COMBUSTION OF LYCOPODIUM PARTICLES IN RANDOM MEDIA
Analytical Model and Predicting the Effect of Heat Loss and Lewis Number

by

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In this paper, a new analytical model is proposed to model combustion of micro organic dust particles. In contrast with previous studies, random combustion of lycopodium particles and analyze the effect of heat loss and different Lewis number on the combustion properties is taken which has not be considered before this. It is assumed that flame structure is consisted of a preheat-vaporization zone, a reaction zone and a post flame zone. Then, different Lewis numbers are applied in governing equations. To perform the random model of particle combustion, source term in energy equation has been modeled by means of random states for volatilization of particles in preheat zone. Therefore, different groups which contains random amount of particles and sense a random temperature in the preheat zone has been considered. In this analysis, the impact of random combustion, Lewis number, and particles diameter on the combustion properties of lycopodium particles such as burning velocity, flame temperature and effective equivalence ratio are studied. Consequently, comparison made between results obtained from random model by experimental data, indicated that the random model have a better agreement with experimental data than non-random model.

Key words: *random combustion, flame temperature, burning velocity, heat loss, organic particles*

Introduction

The waste byproduct of many industrial processes such as woodworking, paper manufacturing, food processing and metalworking can be used as an energy source. Therefore, the consumption of micro-nanosized particles increased significantly in industries and laboratories. These suspended particles can lead to some serious hazard. As a result, hazard evaluation and the establishment of preventive methods for dust explosions have become important [1-3]. Sun *et al.* [4, 5] experimentally examined the behavior of iron particles across upward and downward flame propagation near the combustion zone, and consequently the velocity and number density profiles of particles were calculated from these data.

Many studies have been published on combustion of organic dust particles within the last few years. Proust [6, 7] measured laminar burning velocities and maximum flame temperatures for some combustible dust-air mixtures (starch dust-air mixtures, lycopodium-air mixtures and sulphur flour-air mixtures). Ross *et al.* [8] investigated the time required for devolatilisation of six different sized coals in a bench scale atmospheric fluidized bed reactor by

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measuring the center temperature response. Han *et al.* [9] conducted the experimental study to elucidate the structure of flame propagating through lycopodium dust clouds in a vertical duct. The maximum upward propagating velocity was 0.50 m/s at a dust concentration of 170 g/m^3. Kurdyumov *et al.* [10] numerically investigated the propagation of premixed laminar flames with different Lewis numbers in open ducts of circular cross-section in a thermal-diffusive model. It was found that when the Lewis number is less than unity, the flame velocities in ducts with an isothermal wall may exceed those in ducts with an adiabatic wall of the same diameter. Baghsheikhi *et al.* [11] investigate the symmetrical combustion of an isolated coal particle with the fuel pyrolysis effect. It is revealed that the entrance of pyrolysis effect into the governing equations leads to the reduction in the film radius and consequently a reduction in transfer number. In another work by Shahidi *et al.* [12] studied heat transfer and pressure drop behavior of MWCNT-water nanofluid turbulent flow inside vertical coiled wire inserted tubes with constant heat flux boundary condition were investigated experimentally and numerically.

In experimental work on dust particles, Ryu *et al.* [13] established an experiment set up to study the fuel properties, equivalence ratio and particle size of different particles compositions. Liu *et al.* [14] investigated the flame propagation through a hybrid mixture of coal dust and methane in a combustion chamber. In this work, the flame propagation speeds and maximum flame temperatures of the mixture were been analyzed.

Kuo and Hsi [15] did explore ignition in which single wooden spheres were warmed in a hot air stream. Three types of wood were utilized. The single wooden spheres were oven-dried and presented to different temperatures and floods of air with various stream rates. Bidabadi and Rahbari [16] presented a model in which the flame propagation through lycopodium dust particles containing uniformly distributed volatile fuel particle. In this research, they have presented the effect of temperature difference between gas and particle on the combustion characteristics of micro organic dust particles. Furthermore, in previous study [17], flame propagation through micro-organic dust particles which distributed uniformly in domain was investigated, and the effects of different Lewis and Damkohler numbers of the organic dust particles were specified.

The presents work is a development on combustion of micro-organic particles that modeled in random media. The particles have been distributed in the preheat zone randomly and the effect of non-unit Lewis numbers has been considered. It is also presumed that the fuel particles vaporize first to yield a gaseous fuel, which is oxidized in gas phase. The flame structure is divided into three zones including a preheat-vaporization zone where the rate of chemical reaction is small, an asymptotically thin reaction zone where the convection and the rate of vaporization of the particles are negligible and finally post flame zone where the rates of chemical reaction and vaporizations are presumed to be small.

Governing equations

In the present article, previous model published by Bidabadi and Rahbari [16] and Bidabadi *et al.* [17] is developed to analyze the effect of random distribution of particles and different lewis number on the flame characteristics. All external forces including gravitational effects and body forces of the tube are assumed to be negligible. Also, heat transport by radiation is negligible. It is assumed that the particle temperature is approximately equal to the gas temperature. It is considered that Reaction occurs in a thin zone O(ε) whereas preheat and post flame zones have considerable length. This assumption is based on high Zeldovich number:

$$\mathrm{Ze} = \frac{E(T_f - T_u)}{\mathrm{R}T_f^2} \tag{1}$$

The subscribes f and u denote the flame and the ambient reactant stream conditions, respectively. In this analysis, it is presumed that the fuel particle decomposes to vaporize. The vaporization kinetics are assumed to be represented by the following expression:

$$w_V = An_s 4\pi T^n r^2 \tag{2}$$

where A is the parameters characterizing rate of vaporization, n – the constant quantity, and T – the gas temperature, respectively. Since the production from vaporization is CH_4, the gas properties are considered same as CH_4.

The governing equations for this model can be written:

– mass conservation

$$\rho\upsilon = \text{constant} \tag{3}$$

– equation of state

$$\rho T = cte \tag{4}$$

– gaseous fuel conservation

$$\rho\upsilon\frac{\mathrm{d}Y_F}{\mathrm{d}x} = \rho_u D_u \frac{\mathrm{d}^2 Y_F}{\mathrm{d}x^2} - w_F\frac{\rho_u}{\rho} + w_v\frac{\rho_u}{\rho} \tag{5}$$

In which ρ and υ denotes density and flow velocity. Solid fuel conservation defined:

$$\rho\upsilon\frac{\mathrm{d}Y_S}{\mathrm{d}x} = -w_v\frac{\rho_u}{\rho} \tag{6}$$

– energy conservation:

$$\rho\upsilon C\frac{\mathrm{d}T}{\mathrm{d}x} = \lambda_u\frac{\mathrm{d}^2 T}{\mathrm{d}x^2} + w_F\frac{\rho_u}{\rho}Q - w_v\frac{\rho_u}{\rho}Q_\upsilon \tag{7}$$

where Y_F is the mass fraction of fuel, Y_s – the mas fraction of particles, w_F – the reaction rate, and w_v – the rate of vaporization, respectively. The procedure of obtaining the expression for C in eq. (7) are as follows. Total exchanged heat in eq. (7):

$$Q = (m_s + m_g)C(T_b - T_u) = m_s C_s\Delta T + m_g C_g\Delta T \tag{8}$$

where

$$\rightarrow C = \frac{m_s}{m_s + m_g}C_s + \frac{m_g C_g}{m_s + m_g} \tag{9}$$

In previous equation the heat capacity C is the combined heat capacity of the gas, C_p – the specific heat of the gas at constant pressure, and C_s is the specific heat of the particles. Now in domain we have N_2, O_2, H_2O, CO_2, and CH which are in gas phase. Solid particles that are lycopodium which more than 80% of it formed by CH_4 which is inside of it. Therefore, the mass of particles are negligible in compare with the gases mass:

$$\frac{m_g}{m_s + m_g} = \frac{m_g}{m_g} = 1 \tag{10}$$

$$\frac{m_s}{(m_g + m_s)} = Y_s = \frac{\rho_s v_s}{\rho\upsilon} = \frac{\overset{4}{\overline{3\pi r^3\rho_s n_s}}}{\rho\upsilon} = \frac{4\pi r^3\rho_s n_s}{3\rho} \tag{11}$$

From definition in (9)-(11), it can be find:

$$C = Y_s C_s + C_g = \frac{4\pi r^3 C_s\rho_s n_s}{3\rho} + C_g \tag{12}$$

There is no difference between C_g and C_p. So the heat capacity correlation is evaluated:

$$C = C_p + \frac{4\pi r^3 C_s \rho_s n_s}{3\rho} \tag{13}$$

The reaction rate w_F appearing in eqs. (5) and (7) can be written:

$$w_F = \upsilon_F W_F K_F C_F \tag{14}$$

In eqs. (14), C_F and W_F are, respectively, the molar concentration and molecular weight of the fuel. In previous equation K_F is the constant rate of the overall reaction:

$$K_F = B \exp\left(-\frac{E_a}{\mathrm{R}T}\right) \tag{15}$$

Boundary conditions for governing equations:

$$\begin{gathered} x = -\infty,\ Y_F = 0,\ T = T_u,\ Y_S = Y_{Fu} \\ x = +\infty,\ Y_F = \text{finite},\ T{=}T_b \end{gathered} \tag{16}$$

Non-dimensionalize of the governing equations

Dimensionless parameters are defined:

$$\begin{gathered} y_s = \frac{Y_S}{Y_{FC}},\ z = \frac{\rho_u \upsilon_u C}{\lambda_u} x,\ y_f = \frac{Y_F}{Y_{FC}} \\ \theta = \frac{T - T_u}{T_f - T_u},\ m = \frac{\rho\upsilon}{\rho_u \upsilon_u} \end{gathered} \tag{17}$$

where T_f is the maximum temperature attained in the reaction zone. The quantity Y_{FC} – the have find from the following equation:

$$Y_{FC} Q = C(T_f - T_u) \tag{18}$$

From eq. (17), θ and y_f are the dimensionless gas temperature and mass fraction of the gaseous fuel, respectively. In this step by introducing the definitions in eq. (17) into eqs. (5)-(7) and using eq. (18) the following non-dimensional equations:

$$m = \frac{\mathrm{d}\theta}{\mathrm{d}z} = \frac{\mathrm{d}^2\theta}{\mathrm{d}z^2} + w\frac{\rho_u}{\rho} - q\gamma y_s^{2/3}\theta^n \tag{19}$$

$$m = \frac{\mathrm{d}y_F}{\mathrm{d}z} = \frac{1}{\mathrm{Le}}\frac{\mathrm{d}^2 y_F}{\mathrm{d}z^2} - w\frac{\rho_u}{\rho} + \gamma y_s^{2/3}\theta^n \tag{20}$$

$$m + \frac{\mathrm{d}y_s}{\mathrm{d}z} = -\gamma y_s^{2/3}\theta^n \tag{21}$$

Parameters w, γ, Le, and q that appears in eqs. (19)-(21):

$$\begin{gathered} w = \frac{\lambda_u w_F}{(\rho_u \upsilon_u) 2 C Y_{FC}},\quad \mathrm{Le} = \frac{\lambda_u}{\rho_u C D_u} \\ \gamma = \frac{4.836 A n_u^{1/3} \lambda_u (T_f - T_u)^n}{\upsilon_u^2 \rho_u^{4/3} C Y_{FC}^{1/3} \rho_S^{2/3}},\quad q = \frac{Q_\upsilon}{Q} \end{gathered} \tag{22}$$

The dimensionless form of the boundary conditions for these equations is:

$$\begin{gathered}\text{at } z=\infty, \quad \theta=\theta_b=\frac{T_b-T_u}{T_f-T_u}, \quad y=\text{finite} \\ \text{at } z=-\infty, \; \theta=0, \; y_F=0, \; y_s=\alpha\end{gathered} \tag{23}$$

where $\alpha = Y_{Fu}/Y_{FC}$ that Y_{Fu} is the gaseous fuel contained in the ambient reactant stream and Y_{Fu} is defined in eq. (18). In this research, we neglect the quantity, q, which is the ratio of heat required to vaporize the fuel particles to the overall heat release by the flame, because it is too small in comparison with other parameters. The quantity m can be considered equal to unity, which is the usual assumption for solving the governing equations. By considering these assumptions in all zones, non-dimensional governing equations are obtained as:

$$\frac{\mathrm{d}\theta^0}{\mathrm{d}z}=\frac{\mathrm{d}^2\theta^0}{\mathrm{d}z^2}+w\frac{\rho_u}{\rho} \tag{24}$$

$$\frac{\mathrm{d}y_F}{\mathrm{d}z}=\frac{1}{\mathrm{Le}}\frac{\mathrm{d}^2 y_F}{\mathrm{d}z^2}-w\frac{\rho_u}{\rho}+\gamma y_s^{2/3}\theta^n \tag{25}$$

$$\frac{\mathrm{d}y_s}{\mathrm{d}z}=-\gamma y_s^{2/3}(\theta^0) \tag{26}$$

Combustion in random media

Physics of random model

It is obvious that different particles have also different preparation conditions. So the amount of energy that release from these particles which are a function of preparation conditions, would vary along the flame front. These preparation condition caused on some combustion properties such as flame temperature, burning velocity and the amount of released energy since preparation condition for different fuel particles are random and different.

In this work, we have considered an especially randomly distributed cloud of organic dust particles. The lycopodiom point like sources are volatilizable and it will be assumed that after the vaporization, the gaseous fuel evaluated is methane. Our last model have been extended to investigate effect of random distribution of sources on some important parameters such as burning velocity, flame temperature and, *etc.* the physics of problem that shows how the particles are vaporized and combustion regions in random media has been illustrated in fig. (1). In this model for considering the random effect, the sources are distributed randomly in the preheat zone.

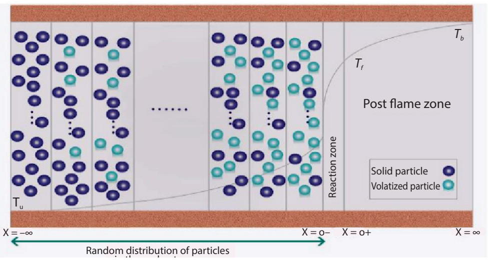

Figure 1. Random distribution of particles in the preheat zone

It is obvious from energy equation that amount of fuel released from particles, is a function of size of particles, number density and temperature of particles in the preheat zone. In this work, we assumed that all of particles have the same size.

Number density can be calculated as a function of equivalence ratio, ϕ_u. Mass fraction of fuel Y_{Fu} available in the reaction zone could be find:

$$Y_{Fu}=\frac{4\pi r_u^3 n_u \rho_s}{3\rho_u} \tag{27}$$

The quantity Y_{Fu} is related to the equivalence ratio:

$$\phi_u \frac{17.18Y_{Fu}}{1-Y_{Fu}} \tag{28}$$

By presuming that $n_s = n_u$ at the ambient conditions and finding Y_{Fu} as function of ϕ_u from previous relation, the number density can be calculated:

$$n_s = \frac{3\rho_u\phi_u}{4\pi r_u^3\rho_s(17.18+\phi_u)} \tag{29}$$

For each value of ϕ_u the number density are different. In real condition distribution of fuel along the flame front is random and the situation for different particles are different. According to the fig. 1, temperature through the preheat zone vary from ambient temperature to the flame temperature and particles sense different temperatures between these two temperature. So that amount of volatized fuel would be different according to its temperature. At the end of preheat zone some of sources remain solid and some of them convert to gas. Along the preheat zone, these properties are not the same for each group of particles so the amount of volatized fuel at the end of preheat zone would vary along the flame front. For modelling, we have modeled the source term in the equation of energy by considering random situation for volatizing of particles in preheat zone. For this goal, different groups of particles were assumed. Each group contained random amount of particles and these particles sensed a random temperature between ambient and flame temperature in the preheat zone. The net available fuel would be the sum of volatized fuel from each group. At this point, we introduce the equations of random modelling of particles in the preheat zone and flame front:

$$n_{s,t} = \sum_{j=1}^{g} n_{s_j} \tag{30}$$

$$\omega_{v,t} = \sum_{j=1}^{g}\omega_{v_j} = \sum_{j=1}^{g} 4\pi r^2 A n_{s_j} T^n_j, \quad T_u < T_j < T_f \tag{31}$$

where parameter, g, represent the number of particle groups. The number density of each group can vary from zero to, $n_{s,t}$. The net rate of reaction would be calculated:

$$\omega_F = \sum_{j=1}^{g}\omega_{F_j} = v_f K_F \sum_{j=1}^{g}\omega_{v_j} \tag{32}$$

$$\omega_F \frac{\rho_u}{\rho} Q = \sum_{j=1}^{g}\frac{\rho_u}{\rho} Q\omega_{f_j} \tag{33}$$

In random distribution of particles, the condition for different groups of particles would not be the same. The non-dimensional governing equations and boundary needed for solving these governing equations at the three combustion zones.

Heat loss effect

To investigate the effect of heat loss on the random combustion of lycopodium particles, the energy conservation equation considering the term of loss:

$$\rho v C\frac{\mathrm{d}T}{\mathrm{d}x} = \lambda_u\frac{\mathrm{d}^2T}{\mathrm{d}x} + \omega_f\frac{\rho u}{\rho}Q - \omega_v\frac{\rho_u}{\rho}Q_v - \frac{\rho_u}{\rho}Q_1 \tag{34}$$

In eq. (34) heat loss term, Q_1, is proportional to $(T - T_u)$:

$$Q_L = k(T-T_u) \tag{35}$$

By considering the assumptions of problem, the equations will be expanded in each zone. According to the solution carried out before in this work, non-dimensionalization is performed, and the final form of the non-dimensional equations are:

$$\frac{\mathrm{d}\theta^0}{\mathrm{d}z}=\frac{\mathrm{d}^2\theta^0}{\mathrm{d}z^2}+w\frac{\rho u}{\rho}-k\theta^0 \tag{36}$$

$$\frac{\mathrm{d}y_F}{\mathrm{d}z}=\frac{1}{\mathrm{Le}}\frac{\mathrm{d}^2 y_F}{\mathrm{d}z^2}-w\frac{\rho_u}{\rho}+\gamma y_s^{2/3}\theta^n \tag{37}$$

$$\frac{\mathrm{d}y_s}{\mathrm{d}z}=-\gamma y_s^{2/3}(\theta^0)^n \tag{38}$$

Constant parameters

In the combustion of lycopodium particles, it is supposed that the particles vaporize and yield to the methane structure. The summery of chemical kinetic parameters of lycopodium particles and air properties which used in the calculation and plotted figures is given in tab. 1.

The adiabatic flame temperature considering the random effects is calculated and then the heat capacity is measured from eq. (13) and the results for these values as a function of equivalence ratio are shown in fig. 2 In these calculations, the combustion products are assumed to be N_2, O_2, H_2O, CO_2, and CH_4.

Table 1. Properties of licopodium particles

Symbol	Value	Unit
A	$3.4 \cdot 10^{-6}$	[gcm^{-2}ks^{-1}]
B	$3.5 \cdot 10^{6}$	[moles^{-1}]
E	105	[KJmole^{-1}]
C_s	5.68	[KJkg^{-1}K^{-1}]
C_p	1.0048	[KJkg^{-1}K^{-1}]
ρ_s	1000	[kgm^{-3}]
ρ_u	1.13	[kgm^{-3}]
λ	$1.465 \cdot 10^{-4}$	[KJm^{-1}s^{-1}K^{-1}]

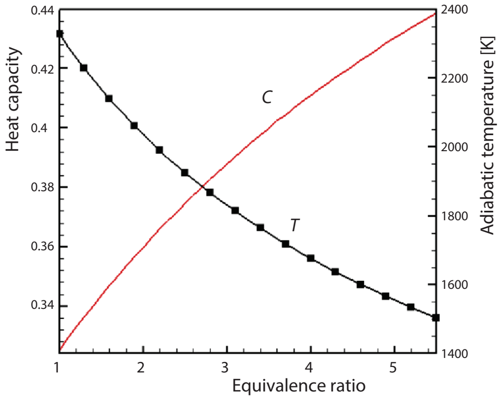

Figure 2. Variation of heat capacity and adiabatic temperature as a function of equivalence ratio

Result and discussion

Refer to explanation in the introduction, the gaseous fuel evolving from the lycopodium particles is assumed to be methane. In this section, the results evaluated from this model with lycopodium particles that are distributed randomly in preheat zone have been comprised with the state that the clouds of particles are scattered uniformly. For illustrating the accuracy of this model, we plot the fig. 3 which values obtained for variation of burning velocity by considering thermal resistance effects as a function of mass concentration compared with experimental data by Han *et al.* [9] and analytical data published by Seshadri *et al.* [18].

As seen in fig. 3 both the presented random and non-random model have a reasonable compatibility with experimental data however the random model has a better agreement.

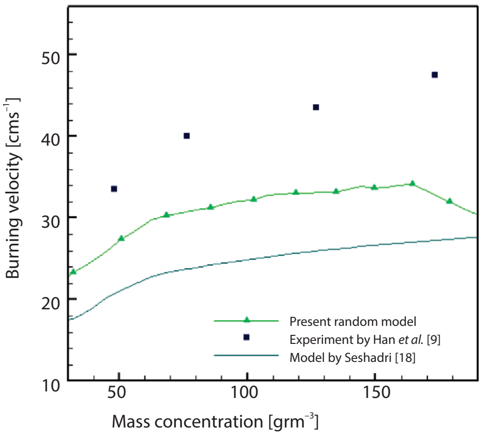

Figure 3. Comparison between experimental data by Han *et al.* [9] and analytical model by Seshadri [18] with presented random model

The effect of random combustion

In figs. 4 and 5, burning velocity υ_v is plotted as a function of equivalence ratio both for random and non-random model and various radius of lycopodiom particles. It can be seen that, decreasing the radius of the particles and increasing the equivalence ratio increases the burning velocity. It is necessary to note that when the radius of particles decreases, the number of gaseous and solid particles in the constant control volume increases, which results in increasing the burning velocity.

Figures 4 and 5 indicates difference between curves of random and uniform distributed particles. As presented in this figures, the value of burning velocity goes up due to the random effect for $r = 10$ μm and decrease for $r = 30$ μm and $r = 50$ μm in comparison with the case in which the sources are distributed uniformly. It is due to this fact that in small particle radiuses, particles need less energy for vaporizing and they would vaporize easier but in larger radius, they need more energy and probability for vaporization would decrease and hence random mode which is very like the actual condition, represent smaller amount of burning velocity for larger particles and greater for smaller particles than the amounts presented by non-random

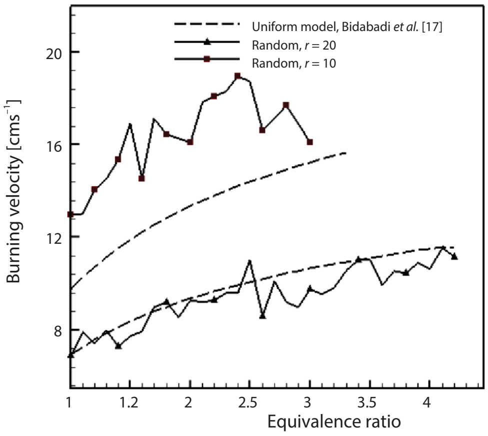

Figure 4. Variation of burning velocity as a function of equivalence ratio, comparison between random and uniform model

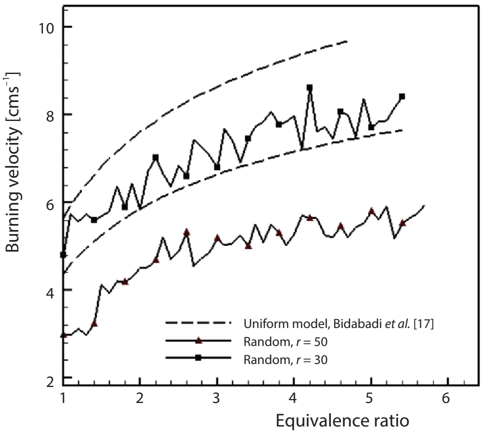

Figure 5. Variation of burning velocity as a function of equivalence ratio, comparison between random and uniform model

modes. In figs. 6 and 7 the calculated results for flame temperature and adiabatic temperature are presented for both random and non-random effect and different radius of the particles. The curve with respect of random disperse is plotted with curve that particles distributed uniformly in the preheat zone.

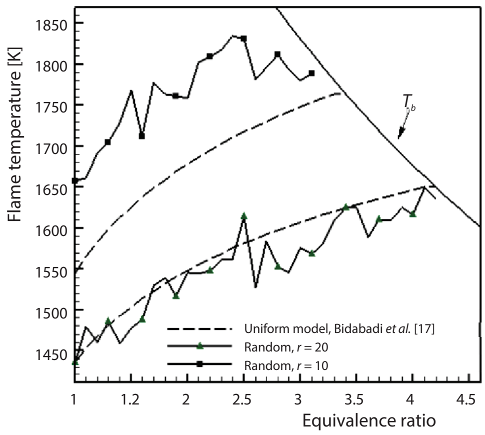

Figure 6. Variation of flame temperature, comparison between random and uniform model

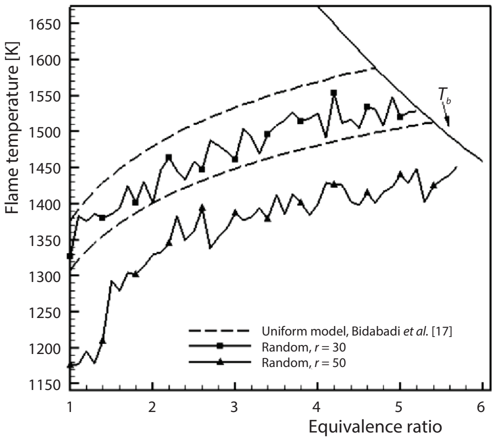

Figure 7. Variation of flame temperature, comparison between random and uniform model

As it can be seen, flame temperature increases when the equivalence ratio goes up, due to the fact that higher equivalence ratio leads to increase amount of reactant energy, therefore, the flame temperature increases. Also, in the specific equivalence ratio, decreasing the particle radius increases the flame temperature, which demonstrates that the mixture approaches to a purely gaseous combustible mixture. The behaviors of the curves that represent the random effects are the same and all of them are fluctuating due to random effects. There is a difference between curves in which the random and uniform distributed particles are presented. As the reason mentioned in previous paragraph, For r = 10 μm the random model shows a greater amount of flame temperatures. Also it can be seen, increasing particle radius difference between random and non-random mode would decrease and after a while for r = 30 μm and r = 50 μm the amount of flame temperature represented by random mode is smaller than non-random mode. This is due to the fact that at small radiuses, particles need less energy to vaporize and at the constant equivalence ratio, number density is greater for smaller particles.

The effective equivalence ratio ϕ_g as a function of ϕ_u illustrated in fig. 8 for different radius of particles. As the same previous figures in this figure again we reflect the random effect and curves that represents these effects are plotted. Previous figure demonstrates that although ϕ_u is larger than unity, the corresponding values of ϕ is less than unity. This is probably due to the coupling between the kinetics of vaporization and the kinetics of oxidation.

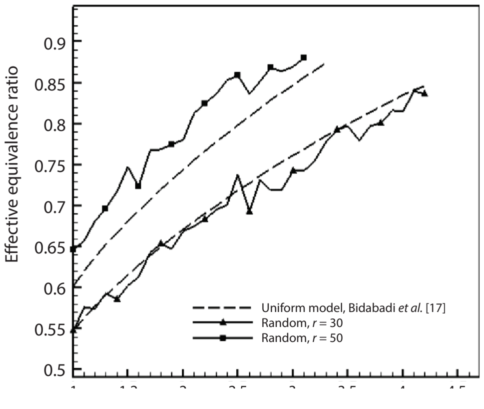

Figure 8. The ϕ_g as a function of equivalence ratio, comparison between random and uniform model

The effect of heat loss and Lewis number

The Lewis number is defined as the ratio of thermal diffusivity to mass diffusivity. In previous work [16], we presumed the Lewis number is equal to unit. But in this study the effect of different Lewis number has been considered. Figure 9, depicts the flame temperature behavior as a function of equivalence ratio for different Lewis number. It can be seen that flame temperature decreases when the Lewis number goes up due to fact that increasing in thermal diffusivity per mass diffusivity which leads to the lower heat transfer to the particles in combustion. Also an increase in Lewis number, leads to reduction in mass diffusivity which implies gaseous fuel decrease in the reaction zone.

Figure 10 illustrates the variation of burning velocity, including the effect of random distribution of particles, as a function of equivalence ratio either with or without heat-loss effect. As it shown in this figure, decreasing the radius of the particles and growing up the equivalence ratio lead to increase the burning velocity. In addition, it is noticeable that the value of burning velocity decreases due to the heat-loss effect in comparison with the case in which the heat-loss term is neglected.

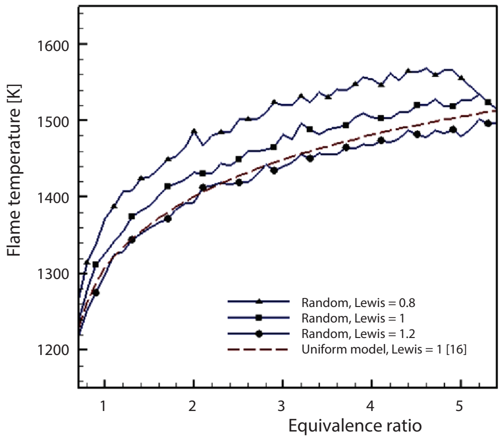

Figure 9. Variation of flame temperature for different Lewis numbers as a function of equivalence ratio

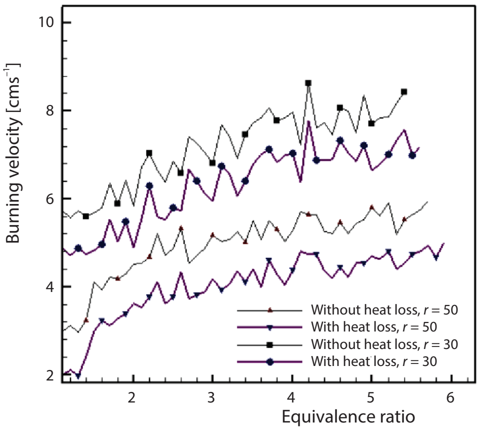

Figure 10. Variation of burning velocity as a function of equivalence ratio by considering heat loss effects

Conclusion

In this work, random combustion of lycopodium particles has been modeled and in order to demonstrate the accuracy of the model proposed here, we made a comparison between the results obtained from this model, experimental results Han *et al.* [9] and published model, in which the condition was for the particles that are distributed uniformly Seshadri [18]. As seen in figures presented in this work, the behavior for the remarkable parameters such as variation of the burning velocity and flame temperature as a function of the equivalence ratio was similar for both random and uniform models, however it is obvious that the random calculations have a better agreement with the experimental data. Due to the random effects the curves are fluctuating, but tendency of these curves are the same as the previous model that the dust particle were distributed uniformly. It is noticeable that this model yields to more realistic and comprehensive prediction in the combustion physics of organic dust particles.

Nomenclature

A – parameter characterizing rate of vaporization of fuel particles defined in eq. (2)
B – frequency factor characterizing rate of gaseous fuel oxidization
b – scaled mass fraction of fuel at the boundary between the reaction and convection zones
C – heat capacity of mixture defined in eq. (13)
C_F – molar concentration of fuel
C_p – heat capacity of the gas
C_s – heat capacity of a solid particle
D_u – diffusion coefficient
E_a – activation energy of fuel
K_F – rate constant of the gas-phase reaction
k – thermal conductivity
Le – Lewis number defined in eq. (22)
m – defined in eq. (17)
n_s – local number density of particles (number of particles per unit volume)
n_u – number density of particles in ambient reactant stream
Q – heat release per unit mass of consumed fuel particles
Q_υ – heat associated with vaporizing unit mass of fuel
Q_l – heat loss defined in eq. (35) per unit mass of fuel
q – defined in eq. (22)
R – gas constant
r – radius of particle
T – temperature
W_F – molecular weight of gaseous fuel
w – defined in eq. (22)
w_F – reaction rate characterizing consumption of gaseous fuel defined in eq. (14)
w_v – vaporization rate of fuel particles
x – spatial co-ordinate
Y – mass fraction
Y_{FC} – defined in eq. (18)
YFf – mass fraction of fuel at the reaction zone
Y_{Fu} – gaseous fuel available in the particles in the ambient reactant stream
Y_F – defined in eq. (17)
Y_s – defined in eq. (17)
Ze – Zeldovich number
z – scaled independent variable defined in eq. (17)

Greek symbols

α – defined in eq. (23)
γ – defined in eq. (22)
θ – variable defined in eq. (17)
θ^0 – value of θ calculated neglecting heat of vaporization
ρ – density of the reactant mixture
ρ_u – density of the unburned mixture
ρ_s – density of a fuel particle
υ – stochiometric coefficient
υ_u – burning velocity calculated neglecting heat of vaporization of fuel particles
ϕ_u – equivalence ratio based on fuel available in the particles in the ambient

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