lambda_u} x, \xi = \frac{3\lambda_u \lambda}{r^2 \rho_u \upsilon_u C \rho_s \upsilon_u C_s}$$

The quantity Y_{FC} is described as

$$Y_{FC} = \frac{C}{Q}(T_f - T_u)\,, \tag{13}$$

where υ_u is the burning velocity in the above equation. Therefore, if these parameters are introduced in Eqs. (4), (6), (7), and (11), the following equations can be rewritten as follows:

$$m\frac{d\theta}{dz} = \frac{d^2\theta}{dz^2} + \omega\frac{\rho_u}{\rho} - q\gamma y_s^{\frac{2}{3}}\theta^n - K\theta \tag{14}$$
$$m\left(\frac{dy_F}{dz}\right) = \left(\frac{1}{L_e}\right)\frac{d^2 y_F}{dz^2} - w\frac{\rho_u}{\rho} + \gamma\theta^n y_S^{\left(\frac{2}{3}\right)} \tag{15}$$
$$m\frac{dy_s}{dz} = -\gamma y_s^{\frac{2}{3}}\theta^n \tag{16}$$
$$\frac{d\theta_s}{dz} = \xi(\theta - \theta_s) \tag{17}$$

where $y_s = 4\pi r^3 n_s \rho_s / 3\rho Y_{FC}$. Several of the parameters such as $\omega, \gamma, q, K, L_e$ are defined as

$$\omega = \frac{\lambda_u w_F}{(\rho_u v_u)^2 C Y_{FC}}, q = \frac{Q_v}{Q}, \kappa = b' Pe^2$$
$$\gamma = \frac{4.836 A n_u^{1/3} \lambda_u (T_f - T_u)}{v_u^2 \rho_u^{4/3} C Y_{FC}^{1/3} \rho_s^{2/3}}, L_e = \frac{\lambda_u}{\rho_u C D_u} \tag{18}$$

Hence, the boundary conditions for these equations are nondimensionalized and defined as follows:

$$\text{At } z \to -\infty \tag{19}$$
$$y_F = 0, y_s = \alpha, \theta = 0$$
$$\text{At } z \to \infty$$
$$y_F = \mathit{finite}, \theta = \theta_b = (T_b - T_u) \big/ (T_f - T_u)$$
$$\text{At } z = 0 \Rightarrow \theta = 1$$

where $\alpha = Y_{Fu}/Y_{FC}$. The quantity q, which is the ratio of the heat required to vaporize the fuel particles to the overall heat release by the flame, is too small and negligible. Moreover, m is considered unity.

Thus, the governing equations are rewritten as

$$\frac{d\theta^\circ}{dz} = \frac{d^2\theta^\circ}{dz^2} + \omega\frac{\rho_u}{\rho} - K\theta^\circ \tag{20}$$
$$\frac{dy_F}{dz} = \left(\frac{1}{L_e}\right)\frac{d^2 y_F}{dz^2} - \omega\frac{\rho_u}{\rho} + \gamma y_s^{\frac{2}{3}}(\theta^\circ)^n \tag{21}$$
$$\frac{dy_s}{dz} = -\gamma y_s^{\frac{2}{3}}(\theta^\circ)^n \tag{22}$$
$$\frac{d\theta^\circ_s}{dz} = \xi\left(\theta^\circ - \theta^\circ_s\right). \tag{23}$$

These equations are solved in each zone using the required boundary conditions.

3. Results

3.1 The effect of the temperature difference between gas and particle

The variation in the dimensionless temperature for gas and particle with Z is plotted in Fig. 1 for $r_u = 20\mu m$. Fig. 2 shows the mass fraction of the particles as a function of Z for different equivalence ratios and for $r_u = 20\mu m$. As shown, the amount of mass fraction decreases with the increasing in the

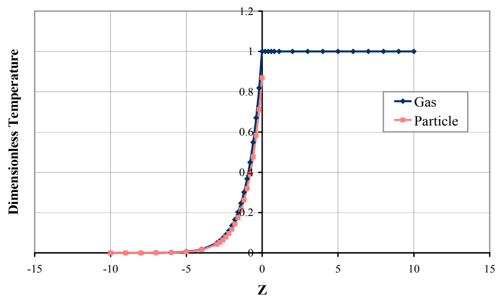

Fig. 1. The variation in the dimensionless temperature with Z.

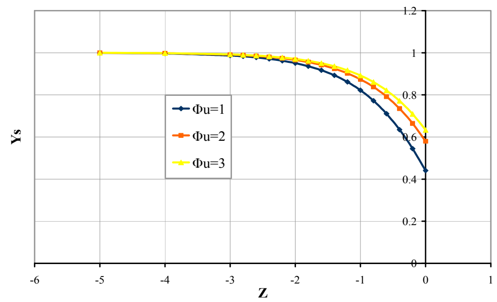

Fig. 2. The mass fraction of the particles for different equivalence ratios.

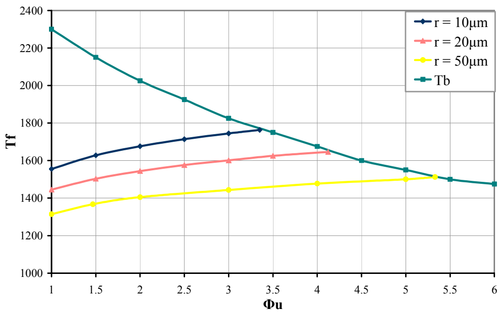

Fig. 3. The variation in the gas flame temperature and adiabatic temperature for different particle radii with equivalence ratio (same as [6]).

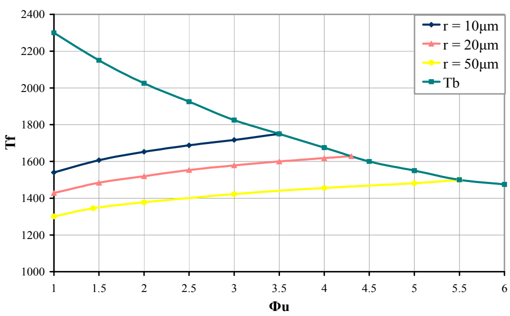

Fig. 4. The variation in the particle flame temperature and adiabatic temperature for different particle radii with equivalence ratio.

distance and a considerable rise in the mass fraction is observed when the equivalence ratio increases.

In Figs. 3 and 4, the flame temperature and adiabatic temperature are presented as a function of Φ for gas and particle, respectively. As seen in these figures, the flame temperature can not exceed the adiabatic temperature, which means that for each radius, there is an acceptable equivalence ratio, and

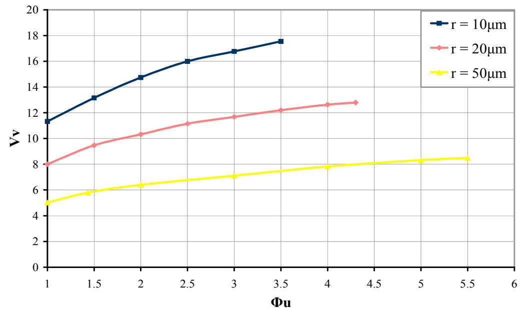

Fig. 5. The variation in the particle burning velocity with equivalence ratio.

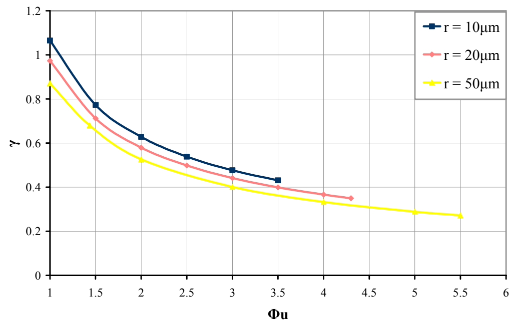

Fig. 6. The variation in γ for the particle with equivalence ratio.

this amount of equivalence ratio changes for different radii. Furthermore, as shown in both Figures, the flame temperature drops for the larger particle size.

Fig. 5 demonstrates the variation in the burning velocity with equivalence ratio for the particle. As presented in this figure, the trend is upward, and increasing the radii causes the burning velocity to plunge due to the increase in the surface area. It should be noted that with the declining values of the radii to zero, the value of the burning velocity is determined for a purely gaseous combustible mixture. Fig. 6 shows the quantity of ɣ as a function of the equivalence ratio for the particle. As can be seen, ɣ declines with the increasing equivalence ratio.

3.2 The effect of different lewis numbers

The Lewis number has a direct impact on the burning velocity. Figs. 7, 8, 9, and 10 show the variation in the burning velocity as a function of the equivalence ratio for various values of Lewis numbers and for the particle radius 10 μm, 20 μm, 50 μm, and 100 μm, respectively. As can be seen, the burning velocity increases by increasing the Lewis number.

3.3 The effect of heat loss

Fig. 11 shows the effect of heat loss on the burning velocity for $r_u = 10, 20\,\mu m$. In order to compare the result for the adiabatic and non-adiabatic situation, the value of heat loss is considered equal to one for the adiabatic condition. A remarkable decrease in the burning velocity occurs when heat loss is considered. This effect is also illustrated in Fig. 12 for the flame temperature, wherein a noticeable decrease in the flame temperature from 1570 to 1530 for $\varphi_u = 1$ and $r_u = 10\,\mu m$, is observed when heat loss is considered.

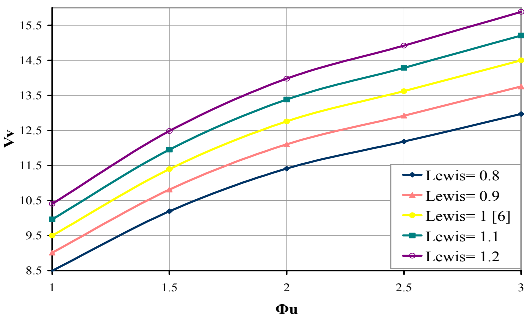

Fig. 7. The variation in the burning velocity with equivalence ratio for different Lewis numbers $(r_u = 10\mu m)$.

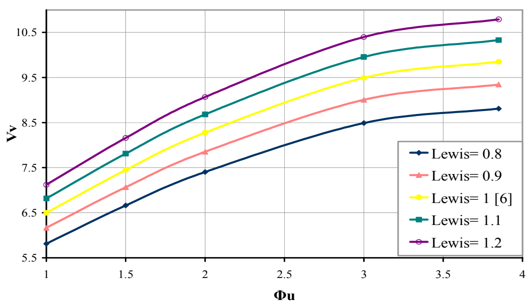

Fig. 8. The variation in the burning velocity with equivalence ratio for different Lewis numbers $(r_u = 20\mu m)$.

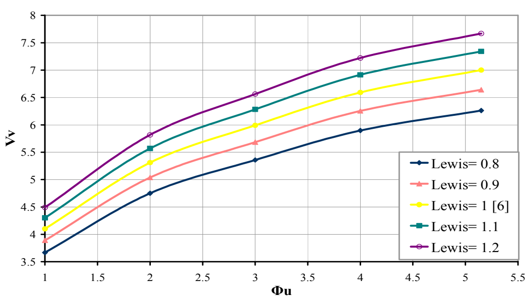

Fig. 9. The variation in the burning velocity with equivalence ratio for different Lewis numbers $(r_u = 50\mu m)$.

Consequently, the variation in the flame temperature with heat loss is plotted in Fig. 13. As observed, the flame temperature goes down and up due to the increasing heat loss for $r_u = 10\,\mu m$ and $r_u = 20\,\mu m$. It should be noted that the increasing part is not physically acceptable because when heat loss increases, it is expected to have a decrease in the flame temperature. Therefore, it is concluded that at this minimum value, the quenching distance phenomenon has occurred.

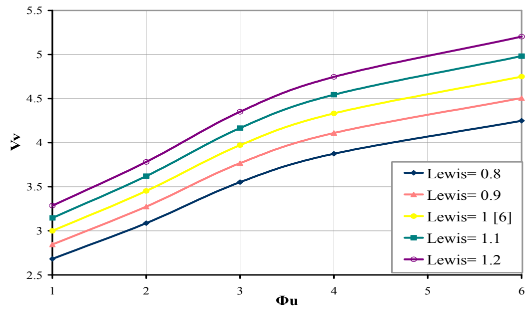

Fig. 10. The variation in the burning velocity with equivalence ratio for different Lewis numbers $(r_u = 100\mu m)$.

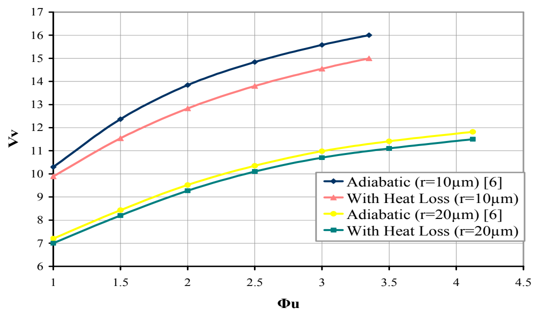

Fig. 11. The variation in the burning velocity with equivalence ratio for adiabatic and non-adiabatic conditions $(r_u = 10, 20\mu m)$.

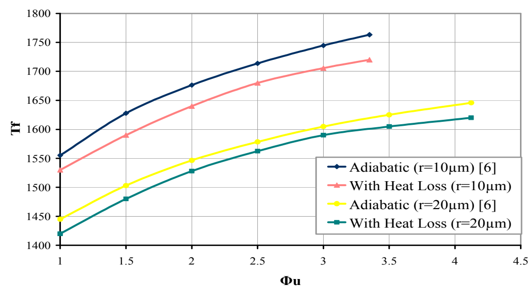

Fig. 12. The variation in the flame temperature with equivalence ratio for adiabatic and non-adiabatic conditions $(r_u = 10, 20\mu m)$.

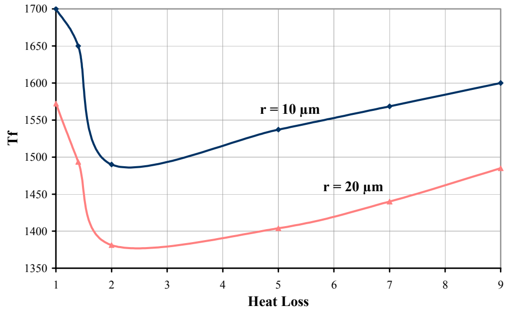

Fig. 13. The variation in the flame temperature with heat loss for $(r_u = 10, 20\mu m)$.

4. Discussion and conclusion

In this article, the effects of the temperature difference between gas and particle, different Lewis numbers, and heat loss from the walls in the structure of premixed flames propagation through lycopodium dust particles are analyzed, and it is observed that the mass fraction of particle increases with the increasing equivalence ratio. In addition, it is shown that the flame temperature is noticeably affected by the heat loss, and a lower temperature is gained in the larger particle size. Moreover, the variation in the flame temperature with heat loss elucidates a kind of fluctuation in the flame temperate, first decreasing to a minimum value and then increasing, clarifying that the increasing part is not physically acceptable due to the quenching distance phenomenon. The burning velocity is another parameter studied in this research, and it is seen that the amount of burning velocity increases with the increase in the Lewis number, and a remarkable drop is perceived in the burning velocity when heat loss is considered, which is contrary to the adiabatic state. It is worth noting that the burning velocity for gas and particle goes up and down when the equivalence ratio and radius increase respectively. Consequently, it can be stated that the combustion parameters such as the burning velocity and flame temperature are modified for particles by considering the temperature difference between gas and particle, different Lewis numbers, and heat loss effects in comparison with the ref. [6].

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