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PREMIXED FLAME PROPAGATION CONSIDERING RADIATIVE HEAT TRANSFER IN NANO LYCOPODIUM PARTICLES

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Abstract: In order to better understand the combustion phenomenon of the nano organic dusts, it is needed to perform some experimental investigations and present some numerical and asymptotic models according to the empirical correlations. In order to investigate the structure of the premixed flames in the combustible systems, containing uniformly distributed volatile fuel particle, in an oxidizing gas mixture, it is assumed that the nano fuel particles vaporize first to yield a gaseous fuel of known chemical structure, which is subsequently oxidized in the gas phase. In this research, a mathematical model for the combustion process of nano organic dusts is presented and solved by using the appropriate asymptotic model. This model is based on the common assumptions in the dust combustion and the crucial impact of radiation on the combustion phenomenon. Consequently, the impression of radiative term on the burning velocity and flame temperature has been presented in nano scale. It must be said that considering the radiative term results to increase in the amount of burning velocity and flame temperature.

Key words: Radiation, Burning Velocity, Nano Lycopodium Particles, Mathematical Model , Flame Temperature

1. INTRODUCTION

Knowledge of organic dust particles combustion needs to be improved and developed both in experimental and theoretical approach due to its importance in science and engineering specially in critical issues of fuel and energy and explosion hazard. Combustion of cloud particles due to complexity of its mechanism is relatively underdeveloped in compare with homogenous combustion. . Thus, it is necessary to utilize a model which can be simple and can be readily verified. The theory of flame propagation in uniformly dispersed, quiescent, gravity free, particle clouds has been developing for decades [1-3]. Many aspects of these theoretical models closely parallel those for premixed gaseous systems. Uniform dispersion of particulates is generally assumed in these models. Some researches have been carried out according the crucial impact of modeling the dust particles. To investigate the burning velocity of laminar flames of lycopodium Kaesche-krische and Zehr [4] fed lycopodium into the lower end of a vertical 2 cm diameter tube. Mason and Wilson [5], who also studied the burning velocity of stationary flames of lycopodium. A valuable model of the lycopodium particles combustion was developed by Seshadri et al. [1] with approximations introduced were that heat transfer by radiation was neglected. Proust [6] described other experimental studies of laminar burning velocities and maximum flame temperature in clouds of starch, lycopodium and sulfur in air.

Han et al. [7, 8] observed some downward propagating flames in the lycopodium particle behind the upward propagating flame.

In this paper, the structure of premixed flames propagating in a uniform cloud of fuel particles is considered. A general treatment of flame propagation supported by volatile fuel particulates should consider both radiative and molecular transport mechanisms. Hence, the radiation term is added and its effects on the combustion of fine lycopodium particles are investigated. Radiative heat transfer plays an important role in the flame propagation. Consequently, this analysis shows that radiative heat transfer is significant in the burning velocity.

2. THEORETICAL ANALYSIS

The analysis is performed in the asymptotic approach, where the value of the characteristic Zeldovich number, based on the gas phase oxidization of the gaseous fuel is large and for rich mixture of fuel. The flame structure consists of a broad preheat-vaporization zone $-\infty < y < 0^-$ in this zone, z_e is considered to be large so chemical reaction between the gaseous fuel and oxidizer is negligible. And a thin reaction zone $0^- < y < 0^+$, and a broad convection zone $0^+ < y < +\infty$.

3. GOVERNING EQUATION

The general equation of radiation transfer is:

$$\frac{dI}{dx} = +K_a I + K_s I - K_a I_b - \frac{K_s}{4\pi} \int_{4\pi} I(\Omega) P(\theta,\Phi) d\Omega \tag{1}$$

The terms on the right of equation (1) are radiation intensity caused by absorption, scattering, emission and incoming scattering brought by other particles respectively. K_s, K_a and I are scattering coefficient, absorption coefficient and radiation intensity respectively. $P(\theta,\phi)$ is phasic function of scattering. The absorption coefficient may be related to the particles size (of diameter d_p) and to particles density (by number n_p); it as supposed that the fraction absorption of monotropic radiation passing through a very thin element of the cloud is the ratio of project solid area of particles to the total area of the containing element. Therefore for the absorption coefficient of gas and particle the following expressions can be written:

The absorption coefficient for gas:

$$K_{ag} = -\frac{1}{\delta} Ln\left(1 - \varepsilon_g\right) \tag{2}$$

The absorption coefficient for particle:

$$K_a = \frac{3}{2} Q_a \frac{\sigma}{\rho_p d_p} \tag{3}$$

And if the scattering of light is done only by particles then, it concludes to:

$$K_s = \frac{3}{2} Q_s \frac{\sigma}{\rho_p d_p} \tag{4}$$

For low Mach number flow and by considering the role of radiation as a mechanism of dust flame propagation, governing equations can be written as follows:

Mass conservation

$$\rho v = const \tag{5}$$

Energy conservation

$$\rho v C \frac{dT}{dx} = \lambda_u \frac{d^2 T}{dx^2} + w_F \frac{\rho_u}{\rho} Q - w_\upsilon \frac{\rho_u}{\rho} Q_\upsilon + \frac{\rho_u}{\rho} K_a I_f \exp\left(K_t x\right) \tag{6}$$

Gaseous fuel conservation

$$\rho v \frac{dY_F}{dx} = \rho_u D_u \frac{d^2 Y_F}{dx^2} - w_F \frac{\rho_u}{\rho} + w_\upsilon \frac{\rho_u}{\rho} \tag{7}$$

The equation governing the mass fraction of the particles neglecting diffusion can be written as:

$$\rho \upsilon \frac{dY_s}{dx} = -w_\upsilon \frac{\rho_u}{\rho} \tag{8}$$

Equation of state:

$$\rho T = const \tag{9}$$

4. NONDIMENSIONALIZATION OF GOVERNING EQUATIONS

The nondimensional parameters are as follow:

$$\theta = \frac{T - T_u}{T_f - T_u}, \theta_s = \frac{T_s - T_u}{T_f - T_u}, y_f = \frac{Y_F}{Y_{FC}}$$
$$m = \frac{\rho \upsilon}{\rho_u \upsilon_u}, z = \frac{\rho_u \upsilon_u C}{\lambda_u} x \tag{10}$$

The quantity Y_{FC} is described as:

$$Y_{FC} = \frac{C}{Q}(T_f - T_u) \tag{11}$$

Where υ_u is the burning velocity in the above equation. So if these parameters are introduced in equations (6) , (7) , (8) , (11), the following equations can be rewritten:

$$m \frac{d\theta}{dz} = \frac{d^2\theta}{dz^2} + \omega \frac{\rho_u}{\rho} + \frac{B'}{V_u^2} e^{\frac{C'Z}{V_u}} - q\gamma y_s^{2/3} \theta^n \tag{12}$$

$$m \frac{dy_F}{dz} = \frac{d^2 y_F}{dz^2} - \omega \frac{\rho_u}{\rho} + \gamma y_s^{2/3} \left(\theta\right)^n \tag{13}$$

$$m \frac{dy_s}{dz} = -\gamma y_s^{2/3} \left(\theta\right)^n \tag{14}$$

The above equation y_s is described as $y_s = 4\pi r^3 n_s \rho_s \big/ \left(3\rho Y_{FC}\right)$. Some parameters such as $\omega, \gamma, q, K, L_e$ are defined as:

$$\omega = \frac{\lambda_u w_F}{\left(\rho_u v_u\right)^2 C Y_{FC}} \quad , \quad \gamma = \frac{4.836 A n_u^{1/3} \lambda_u \left(T_f - T_u\right)}{v_u^2 \rho_u^{4/3} C Y_{FC}^{1/3} \rho_s^{2/3}}$$
$$q = \frac{Q_v}{Q} \quad , \quad \kappa = b' Pe^2 \quad , \quad L_e = \frac{\lambda_u}{\rho_u C D_u} \tag{15}$$

It is assumed that chemical reaction between the gaseous fuel and oxidizer in the reaction zone is negligible. Therefore this assumption is considered in the energy equation and the following expression for the nondimensionalized temperature is derived:

$$\theta^0 = \left(1 + \frac{B'/V_u^2}{(C'^2/V_u^2) - (C'/V_u)}\right) e^Z - \left(\frac{B'/V_u^2}{(C'^2/V_u^2) - (C'/V_u)}\right) e^{\frac{C'Z}{V_u}} \tag{16}$$

Where parameters C', B' are described as follow:

$$B' = \frac{K_a I_f \lambda_u}{\rho \rho_u C^2 (T_f - T_u)} \tag{17}$$

$$C' = \frac{K_t \lambda_u}{\rho_u C} \tag{18}$$

Using equation (16), boundary condition in the reaction zone $0^- < z < 0^+$ is defined as:

$$\left(\frac{d\theta}{dz}\right)_{z\to 0^-} = (1+x) - \frac{xC'}{V_u} \qquad (19)$$

Substituting the nondimensionalized temperature expression, solving equation (14), integrating equation (13) from in the limit $z = -\infty$ to $z = 0^-$ and satisfying the matching conditions in the limits $z = 0^-$ to $z = 0^+$ yield:

$$\frac{3\gamma V_u a^2 x^2 (1+x)}{2C' + V_u} - \frac{3V_u a^2 x(1+x)^2 \gamma}{2V_u + C'} + \frac{4axV_u(1+x)\alpha^{1/3}\gamma}{V_u + C'} +$$
$$\left((1+x)\alpha^{2/3}\gamma\right) - \frac{V_u \alpha^{2/3} x\gamma}{C'} + \left(1/3(1+x)^3 a^2 \gamma\right) - \frac{a^2 x^3 V_u \gamma}{3C'} \qquad (20)$$
$$-\left(a(1+x)^2 \gamma \alpha^{1/3}\right) - \frac{ax^2 \alpha^{1/3} V_u \gamma}{C'} - (1+x) + \frac{xC'}{V_u} = 0$$

5. BURNING VELOCITY

Consequently solving the energy equation in the flame zone, where the rate of heat vaporization of fuel particles is presumed to be zero, and considering the boundary condition in the interface, $z \to 0^-$, $z \to 0^+$ culminate in burning velocity correlation as;

$$V_u = \frac{B'}{C'} + \sqrt{\frac{2(b+1)\upsilon_f \lambda_u B \varepsilon^2 e^{-\frac{E}{RT_f}}}{\rho_u C}} \qquad (21)$$

If the effect of heat vaporization of fuel particles is considered in the burning velocity equation, then the burning velocity equation is followed by:

$$V_v = V_u e^{\left(-\frac{qZ_e}{2}\right)} \qquad (22)$$

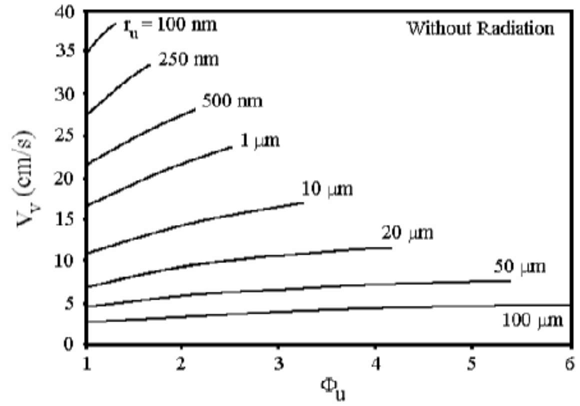
The obtained equations are extracted in order to demonstrate the effect of radiative heat transfer on the important parameters of combustion phenomenon in the organic dust and finally these equations are utilized and plotted as a function of equivalence ration in the following figures.

6. RESULTS AND DISCUSSION

Figure (1) shows the variation of burning velocity with equivalence ratio while the effect of radiative heat transfer isn't considered in the preheat zone. As seen in this figure, decreasing the radius of the particle into the nano scale leads to increasing in the burning velocity quantity. Figure (2) illustrates the calculated value for adiabatic and flame temperature as a function of equivalence ratio for different radius of particle without the influence of radiation. Similarly, the same trend can be seen for flame temperature which means that the value of burning velocity for nano particles is more than micro particles.

Figures (3) and (4) present the effect of radiative heat transfer in preheat zone on burning velocity and flame temperature respectively. Figure (5) illustrates the comparison between the obtained results for two cases: considering the effect of radiative heat transfer in the preheat zone and without considering the heat radiation. As perceived, decreasing the radius values into nano scales results to increase the rate of burning velocity and also it is observed that by considering the radiative term in preheat zone, the value of burning velocity rises in comparison with the case in which the radiation term is neglected.

Figure (6) shows the variation of flame temperature as a function of equivalence ratio for different radiuses for two cases determined above. As seen in this figure, the flame temperature shoots up by increasing the radius values from 250 nm to 100 μm. Also this figure elucidates that the higher flame temperature is gained when the radiation term is included in the preheat zone. It must be said that some radiative energy from post flame zone is added to the preheat zone and this matter causes to increase the temperature in the preheat zone which in turn increases the burning velocity.



Fig, 1: The variation of burning velocity with equivalence ratio

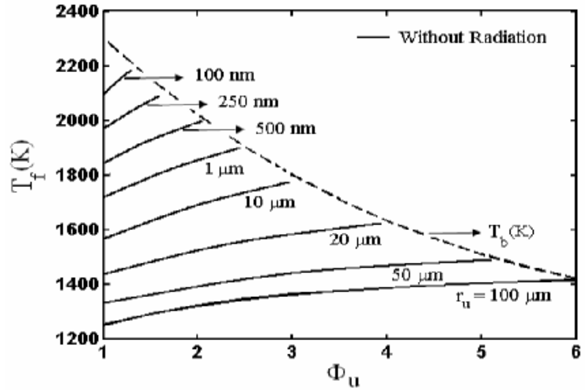


Fig. 2: The variation of flame temperature with equivalence ratio

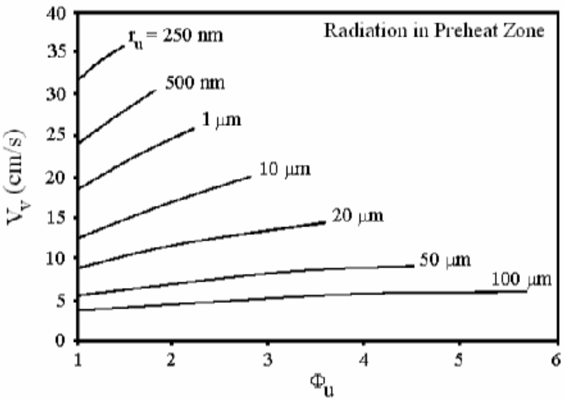


Fig. 3: The variation of burning velocity with radiation in preheat zone

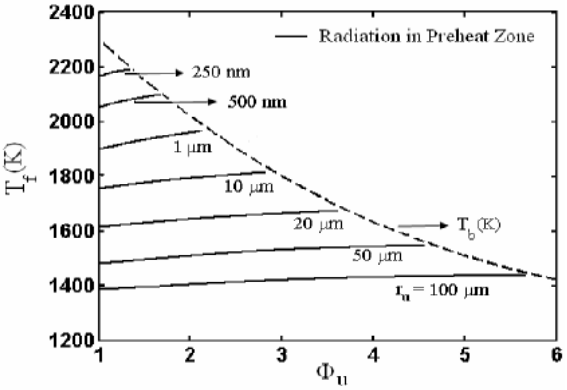


Fig. 4: The variation of flame temperature with radiation in preheat zone

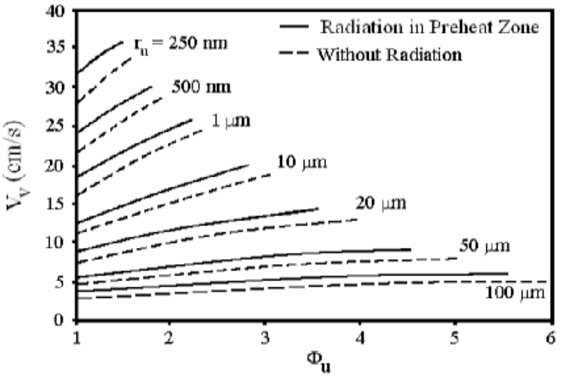


Fig. 5: The variation of burning velocity with and without radiation effect

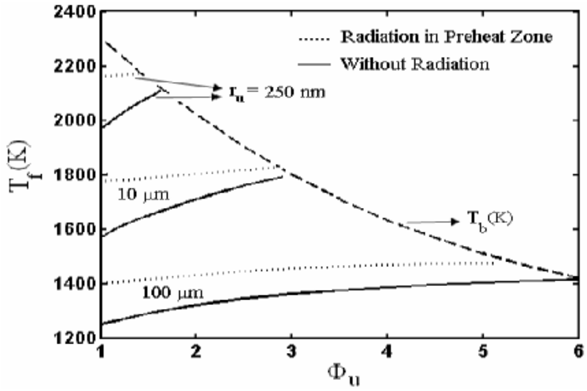


Fig. 6: The variation of flame temperature with and without radiation effect

7. CONCLUSION

This article concentrates on the effect of radiative heat transfer on the combustion characteristics of organic dust particles. Lycopodium particles are used in this research as a reference organic fuel which has a great flammability. In order to clarify this effect, firstly the flame structure is obtained. Then the governing equations and boundary conditions for each zone are extracted and consequently the novel analytical approach is utilized for solving these equations. From this investigation, following conclusions are derived:

1. The value of burning velocity in nano particles is much higher than micro particles.
2. Flame temperature dramatically increases while the radius of particle decreases.
3. Considering the radiative heat transfer culminates to increase in the amount of burning velocity.
4. The higher flame temperature is observed while the radiation effect is taken into account.

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