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Reaction-diffusion fronts of aluminum dust cloud in a system of random discrete sources

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ABSTRACT

Combustion of micron-sized aluminum dust particles was studied numerically in an environment with spatially discrete sources distributed in a random way. A thermal model was employed and developed to estimate flame propagation speed in a lean quiescent reaction medium. The model is based on conduction heat transfer mechanism. The random distribution of heat sources in a discrete environment is described by using the Gaussian random distribution function with different variance numbers. Flame propagation speed is obtained by using the one-dimensional diffusion-reaction equation which includes the source terms. Oxygen is considered as the main oxidizer and nitrogen is considered as the inert gas. Flame propagation speed, the lean flammability limit and the minimum activation energy were investigated as a function of dust concentration and particle diameter. The predicted results were compared with the experimental data and were found to be in a reasonable agreement. It can be concluded that the random model shows better predictions as compared to the uniform model.

1. Introduction

Combustion of powders is an important process used in majority of industrial applications. Therefore, investigation on combustion of both metallic and organic particles in order to specify its characteristics and their relation with the issues like process safety, energy consuming, energy production and environmental issues, has become a popular field of research [1,2].

Among different organic and inorganic types of fuel powder, Aluminum is one of the widely used fuel particle. Because of its high burning rate and enhanced combustion efficiency, it is applied in a variety of applications such as hydrogen production, propulsion and pyrotechnic aluminum compounds [3]. Aluminum powder is a very reactive metal and its oxidation can occur in either thermite or dust explosions. Many researchers have done experiments and analytical studies in order to specify the characteristics of aluminum dust combustion such as; burning time, ignition temperature, burning velocity, quenching distance, activation energy, and flammability limit.

Risha et al. [4] performed an experimental investigation to determine laminar flame speeds of micron/nano-sized aluminum particle-laden aerosols using a Bunsen-burner type dust cloud apparatus. They concluded that the measured laminar flame speeds of Al particle/air mixtures are independent of equivalence ratio due to small variation of flame temperature. Also, they investigated the effect of oxidizer flow velocity in order to determine the influence of jet momentum on particle breakup and laminar flame speed. Julien et al. [5] investigated the free propagation of isobaric flames through aluminum dust clouds in an extensive series of experiments which were performed with suspension of aluminum powder in mixtures of oxygen-nitrogen, oxygen-argon and oxygen-helium in various concentrations of oxygen and aluminum. They concluded that stable flame propagation can only be achieved in rich conditions near stoichiometric status and it is highly affected by the heat conductivity of gas mixtures. Also, they observed that for fuel-rich mixtures, unlike fuel-lean mixtures, oxygen concentration has a strong influence on flame speed. Julien et al. [6] studied the stabilized aluminum flames in the products of methane combustion. It was observed that below the critical aluminum concentration of 120 g/m^3, an incomplete oxidation with a flame temperature close to the

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methane-air flame occurs. Also, the flame speed decreases similar to a flame seeded with inert silicon carbide particles. They found at the aluminum concentration above the critical value, an aluminum flame front rapidly forms and is coupled to the methane flame.

Many analytical and numerical studies were performed for combustion of aluminum dust particles. Jadidi et al. [7] presented a two-dimensional analytical model of combustion of micron-sized aluminum dust cloud in a channel. They assumed a laminar, steady and uniform flow with the purpose of gaining flame speed, quenching distance, lean flammability limit and temperature distribution. They assumed that the particle burning rate in the flame front is controlled by the process of oxygen diffusion. They wrote the equations in two limiting cases: lean and rich mixtures. Furthermore, it was considered that flame structure is consisted of preheat, reaction, and post-flame zones for the lean mixture and preheat and reaction zones for the rich mixture. Huang et al. [8] studied mono-dispersive combustion of aluminum particles in air under lean reaction medium and obtained the flame speed and temperature distribution numerically by solving the energy equation in the flame zone. Also, particle burning rate was modeled as a function of particle diameter and ambient temperature. Their model could predict the effects of particle size, equivalence ratio, and chemical kinetics on the burning characteristics and flame structures of aluminum-particle/air mixtures. They showed that for micron-sized and larger particles, the flame front speed can be correlated with the particle size according to a d^{-m} relationship with, m, which is being 0.92.

Combustion models are highly affected by fuel type and domain simplifications. Most of the existing models in the literature of powder combustion assume a uniform media for the combustion domain. This assumption is one of the common simplification assumptions and it is applied on different cases like particle sizes, particle distribution, particle shapes, temperature field in the domain, etc. From the macroscopic viewpoint of dust combustion, flame propagation is seen in a steady state condition and this assumption seems to be suitable. But from microscopic viewpoint, instabilities are observed in the propagation of the flame front which is directly related to the highly random situation of domain [9]. From microscopic point of view, a collection of particles in gas phase medium forms a discrete domain and particles are distributed randomly. Hence the homogeneous models of dust combustion are not that effective in determining the combustion properties.

A suitable method for modeling this random pattern is using the behavior of diffusion-reaction in heterogeneous media. This means that there is a homogeneous medium, the effective medium, whose diffusive properties are close to those of the real medium when measured on long space-time scales. A process of averaging or homogenization takes place so that the complicated small scale structure of the material is replaced by an asymptotically equivalent homogeneous structure. Front propagation in heterogeneous fluid flows is a fundamental issue in combustion science, and has been an active research area for decades [10,11]. A fascinating phenomenon is that the large time front speed depends strongly on the flow structures. Front dynamics and speed enhancement have been studied mathematically for various flow patterns by analysis of the proto-type models, i.e. the reaction-diffusion advection equations [12,13].

One-dimensional combustion of aluminum powders in a disordered heterogeneous system is investigated. The goal of the present research was to develop a theoretical thermal model for aluminum dust combustion in a random media. For description of the random media, the Gaussian random distribution function is used by means of different variances. Finally, burning velocity is achieved by solving the diffusion-reaction equation including discrete source terms for two different modes of uniform and random distribution of particles in reaction media. Furthermore, the effects of particle size and aluminum dust cloud concentration on the burning velocity have been investigated and the minimum activation energy and the lean flammability limit are estimated as a function of particle size which would be of importance as regards to the safety issues and specifying the situations in which no flame would be generated.

2. Theory

2.1. Governing equations

In the considered model, the kinetics of chemical reaction process is simplified and is modeled by ignition temperature of particles T_{ig} and the amount of released thermal energy Q as the result of combustion. In order to use the present thermal model, it is assumed that gasless combustion occurs in the heterogeneous system [14,15]. Therefore, the sense of ignition temperature becomes apparent. In a gasless combustion system, the particles are considered to be chemically inert in the mixture however; it is assumed that the amount of released heat according to interactions is large enough for a self-sustained propagation flame. The solid particles need to be melted in order to enter the reaction otherwise the components will not be able to mix with each other which is necessary for the reaction to get started. According to experimental data, the combustion of particles will begin immediately after the melting of solid particles and the burning time of the activated particles is negligible in comparison with the time needed for heating of the particles from their initial temperature to the ignition temperature [16]. Then the process of combustion of activated cells can be considered instantaneously.

In the present research, the effects of radiation is disregarded. Bidabadi [17] showed that, the effects of radiative heat transfer in combustion of aluminum dust particles can be neglected. He demonstrated that the ratio of the temperature difference caused by conduction to the temperature difference caused by radiation in aluminum particles is 501. This ratio is also known as Stark number which corresponds to the relative role of heat transfer by conduction to that by radiation. The radiative heat transfer vanishes for the limiting case of a transparent medium. As a matter of fact, when the aforementioned ratio approaches large numbers, heat transfer within the medium is only by conduction. The opposite extreme is when the above said ratio approaches zero. It corresponds to the case in which heat transfer is solely due to radiation. Therefore, when this ratio has a large value for aluminum, thus one can neglect the effect of radiation in the combustion of aluminum particles.

It is considered in the present thermal model that, the temperature of particles would rise up to the ignition temperature and then they would start burning. As a result of combustion of these particles, an amount of energy would be released therefore these burning particles are considered as heating sources for preheating the rest of the unburned particles Fig. 1.

In addition, it is assumed that all particles are spherical. As the results show, the variation of particle temperature with its radius can be neglected. Hence the equation of energy can be written as following:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \nabla^2 T + \frac{\dot{q}}{k} \tag{1}$$

where α is the thermal diffusivity of particles, k is the thermal conductivity of particles, and $\dot{q}$ is rate of heat released. The above equation can be non-dimensionalized by the following definitions: