Applied Thermal Engineering 105 (2016) 474–482

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

A comparative study of different burning time models for the combustion of aluminum dust particles

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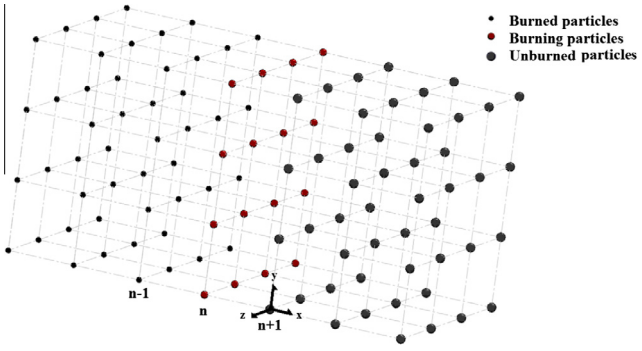
HIGHLIGHTS

- A new thermal model was generated to calculate the flame speed of aluminum dust cloud.
- As the particle size increases, the value of flame speed decreases.
- With the increase of the oxygen mole fraction, the value of flame speed tends to rise.
- The value of flame speed in carbon dioxide is the lowest than the other oxidizers.

GRAPHICAL ABSTRACT

The spatial distribution of particles in dust cloud: Layer $n-1$ (burned particles), layer n (burning particles), and layer $n+1$ (preheating particles).



ARTICLE INFO

Article history:
Received 25 May 2015
Accepted 4 March 2016
Available online 25 March 2016

Keywords:
Heterogeneous combustion
Aluminum
Flame propagation speed
Burning time models
Metals ignition

ABSTRACT

In the present paper combustion of micron-sized aluminum dust cloud has been studied in a quiescent reaction medium with spatially discrete sources. A new thermal model is generated to estimate the flame front speed in a lean reaction environment in different oxidizer concentrations. Different burning time models for aluminum are utilized in the generated thermal model to compare their applicability by using the existing experimental data. The model is based on conduction and radiative heat transfer mechanisms using the heat point source method. The combustion of single-particle was first studied and the solution is presented. Then the dust combustion was investigated using the superposition principle to include the effects of inter-particles. The flame propagation speed as a function of aluminum dust concentration for various particle diameters is studied and the effects of radiation heat transfer are taken into account in the governing equations. In addition, flame speed in different types of oxidizers such as air, carbon dioxide, and water vapor is investigated and nitrogen is considered as the inert gas. A reasonable agreement between the results of the numerical solution of combustion of an aluminum dust cloud and the experimental data was obtained in terms of flame propagation speed. It is found that the value of flame speed of combustion of aluminum dust particles in carbon dioxide reaction medium in a considered dust concentration and particle size, is the lowest compared to the other oxidizers.

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http://dx.doi.org/10.1016/j.applthermaleng.2016.03.022
1359-4311/

Nomenclature

A	area (m^2)
C_d	dust concentration (kg/m^3)
D	diameter (m)
H	Heaviside function
i,j,k	components of Cartesian coordinate
k_p	conduction coefficient (W/m K)
L	distance of two adjacent particles or layers (m)
r	radial distance (m)
t	time (s)
T	temperature (K)
P	pressure (Pa)
Q	energy released from igniter (J)
T_a	relative temperature (K)

Greek symbols

α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
τ	particle burning time (s)
φ	equivalence ratio

Subscripts

f	adiabatic flame temperature
g	ambient gas
ig	ignition
p	particle
∞	ambient property
n	the layer counter
CO_2	carbon dioxide
H_2O	water vapor
O_2	oxygen

1. Introduction

Combustible dusts are fine particles that present an explosion hazard when suspended in air in certain conditions. Dust explosions are common and costly in a wide array of industries such as petrochemical, food, paper and pharmaceutical. Hence, an accurate knowledge of the origin, development, prevention and mitigation of dust explosions is essential. Natural and synthetic organic materials, coal, peat and metals are the materials that can cause dust explosions [1]. Many studies have been done regarding combustion of organic and inorganic dust particles within the last few years. Li et al. [2] studied the effects of particle concentration variation in the primary air duct on combustion characteristics in a test facility with pulverized coal swirl burners. Wang et al. [3] determined the optimum coal concentration in a general tangential-fired furnace with rich-lean burners.

Combustion of inorganic particles is an important field of research. Aluminum powder is widely used in various applications, such as propulsion and pyrotechnic aluminum compounds because of the high burning rate of dust particles and enhanced combustion efficiency. But combustion of dust particles in air has been a serious safety concern for the mining, manufacturing, and energy production industries. Several large-scale accidents have occurred that resulted in loss of life and substantial property damage. Lembo et al. [4] discussed several aluminum dust explosions in the industrial centers at Italian Verbano Cusio Ossola region's during the years of 1990–2000 period. Aluminum powder is a very reactive metal and its oxidation can occur in either thermite or dust explosions [5]. Some important studies have been done during the 1960s and 1970s shortly after the effects of aluminum were conceived [6]. In the early studies, Glassman [7] recognized that metal combustion would be similar to droplet combustion, and therefore the D^2-law should be applied. Many researchers have done experiments to study the burning time and the ignition temperature of aluminum particles.

Belyaev et al. [8] investigated the combustion of aluminum and introduced an equation to estimate the burning time of aluminum as stated below:

$$\tau = 0.67\frac{D_p^{1.5}}{a_k^{0.9}} \tag{1}$$

where D_P is the particle diameter in micrometer and τ is the burning time in millisecond and a_k is a constant parameter.

Friedman and Macek [9] and Macek [10] reported burning time data for combustion of aluminum particle. Their results suggest an exponent of 1.2–1.5 for the particle diameter in Eq. (1). Davis [11] found that an exponent of 1.8 fits his experimental well. Dreizin and Trunov [12] studied combustion of aluminum with a particle diameter of 150 μm in air at room temperature and standard pressure of 1 atm. Their report shows a significant decrease in the aluminum burning time with the increase of oxygen concentration. To consider the effect of different oxidizers, Brooks [13] suggested an effective oxidizer Eq. (2) which includes the concentrations of O_2, CO_2 and H_2O.

$$X_{eff} = C_{O_2} + a_{H_2O}C_{H_2O} + a_{CO_2}C_{CO_2} \tag{2}$$

Beckstead [6] suggested that, with the coefficients of a_{H_2O} and a_{CO_2} at 0.6 and 0.22 respectively, an agreement between different studies can be observed. The Beckstead burning time equation for combustion of aluminum particles has been used in this investigation, and it is stated as follows:

$$\tau = \frac{mD_P^n}{X_{eff}P^{0.1}T_o^{0.2}} \tag{3}$$

where

$m = 0.00244$ for $n = 1.5$,
$m = 0.00735$ for $n = 1.8$,

D_P is the particle diameter in micrometer and τ is the burning time in millisecond. Shoshin and Dreizin [14] suggested that the burning time of aluminum particles is a function of particle diameter.

$$\tau = 310D_P \tag{4}$$

where D_P is the particle diameter in meter and τ is the burning time in second. This equation has also been used in the present study in the generated thermal model for the estimation of flame propagation speed of combustion of an aluminum dust cloud by employing different burning time models. Previous investigations have focused on calculating the burning time and flame temperature of aluminum particle. Brzustowski and Glassman [15] suggested that aluminum burns in the vapor phase.

In the present study, the effects of particle size, oxygen molar fraction and dust concentration on the flame propagation speed of micron-sized aluminum dust cloud have been studied. The discrete heat source method provides the dust combustion model, from the ignition process to final state which includes steady flame propagation, flame quenching or even explosion. This developed method is powerful. Besides the wide range of models generated for dust particle combustion involving mass transfer and chemical kinetics, the present thermal model uses a novel approach for