Research Article
Considering of the Internal Heat Losses and Continues Reaction Rate Effect in Aluminum Dust

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Abstract: In this study, a mathematical model for investigation the effects of internal heat losses on the flame speed and temperature profile in Aluminum Particle Clouds combustion with continues reaction rate have been studied. The present study extended previous results by bridging the theories of the non-adiabatic stationary dust flame and the propagation of premixed flames in one-dimensional channels accounting for heat-losses to particles and environment. The results showed that the effects of heat losses played an important role in flame regimes and flame transition. Furthermore, it was found that convective heat losses significantly decreased the velocity of flame propagation and temperature in post-flame zone. Comparisons between the analytical solutions and the experiment results showed a good agreement.

Keywords: Dust combustion, flame speed, heat loss, non-adiabatic flame, continues reaction rate

INTRODUCTION

The majority of practical applications of aluminum combustion such as solid rocket motors, dust explosions in industry and chemical reactors involve combustion of dust suspensions of small particle sizes (Seshadri *et al.*, 1992; Bidabadi and Sediqhi, 2002). Aluminum, because of its high enthalpy of combustion has been added to propellants and explosives, its extensive use as an energetic material, several research efforts have been directed to understand the mechanism and model the oxidation of aluminum particles (Eapen *et al.*, 2004). Thus, models describing combustion of metals are necessary to design new and control existing propulsion devices and weapon systems (Shoshin and Dreizin, 2003). For specifying the parameters of combustion, a simple model is needed to analyze and take into account the efficient parameters of combustion. Theoretically, the combustion of fine solid particles is yet to be improved in comparison with the monophasic combustion of gases and liquids. This could be mostly attributed to the complexity of such phenomena. However, an equally great obstacle is the special experimental difficulties in generating a uniform and stable dust suspension with repeatable dust concentration (Shuangfeng *et al.*, 2005). Microgravity provides a unique opportunity to examine dust combustion mechanism. In a microgravity environment, it is practically possible to produce a dust cloud of arbitrary concentration and keep the dust particles in suspension during the entire experiment. The current analysis largely follows the approaches of Bidabadi and Sediqhi (2002). But is extended to include the effect of internal heat losses on flame parameters.

Some researchers have been shown that fundamental principles of heat transfer and combustion permits a simplified understanding of aluminum particle combustion in an environment representative of a burning propellant. The model evaluates aluminum particle temperature from insertion into the flame through burnout. An experimental and theoretical modeling for aluminum dust cloud with air as an oxidizer, have been presented by Goroshin *et al.* (1996a, b) and Bidabadi and Sediqhi (2002) and combustion particle-laden flows and parameters have been estimated. In present study a mathematical model of combustion of solid particles will be developed. In previous theoretically model with continues reaction rate, assumed that convective heat loss from gas to particle surfaces is negligible. In convection the regime of flow around the particle must be identified and then the convection heat transfer factors can be derived. In this study the term of convective heat loss has been added to the previous model and its effects on the combustion of fine aluminum particles will be investigated.

THEORETICAL ANALYSIS OF MICRO AND NANO PARTICLE DUST

To model a dust combustion system, it is recognized that many simultaneously occurring process are involved, namely particle oxidation, gas-phase homogeneous reaction and mass, momentum and energy transport. It has been underlined various times

in the literature that the main difference between flames inhomogeneous and heterogeneous mixture is the possibility of radiation heat transfer from the combustion to preheat zone in dust cloud flames. What is usually neglected is that difference mechanisms of particle combustion in the flame zone can also make a strong difference.

In the present model after considering the diffusion regime for particle combustion, explicit algebraic equations are obtained for predicting the flame speed as a function of the initial particle size, concentration and heat loss terms. Combustion of metallic dust (aluminum in particular) is of interest in the present formulation. Very little detailed information has been reported to date on the combustion mechanism of aluminum particles in oxidation atmospheres and there is no universally accepted view point on the detailed mechanism of aluminum ignition. According to the ideas of several investigators, ignition occurs due to the heterogeneous reaction of liquid aluminum with the oxidant through an oxide film, while combustion take place in the gas phase where aluminum vapor reacts with the oxidant. In the present formulation, it is assumed that the combustion reaction occurs in gas phase, forming spherical diffusion flame around the fuel particle.

In this study, a model of aluminum dust combustion is developed. A one-dimensional, premixed uniformly distributed fuel particle in air is assumed to pass through of a planar heat source, perpendicular to the flow direction. The flame model in a premixed suspension is developed in this study which is based on a simple description of suspension dust flame with continues reaction rate model that was previously used by Bidabadi and Sediqhi (2002). Huang *et al.* (2005) show that the heat loss to particle is important. This model is extended to consider the heat loss from gas to wall and particle surface. The major approximations and assumptions are:

- The dust cloud consists of uniformly distributed aluminum particles with air
- The gravitational effects and heat transfer by radiation are neglected
- The particle velocity is approximately equal to the gas velocity
- Collisions and interactions between burning particles are neglected
- The Biota number is very small, suggesting a uniform temperature distribution within each particle
- The thermal conductivity of the gas, λ, is taken to be constant for simplicity.
- The reaction rate during diffusive combustion is proportional to amount of remained fuel in mixture in each time

According to last consideration, in this study controller of reaction rate is available amount of fuel

and regarding to different shape and size of particles it is obvious that combustion cannot particularly end up suddenly and afterwards there must be reaction in post flame zone. In this study reaction rate is proportional to available amount of fuel. Actually in rich mixture, the reaction rate controller is amount of oxygen and in lean mixture, available amount of fuel. In the following we consider reaction rate proportional to available amount of fuel per unit volume:

$$W_F(t) = A_1 \sigma(t) \tag{1}$$

On the other hand, the fuel quantity as a function of time can be calculated by,

$$\sigma(t) = \sigma - \int_{t=0}^{t=t} W_F(t) dt \tag{2}$$

where, σ is fuel mass fraction at time $t = 0$. For solving the above equations to obtain reaction rate two constraints are needed. The first equation is that integrals of reaction rate from $t = 0$ to the end of reaction has to be equal to total available fuel quantity at the first moment:

$$\sigma = \int_{t=0}^{t=\infty} W_F(t) dt \tag{3}$$

To obtain the second constraint, reaction rate value in the beginning of reaction is considered to be σ/τ_c (τ_c is burning time of single particle). By solving Eq. (1) and (2) with constraints and also changing variable the reaction rate is obtained. Bidabadi (1996):

$$W_F(y) = \frac{\sigma}{\tau_c} \exp(-y) \tag{4}$$

For large particles (D > 100 μm), most experimental studies (Friedman and Macek, 1962) indicated that ignition is achieved at a temperature near the melting point of aluminum oxide (i.e., 2327 K). It was conjectured that the particle is covered by an impervious oxide shell and aluminum does not ignite until the oxide shell melts or breaks up near its melting temperature under the effect of aluminum thermal expansion.

For solving the heat transfer equation particularly in convection regime, knowledge about the regime of flow around the particle must be determined because the Nusselt number (Nu), which is one of the important factors in convection heat transfer, depends on the regime flow. Considering Fig. 1 for particle which surrounded by hot gas in preheat zone we can obtained for Nusselt number:

$$Nu = 2 + (0.4 \, \text{Re}^{.5} + 0.06 \, \text{Re}^{.66}) \text{Pr}^{.4} (\mu / \mu_S)^{.25} \tag{5}$$

where,
Re = Reynolds number

Pr = Prantle number
μ_s = The kinetic viscosity

Because of microgravity size of particle and small Re numbers, the Nusselt number is assumed to be equal to 2 for this analysis (Joulin, 1980, 1987). The heat transfer between each particle and surrounding gas, q_c is given by:

$$q_c = Nu \cdot 2\pi r \lambda (T_g - T_s) \tag{6}$$

Goroshin *et al*. (2000) shown that the equation governing heat diffusivity in this problem can be transformed into a linear form by introducing an independent variable x that is related to the spatial coordinate x' as $x = \int_0^{x'} \left(\frac{\rho}{p_u}\right) dx$.

The gas-phase governing equations for low mach flow can be written as: follows:

$$\rho v C_p \frac{dT_g}{dx} = \frac{\lambda d^2 T_g}{dx^2} + w_F Q - n_p 4\pi r \lambda (T_g - T_s) - \alpha (T_g - T_u) \tag{7}$$

$$\rho v = \rho_u s_L \tag{8}$$

$$\rho T = const \tag{9}$$

The heat transfer coefficient between gas and walls sides is computed in the following way:

$$\alpha = \frac{b'\lambda}{d_q^2} \tag{10}$$

where, b' is equal to 8 (Jarosinski, 1986).
By considering the heat transfer between gas and particle generally, we have:

$$\rho_s v C_s \frac{dT_s}{dx} = n_p 4\pi r \lambda (T_g - T_s) \tag{11}$$

where, $\rho_s = n_p \rho_a 4\pi r^3 / 3$ is the bulk density of particles (mass of particles per unit volume). In a mono-dispersed aluminum particle-laden flow, the flame usually consists of three zones: preheat reaction and post flame zone. The first zone is preheat zone (y<0) when the temperature of particles is lower than the ignition temperature and the rate of reaction is equal to zero. The second zone is the reaction zone, (0<y<1) where the particles burn in the diffusion regime and the particles temperature remains approximately constant. The third zone is the post flame zone (1<y) where the temperature of gas decreases asymptotically to the ambient temperature at infinity due to non-adiabatic condition. By using continues model for reaction rate we don't have post flame zone and reaction is existed in this domain. We can obtain the flame speed;

flammability limits and temperature distribution are derived by solving the energy equation in each zone and matching the temperature and heat flux at the interfacial boundaries.

For universal use, we now write the energy and heat transfer equations in terms of a set of dimensionless variables. For this purpose we consider the following dimensionless variables:

$$\theta = \frac{T}{T_u} \ , \ \ \theta_s = \frac{T_s}{T_u} \ , \ \ \mu = \frac{B_{st}Q}{\rho_u C_p (T_{si} - T)}$$
$$y = \frac{x}{S_L \tau_c} \ , \ \ k = \frac{S_L^2 \tau_c}{a_u} \ , \ \ a_u = \frac{\lambda}{C_p \rho_u} \tag{12}$$

For micron and larger-sized particles, which usually burn under diffusion-controlled conditions, numerous data exists on their burning times. Several *d*-models, with *n* ranging from 1.5 to 2.0, have been proposed. Beckstead (2005), almost 400 datum points for single particle combustion times in various oxidizer environments were collected from over ten different sources. Correlations were established and the following particle burning time model was proposed:

$$\tau_c = \frac{C_1 d^{1.8}}{T_0^{0.2} p^{0.1} X_{eff}} \tag{13}$$

where, $X_{eff} = C_{O2} + 0.6 C_{H2O} + 0.22 C_{CO2}$ and C_1 is a constant (= 0.00735). This $d^{1.8}$-law model is employed here in for micron and larger-sized particles.

Since in preheat zone, the thermal difference between gas and walls of the quenching distance is very low so we neglect the external heat loss in this region. Also the particles are gradually consumed in the flame zone, the energy equation for the particle phase is not considered in this region. It is only applied in the preheat zone to solve for the gas temperature at the point of particle ignition and particle ignition temperature is given as an input parameter. We also neglect the heat exchange between the gas and particles in the flame zone. With these assumptions, the governing heat diffusivity equation and the boundary conditions for the problem that illustrated in Fig. 1 can be written in a dimensionless form.

Preheat zone: In the preheat zone chemical reaction between the gaseous fuel and oxidizer is negligible. So the heat source term is omitted in energy conservation equation in this region. Also the heat lose to walls is neglected in this zone.

The conservation of energy equation for the particles is considered in this zone because of the difference between temperature of the gas and particle, so:
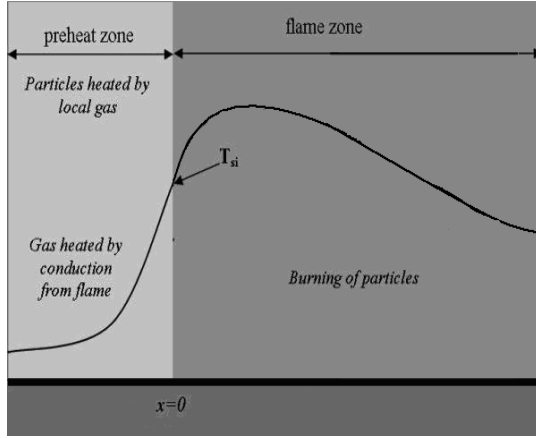
Fig. 1: Structure of flame in monosize suspension

$$\frac{d^2\theta}{dy^2} - k\frac{d\theta}{dy} = k\eta_p\varphi(\theta - \theta_s) \qquad -\infty < y < 0 \qquad (14)$$

The dimensionless energy conservation equation for the solid phase is:

$$\frac{d\theta_s}{dy} = \frac{\theta - \theta_s}{\xi} \qquad -\infty < y < 0 \qquad (15)$$

where, $\xi[(r^2 c_s \rho_s / 3\alpha_u c_p \rho_g)]/\tau_c$ is a ratio of the characteristic particle heat exchange time and burning time of the particle (with r radius) that is close to unity for nonvolatile and Lewis number (Le = 1).

Simultaneously solve the above equations and by matching the boundary conditions the algebraic equation for the nondimantional flame temperature in this zone is found as:

$$\theta = c_1 \exp(k_1 y) + 1 \qquad (16)$$

where,

$$k_1 = 0.5\left(k - 1/\zeta + \sqrt{(k - 1/\zeta)^2 + 4k(\eta_p \varphi + 1/\zeta)}\right) \quad (17)$$

Flame zone: In this zone because of the same temperature of the gas and particles the energy equation of particles and internal heat lose are doesn't need to be considered so the energy conservation equation reduced to:

$$\frac{d^2\theta}{dy^2} - k\frac{d\theta}{dy} = k\eta_w(\theta - 1) - \mu\varphi k(\theta_{si} - 1)\exp(-y) \quad (18)$$
$$0 < y < \infty$$

The parameters, φ, η_w, η_p, in the above equations are defined as:

$$\phi = \frac{B_u}{B_{st}} \ , \ \eta_p = \frac{3B_{st}\tau_c a_u}{r^2 \rho_a} \ , \ \eta_w = \frac{b' a_u \tau_c}{d^2} \qquad (19)$$

The heat loss parameter to wall (η_w) is the ratio of particle burning time to time of heat transfer in the channel. The heat loss term, which is assumed to be linearly proportional to temperature difference between gas and walls (Bidabadi, 1996), is considered for flame between quenching plats and derived quenching distance. The heat loss parameter (η_w) covers a range from 0 to 0.02 which $\eta_w = 0$ belongs to the adiabatic condition.

The boundary conditions for the above differential equations are as following:

$$y \to -\infty \qquad \theta = \theta_s = 1$$

$$y = 0 \qquad \begin{cases} \theta_s = \theta_s^i \\ d\theta/dy\big|_{0^-} = d\theta/dy\big|_{0^+} \\ \theta_{0^-} = \theta_{0^+} \end{cases} \qquad (20)$$

$$y \to +\infty \qquad \theta = 1$$

By solving heat transfer equation in this zone and by matching boundary condition the algebraic equation for the no dimensional flame temperature for this zone is found to be:

$$\theta = c_2 \exp(k_2 y) + 1 + \frac{k\mu\phi(\theta_s^i - 1)\exp(-y)}{(\eta_w - 1)k - 1} \qquad (21)$$

where,

$$k_2 = 0.5\left(k - \sqrt{k^2 - 4k\eta_w}\right) \qquad (22)$$

Also by matching the temperature and heat flux in the boundary of two zones C1 and C2 can be found and finally the algebraic equation for the no dimensional flame speed (k) is found to be:

$$\frac{1}{\mu\varphi} = \frac{1 + K_2}{(K_2 - K_1)(1 + K_1\xi)[(\eta_w - 1)k - 1]} \qquad (23)$$

In above equation if we neglected heat transfer to particles (i.e., $\eta_p \to 0$), the equation reduces to bidabadi's resent result without internal heat loss (Jarosinski, 1986).

RESULTS AND DISCUSSION

Figure 2 presents the predicted flame speed as a function of equivalence ratio for fuel lean aluminum-air mixtures. Particle diameters are 5.4μm. The corresponding ignition temperatures are 2100 K,
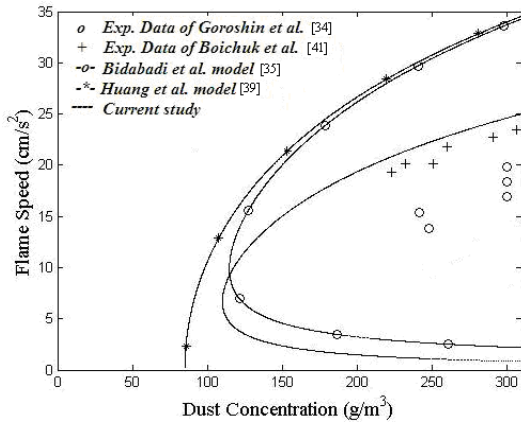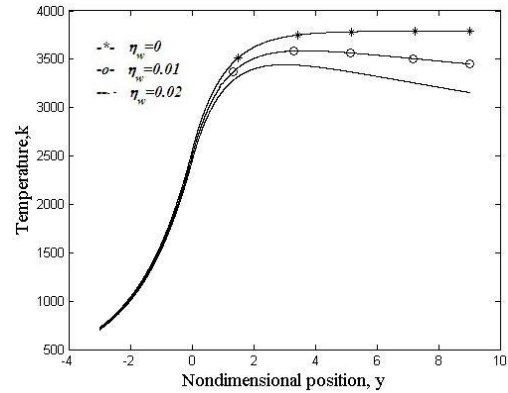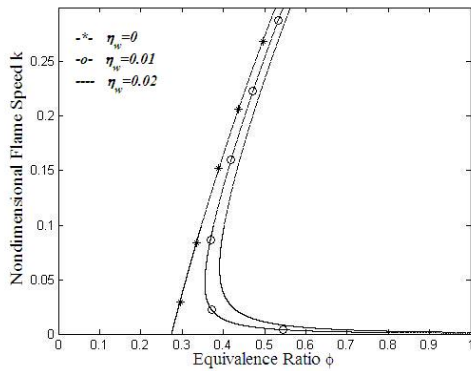
Fig. 2: Dependence of flame speed to dust concentration

Fig. 3: Dependence of non-dimensional flame speed k to equivalence ratio at different value of η

Fig. 4: Comparing the temperature profiles in three models

Fig. 5: Temperature profiles with different value of η

Fig. 6: The comparison of flame speed arises from analysis for various diameters

respectively. Results show that the flame speed increases with an increase in particle concentration under fuel-lean conditions. Experimental results (Goroshin and Lee, 1999) for aluminum-air combustion, with dust concentration ranging from 210 to 310 g/m³, are also presented in Fig. 2. It is observed that the new model in comparing with the old model belonged to Bidabadi and Sediqhi (2002) and Huang

et al. (2005) is nearer to the experimental results, which can indicate the effect of heat loss. Figure 3 shows the decreasing of η which also indicates the rate of heat loss causes the increasing of flame speed. And in adiabatic case in which heat loss is zero, the flame speed is max. The theoretical model over-predicts the flame speeds, possibly due to the neglect of radioactive heat loss from the flame to the surroundings in the analysis.

Also as it is observed in Fig. 4 in current study temperature in flame zone lower than previous results with constant reaction rate also in preheat zone near the flame temperature grater that old model's temperature profile. However in post flame zone temperature reach to the ambient temperature at infinity due to non-adiabatic condition. Figure 5 shows with increasing heat loss to walls the gas temperature decreases. Also the effect of heat loss parameter (η) on temperature profile in preheat zone is low, which this is because of little difference between gas temperature and walls. But in post flame zone in which the mixture temperature is high; the increasing of heat loss is more efficient.

Figure 6 indicates the calculated flame speed as a function of particle radius for aluminum-air mixtures under fuel-lean conditions. The flame speeds increase

with decreasing particle size. As expected, the maximum flame speeds are achieved when the particle size approach the molecular limit. In solving velocity equation in terms of concentration for none zero value of η two answers will be gained which the smaller value is unstable. The appearing point of the second answer or in the other words the minimum concentration point is bifurcation point. In this way we can predict lean flammability limit (i.e., the flame extinguishes at the less dilute of flame spreading.).

CONCLUSION

The present results show that flame propagation velocity depends on the particle size, it means that for the same global particle mass concentration in air the flame speed increase whit decreasing particle size. The cloud flame propagation velocity depends also on the particle concentration. The global evolution of the velocity versus concentration of Al particle clouds shows different trends.

An algebraic equation for the flame speed was obtained for particle-laden flows. It is shown that internal heat losses from gas to the particles play major roles in affecting flame propagating speed. The effect of particle size, on the burning characteristics of aluminum-oxidizer mixtures, has been investigated with a suitable modeling of particle burning time, ignition temperature and heat loss parameters.

Also it is observed that experimental results in lower than theoretical model. This indicates that the effects of radiation heat loss play a very important role on flame regimes, transition and velocity of propagation and therefore it should not be neglected. The future study on dust combustion planned by the authors will permit verification of the developed theory in a wide range of particle sizes and for different kind of heat loss such as radioactive heat loss to environment.

NOMENCLATURE

P	Gas density
V	Velocity
T	Temperature
S_L	Flame speed
C_p	Specific heat of gas the at constant pressure
w_F	Mass consumption rate of particle
R	Radius of particle
Q	Heat of reaction per unit mass of fuel
n_p	Number density of particle
d_q	Width of the channel
C_s	Specific heat of particles
ρ_a	Material density of aluminum
B	Dust concentration
τ_c	Combustion time
θ	Non-dimensional gas temperature
y	Non-dimensional coordinate
k	Non-dimensional flame speed

μ	Non-dimensional dust concentration
p	Pressure in atmospheres
T_0	Initial temperature in Kelvin
d	Particle diameter in μm
θ_{si}	Non-dimensional ignition temperature of solid Particles
φ	Equivalence ratio
η_w	Heat loss parameter to environment
η_p	Heat loss parameter to particles
a_u	Thermal diffusivity of gas
X_{eff}	Effective oxidizer mole fraction
g	Gas phase
s	Solid phase
u	Unburned mixture
st	Stoichiometric.

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