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Flame propagation of boron dust particles in heterogeneous media

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ABSTRACT

In this paper the combustion of boron dust clouds has been studied numerically in an environment with spatially discrete sources. A thermal model has been generated to estimate the flame propagation speed in various dust concentrations. Furthermore, flame speed as a function of particle diameter has been studied. The results show a very good agreement with the theoretical and experimental data. Also, in this case, a comparison between dust cloud combustion models has been made. Flame front propagation as a function of oxygen mole factor and pressure for certain particle sizes has been studied.

1. Introduction

Dust explosions have been a recognized threat to humans and property for a long time. There are many comprehensive reports of explosions caused by combustion of dust clouds. One of the earliest reports known is Count Morozzo's (1795) [1] detailed analysis of an explosion in the flour warehouse in Turin in 1785. Therefore, modeling and predicting of dust clouds combustion are so important to control and prevent explosions. Flame propagation speed under different conditions is a remarkable research for explosion prevention. Principally boron is an attractive fuel for air-breathing missile engines due to its high volumetric heat of combustion. Boron has the highest volumetric energy density of any element, making it attractive for use as a potential fuel. In combustor design for engines burning boron powders, information regarding laminar flame speed in boron–oxygen-diluent (e.g. boron-air) dust clouds and its dependency on various parameters is important for proper design of flame-bolding regions [2]. Combustion of metallic powders is a challenging scientific subject that also has significant practical applications. Since the combustion of inorganic particles is a high exothermic chemical reaction, their applications in many industrial operations are significant and efficient.

King [2] theoretically studied combustion of boron dust clouds. He presented a detailed model of boron–oxygen–nitrogen dust-cloud flame considering the details of boron particle ignition and the effects of oxygen depletion so as to develop and use it for prediction of flame speed. Moreover, he investigated boron particle burning time with a simplified model similar to that of Cassel et al. [3].

Many studies have been carried out by Bidabadi et al. [4–14] in order to investigate the characteristics of dust cloud's combustion.

Foelsche et al. [15] studied the ignition and combustion of boron particles at high pressures and temperatures. Their analysis allows for the investigation of the effects of, particle size, temperature and pressure on boron particle ignition and combustion delay.

Also, King [16] studied the ignition and combustion of boron particles and clouds. He investigated boron particle burn time by diffusion model.

King [17] modeled "clean" surface boron, by diffusion-controlled droplet gasification formulas (d^2 law) for large particles ($d \geq 30$ μm). Moreover, he investigated the fundamental aspects of boron dust particle ignition. His analysis allows for the investigation of the effects of boric oxide coating on particle ignition time. This study derived transient differential equations describing the generation and removal of the oxide and associated thermal effects along with heat transfer between the particle and the surrounding. Li and William [18] modeled kinetic-controlled combustion formulas (d law) for small particles ($d \leq 10$ μm).

Propagation of diffusion front in reactive, heterogeneous media consisting of two spatially separated phases is common in many fields such as chemical kinetics, combustion, and biology [19]. Often, the approach used for modeling front's propagation in discrete systems is to average the source terms with a spatially continuous function [18].

Goroshin et al. [20] 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

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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. [21] investigated the effect of discreteness on heterogeneous flames and propagation limits in regular and random particles. Also Mendez et al. [22] studied the speed of reaction–diffusion fronts in spatially heterogeneous media.

In the present study, the effects of particle size, oxygen mole fraction and dust concentration on flame propagation of micron-sized boron dust particles are studied theoretically. The discrete heat source method provides the dust combustion model, from ignition process to final state which includes steady flame propagation, flame quenching or even explosion. This is a powerful developing method. Beside wide range of models generated for dust particle's combustion which involve mass transfer and chemical kinetic that make them complicated problems, the present thermal model uses a novel approach in order to theoretical simulation of inorganic dust particle's combustion. The model is based on conduction heat transfer mechanism.

2. Thermal model

The mechanism of the dust cloud's combustion is a very complex process. The difficulty of the study is as a result of various processes such as: heating, evaporation, mixing with oxidizer, ignition, burning and quenching of particles in the dust cloud. In 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.

When the ignition system provides the minimum amount of energy to the dust cloud, the temperature of particles in the first layer is increased to the ignition temperature. As these particles start to burn, they act as heat sources 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 particles as shown in Fig. 1. The temperature increase of particles in the preheated zone as a result of only conduction heat transfer mechanism is expressed based on the superposition principle.

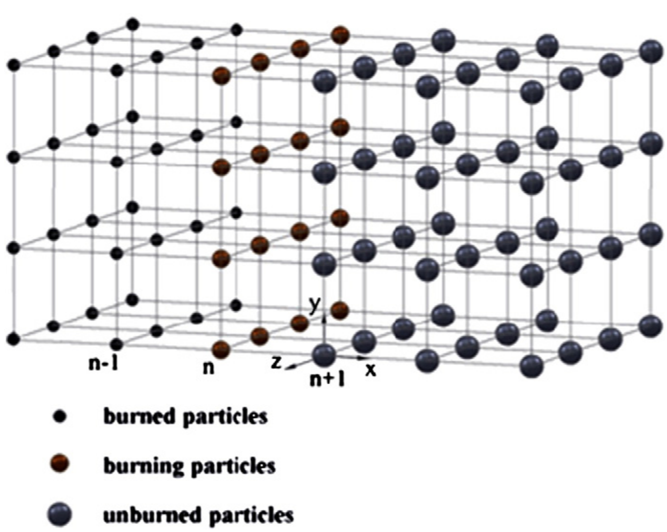

Fig. 1. The spatial distribution of particles in dust cloud: Layer n − 1 (burned particles), layer n (burning particles), and layer n + 1 (preheating particles) [24].

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

1. The particle is spherical and the flame diameter remains constant and is equal to the particle diameter.
2. The thermal properties of the media and particles are independent of temperature.
3. There is an equal and constant space between the particles distributed in the dust cloud.
4. A constant rate of energy release is considered during the combustion of a single particle.
5. For simplicity, the radiation heat transfer in the boron dust cloud is neglected and only conduction heat transfer has been considered.

A relation for burning time of a single boron particle is presented by king [16]. As mentioned earlier, the mode of the combustion of micron-sized boron particles is a diffusion-controlled regime. Also boron undergoes a heterogeneous combustion in oxygen with the oxide coating on the particles. The burning time of boron particles in diffusion-controlled regime can be obtained from the following relation:

$$t_b = \frac{\rho_B}{8\rho_g D_{O_2,\infty} \ln\left(1 + 0.677 X_{O_2,\infty}\right)} d_{p,I}^2 \tag{1}$$

where t_b is the burning time of boron particle in diffusion-controlled regime, ρ_B is the boron particle density, $d_{p,I}$ is the initial diameter of the boron particle, ρ_g is the ambient gas density, $\rho_g D_{O_2,\infty}$ is the density-diffusion product, and $X_{O_2,\infty}$ is the mass fraction of oxygen in the ambient gas far from the particle surface.

Moreover, the combustion time of boron particles from d^1 law expression has calculated to generate simplified closed-form flame speed expression [2]:

$$t_b = \frac{r_{p,I}}{k_R P Y_{O_2,\infty}} \tag{2}$$

where the parameters are defined in the nomenclature table.

To model the single-particle combustion and the time–place temperature distribution of its domain, the energy equation in spherical coordinates is used:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial T_a(r,t)}{\partial r}\right) = \frac{1}{\alpha}\frac{\partial T_a(r,t)}{\partial t} \tag{3}$$

$$\left\{\begin{array}{l} k_p A \dfrac{\partial}{\partial r} T_a(r,t) = \dot{q} \times Heaviside(\tau - t), @r = r_p \\ T_a(\infty, t) = 0 \\ T_a(r,0) = 0 \end{array}\right\}$$

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

$\dot{q}$ is the rate of heat release of a single particle from its surface during the burning time which is defined below as [23]:

$$\dot{q} = A k_p \left(T_f - T_\infty\right) r_{p,I}^{-1}. \tag{4}$$