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Full Length Article

Flame propagation through heterogeneous combustion of hybrid aluminum-boron poly-disperse particle suspensions in air

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ABSTRACT

In this paper, flame propagation through heterogeneous hybrid aluminum-boron dust cloud including the effect of particle Poly-dispersion was simulated. Particles were distributed randomly within a three-dimensional domain. A discrete thermal model based on heat transfer between distinct metallic particles was developed to estimate flame propagation speed in the mixture. The flame propagation speed of the hybrid dust cloud in air was calculated for a range of total particle concentrations and different aluminum and boron partial concentrations. The presented results showed that the flame front velocity increases as the weight percentage of aluminum particles increase. In addition, adding aluminum to boron dust cloud can improve the flame propagation speed. To investigate the roles of conduction and radiation as well as radiative heat loss, time variations of particle temperatures when only one of the heat transfer mechanisms is present were evaluated and discussed. Careful examination of the numerical results showed that conduction heat transfer had the dominant role in aluminum and boron aero-suspension combustion.

1. Introduction

Metallic particle combustion has received considerable attention during the last decades due to their favorable energetic properties [1]. Aero-suspensions of metallic powders such as beryllium, boron, magnesium, aluminum, titanium and iron air mixtures have high values of burning energy with respect to hydrocarbon fuels on mass and volumetric basis [2]. Cost and availability [3] as well as environmentally benign combustion products of metal powder fuels are other motivations for the use of these fuels as alternatives to conventional hydrocarbon fuels. For instance in chemical looping combustion systems (CLC), metal powders can be used as oxygen carriers in order to prevent CO_2 dilution with flue gases [4]. Additionally, metal powders can be used as transportation fuels in metal-fuel cycles. Clean primary energy is used to reduce metal oxides into metal fuels, which are then transported and sold for energy production. The metal oxides can be collected and recycled back into metal fuels, closing the energy cycle [5].

Among the abovementioned metal particle air suspensions, boron is of particular significance as it possesses the highest energy density per unit volume and mass [6]. This property becomes more important in volume-limiting applications such as air-breathing ramjet engines. Boron's theoretical potential as a fuel has motivated extensive researchers at understanding its key combustion mechanisms and characteristics. Experimental studies on elemental boron particle [7,8] indicated that boron particle combustion always occur in two consecutive stages. The first stage is believed associated with burning of boron particles while they are still covered with a pre-existing boron oxide layer. The second stage is generated by full-fledged combustion of uncoated boron particles. King [9,10] introduced a detailed theoretical model for both single boron particle and boron dust cloud combustion in oxygen-nitrogen media to predict flame speed and particle burning time. An extensive experimental investigation on ignition and combustion of boron particles at high pressures and temperatures in nitrogen-diluted hydrogen/oxygen mixture is conducted by Foelsche et al. [11]. This study demonstrates that boron particle lifetimes at elevated pressures are sufficiently short to make particles smaller than 20 μm suitable for high-speed air-breathing propulsion applications. Mohan et al. [12] developed a combustion model from high-speed photographs of the ignition and combustion of laser-ignited boron particles. Effect of particle diameter on the ignition temperature of boron at different ambient temperatures and atmospheric pressure as well as burning rate of boron particles as a function of ambient oxygen concentration is represented in this model.

Jain et al. [13] conducted a set of experiments to study ignition behavior of boron powder by using thermogravimetry coupled with simultaneous differential thermal analysis. The effects of partial

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Nomenclature

Symbols

x,y,z	the dimensional Cartesian coordinate system (m)
IM,JM,KM	maximum numbers of nodes in x, y and z direction
$\Delta x,\Delta y,\Delta z$	the lengths of cells in x, y and z direction (m)
Cd	dust cloud concentration (kg/m^3)
T	temperature (K)
P	pressure (atm)
r	distance from a particle (m)
t	time (s)
d	particle diameter (m)
$\dot{q}$	heat rate released from surface (J/m^2 s)
Q	heat (J)
C	specific heat (J/kg)
v	flame propagation speed
L	ignited particle
B	burning particle
Nu	Nusselt number
$\bar{d}$	representative diameter
f	dimensionless diameter polydispersity
n	the number of particles
X	mass fraction

Subscripts

ave	average
p	particle
P	constant pressure
a	air
Al	aluminum
B	boron
m	target particle
∞	ambient
sur	surrounding media near a burning particle
$Cond$	conduction
Rad	radiation
$Loss$	heat losses
abs	absorption
s	scattering
ε	emission capability
igS	ignition system
i	the kind of powder (aluminum or boron)

Superscripts

0	initial
n	old time step
$n+1$	new time step

Greeks

α	thermal conductivity (m/s^2)
τ	the burning time of particles (s)
ξ	weight percentage

pressure of oxygen, boron powder particle size and heating rate on ignition temperature was investigated. Additionally, effect of presence of carbon was studied and it was found that carbon retards the oxidation process of boron and consequently raise the ignition temperature. Effect of temperature, particle size and fluorine additives on ignition delay time of 1–15 μm boron particles in oxygen and oxygen/fluorine atmospheres at a high pressure shock tube is investigated by a series of experiments by Krier et al. [14]. Recently Bidabadi et al. [15] has introduced a model to predict boron dust cloud combustion characteristics, considering boron particles as discrete heat sources. The model is based on heat diffusion between particles and burning time of single particles. Flame propagation speed as a function of particle diameter and particle concentration is obtained in this work.

Suitability of any fuel depends not only on its energetic effects but also on rapidity of its combustion. High ignition temperatures of boron particles and their long burning times determine some difficulties in organizing boron combustion [16]. High ignition temperature of boron particles along with its relatively low flame temperature (2480 K at atmospheric pressure), is a limiting factor for heat transfer from the flame zone to the preheating zone due to limited temperature gradients. Under this condition unstable flame propagation and flame extinction occurs. For instance in boron-oxygen mixtures with partial oxygen pressures $P_{ox} = 0.04–0.07$ MPa, it is not possible to achieve steady flame propagation. Only short periods of flame propagation with subsequent extinction of the process can be observed [16]. A practical solution to tackle this difficulty is to introduce some other fast-burning additive fuel particles to suspensions of boron particles. Short burning times of magnesium and aluminum particles makes them suitable selections for this purpose. In view of the afore-said importance the main objective of the present paper is to present a simulation of hybrid aluminum-boron dust cloud combustion in air. A suspension of aluminum and boron particles are dispersed randomly in a spatial domain. The oxidizer is air with 21% oxygen and 79% nitrogen. The study is focused on the effect of aluminum and boron mass fractions on combustion characteristics, and a fixed oxygen concentration is used for all cases. The combustion process is assumed to be isobaric and takes place at 1 atm. This work extends the one dimensional thermal model for mono-sized boron oxygen mixtures [15] to a three dimensional model. In addition, the inter particle radiative heat transfer as well as random distribution of particles are considered in the present model. Furthermore, the diameter polydispersity for both aluminum and boron particles are included using the Rosin-Rammler and Nukiyama-Tanasawa distributions. To identify the flame front position, the locations of ignited particles are evaluated in these simulations.

2. Discrete model

Dimensionless combustion time, which is defined as the ratio of the particle combustion time to heat diffusion time between particles, determines whether the flame propagation regime is discrete or continuous [17]. If the dimensionless combustion time is significantly lower than unity, the combustion regime is discrete; conversely, when the combustion time is considerably higher than unity the source energy release time is large and combustion can be considered continuous. In the limit of widely spaced particles or low thermal diffusive media the flame propagation is controlled by energy transfer from particle to particle and spatial averaging is no longer appropriate. In the present model, a cubic control volume is introduced in order to investigate particle combustion phenomenon. Considering aluminum and boron particle properties, medium thermal characteristics and particle burning times, low value of dimensionless combustion time is expected. Therefore the spatial discreteness of sources needs to be taken into account in the combustion modeling. Particle distribution within the control volume, which is shown in Fig. 1, was done in a way that satisfied both randomization and polydispersity. The randomization method for particle distribution is introduced in Section 2.1, and methods of dispersal of particle diameters are described in Section 3.