Spark ignition critical conditions for aluminum-air suspension

K M Moiseeva and A Yu Krainov
Tomsk State University, Tomsk, 634050 Russia

E-mail: Moiseeva_KM@t-sk.ru

Abstract. We have numerically solved the spark ignition problem of aluminum-air suspension. The aim of the research was to determine the critical ignition conditions for an aluminum powder depending on the size and mass concentration of the particles. According to the obtained result an increase in the particle size leads to an increase in the minimum energy which is required to ignite the suspension and make it possible the combustion front to propagate. With an increase in the mass concentration of the particles and under the excess oxidant ratio close to unity the minimum energy of the spark ignition tends to the same value and becomes independent on the mass concentration of the particles.

1. Introduction
A review on theoretical and experimental studies devoted to the ignition and combustion of aluminum powder in an oxidizing ambient is presented in [1]. The papers [2 – 5] provide studies on the regularities of combustion front propagation in an aluminum-air suspension in case of focal or spark ignition. The studies investigate the propagation velocity of the combustion front as a function of the particle size, the excess oxidant ratio (or the aluminum mass concentration), and the percentage of oxygen in the oxidizing ambient.

The normal propagation velocity of the combustion front in aluminum-air suspension increases with increasing mass concentration of the particles in the mixture and/or with decreasing in the size of aluminum particles [2]. For the aluminum powder ASD-1 in an oxidizing ambient with 20% of oxygen the normal flame velocity goes down with increasing mass content of aluminum powder and for mass concentration 0.25 ÷ 0.55 kg/m$^3$ is in the range 0.14 ÷ 0.17 m/s [3 – 4]. Authors in [5] experimentally investigate the propagation velocity of the combustion front along a pipe with one open end for a suspension with aluminum particles with diameter of 5.4 μm. The apparent flame propagation velocity was determined from the experiment and it was shown that for fuel-rich mixtures the apparent propagation velocity of the combustion front converges to the same value, which is about 0.8 m/s according to [5].

In the present paper we have numerically investigated the problem of the aluminum powder spark ignition. The aim of the research was to define critical conditions of spark ignition depending on particle size and mass concentration of aluminum powder.

2. Mathematical model
The formulation of the problem is based on physical and mathematical statements [6, 7] and was made under the following assumptions: a monodisperse suspension of aluminum powder with the initial particle mass concentration $\rho_{kb}$, and the initial particle size $r_{Al,0}$ is uniformly distributed in the air; the
instantaneous filiform ignition source is located in the center; the outer boundary of the computational domain is supposed to be infinitely far from the ignition source; the electrode heat loss is neglected. The diffusion and thermal conductivity coefficients of the gas depend on temperature [6]. The combustion of aluminum particles is described on the basis of experimental data [8], the ignition of an aluminum particle occurs upon reaching the ignition temperature $T_{i}$. The rate of a heterogeneous chemical reaction on particles is described taking mass transfer into account [9]. The model includes the thermal and dynamic interaction between particles and gas. As an aluminum particle burns the radius of unburnt aluminum in the particle $r_{Al}$ decreases, the radius of the whole particle $r_{k}$ grows due to the oxide layer buildup. Before chemical reactions in the particle $r_{k} = r_{Al0}$.

The mathematical model is based on the dual-velocity two-phase model of the reacting gas-dispersion medium [10]. The system of equations includes the mass-conservation equation, the impulse-conservation equation, the total energy-conservation equation of the gas and the particles taking into account the thermal conductivity and the chemical reactions in the gas and on the particle surface, the mass-conservation equation of the gas mixture components considering diffusion and combustion and the particle burn-out equation. The mathematical formulation of the problem under the made assumptions has the following form:

$$\frac{\partial \rho_{s}}{\partial t} + \frac{\partial \rho_{s} u_{t}}{\partial r} = -rG, \quad (1)$$

$$\frac{\partial \rho_{s}(u_{t} + \frac{v_{t}}{\rho_{s}})}{\partial t} + \frac{\partial \rho_{s}(u_{t}^2 + v_{t}^2)}{\partial r} = p - r_{v_{t}} + r_{u_{t}} - rG u_{t}, \quad (2)$$

$$\frac{\partial \rho_{s}(\epsilon_{s} + 0.5 v_{t}^2)}{\partial t} + \frac{\partial \left[\rho_{s}(\epsilon_{s} + 0.5 v_{t}^2) + p u_{t}\right]}{\partial r} = \frac{\partial}{\partial r}\left[r_{b} \left(\frac{\partial T_{b}}{\partial r}\right)\right] + rG\left(c_{T_{b}} u_{t} + \frac{v_{t}^2}{2}\right) - r_{u_{t}} T_{b} + r_{e_{s}} e_{s}(T_{i} - T_{b})\right],$$

$$\frac{\partial \rho_{o2}}{\partial t} + \frac{\partial \rho_{o2} u_{t}}{\partial r} = \frac{\partial}{\partial r}\left[r_{D_{o2}} (r_{o2}) \frac{\partial \rho_{o2}}{\partial r}\right] - rG, \quad (4)$$

$$\frac{\partial \rho_{k}}{\partial t} + \frac{\partial \rho_{k} u_{t}}{\partial r} = rG, \quad (5)$$

$$\frac{\partial \rho_{k}(\epsilon_{k} + 0.5 u_{t}^2)}{\partial t} + \frac{\partial \rho_{k}(u_{t} + \frac{v_{t}}{\rho_{k}})}{\partial r} = r_{v_{t}} + r_{u_{t}} - rG u_{t}, \quad (6)$$

$$\frac{\partial \rho_{l}(\epsilon_{l} + 0.5 v_{t}^2)}{\partial t} + \frac{\partial \rho_{l}(u_{t} + \frac{v_{t}}{\rho_{l}})}{\partial r} = -r_{a_{l}} e_{l}(T_{i} - T_{l}) + \frac{rOG}{a_{l}} - rG\left(c_{T_{l}} u_{t} + \frac{v_{t}^2}{2}\right) + r_{r_{l}} u_{l}, \quad (7)$$

$$\frac{\partial m_{s}}{\partial t} + \frac{\partial m_{s} u_{t}}{\partial r} = 0, \quad (8)$$

$$p = \rho_{s} r_{g} T_{s}, \quad (9)$$

$$T_{g}(r,t) = T_{b} + \frac{Q}{4\pi k_{f} f_{g}} \exp\left(-\frac{r^2}{4\chi_{f} f_{g}^2}\right), \quad (10)$$

$$\rho_{k}(r,t) = \rho_{ib}, \quad u_{k}(r,t) = u_{ib}(r,t) = 0, \quad \rho_{l}(r,t) = \rho_{ib}, \quad n_{l}(r,t) = n_{ib}, \quad (10)$$
\[
\frac{\partial \rho(0, t)}{\partial r} = \frac{\partial \rho_{02}(0, t)}{\partial r} = \frac{\partial T_r(0, t)}{\partial r} = 0, \quad u_r(0, t) = 0, \quad \text{(11)}
\]
\[
\frac{\partial \rho_k(0, t)}{\partial r} = \frac{\partial n_k(0, t)}{\partial r} = \frac{\partial T_k(0, t)}{\partial r} = 0, \quad u_k(0, t) = 0, \quad \text{(12)}
\]
\[
\frac{\partial \rho_{02}(\infty, t)}{\partial r} = \frac{\partial T_r(\infty, t)}{\partial r} = 0. \quad \text{(13)}
\]

The following notations are used in (1) - (13): \( t \) is the time, \( r \) is the radius coordinate, \( \rho_k \), \( \rho_{02} \) are gas and oxygen partial densities, \( \rho_k \) is the aluminum particle mass per unit volume, \( u \) is the velocity, \( r_k \) is the particle radius, \( p \) is the pressure, \( \lambda \) is the thermal conductivity coefficient, \( \lambda = \lambda_\alpha \left(\frac{T}{T_c}\right)^{2/3} \), \( D \) is the diffusion coefficient, \( D_g(T_g) = \lambda_\alpha(T_g) \left( c_p \rho_g \right) \), \( Q \) is the reaction heat on the particle surface, \( T \) is the temperature, \( \eta \) is the the absolute viscosity coefficient of the gas. \( \alpha_k = N_u k\lambda_k \left(2r_k\right) \) is the gas-particles heat exchange coefficient, \( \varepsilon_g = \frac{p}{\left(\rho_g \gamma - 1\right)} \) is the gas internal energy, \( \gamma = c_p/c_v \) is the adiabatic exponent, \( \varepsilon_k = \varepsilon_k T_k \) is the particle internal energy, \( G \) is the rate of particle mass changing during combustion, \( S_g = 4\pi r_k^2 \) is the particle surface area, \( S_m = \pi r_k^2 \) is the particle cross-sectional area, \( \tau_r = n_k F_u \) is the friction force, \( F_u = C_r S_m \rho_g \left( u_k - u_g \right) u_k \) is the interaction force of a single particle with the gas, \( C_r = 24 \left[1 + 0.15 R_{0.59} \right] / R_e \) is the friction coefficient, \( R_e \) is the Reynolds number, \( N_u k = 2 + \left( N_u^2 + N_u^2 \right)^{1/2} \) is the Nusselt number, where \( N_u = 0.664 R_{0.5} \), \( N_u = 0.037 R_{0.8} \) [7], and \( \alpha_k \) is the oxygen stoichiometric coefficient in reaction with aluminum particles. Indexes: \( b \) indicates the initial values of the parameters, \( k \) indicates the particle parameters, \( g \) indicates the gas parameters, and \( Al \) indicates the aluminum parameters inside the oxide layer.

The summands on the right side of equations (1) - (8) which is responsible for the chemical interaction of the gas and particles, depend on the radius of aluminum inside the oxide layer of the particle. The summands responsible for the inertial and thermal interaction are defined by the radius of the whole particle consisting of aluminum and oxide layer. To determine the rate of mass change of the particles during their combustion we assume that the combustion product of aluminum is the aluminum oxide \( Al_2O_3 \), which envelops the particle; the particle density does not change during the combustion. The initial aluminum particle mass is \( m_{Al,0} \), the current mass value is \( m_{Al} \). The mass of the unreacted part of aluminum in the particle is defined as:

\[
m_k = m_{Al} + \frac{\mu_u + (3/2) \mu_o}{\mu_{Al}} (m_{Al,0} - m_{Al}). \quad \text{(14)}
\]

Under the assumption that \( \rho_k^0 \) is constant value we have the following expression:

\[
m_k = \frac{4}{3} \pi \rho_k^0 r_k^3 = \frac{\rho_k}{n_k}. \quad \text{(15)}
\]

The radius of the unburnt aluminum \( r_{Al} \) is defined from number of particles in unit volume \( n_k \) and aluminum particle mass per unit volume \( \rho_k \), and can be determined from (15) and (14)

\[
m_k = \frac{4}{3} \pi \rho_k^0 \left( r_{Al}^3 + \frac{\mu_u + (3/2) \mu_o}{\mu_{Al}} (r_{Al,0} - r_{Al}) \right), \quad \text{the particle radius} \ r_{Al} \text{ is defined as:}
\]
\[ r_{al} = \left( \frac{\mu_{al}}{3/2 \mu_{al}} r_{al0}^3 - \frac{\rho_k}{4n \pi \rho_k^0} \right) \frac{2 \mu_{al}}{3 \mu_{al}} \right)^{1/3}, \]  
(16)

where \( \mu_{al}, \mu_{al0} \) are oxygen and aluminum molar masses. The equation of the particle radius \( r_c \):

\[ r_c = \frac{3 \rho_k^0}{4 \pi \rho_k^0 n_k}. \]  
(17)

To simplify the aluminum particle combustion model we assumed that the aluminum oxide \( \text{Al}_2\text{O}_3 \) has a sphere shape. This assumption was made to determine the current radius of an aluminum particle and do not affect the burning rate of the particle which was defined using experimental data [8].

The rate of the particle mass change accounting the diffusional resistance of the reaction has the following form:

\[ G = \alpha_i n_i \rho_i^0 S_{al} \frac{k(a_{o_2} r_{al}) \beta_i}{(k(a_{o_2} r_{al}) + \beta_i)}, \]  
(18)

where \( k(a_{o_2} r_{al}) = k_o \alpha_i^0 9/4 \sqrt{r_{al}} \) is the combustion law of a single particle in the oxidant-rich environment, \( S_{al} = 4\pi r_{al}^2 \) is the area of the unburnt aluminum in the particle, \( k_o \) is the constant of the chemical reaction rate, \( \beta_m = \lambda_\alpha (T) Nu_B \left( c_r \rho_g r_k \right) \) is the particle mass-transfer coefficient, \( \rho_k^0 \) is the aluminum density.

The methodology to solve the equation system of our mathematical model is described in detail in [6]. The problem (1) – (18) was solved numerically by S.K. Goduvov’s method. The solution of the equations for particles was carried out using the decay of discontinuity algorithm in an environment without its ‘own’ pressure [12]. The spatial step in ignition source area was set equal to \( \Delta h_{const} = 10^{-6} \) m. The spatial step increased according to the rule \( \Delta h_{i+1} = 1.01 \cdot \Delta h_i \) after coordinate \( r = 10^3 \) m. The time step was determined from the Courant condition.

3. Results and discussion

The solution of the problem (1) – (18) was conducted at the following physical quantities:

\[ Q = 36.6 \text{ MJ/kg}, \quad k_o = 1.11 \cdot 10^9 \text{ m}^{1/5} \text{s}^{-1}, \quad \alpha_i = 0.889, \quad \lambda_\alpha = 0.025 \text{ W/(m} \cdot \text{K}), \quad \mu_{al} = 27 \cdot 10^{-3} \text{ kg} / \text{mol}, \quad \mu_{o} = 16 \cdot 10^{-3} \text{ kg} / \text{mol}, \quad \gamma = 1.39, \quad c_{r,g} = 1065 \text{ J/(kg} \cdot \text{K}), \quad c_k = 904 \text{ J/(kg} \cdot \text{K}), \quad T_b = 300 \text{ K}, \quad \rho_k^0 = 2380 \text{ kg} / \text{m}^3, \quad \eta = 2 \cdot 10^{-3} \text{ Pa} \cdot \text{s}, \quad \rho_{o_{2,b}} = 0.264 \text{ kg} / \text{m}^3, \quad \rho_{a} = \rho_{b}/R T_b, \quad \rho_b = 0.1 \text{ MPa}, \quad T_k = 1400 \text{ K}.

The initial particle radius varied within the range of \( r_i = r_{al0} = 10^{-3} + 4 \cdot 10^{-6} \) m, particle mass concentration was \( \rho_{al} = 0.07 \pm 0.3 \text{ kg} / \text{m}^3 \). The aim of the research was to determine the minimum spark energy \( Q_c \) which is required to form a combustion front in an aluminum-air suspension and allow it to propagate along the volume. The result of the calculations is presented in Figs. 1–2.

The dependence of the minimum energy \( Q_c \) on the initial mass concentration of aluminum powder in the air is plotted in Figure 1 for particle radiiues \( r_{al0} = 0.6 \mu m \) (curve 1) and 0.5 \( \mu m \) (curve 2). An increase in the particle size leads to an increase in the minimum energy which is necessary to ignite and allows the combustion front to propagate in the aluminum-air suspension. As mass concentration of the particles increase and excess oxidant ratio is close to unity (stoichiometric mixture \( \rho_{ab} \approx 0.274 \text{ kg/m}^3 \)), the minimum energy of the spark ignition converges to the same value and practically becomes independent of \( \rho_{ab} \). The dimension of the ignition energy is \( \text{J/m} \) (Figure 1a). To define the energy in \( J \), the anode-cathode spacing has to be taken into account, which ranges from
4·10^{-3} to 6·10^{-3} m [13]. The calculation results in the dimension [J] for the anode-cathode distance 4·10^{-3} m are shown in Figure 1b.

The dependence of the spark ignition minimum energy on the particle size for the mass concentration of aluminum powder \( \rho_{al} = 0.25 \text{ kg} / \text{m}^3 \) (curve 1) and \( \rho_{al} = 0.3 \text{ kg} / \text{m}^3 \) (curve 2) is shown in Figure 2. As can be seen from the figure, for particle radius less than 0.6 \( \mu \text{m} \) the minimum energy of the spark ignition slightly changes with the change of the particle mass concentration.

![Figure 1](image1.png)

**Figure 1.** The minimum spark ignition energy depending on aluminum particle mass concentration. Dimension \( J/m \) (a), anode-cathode distance \( 4·10^{-3} m \) (b), 1 – \( r_{AlO} = 6·10^{-7} m \), 2 – \( r_{AlO} = 5·10^{-7} m \)

![Figure 2](image2.png)

**Figure 2.** The minimum spark ignition energy depending on aluminum particle radius. Dimension \( J/m \) (a), anode-cathode distance \( 4·10^{-3} m \) (b), 1 – \( \rho_{al} = 0.25 \text{ kg} / \text{m}^3 \), 2 – \( \rho_{al} = 0.3 \text{ kg} / \text{m}^3 \)

**4. Conclusion**

We have numerically investigated the problem of the spark ignition for a monodisperse aluminum-air suspension. It has been shown that for particles of radius less than 0.6 \( \mu \text{m} \), the minimum energy of a spark ignition converges to the same value as the excess oxidant ratio tends to unity (stoichiometric
mixture $\rho_{kb} \approx 0.274 \text{ kg/m}^3$). For large particles there is a significant dependence of the minimum energy of spark ignition on the mass concentration of particles.

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