Journal of Hazardous Materials 176 (2010) 146–153

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Mathematical modeling of velocity and number density profiles of particles across the flame propagation through a micro-iron dust cloud

Mehdi Bidabadi*, Ali Haghiri, Alireza Rahbari

Department of Mechanical Engineering, Iran University of Science and Technology (IUST), Combustion Research Laboratory, Narmak, Hangam St., Tehran, Iran

ARTICLE INFO

Article history:
Received 2 August 2009
Received in revised form 25 October 2009
Accepted 31 October 2009
Available online 10 November 2009

Keywords:
Thermophoretic force
Analytical approach
Dust explosion hazard
Velocity profile
Concentration profile

ABSTRACT

In this study, an attempt has been made to analytically investigate the concentration and velocity profiles of particles across flame propagation through a micro-iron dust cloud. In the first step, Lagrangian particle equation of motion during upward flame propagation in a vertical duct is employed and then forces acting upon the particle, such as thermophoretic force (resulted from the temperature gradient), gravitation and buoyancy are introduced; and consequently, the velocity profile as a function of the distance from the leading edge of the combustion zone is extracted. In the resumption, a control volume above the leading edge of the combustion zone is considered and the change in the particle number density in this control volume is obtained via the balance of particle mass fluxes passing through it. This study explains that the particle concentration at the leading edge of the combustion zone is more than the particle agglomeration in a distance far from the flame front. This increase in the particle aggregation above the combustion zone has a remarkable effect on the lower flammability limits of combustible particle cloud. It is worth noticing that the velocity and particle concentration profiles show a reasonable compatibility with the experimental data.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Dust explosion is one of the most challenging and dangerous hazards in industries that manufacture, process, generate, or use combustible dusts. It has been a recognized threat to humans and property for the last 150 years [1]; hence, an accurate knowledge of the explosion hazards is essential [2].

With the advancement of powder technology 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. In spite of significant efforts to obtain information on the explosibility of dusts, the fundamental mechanisms of flame propagation in dust suspension have not been studied sufficiently [3,4].

Associating with the importance of dust explosion and flame propagation through dust particles, Sun et al. [5–8] experimentally examined the behavior of iron particles near the combustion zone across upward and downward flame propagating and consequently, the velocity and number density profiles of particles were calculated from these researches. Similarly, the same study has been carried out by Han et al. [9]. They experimentally explained the flame propagation mechanism through lycopodium dust cloud based on dust particles' behavior. Cashdollar and Zlochower [10] conducted a study of the explosibility of various metals and other elemental dusts, with a focus on the experimental explosion temperatures.

Bidabadi and Rahbari [11] analytically investigated the flame propagation through lycopodium dust particles and explored the flame structure mechanism and the effect of temperature difference between gas and particles on the combustion characteristics. In another study, Bidabadi and Rahbari [12] presented a novel analytical model for predicting the heat loss and Lewis number effects on the combustion of lycopodium particles.

Furthermore, in our previous study [13], various aspects of flame propagation and the structure of combustion zone were analytically investigated and the effects of different Lewis and Damköhler numbers and the initiation of particles vaporization on the combustion phenomenon of the organic dust particles were completely specified.

One of the important phenomena in flame propagation through a combustible mixture of dust particles and air is the impact of temperature gradient (i.e., thermophoretic force) on dynamic behavior of particles which has found numerous applications in the aerosol technology field. In a temperature gradient field, small particles move in the direction opposite to the temperature gradient, resulting in the thermophoresis which has a significant influence on the behavior of soot particles. Thus, in explaining the transport of soot particles, the consideration of thermophoretic effect is essential,

---

* Corresponding author. Tel.: +98 21 77 240 197; fax: +98 21 77 240 488.
E-mail address: bidabadi@iust.ac.ir (M. Bidabadi).

0304-3894/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2009.10.130

as demonstrated by Gomez and Rosner [14] for diffusion flames. In addition, thermophoretic effects on spherical aerosol particles have been studied extensively for a wide range of temperatures and flow conditions [15–17]. Batchelor and Shen [18] investigated the thermophoretic deposition of particles flowing over a cold surface. There are several researches investigating the amount of soot deposition to solid media inserted in diffusion flames [19,20], demonstrating that sharp temperature gradient by the existence of cold solid surface induced the thermophoretic effect and promoted soot deposition. However, Ono et al. [21,22] reported that the thermophoretic velocities evaluated by the two equations are much smaller than the values measured in their experiments independent of agglomeration size. They also showed that soot agglomerates under thermophoretic forces behave as individual fine primary particles in the free-molecular regime rather than as large size particles in the slip-flow regime.

Tsai and Liang [23] presented a rational correlation for evaluating the effect of thermophoresis on aerosol particle deposition from laminar flow systems. Zheng [24] reviewed the existing theories and data in two major categories, for spherical particles and for non-spherical particles, as well as the various techniques in making thermophoresis measurements. Wang [25] explained the effect of thermophoresis on particle deposition rate from a natural convection flow. Walsh et al. [26] developed a model in order to investigate the thermophoretic deposition of aerosol particles on the wall of a relatively cool cylindrical tube.

A one-dimensional, steady-state theoretical analysis of flame propagation mechanism through micro-iron dust particles based on dust particles' behavior with special remark on the thermophoretic force for small Knudsen numbers (i.e., near continuum limit) is presented in this paper. A discrete trajectory approach (Lagrangian method) is proposed and the physical mechanisms controlling particle transport such as gravitation, buoyancy and thermophoretic forces are taken into account. Consequently, the number density and velocity profiles of particles near a flame propagating through an iron particle cloud are analytically determined. This study shows that the number density profile of micro-iron particles across the leading edge of the flame front decreases with increase in the distance from the combustion zone leading edge. It is worth noticing that the present analytical model is specifically suitable for further improvement of numerical computer codes (e.g., Dust Explosion Simulation Code (DESC)) to simulate the flame propagation in accidental dust explosions involving fine iron dust. In a broader perspective, this kind of simulation becomes more important in tailoring systems for dust explosion isolation, venting and suppression. Moreover, the measured profiles of velocity and number density of iron particles are in a good agreement with the published experimental results.

2. Lagrangian iron particle equation of motion

In the present study, it is assumed that the micro-iron particles are suspended in air and ignited by an electric spark near the bottom end of a vertical duct, and then flame propagates upwardly through combustible dust mixture in this duct, as seen in Fig. 1(a). It should be noted that there is a strict distinction between flame velocity and burning velocity. So that, the flame speed (flame velocity) is obtained from camcorder records by measuring the time interval for the flame to propagate a known distance between two markers, but a volumetric consumption rate of reactant per unit flame area is known as burning velocity. The reactive mixture expands quickly during the combustion phenomenon and hence, the flame seems to be a moving piston acting on both the burned and unburned mixtures, leading to an increase in gas density in front of the flame front and acting as an expansion flow in the flow field. Consequently, the iron dust particles follow the bulk gaseous motion in the unburned zone to form a distribution of particles concentration toward the leading edge of the combustion zone.

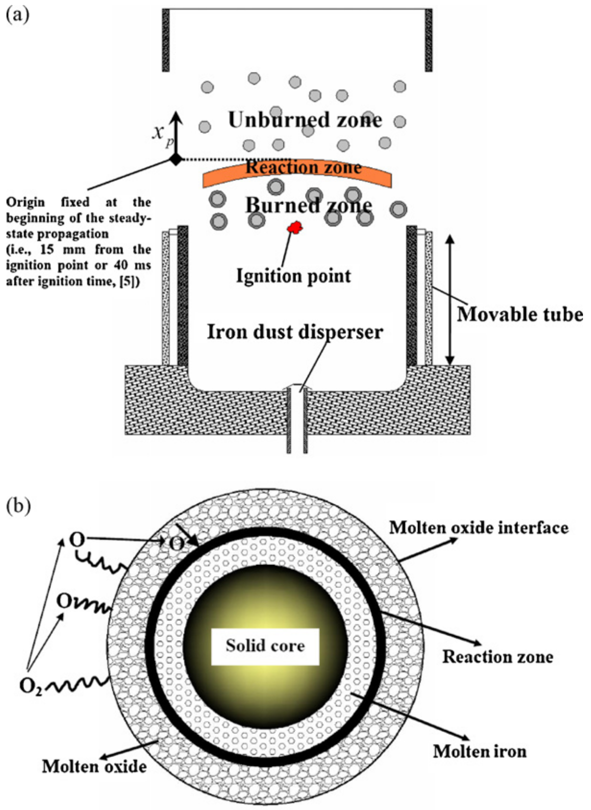

Fig. 1. (a) The flame structure of the combustible mixture of micro-iron dust particles and air; (b) the schematic of iron oxidation process at the combustion reaction.

It is worth noticing that the turbulence within the chamber is induced by both the jetting effects of pneumatic dispersion systems and the shear layer near the chamber wall owing to the expansion of combustion products. The turbulence increases [27] the combustion reaction rate around the combustion zone and enhances the heat transport among the particles. This will lead to the acceleration of the flame propagation. But in the most experimental studies (e.g., Sun et al. [5,7,8]) carried out on the flame propagation through particle cloud, the main effort was to reduce the aforementioned factors. In order to decrease the jetting effects of pneumatic dispersion systems in inducing the turbulence in the combustion process, the following instructions are used by the researchers:

The dust is dispersed at the base of a conical chamber through the impact of a high velocity cylindrical jet issuing from an adjustable circular slot. A combustion chamber where combustion experiments are performed is connected to the dispersion chamber through an 8° conical diffuser. The diffuser provides expansion and laminarization of the dust flow which is initially turbulent in the dust disperser [28]. In addition, a set of quenching plates with a gap about 3.5 mm between plates is also installed in the beneath part of the chamber. This set serves as a flame arrestor to prevent flash back into the dispersion system and also helps to laminarize the dust flow after it exits from the dust disperser.

Furthermore, in order to annihilate the tube wall effect in inducing the turbulence generation during the flame propagation

Download English Version:

https://daneshyari.com/en/article/580545

Download Persian Version:

https://daneshyari.com/article/580545

Daneshyari.com