Study of Laminar Flame Propagation through Fuel-Rich Aluminum Dust Clouds

N. Moallemi, M. Bidbadi, M. Jadidi, M. E. Hosseini

Department of Mechanical Engineering, Islamic Azad University, Jask Branch, Jask, Iran

Abstract: A theoretical model is constructed to describe a one-dimensional, laminar, steady, freely propagating flame in a particle/oxidizer mixture. The analysis is concerned with fuel-rich mixtures and is extended to consider the heat loss of gas to particles with an assumption that the particle burning rate in the flame front is controlled by the process of oxygen diffusion. The flame is assumed to consist of two zones: preheat and flame regimes. By solving the energy equation in each regime and matching the temperature and heat flux at the interfacial boundaries, an algebraic equation for the flame speed is obtained. The analysis allows for the investigation of the effect of particle size, ranging from nano to micro meters in diameter, on the burning characteristics of aluminum oxidizer mixtures. Calculated values of burning velocity and flame temperature are in a good agreement with experimental data.

Key words: Analytical model; dust combustion; Fuel-rich mixture; Nano/Micro particle; Burning velocity.

INTRODUCTION

Metal powders are often used as additives in propellants, explosives, or pyrotechnics because of their high enthalpy of combustion (Divekar et al., 2003) and (Price et al., 1984). Addition of metal powders to propellants is also known to improve the combustion stability in rocket engines (Summerfield and Krier, 1969). The most common metal additive is aluminum, which is relatively inexpensive, is safe to handle, and has a relatively high volumetric combustion enthalpy. However, the potential of aluminum as a fuel is often underutilized. Aluminum particles ignite at fairly high temperatures and they often melt before ignition. Ignition and combustion of aluminum have been actively studied over the last 5 decades and a large body of experimental data was accumulated (Brooks and Beckstead, 1995; Dreizin, 1996; Dreizin, 1999; Bucher et al., 1999; Shoshin and Dreizin, 2003; Chen and Fan, 2005; Beckstead, 2005; Sun et al., 2006). Although aluminum particles have long been employed as a fuel ingredient in solid propellant, most previous work has been focused on micron or larger-size particles. Very limited effort (Parr et al., 1999; Il'in et al., 2001; Kwon et al., 2003; Huang et al., 2005; Risha et al., 2005; Huang et al., 2007; Escot Bocanegra et al., 2007) was made to investigate the combustion of nano-sized aluminum particles, especially when they are used as a primary fuel in gaseous oxidizer systems. Nano-metallic particles feature lower ignition temperature, faster burning rate, and consequently shorter burning time, because of their high specific surface area (high reactivity), as compared with micron or larger-size particle. Particle diameter plays a significant role in determining the relevant combustion mechanisms by affecting the characteristic transport diffusion time relative to the chemical kinetics time. A large diameter particle at high pressure may burn under diffusion-controlled conditions, whereas a small particle at low pressure may burn under kinetically controlled conditions (Yetter and Dryer, 2001). The oxidizer type also has strong effects on aluminum particle combustion, since the flame and surface temperatures can be affected by transport in the surrounding gas. However, the flame characterization of an aluminum dust cloud is much more complex than that of a single particle, and few studies exist in the literature. Cassel (1963) conducted an experimental study of the flame propagation in aluminum dust-air mixtures using a Bunsen-type and a flat dust flame burner. Ballal (1983) examined the burning velocity of a flat flame in an aluminum-air dust cloud in a microgravity environment by means of a freely falling tube. In these pioneering works of Cassel (1963) and Ballal (1983), lean dust mixtures were investigated, and the burning velocities were found to increase with dust concentrations. More recently, Goroshin et al. (1996a) measured the flame speed of aluminum dust in various oxidizer environments in a vertical Pyrex tube over a wide range of dust concentrations of 0.13-0.60 mkg \( \text{m}^3 \) (0.42 < \( \phi \) <2.0 for dust-air mixtures). The particles diameter was around 5,4 \( \mu \text{m} \). Three different stages of flame propagation were observed: laminar flame, oscillation flame, and turbulent accelerating flame. The influence of dust concentration on flame development appears to be weak for rich mixtures. A theoretical model was also proposed by Goroshin et al. (1996a). Goroshin et al. (1996b) also established an experimental apparatus capable of producing Bunsen-type premixed dust flames of rich aluminum mixtures. The dust mass concentration covered a range from 0.25 to 0.60 kg/m\(^3\), corresponding to the equivalence ratio, \( \phi \), of 0.81-1.9. In both experiments Goroshin et al. (1996a, 1996b), the burning velocity was shown to be a weak function of dust concentration for fuel rich mixtures, a phenomenon that can be
attributed to the weak dependence of particle burning rate on the flame temperature in the diffusive regime. Shoshin and Dreizin (2004) constructed a lifted-flame aerosol burner (LLFAB) for measuring laminar flame speeds of fuel-rich aluminum-air aerosols with particle mass concentrations of 0.4-1.4 kg/m³ (1.3 < φ < 4.5). A decrease in the flame speed at a very high mass concentration was observed. Combustion of dual-fuel particle-laden flows were also examined by Boichuk et al. (2002) for aluminum-boron dust mixtures, and by Goroshin et al. (2000) for aluminum-manganese dust mixtures. Risha et al. (2005) recently examined the flame characteristics of bimodal nano and micro-sized aluminum particle/air laden flows using a Bunsen-burner type apparatus, similar to the experiment of Goroshin et al. (1996b). The particle compositions ranged from 100% micro-sized particles (5-8 μm) to mixtures with 30% nano-particles (100 nm) by mass. The overall fuel concentration varied from 0.26 to 0.45 kg/m³ (0.81 ≤ φ ≤ 1.62). Tests indicated that an increase in percentage of nano particles within the mixture enhanced its flame speed. Huang et al. (2007) theoretically examined various parameters, such as the particle composition, equivalence ratio and particle size, on the burning behavior of bimodal nano/micro sized aluminum particle/air mixtures in detail. Also, Huang et al. (2005) studied the combustion of nano-sized aluminum particles with various oxidizers, including oxygen, air, and water, in a well-characterized laminar particle laden flow by means of both numerical and theoretical approaches. The theoretical model was concerned with one-dimensional, steady, laminar, fuel-lean mixtures and considered the heat loss of gas to particles.

In the present work, theoretically the combustion of aluminum particles for fuel-rich mixture is studied in a well-characterized laminar flow. The specific objectives are: (1) to investigate the flame speed and structure of aluminum particle laden flows and (2) to study the effect of particle size, ranging from nano to micrometer in diameter, on the burning characteristics of aluminum particle/oxidizer mixtures.

**MATERIALS AND METHODS**

A theoretical model is constructed to describe a one-dimensional, freely propagating flame in a particle/oxidizer mixture. The analysis largely follows the approach of Goroshin et al. (1996a), but is extended to consider the heat loss of gas to particles, as will be shown later. In the diffusion regime, it is assumed that the rate of reaction after ignition is controlled by the rate of oxygen diffusion from the surrounding gas to the particle surface (or to a zone close to the particle surface). Figure 1 illustrates the presumed flame structure for fuel-rich mixture (φ ≥ 1):

![Figure 1: Structure of aluminum particle dust flame at fuel-rich condition.](image)

The assumed flame structure consists of a preheat zone and reaction zone. The major assumptions and approximations are:

1. The dust cloud consists of uniformly distributed, equal-sized aluminum particles and gaseous oxidizer.
2. The gravitational effects and heat transport by radiation are neglected, although they may play important roles in flame propagation. In addition, the total emissivity of the aluminum flame is apparently low, due to the very small radiation absorption coefficient of the submicron aluminum oxide particles (Goroshin et al., 1996a).
3. The particle velocity is equal to the gas velocity.
4. The Biot number, Bi=h/λ, is very small, which implies that the temperature of each particle is uniform.

The heat transfer between each particle and surrounding gas is given by

\[
q = h A (T - T_s) = \frac{Nu \cdot \lambda}{2r} 4 \pi r^2 (T - T_s) = 4 \pi r \lambda (T - T_s)
\]

(1)
Where $Nu = k d / \lambda \approx 2$ is a constant Nusselt number (Joulin, 1980, 1987).

(5) The ignition temperature of dust cloud is close to the ignition temperature of a single particle, $T_{si}$. Note that the aluminum particle is covered with an impervious oxide shell and the melting temperature of aluminum oxide is 2350 K. Normally, aluminum does not ignite until the oxide shell melts. The aluminum thermal expansion, however, is much greater than the oxide shell. This excessive stress can fracture the oxide shell, and ignition takes place before the oxide shell reaches its melting point. Besides, the volume percentage of oxide increases with the decrease of particle size.

(6) The initial concentration and the initial particle size are presumed to be known.

Obviously, with the above assumptions, a very idealized flame was constructed. Such a flame does not exist in experimental situations.

For low Mach number flow, the governing equations can be written as follows:

**Mass Conservation:**

\[ \rho v = \text{const.} \]

**Energy Conservation:**

\[ v_x (\rho_x C_x + B C_T) \frac{dT}{dx} = \lambda \frac{d^2 T}{dx^2} + W_F, Q - n_p 4\pi r \lambda (T - T_s) \]  
\[ (2) \]

Where $B$ is mass fuel concentration.

The oxygen conservation equation can be written as follows:

\[ \rho_x v_x \frac{dC(x)}{dx} = D_x \rho_x \frac{d^2 C(x)}{dx^2} + \frac{3}{2} \sum \tau \Gamma C(x) \]  
\[ (3) \]

Here, $C(x)$ is the local molar oxygen concentration, $\Gamma$ is the reaction stoichiometric coefficient (Goroshin et al., 1996a).

The equation of state for an isobaric system is:

\[ \rho T = \text{const.} \]  
\[ (4) \]

The independent variable $x$ is related to the spatial coordinate $x'$ as:

\[ x = \int_0^{x'} \left( \frac{\rho}{\rho_u} \right) dx' \]  
\[ (5) \]

The energy conservation equation for particles is:

\[ (\rho, v, C_x) \frac{dT_x}{dx} = n_p 4\pi r \lambda (T - T_s) \]  
\[ (6) \]

Where $\rho, v, T$ are gas density, velocity, and temperature, respectively. The subscript $u$ denotes the value related to the unburned mixture. $C_p$ the specific heat of gas at constant pressure, $C_x$ the specific heat of particle, $W_F$ the reaction rate characterizing consumption of fuel, $Q$ heat of reaction per unit mass of fuel, $n_p$ the number density of particles (i.e., the number of particles per unit volume), $r$ the particle radius, $T_s$ the particle temperature, $\rho_x = n_p \rho_u 4\pi r^3 / 3$ the bulk density of particles (mass of particles per unit volume) and $\rho_u$ the material density of aluminum.

The reaction zone is presumed to be located at $x = 0$. It is also assumed in Eq. 3 that the local oxygen diffusion coefficient is proportional to the local temperature raised to the power of two: $D = D_0 \left( T/T_{ps} \right)^{1/2}$. The thermal conductivity of the mixture, $\lambda$, is proportional to $T$: $\lambda = \lambda_0 \left( T/T_{ps} \right)$. The reaction rate $W_F$ can be written as:
\[ W_r = \frac{3}{2} \frac{BQ}{\tau_c C_s} C(x) \]  

(7)

Where \( C_u, \tau_c \) are respectively: the initial oxygen concentration and the combustion time of an individual particle, which is assumed to have a weak dependence on temperature. In above equation we neglected from heat transfer to wall.

Introduce the non-dimensional gas and particles temperature, spatial coordinate, non-dimensional oxygen concentration and other non-dimensional parameters as follows:

\[ \nu = C_u B_u \left[ C_s \rho_u \right]^\frac{1}{2}, \quad Le = \alpha/D, \quad \Phi = C(x)/C_s \]

\[ \theta = \frac{T}{T_u}, \quad \theta_i = \frac{T_i}{T_u}, \quad y = \frac{x}{\nu \tau_c} \]  

(8)

With these assumptions, the governing heat diffusivity equation and the boundary conditions for the problem illustrated in figure (1) can be written in a dimensionless form:

**Preheat Zone:**

\[ \frac{d^2 \theta}{dy^2} - \kappa^2 (1 + \nu \phi) \frac{d\theta}{dy} = \kappa^2 \eta (\theta - \theta_i) \]  

(9)

\[ \frac{d\theta}{dx} = \zeta (\theta - \theta_i) \]  

(10)

\[ \frac{d^2 \Phi}{dy^2} - \kappa^2 Le \frac{d\Phi}{dy} = 0 \]  

(11)

\[ \begin{cases} y \to -\infty \Rightarrow \theta = \theta_i, \quad \Phi = 1 \\ y \to 0 \Rightarrow \theta = \theta_0, \quad \theta_i = \theta_0, \quad \Phi = \Phi_0 \end{cases} \]  

(12)

**Reaction Zone:**

\[ \frac{d^2 \theta}{dy^2} - \kappa^2 (1 + \nu \phi) \frac{d\theta}{dy} = -\frac{3}{2} \mu \Phi \kappa^2 (\theta_r - 1) \phi \]  

(13)

\[ \frac{d^2 \Phi}{dy^2} - \kappa^2 Le \frac{d\Phi}{dy} = \frac{3}{2} \phi \kappa^2 Le \Phi \]  

(14)

\[ \begin{cases} y \to 0, \quad \Rightarrow \theta(0^-) = \theta(0^+), \quad \frac{d\theta}{dy}_{0^-} = \frac{d\theta}{dy}_{0^+} \\ y \to +\infty \Rightarrow \theta = 1, \quad \Phi = 0 \\ y \to 0, \quad \Rightarrow \Phi(0^-) = \Phi(0^+), \quad \frac{d\Phi}{dy}_{0^-} = \frac{d\Phi}{dy}_{0^+} \end{cases} \]  

(15)

The parameters, \( \kappa, \eta, \mu, \zeta, \phi \) in the above equations are defined as:

\[ \kappa^2 = \frac{\nu^2 \tau_c}{\alpha_u}, \quad \eta = \frac{3 B_u \tau_c \alpha}{r^2 \rho_u}, \quad \mu = \frac{B_u Q}{\rho_u C_s (T_u - T_s)} \]

\[ \zeta = \frac{3 \alpha C_r \tau B_u}{r^2 \rho_u C_s}, \quad \phi = \frac{B}{B_u} \]  

(16)

Here Parameter \( \kappa \) is a non-dimensional flame speed, \( \mu \) is the parameter that characterizes the heat productivity of combustion, \( \zeta \) is a ratio of combustion time of the particle and the characteristic particle heat exchange time.
The current analysis requires the particle ignition temperature, $T_{\text{ign}}$, and burning time, $\tau_c$, be specified as input parameters, both of which are a function of particle size and these two parameters were obtained from Ref. (Huang et al., 2007). By solving the energy conservation equation for each zone and matching the resultant temperature and heat flux at the interfacial boundaries, an algebraic equation for the flame speed can be obtained:

$$
\frac{M_1}{k^2}(\kappa^2L_e - Z_2)(\kappa^2(1 + \nu\phi) - Z_2) = \frac{3\mu L_e \zeta}{2 M_1 + \zeta}
$$

(17)

Where $Z_2$ is defined as follow

$$
Z_2 = \frac{k^2L_e}{2} \left(1 - \sqrt{1 + \frac{6\phi}{k^2L_e}}\right)
$$

(18)

And

$$
M_1 = \frac{(\kappa^2(1 + \nu\phi) - \zeta) + \sqrt{(\kappa^2(1 + \nu\phi) - \zeta)^2 + 4\kappa^2(\zeta(1 + \nu\phi) + \eta)}}{2}
$$

(19)

In the above Equation, if we neglected the heat transfer from gas to particle and set $\eta = 0$, the equation reduces to Goroshin’s equation (Goroshin et al., 1996b).

The non-dimensional oxygen concentration at ignition point can be found from the solution of the oxygen transfer equations and is:

$$
\Phi_0 = \frac{2}{1 + \sqrt{\frac{1 + 6\phi}{k^2L_e}}}
$$

(20)

RESULTS AND DISCUSSION

By solving the heat transfer equation in each zone and by matching the heat fluxes obtained from this solution on the boundary of preheat and reaction zones, the temperature distribution can be obtained. Figures 2 and 3 shows that the gas phase temperature is a function of length for nano/micron-sized aluminum particles flame with $\phi = 1.5$. Particles diameter in the figures 2 and 3 are 5.4 µm and 250 nm, respectively. The combustion of nano particles soon increases the gas temperature above 3000 K and the larger-sized particles continue to burn and gradually increase the gas temperature to its maximum value around 3600 K.

Fig. 2: Temperature profiles for micron-sized aluminum particles.
Fig. 3: Temperature profiles for nano-sized aluminum particles.

Figure 4 shows the predicted burning velocity as a function of equivalence ratio for various particles diameters. The burning velocity gradually decreases with increasing equivalence ratio. Also the calculated burning velocity increases with decreasing particle diameter. The ratio of the surface to the volume of particle and reactivity of particle increases as particle diameter decreases; and as a result, burning velocity increases.

Fig. 4: Flame speed as function of particle diameter in fuel-rich aluminum-air.

Fig. 5: Flame speed as function of equivalence ratio in fuel-rich aluminum-air.
In the figure 5, the burning velocity obtained from current theoretical model for particle diameter equal to 5.4 µm is compared with experimental data. Experimental results for fuel-rich aluminum-air mixture, with dust concentration ranging from 310 to 540 g/m³, are presented in this figure.

As we see, analytical results perfectly agree with experimental ones. Compared with Goroshin’s analytical results, presented model results have been approached to experimental that. This event happens because of considering heat losses term to particle.

The theoretical model over-predicts the flame speeds, possibly due to the neglect of heat loss from the flame to the surroundings in the analysis. Also 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.

Figure (6) shows a comparison on experimental result of burning velocity with presented analytical model which particles diameter is 250nm. We see a good agreement between the results.

![Flame speed as function of equivalence ratio in fuel-rich aluminum-air.](image)

**Fig. 6:** Flame speed as function of equivalence ratio in fuel-rich aluminum-air.

**Conclusion:**

In this paper, a simple analytical model for burning velocity and temperature distribution of fuel-rich mixture, ranging from nano to micro meters in diameter of aluminum particles, with heat loss of gas to particles was studied. Since there exists heat loss of gas to particles in reality thus ignoring this term does not indicate real case. By solving the energy equation in each regime and matching the temperature and heat flux at the interfacial boundaries, one algebraic equation for the burning velocity can be obtained. Reasonable agreement between theoretical results and experimental data was obtained in terms of burning velocity and gas temperature profile. It is shown that heat losses from gas play major roles in affecting flame propagating speed. The global evolution of the velocity versus concentration of nano-sized and micro-sized aluminum particle clouds show different trends. The present results show that nano-sized aluminum particle clouds burn faster than micro-sized particle clouds for the same global particle mass concentration in air. Flame speeds with heat loss of gas to particles reported in this paper were slightly better that previous works.

**REFERENCES**


