MODELING FLAME PROPAGATION OF COAL DUST CLOUD COMBUSTION IN HETEROGENEOUS ENVIRONMENT

Mehdi Bidabadi*, Moein Mohammadi**, Shafagh M. Bidokhti**, Sina H. Yousefi**, Alireza K. Poorfar***

* Professor, School of Mechanical Engineering, Iran University of Science and Technology.
** MSc Student, School of Mechanical Engineering, Iran University of Science and Technology.
*** PhD Student, School of Mechanical Engineering, Iran University of Science and Technology.

(Corresponding author's E-mail address: sh_mollazadeh@mecheng.iust.ac.ir)

ABSTRACT: In the present work, combustion of a quiescent coal dust cloud has been studied in the media with spatially discrete sources by means of numerical approach. The thermal model has been generated to estimate the flame propagation speed with various dust concentration in air. Oxygen and Nitrogen have been considered as the main oxidizer and the inert gas, respectively. The model uses discrete heat sources to analyze dust combustion of coal particles with the diameter of 50 µm without considering the volatile matter. The burning process is supposed to be of diffusion type for obtaining burning time. Flame speed as a function of particle diameter has been studied. Furthermore, minimum ignition energy as a function of dust concentration for different particle sizes has been studied. Reasonable agreement between the numerical solution of micron sized coal dust cloud combustion and experimental data was obtained in terms of flame propagation speed and minimum ignition energy.

Keywords: Coal Dust Cloud – Discrete Combustion – Flame Propagation Speed – Minimum Ignition Energy.

INTRODUCTION

Dust explosion has been a recognized threat to humans and industries for the last 150 years [1-6]. The occurrence of three fatal combustible dust explosions within one year in 2003 prompted the U.S. Chemical Safety and Hazard Investigation Board (CSB) to commence a broader study on the extent, nature and prevention of combustible dust fire and explosion hazards.

Methane and coal dust explosions are the most feared hazards in the coal industry worldwide. The large majority of these explosions originates from or occurs around sealed mine areas [8]. Such events have prompted industries to study dust combustion characteristics to seek the means to reduce the effects of dust combustion.

Thus, a precise knowledge of dust explosion's hazards is essential to estimate the consequences of a dust explosion and to select the adequate methods of protection such as venting (e.g., explosion relief vents) and suppression systems.

Propagating diffusion fronts in reactive, heterogeneous media consisting of two spatially separated phases are common in many fields such as chemical kinetics, combustion, biology, etc. [9]. Also, fire dynamics and modeling of fire spreading are some of important examples in heterogeneous media.

Goroshin et al. [10] studied the effects of the discrete nature of heat sources on flame propagation in particulate suspensions. They have illustrated the effect of the discrete nature of the heat sources on flame propagation by comparing flame speeds calculated both from continuous and discrete models in lean Aluminum and Zirconium particle-gas suspensions. It has been reported in their work that lower flame speeds and a weaker dependence of the speed on Oxygen concentration are predicted by the discrete flame model.

Tang et al. [11] investigated the effect of discreteness on heterogeneous flames and propagation limits in regular and random particles. Also Mendez et al. [12] studied the speed of reaction-diffusion fronts in spatially heterogeneous media.

Because of coal reaction with oxygen in the air, which is an exothermic reaction even in ambient condition, and probability of its thermal runaway, combustion of coal is an important safety issue in mines [13]. To prevent disasters in coal mines and also to improve fundamental understanding of the phenomenon research on the combustion of coal dust cloud has been conducted for a long time. Also pulverized coal combustion is mainly used as an energy source in practical use. The pulverization of coal into fine particles are made to increase the specific surface area to enhance the rate of heat and mass transfer between the coal particles and surrounding hot gases. This, on the other hand, will increase the importance of the continuity or discreteness of the system.

Regarding flame stability, flame propagation behaviour in coal dust clouds seems to be one of the important properties for predicting the performance of a new burner [14]. Most of the experimental studies mainly deal with the influence of coal composition on combustion of coal and different stages of coal combustion [15]. Numerical studies on the other hand, deal with the modelling of different stages of combustion process.

It should be noted that available experimental results are in poor agreement with each other, apparently, because of different test conditions and differences in internal structure of particles examined.

Bermudez et al. [16] investigate a mathematical model for combustion of coal particles with a simplified kinetic model. Their model included the change in diameter of the particles. Kun Li et al. [17], also, studied particle combustion by considering both volatile and carbon reaction. In their model they assumed the flame to move from off the particle to the surface of the particle after a homogenous burning process.

In the present study, the effects of particle size and dust concentration on flame propagation of micron-sized dust particles in media with spatially discrete sources are studied numerically. A thermal model based on discrete heat sources viewpoint has been utilized. Flame propagation speed as a function of dust concentration has been studied. Also the minimum ignition energy as a function of dust concentration in different particle diameters has been studied.

THERMAL MODEL

The mechanism of the combustion of dust clouds is a very complex process. The difficulty in their study is due to various processes such as: heating, evaporation, mixing with oxidizer, ignition, burning and quenching of particles in the dust cloud. In the study of flame propagation in dust clouds, particle size and dust concentration play very important roles. Also, the interaction between the particles in the mixture always makes the dust combustion an unstable process. Heat transfer is the dominant phenomenon in the process of flame propagation in dust clouds.

A thermal model based on heterogeneous combustion in three-dimensional space, which relies on the following assumptions, has been generated:

1. Particles, burning in air, are assumed to be spherical and the flame diameter remains constant and is equal to the particle diameter.
2. The ignition is supposed to occur in a layer of particles simultaneously so the flame propagation will be of planar type.
3. The burning process is quasi-steady.
4. The physical and thermal properties of particles and the ambient, such as thermal conductivity, specific heat and density are assumed constant during the burning process.
5. Gravitational forces are neglected to overcome the buoyancy effects.
6. There is an equal and constant space between the particles distributed in the dust cloud.
7. A constant rate of energy release is considered during the combustion of a single particle.
8. For simplicity, the radiation heat transfer in the coal dust cloud is neglected and only conduction heat transfer has been considered.
9. For simplicity, the volatile matter has been neglected, which is applicable for less volatile coal particles.

Levendis et al. [18] present a relation for burning time of a single micron-sized char particle. The combustion mode of micron-sized coal particles is a diffusion-controlled regime. In addition, char undergoes a heterogeneous combustion in oxygen. The burning time of char particles in diffusionally controlled regime can be obtained from the following relation [18]:

$$t_{b_{diff}} = \frac{\pm_a (d_{p,i}^2 - d_{p,f}^2) R T_m}{56 D_{O_2,\infty} \ln(1+0.75 Y_{O_2,\infty})} \qquad (1)$$

Where $t_{b,diff}$ is the burning time of char particle in diffusion-controlled regime, $\pm_a$ is the apparent density of coal particle, $d_{p,i}$ and $d_{p,f}$ are the initial and final diameter of the particle. R is the ideal gas constant, T_m is the mean temperature in the film, $D_{O_2,\infty}$ is the mass diffusivity of oxygen into the air, and $Y_{O_2,\infty}$ is the mass fraction of oxygen in the ambient gas far from the particle surface.

When the ignition system provides the minimum amount of energy to the dust cloud, the temperature of first layer of particles is increased to the ignition temperature. As these particles start to burn, they act as a heat source in the dust cloud system and cause the temperature of the surrounding region to rise. The temperature rise in the other particles is calculated as the sum of thermal effects from the burned and burning particles. In case a high-enough temperature is provided, the combustion process will proceed to the other layers as

shown in Figure 1. The temperature increase of particles in the preheated zone because of only conduction heat transfer mechanism is expressed based on the superposition principle.
In order to model the single-particle combustion and the time-place temperature distribution of its domain, the energy equation in spherical coordinates is used [19]:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T_a(r,t)}{\partial r}\right)=\frac{1}{\sim}\frac{\partial T_a(r,t)}{\partial t} \qquad (2)$$

Where $T_a(r,t)$ is $T(r,t)-T_\infty$, and T_∞ is the ambient temperature. The boundary and initial conditions of the above equation are:

$$\begin{Bmatrix} k_p A\frac{\partial}{\partial r}T_a(r,t)=\dot{q}\times Heaviside({}^{2}-t), @\, r=r_p \\ T_a(\infty,t)=0 \\ T_a(r,0)=0 \end{Bmatrix} \qquad (3)$$

Here $\dot{q}$ is the rate of heat release of a single particle from its surface during the burning time, which is defined as below [20]:

$$\dot{q}=Ak_p(T_f-T_\infty)r_p^{-1} \qquad (4)$$

Bidabadi et al. [19] have obtained the space-time temperature distribution of particles through the whole domain as:

$$T_a(r,t)=(T_f-T_\infty)\frac{r_p}{r}\left[erf\left(\sqrt{\frac{(r-r_p)^2}{4\sim t}}\right)-Heaviside(t-{}^{2})erfc\left(\sqrt{\frac{(r-r_p)^2}{4\sim(t-{}^{2})}}\right)\right] \qquad (5)$$

$$T_s=\sum_i\sum_j\sum_k T_a(i,j,k)(r_{i,j,k},t_{ig,i}) \qquad (6)$$

T_a is the space-time distribution of temperature around a single burning particle and beyond, and T_s is the total effect of burning and burned particles which is indicative of the temperature of medium fluid around a particle in the preheated zone. $T_\infty=300K$ and $T_f=2172$ are the considered values. The space between the target particle and each particle placed at i, j, k is presented by:

$$r_{i,j,k}=L\sqrt{i^2+j^2+k^2} \qquad (7)$$

Where L is the space between two adjacent layers and defined by the following equation by Bidabadi et al. [19]:

$$L=(\circledR d_p^3 {}^{\circ}{}_p/6C_d)^{1/3}$$
(8)

Where ${}^{\circ}{}_p$ is the particle density, C_d is the dust cloud concentration, and d_p is the particle diameter.
The flame propagation speed is defined as the ratio of the space between two adjacent layers to the difference of their ignition times [21]. As mentioned earlier, since micron-sized particles are being dealt with, the formulation presented by Glassman and Yetter [22] is utilized here. Figure 1 shows the spatial distribution of particles in dust cloud.

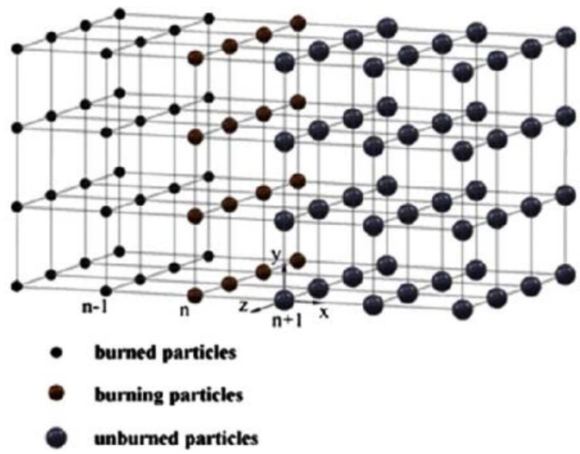

Figure 1. The spatial distribution of particles in dust cloud: Layer n−1(burned particles), layer n (burning particles), and layer n+1 (preheating particles) by Bidabadi et .al [19]

The ignition time of a single particle in a layer can be the representative of the ignition time of the mentioned layer. The particle is assumed to be positioned at the origin of the local coordinate system [19].

Results and discussion

A computer code has been generated to calculate the burning speed of each layer after the release of the energy from the ignition system. As soon as the minimum amount of energy to the dust cloud is provided, the temperature of the particles is increased to the ignition temperature and combustion takes place. Beyond the first layer ($n > 1$), the preheating of layers is influenced by the burning of the preceding layers in addition to the ignition system. Thus, when a layer's temperature reaches the ignition temperature, the relevant time is recorded as the ignition time of that layer. Flame propagation speed is determined by dividing the distance between two adjacent layers L by the difference between ignition times of these two layers. If we assume that conduction is the only mechanism of flame propagation, the rise of particle's temperature will be a function of thermal diffusivity α. The higher this value, the sooner the adjacent layers reach the ignition temperature and the flame propagation speed increases.

Figure 2 shows the variation of the flame propagation speed as a function of dust concentration for particles with 50«*m* diameter. As can be seen in Figure 2, with the increase of dust concentration, flame propagation speed tends to increase as it happens in experimental data. The difference may be attributed to three reasons. First, this model did not consider the volatile matter in the process of combustion; therefore, the flame speed is less than the experimental values. Second, the experimental condition for coal combustion studies differs largely with the assumption made in theoretical models. Finally, neglecting the effect of radiation has a major part in this difference.

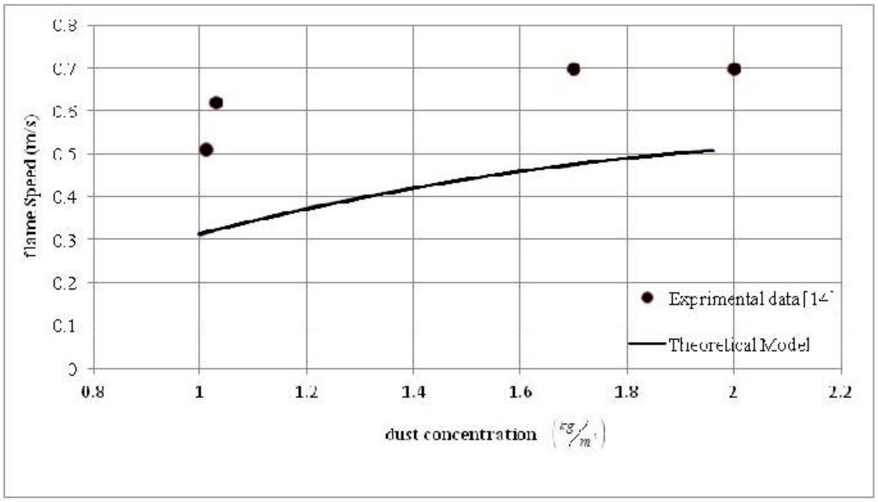

Figure 2. Flame propagation speed as a function of dust concentration for 50«m particles

The propagation speed in terms of particle diameter is studied in Figure 3.
Figure 3 shows that for coal particle diameters smaller than 50 micron, the flame speed rises faster with decrease in particle diameter. But for particles with diameter greater than 50 micron the rate of changes begins to slow down.

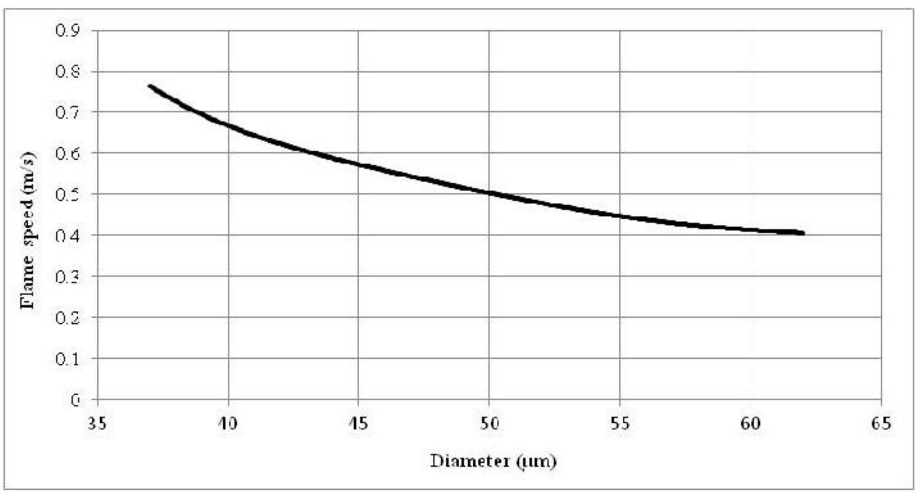

Figure 3. Flame speed as a function of particle size

The minimum ignition energy for a layer in the presumed discrete media as a function of dust concentration for different particle sizes is demonstrated in Figure 4. As one could see, with the rise of dust concentration, minimum ignition energy decreases. The amount of energy after a certain value of dust concentration reaches a point that no significant changes can be seen. Moreover, with increasing the particles diameter, as it was expected, the minimum ignition energy increases.

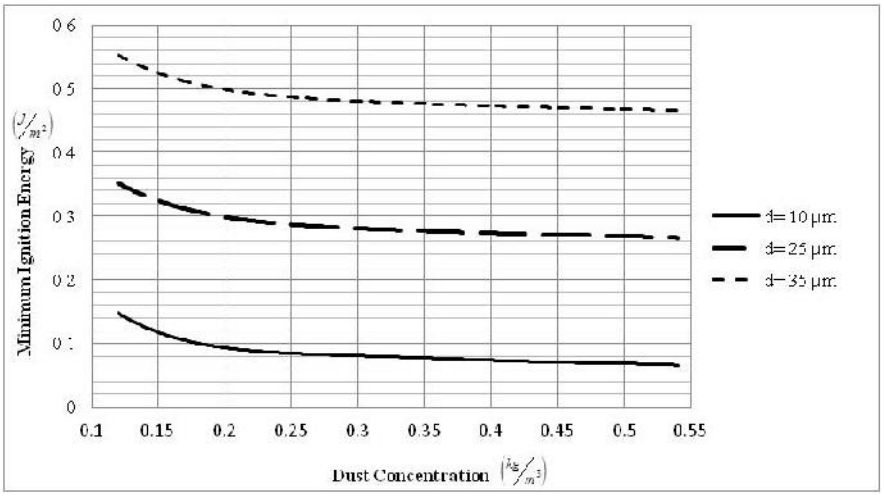

Figure 4. Minimum ignition energy as a function of dust concentration in different particle diameters

CONCLUSION

In this study, flame propagation of micron-sized coal dust particles in an environment with spatially discrete sources is numerically investigated. A computer code has been generated in order to study the effects of dust concentration and particle size on flame propagation speed. The results indicate that with the increase of dust concentration, flame propagation speed tends to increase. In addition, Flame propagation speed is studied as a function of particle size for coal-air suspension. It is shown that as the particle size increases, the value of flame speed decreases and after a certain diameter, the rate of flame speed change tends to decelerate. Furthermore, minimum ignition energy as a function of dust concentration for different particle diameters is illustrated. It is observed that minimum ignition energy tends to have lower values as the particle size decreases. The numerical results indicate that the thermal model presented here is an effective model for the estimation of flame front speed in various dust concentrations under different initial conditions.

NOMENCLATURE

A	Particle croos section
C_d	Dust cloud concentration
D_b	Mass diffusivity of oxygen into the air
$d_{p,i}$	Initial diameter of the particle
$d_{p,f}$	Final diameter of the particle
i, j, k	Points in the coordinate system

k_P	Thermal conductivity
L	Space between two adjacent layers
$\dot{q}$	Rate of heat release of a single particle from its surface during the burning time
R	Ideal gas constant
r	Particle diameter
r_p	Particle diameter
$r_{i,j,k}$	The space between the target particle and each particle
T_f	Flame temperature
T_∞	Ambient temperature
T_s	Temperature of burning and burned particles
T_a	Distribution of temperature around a single burning particle
T_m	Mean temperature in the film
$t_{b_{diff}}$	Burning time of char particle in diffusion controlled regime
t	Time
$t_{ig,i}$	Ignition time of single particle
$Y_{O_2,\infty}$	Mass fraction of oxygen in the ambient gas far from the particle surface
~	Thermal diffusivity
°$_p$	Particle density
²	Burning time
±$_a$	Apparent density of coal particle

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