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Modeling quenching distance and flame propagation speed through an iron dust cloud with spatially random distribution of particles

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ABSTRACT

In this research combustion of iron dust particles in a medium with spatially discrete sources distributed in a random way has been studied using a numerical approach. A new thermal model is generated to estimate flame propagation speed and quenching distance in a quiescent reaction medium. The flame propagation speed is studied as a function of iron dust concentration and particle diameter. The predicted propagation speeds as a function of these parameters are shown to agree well with experimental measurements. In addition, the minimum ignition energy has also been investigated as a function of equivalence ratio and particle diameter. The quenching distance has been studied as a function of particle diameter and validated by the experiment. Considering random distribution of particles, the obtained results provide more realistic and reasonable predictions of the combustion physics compared to the results of the uniform distribution of particles.

1. Introduction

Dust explosions are a recognized threat to humans and property for the last 150 years (Eckhoff, 2003). Many combustible dusts allow a flame to propagate through the fuel particles if dispersed as a cloud in air and ignited, in a manner similar to (though not identical to) the propagation of flames in premixed fuel oxidant gases (Proust, 2006). Such dusts include common foodstuffs like sugar flour, cocoa, synthetic materials such as plastics, chemicals and pharmaceuticals, metals such as aluminum and magnesium, and traditional fuels such as coal and wood (Abbasi and Abbasi, 2007).

One of the earliest recorded and the most serious of the accidents triggered by dust explosion occurred at Leiden, the Netherlands, on 12 January 1807 (Abbasi and Abbasi, 2007). Similar disasters induced by metal dust occurred in 2011 in which three iron dust flash fires occurred over a period of five months and killed five workers at the Hoeganaes Corp. facility in Gallatin, Tennessee. These three events are examples of hazard identification and general drift in the management of safety barriers. Most of these accidents occurred during maintenance activities. They could have been prevented if the risk status of the system had been known. A comprehensive review of dust explosions cases and causes was presented by Abbasi and Abbasi (2007). Accidental dust explosions are highly undesirable in any plant, yet an explosion hazard always exists wherever dusts are produced, stored or processed, whenever a threshold quantity of powdered flammable material is present in the air. With the advancement of powder technologies for materials processing, and the increase of powder handling processes, hazard assessment and the establishment of preventive methods for dust explosions have become more important from the view point of industrial loss prevention. Therefore, a correct understanding of the combustion mechanism is necessary in order to minimize the probability of occurrence of such events in the future.

The combustion of metallic particles used in a variety of industrial applications is a highly exothermic event. Basic mechanisms of combustion of such two-phase mixtures are not well understood because of two major problems facing the research in combustion of dust particles (Hanai et al., 2000). The first is the complex nature of processes involving the physical and chemical properties of the fuel. The second relates to the size, shape and spatial distribution of the particles. Iron is regarded as a non-

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volatile metallic fuel, and the oxidation process takes place as a heterogeneous surface reaction. The major characteristic feature of iron combustion is that it burns heterogeneously in air: the oxidation reaction occurs at the surface of iron particle, and no flame is observed in the gaseous oxidizer phase. Iron particles do not evaporate during the combustion process, and the combustion product, iron oxide, remains in the condensed phase.

Sun et al. (1990), Sun et al. (1998) experimentally examined the combustion zone propagating through an iron particle cloud and the process of iron particle combustion. They have demonstrated that the burning time of an iron particle is proportional to the non-dimensional diameter when its diameter is small; as the iron particle diameter becomes larger, the burning time increases with a power of the non-dimensional diameter. Sun et al. (2006) experimentally studied the concentration and velocity profiles of iron particles across up- and downward flame propagation in the vicinity of the combustion zone. Bidabadi et al. (2010) proposed a mathematical model based on utilizing the Lagrangian equation of motion and the effective thermophoretic, gravitational and buoyancy forces acting on the particles in order to represent the velocity profile of the micro-iron dust particles. Bidabadi and Mafi (2012, 2013), theoretically investigated the evolution in combustion temperature and burning time of a single iron particle in air, and proposed an analytical model that agreed with the experimental findings. Beach et al. (2007) investigated the combustion of iron nanoparticles as a potential alternative fuel, in which the burning time of iron particles was calculated for both spherical and disc shaped iron particles using the heat balance and chemical kinetic theories.

There are two general approaches to model dust combustion: the continuous or macroscopic approach and the discrete or microscopic approach. From the microscopic viewpoint, the propagation of the flame front is inherently unsteady, as it migrates from particle to particle (Mukasyan et al., 1996; Rogachev et al., 1994). The spatial distribution of particles strongly influences the flame propagation (Tang et al., 2009a,b). In contrast, in the traditional continuous or macroscopic approach to model particles in a gaseous suspension, the discrete nature of the heat sources is averaged to yield a mean propagation speed. Continuous models of dust combustion cannot usually capture the lean flammability limit concentration or the threshold particle diameter, dust concentration and heat release. Indeed, it can be demonstrated that the flammability limit depends on spatial distribution of particles (Rashkovskiy et al., 2010).

A new thermal model has been generated to estimate the flame propagation speed for micron-sized iron particles under various dust concentrations and sizes in air. This discrete heat source method provides a dust combustion model, from ignition process to the final state, including steady flame propagation, flame quenching and explosion.

In the current research paper, the combustion of iron particles distributed uniformly in space is studied. As a further improvement to the model, a random distribution of particles is used in the governing equations to predict the flame features, such as; flame propagation speed, minimum ignition energy, and quenching distance. The model starts by considering single particle combustion to obtain a space-time temperature distribution. The ensemble reacting front in the suspended dust combustion is then considered using the superposition principle to include the effects of surrounding particles. All the burned and burning particles are considered as heat sources, and the channel walls are assumed to behave as heat sinks. Finally, the flame propagation speed and quenching distance in the narrow channel are determined.

2. Discrete thermal model

The combustion of dust clouds is a complex process, involving particle heating, evaporation, intermixing with oxidizer, ignition, burning and quenching of particles. Particle size and dust concentration and distribution of the particles clearly play very important roles. Reaction-diffusion phenomena have been modeled extensively in homogeneous media where the reactants are distributed continuously in space. In a homogeneous system, the heat source term does not depend on spatial coordinates and a solution can be obtained by solving a set of scalar, ordinary differential equations. However, in heterogeneous media, the reactants form a separate phase within a diffusive medium causing the reaction to occur locally around the boundaries or inside the sources. Unlike homogeneous media, the reaction is localized at the position of the heterogeneities and the heat source term depends explicitly on the coordinates of the reacting sources in the domain (Tang et al., 2009a,b).

2.1. Uniform distribution

In the uniform distribution approach, dust particles are assumed to be uniformly dispersed in air as shown schematically in Fig. 1.

The ignition system provides the minimum necessary energy to the dust cloud, raising the temperature of some particles to the ignition temperature. As these particles start to burn, they act as a heat source and cause the temperature of the surrounding region to rise. The temperature rise in the other particles is calculated as the linear superposition of thermal effects from the burned and burning particles. Particle ignition is assumed to take place once the particle reaches a minimum temperature $T_{ig} = 850$ K (Tang et al., 2009a,b), and the combustion process propagates to other particles. The mixture is assumed to be stagnant, so that the temperature increase of particles in the preheated zone is assumed to be an exclusive result of conduction heat transfer through the gaseous medium (Bidabadi et al., 2013).

The thermal model generated in this study for the uniform particle distribution model is based on heterogeneous combustion in three-dimensions. The model relies on the following assumptions:

1. Each particle is spherical in shape, and the associated flame diameter remains constant and equal to the particle diameter (Sun et al., 1990).
2. No oxide layer surrounds the iron particles.
3. The thermal properties of the medium and particles are independent of temperature.

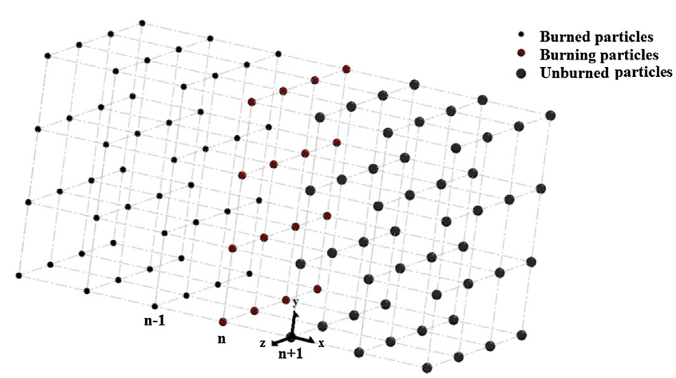

Fig. 1. Spatial distribution of particle in a uniform dust cloud: layer $n-1$ represents (burned particles), layer n (burning particles), and layer $n+1$ (preheating particles).