Study on Hybrid Combustion of aero-suspensions of Boron-Aluminum Powders in a Quiescent Reaction Medium

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Abstract

The present research deals with a hybrid combustion of aluminum/boron dust particles in a heterogeneous quiescent reaction medium with spatially discrete heat sources. A developed thermal model is employed to estimate flame propagation speed in a reaction medium. The burning velocity and minimum ignition energy are studied parametrically as a function of dust concentration and particle diameter for different percentages of boron powder in a hybrid mixture of aluminum/boron dust cloud. The model shows that the addition of boron powder as a component of the mixture decreases the burning rate and causes a higher amount of minimum ignition energy needed for ignition, owing to the role of boron as a heat sink. Comparison of the simulation results with the available experimental data shows that the model captures the flame propagation speed as a function of particle concentration, except at very low concentrations.

Keywords: Hybrid combustion; Heterogeneous combustion; Boron-Aluminum powders;

Metals ignition

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1. Introduction

Industrial processing of materials in the nano to micron sized scales has increased in the past few decades. Combustion of micron-sized metallic dust clouds has therefore gained attention, as it is relevant in propulsion systems, furnaces, and material safety. Despite the extensive research conducted in this area (Bidabadi et al.,2016;Sun et al.,2006;Chen and Fan,2005) the combustion processes of dust particles are not fully understood, and more research is required. A key driver for the research is the prevention of dust cloud explosion as a hazard for the process operation and the surrounding environment. Explosions can happen in any situation where fuel particles are present at sufficiently high concentration, in the vicinity of an ignition source with a sufficient amount of energy. Several accidents have occurred with significant damages and loss of life, such as; the three explosions in the USA in 2003, which were caused by combustible powders. These accidents forced the U. S. Chemical Safety and Hazard Investigation Board to appoint a group to further developing methods for understanding dust cloud combustion phenomena(Joseph and Team,2007). These accidents have not stopped or controlled and once a while a devastating explosion being reported with lots of properties damage and human injuries.

Key parameters in understanding and preventing combustion of dust particles are the burning velocity, as well as the minimum ignition energy of the dust cloud as a function of concentration and particle diameter. The propagation of flames through metallic dusts has been the topic of many studies, owing to the high energy density of certain metals as propellants, particularly aluminum, boron, magnesium, iron, zirconium, and beryllium. Boron offers the highest energy release per unit mass, but the particular combustion characteristics such as ignition and propagation, burning, and blending with oxidizer are rather complex and slow (Ulas et al., 2001). In fact, full oxidation is often impeded by the generation of a liquid oxide layer on the particles, which slows down

molecular transport and combustion (Hussmann and Pfitzner, 2010). Therefore, although the heat of combustion per unit volume in boron dust cloud combustion can be high, its applications have been limited. Beryllium has the next highest energy release per unit mass after boron, yet it is not widely used because of its toxicity. Aluminum is, therefore, the most used and convenient metal in propulsion systems.

The combination of different metal particles in a hybrid suspensions, offers both opportunities and potential hazards. Propellants in aerospace and propulsion applications can be optimized for the amount of the energy release rate and total energy density. As a potential hazard, hybrid suspensions can be formed in manufacturing processes. The present study models the expected combustion characteristics of hybrid cloud combustion systems, based on fundamental thermodynamic and transport properties of the hybrid components.

A number of studies on metallic combustion characteristics and hybrid multi-component cloud combustion have been performed numerically and experimentally. King (1975) studied laminar flame speeds of boron-oxygen-nitrogen dust clouds both experimentally and analytically. He developed a detailed model of boron-oxygen-nitrogen dust-cloud flames including consideration of the details of boron particle ignition and the effects of oxygen depletion and parameters such as effects of initial temperature, pressure, initial oxygen mole fraction, particle mass fraction, initial particle size, and initial thickness of the oxide coating on the particles and found very good agreement with the experimental data. A comprehensive numerical model was developed by Yetter et al. (1996) to study the ignition of a boron particle. This model included the detailed chemistry of heterogeneous reactions with physical absorption occurring at the boron oxide/gas interface. Aluminum particles have long been employed as an additive in solid propellants to increase the specific impulse of a rocket motor, and many studies have been conducted to investigate particulate

aluminum combustion. Beckstead (2004) presented a comprehensive study on the combustion characteristics of aluminum combustion, focused on the burning time of individual particles. The fundamental concepts for control of aluminum combustion at different initial temperatures and environments were discussed, and combustion data from over ten different sources with almost 400 data points were catalogued and correlated. Marino (2008) determined the ignition temperature of aluminum particles at different diameters. He derived a best fit expression for the ignition temperature as a function of particle diameter. Ballal (1980,1983) conducted theoretical and experimental studies to investigate dust cloud combustion features for metal dusts of Al, Mg, and Ti. The role and effects of radiative heat transfer and chemical reactions were discussed, as well as the effect of particle size and dust concentration on quenching and minimum ignition energies.

Whereas there have been a number of studies on single-metal dust cloud combustion, there have been only few studies on hybrid material cloud combustion systems. Considering the boron-aluminum system, the high ignition temperature and long ignition time of single boron particle are less desirable for a propellant, in spite of its high energy density. However, studies by Boichuk et al. (2002) showed that the addition of slowly burning boron to rapidly burning aluminum stabilizes the overall oxidation process. In these studies, boron was found to act as an inert heat sink, resulting in a considerable decrease in the flame speed. He suggested the flame speed scales as:

$$S = \sqrt{\frac{k}{\tau_b}\frac{1}{c_p}\frac{T_f - T_i}{T_i - T_\infty}} \tag{1}$$

where k and c_p are the mean thermal conductivity and effective mean heat capacity of the suspension, τ_b combustion time of the boron/aluminum mixture, T_f the flame temperature, T_i the

ignition temperature, and T_∞ the ambient cloud temperature. There have been no other studies of boron-aluminum particle suspensions.

In the field of dispersed particle combustion, there are two general approaches: 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 (Hwang et al.,1997; Mukasyan et al.,1996; Rogachev et al.,1994). The spatial distribution of particles can also strongly influence the flame propagation (Tang et al.,2009; Varma et al., 2001). In contrast to 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. The continuous models of dust combustion cannot usually capture the behavior of limit phenomena such as the lean flammability concentration or particle diameter. Indeed, it can be demonstrated that the flammability limit depends on the spatial distribution of particles (Rashkovskiy et al.,2010). The present thermal model uses the discrete particle model for simulation of dust particle combustion. The main objective of the present work is to perform an investigation of the effect of boron powder fraction on the burning velocity of micron-sized aluminum dust particles. The burning velocity and minimum ignition energy are obtained for a range of dust concentrations and particle sizes.

2. Mathematical modeling

2.1. Governing equations and boundary conditions

The combustion of dust clouds is a complex phenomenon, which includes particle heating, evaporation, ignition, and diffusion of products and heat in suspending mixture. In a homogeneous reaction medium, 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 a heterogeneous medium, the reactants form a separate phase within a diffusive medium, causing the reaction to occur locally around the boundaries or inside the sources. The reaction is localized at the position of the heterogeneities, and therefore the heat release rate is non-uniformly distributed within the domain (Tang et al., 2009).

The heat transfer from the reaction zone through the medium is a key mechanism in propagation. Julian et al. (2015) determined experimentally that the flame speed of stable metallic dust flames is a strong function of the heat conductivity of the gaseous mixture surrounding dust particles. Bidabadi (1996) investigated the role of radiative heat transfer compared to conduction in a dust cloud combustion for a premixed dust-air mixture in a transparent environment and presented the following relation for estimating the ratio f of effects of radiation relative to conduction (Sparrow and Cess,1978) :

$$f = (k^{-1}\delta_f K_a \sigma {T_f}^3) \tag{2}$$

where k is the thermal conductivity of air, δ_f the flame zone thickness, K_a the radiative absorption coefficient, σ the Stefan-Boltzmann coefficient and T_f the flame temperature. In mixtures of air and aluminum, for typical particle sizes smaller than 10 μm, and stoichiometric dust concentrations, f is of order $\frac{1}{500}$ (Bidabadi, 1996). In the current hybrid mixture of aluminum and boron, a similar ratio applies, so that one can neglect radiation.

The geometric configuration assumes that particles have been distributed uniformly in a cubic control volume, as shown in Fig. 1. Although, in a real system dust particles are not dispersed uniformly in space and are not necessarily stationary, the assumption of stationary is reasonable before the effects of gravity gives rise to settling, or upwards movement appears due to the heat

release. Previous work has shown that realistic predictions are obtained with these approximations (Bidabadi et al.,2013). A cubic control volume is considered in three-dimensional space, where fuel particles of either boron or aluminum fill the nodes in each layer to create a uniform distribution of particles and then a one-dimensional flame passes through the particles.

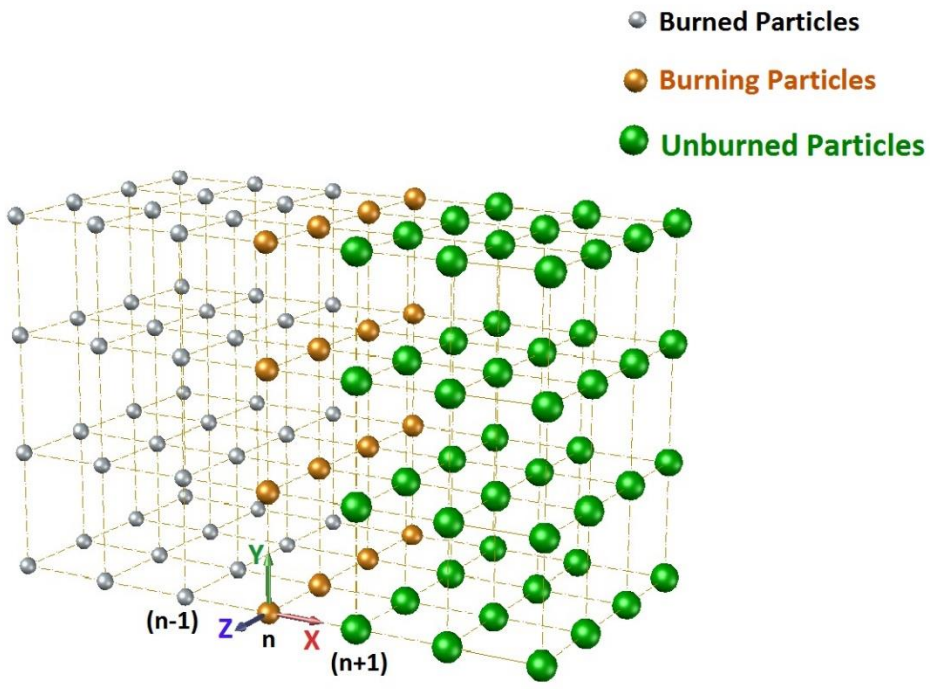

Fig.1. Assumed spatial distribution of particles, showing layer *n* containing burning particles, surrounded adjacent layers containing products (*n*-1) or preheated particles (*n*+1).

The ignition system provides the minimum necessary energy to the dust cloud, raising the temperature of some particles up 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}, after which the combustion process propagates to other particles. The

mixture is assumed to be stagnant, so that the temperature increase of particles in the preheating zone is assumed to be the result of conduction heat transfer through the gaseous medium.

The thermal model generated in this study for the uniform particle distribution model is based the following assumptions:

1. Each particle is spherical in shape (Boichuk et al.,2002) and the associated flame diameter remains constant and is equal to the particle diameter.
2. The thermal properties of the medium and particles are constant, as presented in Table 1.
3. The Biot number for the burning particles is negligible, therefore particles are represented by a single temperature.
4. Particles are spaced by a uniform distance.
5. The reaction of a particle proceeds at a fixed rate, releasing a corresponding rate of energy.
6. Particles are assumed to burn in a diffusion-controlled regime.

To model the single-particle combustion and the temperature distribution throughout the gaseous domain in a purely conductive process, the one-dimensional, unsteady energy equation in spherical coordinates *r* with an origin at the center of the particle, and time *t* is solved:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T_a}{\partial r}\right)=\frac{1}{\alpha}\frac{\partial T_a}{\partial t} \tag{3}$$

where $T_a(r,t)$ is equal to $T(r,t)-T_\infty$ and T_∞ is the ambient temperature, and α is the gas phase diffusivity. The boundary and initial conditions for the equation above are given as:

$$k_p A\frac{\partial T_a}{\partial r}=Ah\big(T_f-T_\infty\big)H(\tau_h-t), \qquad at\ r=r_p,$$

$$T_a(\infty,t)=0,$$

$$T_a(r,0)=0, \tag{4}$$

where k_p is the particle thermal diffusivity, $A = 4\pi r_p^2$ is the particle cross sectional area, h is the convective heat transfer coefficient, and *H* is the Heaviside function. The time τ_h is the particle burning time, so that heat is transferred only during the time$t < \tau_h$. The heat transferred by the particle to the surroundings is assumed to be equal to that generated during combustion. The heat transfer coefficient h is estimated from the convective heat transfer coefficient for a spherical particle in a purely conductive process the Nusselt number, estimated as (Hanai et al.,2000):

$$\text{Nu} = 2\,h\,r_p/k_P \cong 2 \tag{6}$$

Therefore, the rate of heat transfer is calculated by:

$$\dot{q} = Ak_P\left(T_f - T_\infty\right)r_p^{-1} \tag{7}$$

Note that the temperature of the flame is a function of the total heat release per unit mass of the reactant. The solution of equation (3) with the boundary conditions (4) can be obtained through the whole domain assuming linear superposition of solutions

$$T_a(r,t) = \left(T_f - T_\infty\right)\frac{r_p}{r}\left[\text{erfc}\sqrt{\frac{\left(r-r_p\right)^2}{4\alpha t}} - H(\tau_h - t)\ \text{erfc}\sqrt{\frac{\left(r-r_p\right)^2}{4\alpha(\tau_h - t)}}\right] \tag{8}$$

$$T_s = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} T_a\left(r_{i,j,k}, t\right) \tag{9}$$

where T_s is the total superposition of the effect of reacting and product particles.

The spacing between the target particle and each particle placed at *i*, *j*, *k* is represented by:

$$r_{i.j.k} = L\sqrt{i^2 + j^2 + k^2} \tag{10}$$

where *L* is the mean spacing between two adjacent layers and determined from the mass dust concentration c_d, defined as:

$$L = \left(\frac{\pi d_p^3 \rho_p}{6\, c_d}\right)^{1/3} \tag{11}$$

The resulting flame propagation speed is defined as the ratio of the spacing between two adjacent layers to the difference of their ignition times in the discrete domain.

$$S = L/\left(t_{ig,n+1} - t_{ig,n}\right) \tag{12}$$

where the ignition time t_{ig} is obtained by the ignition criterion $T > T_{ig}$.

The energy release for the igniter is assumed to be sudden, and it is presented by a Dirac delta function in the present paper. The igniter's distance to the nearest layer is assumed to be L and the energy release occurs in a plane parallel to layers. The calculation is initialized by considering a one-dimensional point with energy input Q per unit area, followed by solving the one-dimensional heat equation for the temperature riseT_a:

$$\frac{\partial^2 T_a}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T_a}{\partial t} \tag{13}$$

The boundary conditions for the governing equation are:

$$T_a(x, 0) = 0$$

$$T_a(\infty, t) = 0$$

$$k\frac{\partial T_a}{\partial x} = \frac{1}{2}Q\delta(t) \qquad at\ x = 0 \tag{14}$$

where $\delta(t)$ is the Dirac delta function. The analytical solution to Eq. (13) subjected to the boundary conditions (14) obtained as follows:

$$T_a(x, t) = \frac{Q\alpha}{k}\frac{1}{\sqrt{\pi\alpha t}}\exp\left(\frac{-x^2}{4\alpha t}\right) \tag{15}$$

Equation (15) is assumed as an initial condition for the calculation of flame propagation speed.

An algorithm is developed to propagate one-dimensional thermal wave, igniting the stationary particles along a three-dimensional lattice. Following the initial heat released by the igniter, the temperature of the first layer at the considered location is calculated. When the temperature of the particles in the first layer reaches the ignition temperature, it is recorded as the ignition time of the first layer, and the calculations continue to find the ignition time of the subsequent layers. Beyond the first layer ($n > 1$), the preheating of layers is influenced by the burning of the preceding layers in addition to the ignition system. Thus, when a layer temperature reaches the ignition temperature, the relevant time is recorded as the ignition time of that layer. Flame propagation speed is determined by dividing the distance between two adjacent layers L by the difference in ignition time of these two layers.

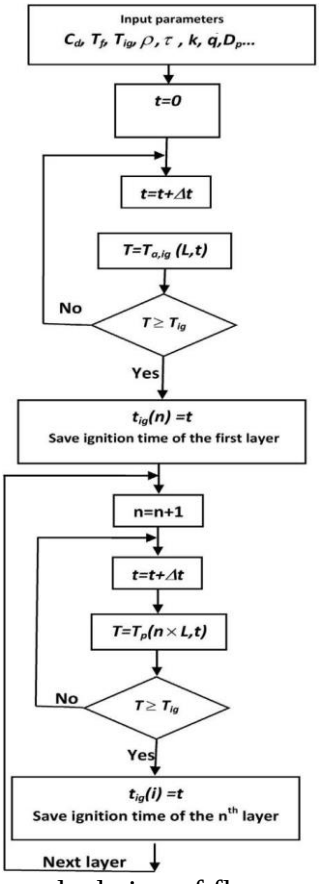

Fig.2. Algorithm of the code for the calculation of flame velocity and ignition time of particle cloud layers.

2.2. Hybrid mixture combustion characteristics

The model developed for single component materials has been adapted to the present hybrid mixtures. The thermo-physical properties of the mixture are modelled as a weighted average of their respective mass fractions. All properties are assumed to be constant with temperature, and taken to be those at 300 K. The surrounding medium is assumed to be composed of 21% oxygen and 79% nitrogen. Metal particles react with oxygen in the reaction medium and nitrogen acts as a neutralized gas.

Although it would be possible to calculate the flame propagation through a mixture of individual particles of aluminum and boron particles, in the present approach, a weighted average approach is taken to determine the effective properties Γ_h of a hybrid solid particle (Boichuk et al.,2002):

$$\Gamma_h = \varphi\Gamma_{al} + (1-\varphi)\Gamma_b \tag{16}$$

where Γ_{al}, Γ_b are primary properties of pure components which are defined in Table 1 and φ is the mass fraction of aluminum. Note that whereas in general this is reasonably straightforward for intensive properties, the averaging of ignition temperatures is not necessarily a normal approach. However, as will be demonstrated, the results appear to indicate good agreement. Further studies could be performed on the sensitivity to these assumptions.

King (1982) presented two sets of equations for estimating the burning time of boron particles in a suspension with nitrogen and oxygen: one based on d^2-law, known as the detailed model, and another based on a d^1-law, introduced as a simplified model. The latter (King, 1975) is employed in the current research. For micron-sized particles ($d_p < 10$ μm) the ignition temperature is almost constant and equal to $T_{ig_b} = 1900$ K, and the burning time τ_b is approximately given as:

$$\tau_b = \frac{d_{p,0}}{2K_r P_\infty Y_{o_2}} \tag{19}$$

where τ_b is the burning time in microseconds, $d_{p,0}$ is the initial diameter of the particle, P_∞ the ambient gas pressure, Y_{O_2} is the mass fraction of oxygen in the ambient gas far from the particle surface, and K_r is a dimension-dependent constant, as defined in Table 1.

Since aluminum has been added to propellants for many years as an extra energy source for the propellant, several experimental studies have been conducted in order to determine the burning time and ignition temperature of aluminum particles (Belyaev et al.,1968; Shoshin and Dreizin, 2006). Beckstead (2004) proposed the burning time τ_{Al} for aluminum particle in various oxidizers and different initial pressures and temperatures based on experimental findings as below:

$$\tau_{al} = \frac{a {d_{p,0}}^m}{Y_{eff}\, {P_\infty}^{0.1} {T_\infty}^{0.2}}, \begin{cases} Y_{eff} = Y_{O_2} + 0.6\, Y_{H_2O} + 0.22\, Y_{CO_2} \\ a = 0.00735\,, m = 1.8 \end{cases} \quad (20)$$

where $d_{p,0}$ is the initial diameter in μm, Y_{eff} is the oxidizer effective mass fraction, P_∞ and T_∞ are the ambient pressure (bar) and temperatures (K).

The ignition temperature of aluminum particles used in the current model was determined by Marino (2008) as:

$$T_{ig} = 34.5\, d_{p,0} + 789.1 \quad (21)$$

where $d_{p,0}$ is the initial particle diameter in micrometer, and T_{ig} is the ignition temperature in Kelvin.

Boron Properties	**Value**	**Units**	**Ref.**
c_P	1107	J/kg K	(Bergman et al., 2011)
k_P	27	W/m K	(Bergman et al., 2011)
ρ_P	2500	kg/m^3	(Bergman et al., 2011)
T_f	2358	K	(King , 1975)
T_{ig}	1900	K	(King , 1975)
K_r	5×10^{-4}	-	(King , 1975)
Aluminum Properties	**Value**	**Unit**	**Ref.**
c_P	903	J/kg K	(Bergman et al., 2011)
k_P	237	W/m K	(Bergman et al., 2011)
ρ_P	2700	kg/m^3	(Bergman et al., 2011)
T_f	3400	K	(Bidabadi et al., 2013)
T_{ig}	$T_{ig} = 34.5\, d_{p,0} + 789.1$	K	(Marino , 2008)
Air Properties	**Value**	**Unit**	**Ref.**
$\boldsymbol{\rho}_\infty$	1.1614	kg/m^3	(Bergman et al., 2011)
T_∞	300	K	(Bergman et al., 2011)
c_P	1.005	kJ/kg K	(Bergman et al., 2011)
k_∞	0.0257	W/m K	(Bergman et al., 2011)

Table 1. Thermo-physical properties of boron and aluminum particles and air used in the simulation.

Validation measurements of the resulting flame speeds were performed as described by Boichuk et al.(2002), using aluminum-boron particles in which particles of a mean diameter of 6 μm were mixed at the desired ratio prior to the test. Tests were performed in a vertical, semi-open quartz tube 0.036 meters in diameter and 1-meter long and ambient air used as the medium gas. Ignition was initiated near the upper open end of the tube with an electric spark.

A stationary flow of dispersed particles in the test section was produced by using of a special device, consisting of a piston powder dispenser and a ring-shaped slotted atomizer. The mixture delivery was stopped just before ignition. In order to regulate concentration of dispersed particles in the mixture, the rate at which powder was dispensed into the atomizer with the aid of an adjustable electromechanical system was measured. The visible front speed and the structure of flame was captured with an FOR-2 photo electronic recorder and an SKS-1M "Krasnogorsk" motion-picture camera.

The normal flame propagation velocity was determined experimentally by measuring the visible velocity of the flame (V_V) and the ratio of the surface area of the flame (S_S) to its base area (S_b). The propagation velocity V_n was then determined using the relationship $V_n = V_V \frac{S_b}{S_s}$. The flame-front surface S_S was assumed to be the area enveloping the visible glow zone with the shape of a paraboloid of revolution facing the initial mixture.

3. Results

Simulations were performed to determine the flame propagation speed as a function of the input parameters boron mass fraction, dust concentration, and particle diameter.

Figure 3 shows the simulation results and measured values (Boichuk et al.,2002) for flame propagation speed as a function of dust concentration for mono-disperse particles of 6 μm diameter at ambient conditions, as a function of boron mass fraction.

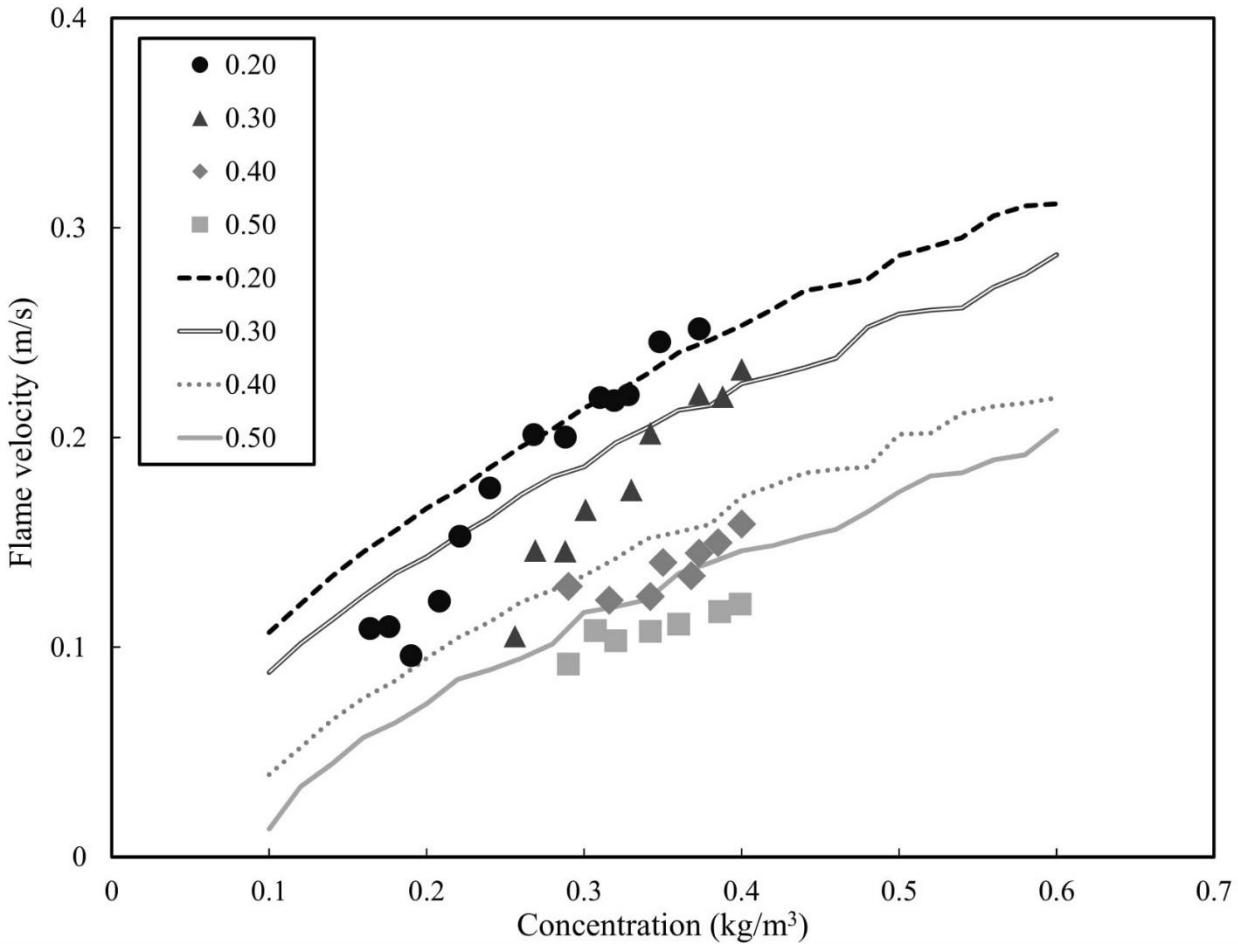

Fig.3. Experimental measurements (solid symbols) and simulation results (lines) for flame speeds in air-particle suspensions with mean particle diameter of 6 μm at P_∞ =1 bar, T_∞=300 K. The legend indicates the mass fraction of boron in the hybrid mixture.

The concentration of fuel particles increases the total energy release, which increases the temperature of the preheated zone, and decreases the mean distance between adjacent layers, which decreases the preheating time. The final result is an increase in the flame propagation speed, as

measured in the experiment, which is correctly captured in the simulations. The flame speed decreases with the increase in boron content, because of the increase in the ignition temperature of the hybrid mixture relatively to pure aluminum (as shown in Table 1). This increase in temperature is assumed to be linearly proportional to the boron content. Therefore, prior to ignition, boron acts largely as an inert heat sink for the heat released during the combustion process, absorbing more energy compared to the aluminum particle to be ignited. At high boron mass fractions, the heat released during aluminum combustion is not sufficient to ignite hybrid particles as quickly, resulting in significant reduction in the flame speed value.

The agreement between model and experiment is good, even though the model is built assuming a hybrid particle with a given boron content rather than the experimentally measured separate particles of boron and aluminum. The largest discrepancies appear at the lowest boron mass concentrations, and lowest particle concentrations, where the simulations predict significantly higher flame speeds than indicated in the measurements. Note however that there are significant fluctuations in the measurements reported at those low boron mass fraction, possibly owing to difficulties in the measurements of surface area in the high energy release, low concentration mixtures.

The encouraging agreement allows one to make predictions of the effect of particle diameter on the flame propagation, for different boron mass fractions and a fixed dust concentration of $c_d = 0.4$ kg/m^3 (Fig. 4). Larger particle diameters and higher boron contents lead to a decrease in flame speed, as larger particles require more energy to reach the ignition temperature (Eq. (21)). Further, the inter-particle distance for a given mass concentration becomes shorter for larger particles, contributing to the increase in flame speed.

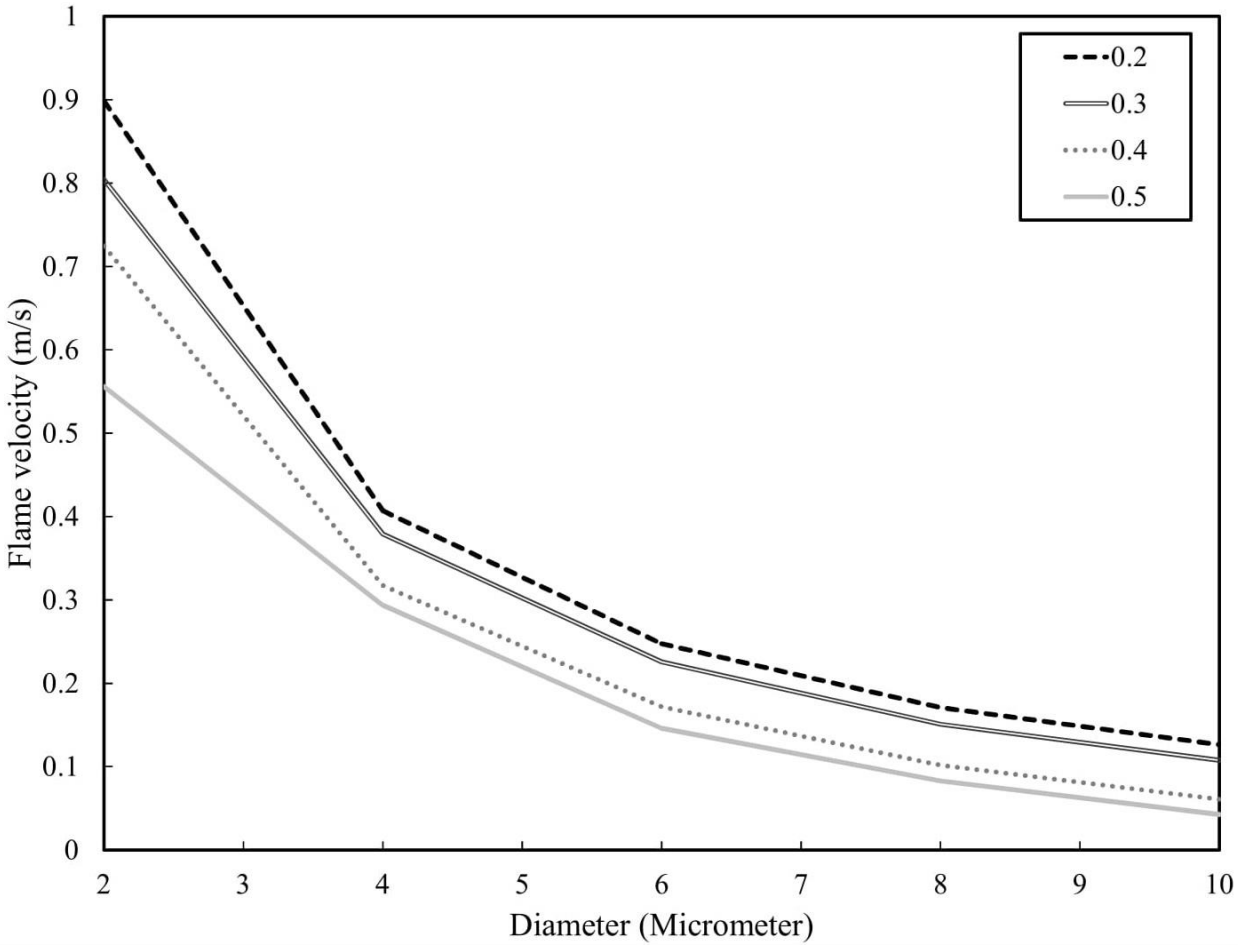

Fig.4. Simulated effect of the initial particle diameter on flame speed, for different boron mass fractions (P_∞ =1 bar, T_∞ = 300 K).

As expected, the increase in boron content leads to an increase in the minimum ignition energy over a range of concentrations (Figure 5). Conversely, the required MIE decreases with the higher energy release rate and shorter mean distance between the neighboring particles at higher dust concentrations.

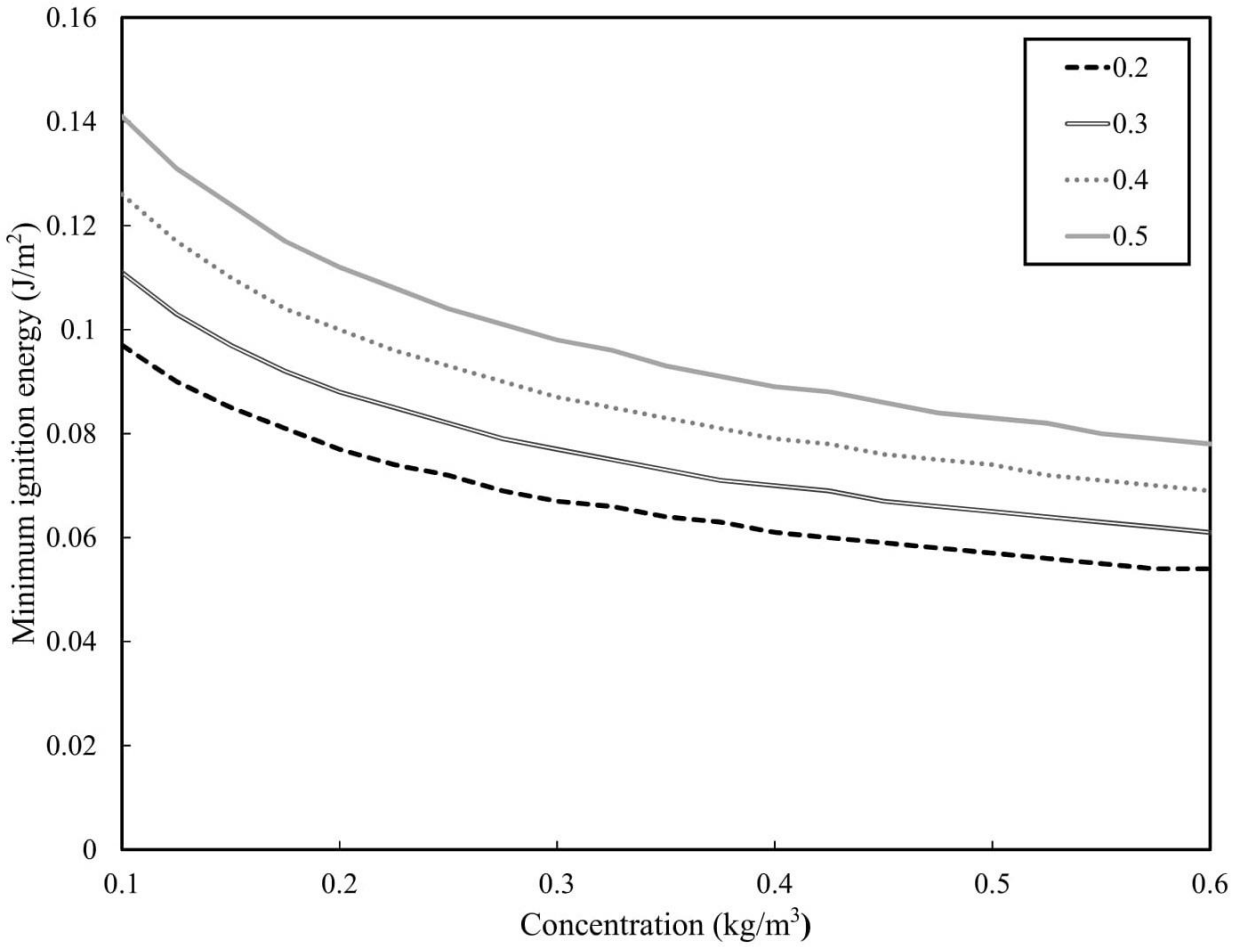

Fig. 5. Calculated minimum ignition energy as a function of concentration, for different boron particles mass fractions with the mean particle diameter of 6 μm at P_∞ = 1 bar, T_∞ = 300 K.

Finally, the MIE is considered as a function of particle diameter as a function of a given concentration $c_d = 0.4$ kg/m^3. As particle size increases at a fixed concentration, the total energy required to heat the mixture up to the ignition temperature increases, which increases the minimum ignition energy, yet the distance between neighboring particles decreases, which counteracts this effect to some extent.

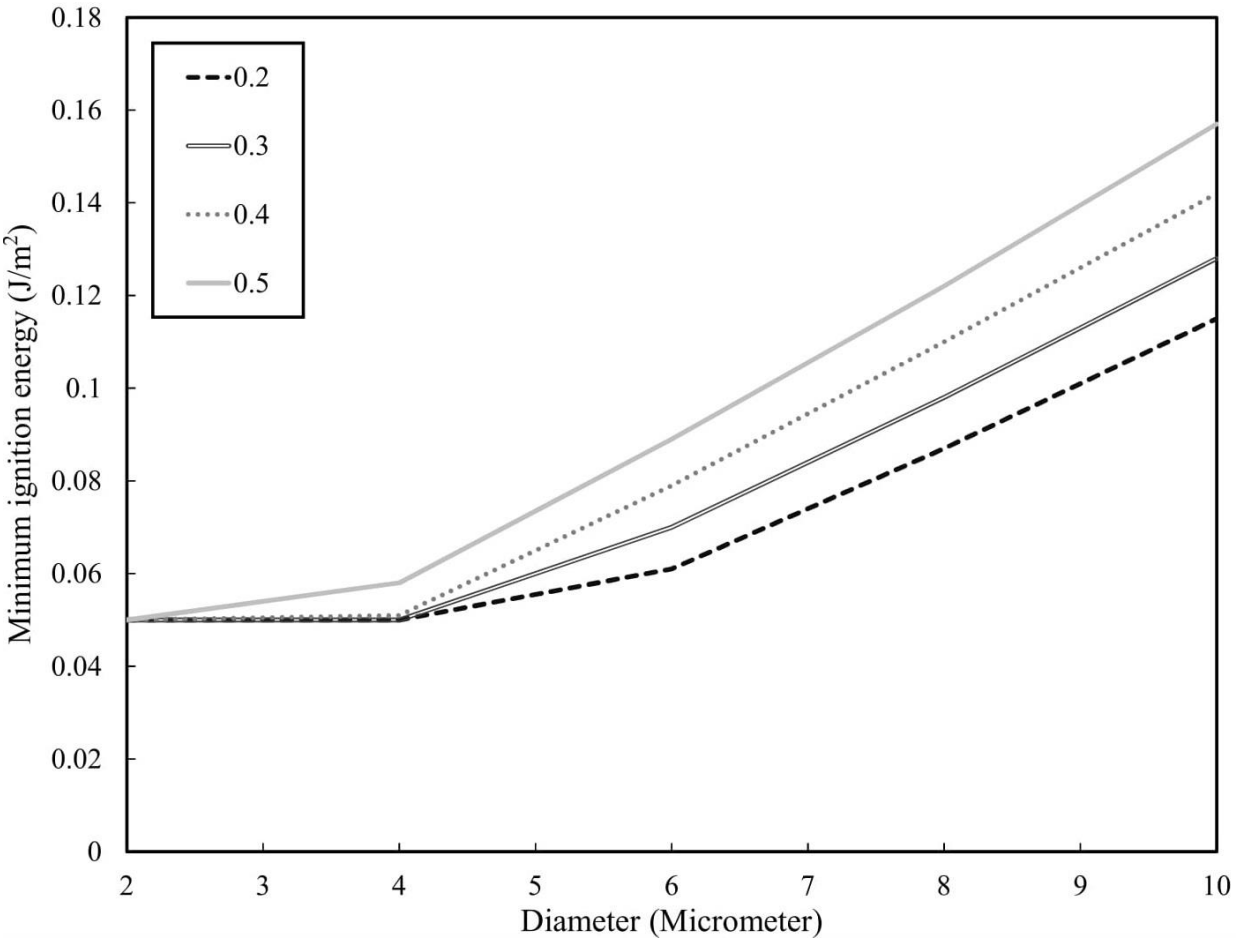

Fig.6. Minimum ignition energy as a function of particle diameter for different boron particle mass fractions for P_∞ =1 bar, T_∞ = 300 K.

4. Conclusion

A model for flame propagation through stationary metal dusts, based on planar propagation through a discrete environment of uniformly distributed particles, has been adapted to consider particles made up of mixtures of boron and aluminum particles, to represent the behavior of mixtures. The model shows that the effects of the increase of boron dust mass fraction are consistent with the idea that boron addition acts primarily as a heat sink in the mixture, consuming

the energy released by combustion, so that the flame speed decreases and the minimum ignition energy increases. The predictions for flame speed are in good agreement with the existing data, although significant discrepancies do exist at low concentrations. The effects of particle size and concentration are as predictable from the behaviour of single component particles with increased inert fractions.

5. Nomenclature

A	Area (m^2)
c_d	Dust concentration (kg/m^3)
Y	Oxidizer mass or molar fractions
d	Diameter (m)
D_{O_2}	Oxygen diffusivity coefficient (m^2/s),
f	Stark number
H	Heaviside function
h	Convective heat transfer coefficient
i, j, k	Components of Cartesian coordinate
k	Conductivity (W/m K)
L	Distance of two adjacent particles or layers (m)
r	Radial distance (m)
t	Time (s)
t_r	Relative time between the ignition of two neighboring layers
T	Temperature (K)
P	Pressure (Pa)
V	Propagation velocity (m/s)
S	Area of the flame (m)
Q	Energy released from igniter (J)

Greek symbols

α	Thermal diffusivity (m^2/s)
ρ	Density (kg/m^3)
τ	Particle burning time (s)
φ	Aluminum content
σ	Stefan-Boltzman coefficient
δ	Flame zone thickness
Γ	effective properties of particle

Subscripts

a	Burning zone
f	Flame
g	Ambient gas
ig	Ignition

p	Particle
eff	Effective
h	Hybrid particle
al	Aluminum particle
b	Boron particle, base area of flame
v	Visible velocity
s	Surface area of flame
n	Fame-front surface
0	Initial amount

6. References

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Figures captions:

Fig.1. Assumed spatial distribution of particles, showing layer *n* containing burning particles, surrounded adjacent layers containing products (*n*-1) or preheated particles (*n*+1).

Fig.2. Algorithm of the code for the calculation of flame velocity and ignition time of particle cloud layers.

Fig.3. Experimental measurements (solid symbols) and simulation results (lines) for flame speeds in air-particle suspensions with mean particle diameter of 6 μm at P_∞=1 bar, T_∞=300 K. The legend indicates the mass fraction of boron in the hybrid mixture.

Fig.4. Simulated effect of the initial particle diameter on flame speed, for different boron mass fractions (P_∞ =1 bar, T_∞ = 300 K).

Fig. 5. Calculated minimum ignition energy as a function of concentration, for different boron particles mass fractions with the mean particle diameter of 6 μm at P_∞ = 1 bar, T_∞ = 300 K.

Fig.6. Minimum ignition energy as a function of particle diameter for different boron particle mass fractions for P_∞ =1 bar, T_∞ = 300 K.

Table caption:

Table 1. Thermo-physical properties of boron and aluminum particles and air used in the simulation.