# FLAME PROPAGATION OF MICRON SIZED ALUMINUM DUST CLOUD IN OXYGENATED MEDIA WITH DIFFERENT NEUTRALIZE GAS

by

***Mehdi BIDABADI*** * ***and Vahid BORDBAR***

Combustion Research Laboratory, School of Mechanical Engineering,
Iran University of Science and Technology, Tehran, Iran

Original scientific paper
https://doi.org/10.2298/TSCI170722214B

*In this research an analytical study has been conducted to determine flame propagation speed and quenching distance of aluminum dust particle in an oxygenated medium with different neutralized gas including nitrogen, argon, and helium which acts as the oxidizer carrier gas. Flame propagation speed as a function of aluminum dust cloud concentration has been studied based on a thermal diffusion model. Additionally quenching distance for different dust particle concentration in the intended neutralize gas is investigated. Reasonable agreement between the present analytical model and experimental results reported in literature has been observed in terms of flame propagation speed in different dust concentrations.*

Key words: *aluminum dust cloud, discrete heat source model, neutralize gas, flame speed, quenching distance*

## Introduction

Combustion of premixed metallic dust cloud in a gaseous oxidizing medium is crucially important for many areas of technology like dust explosion hazards and modern propulsion systems. However, the understanding of metal dust combustion mechanism is still in rudimentary stages. Very limited data are available in the literature on the combustion of nonvolatile, nonorganic dusts such as metals [1]. Among metallic dust combustion aluminum finds a special place. Eckhoff [2] discussed several aluminum powder explosions in various industrial plants that either produced aluminum powder or handled it as part of the process. Aluminum powders or dusts can represent significant dust explosion hazards in industry, due to their relatively low ignition energy and high explosivity [3]. Aluminum powder is a very reactive metal and its oxidation can occur either in thermite or in dust explosions [4]. Therefore, safe handling of aluminum powders might be significant for aluminum industries in terms of hazards suppression. Besides aluminum dust safety aspects aluminum particles are used in propulsion and energy-conversion applications due to their favorable energetic properties [5]. Aluminum is an excellent energetic material with important applications particularly in propulsion. Aluminum is considered as an additive to industrial propellants for many years [6]. Aluminum is also used in explosives to increase the energy of reaction [7, 8]. Elemental aluminum is appealing as an enhancing agent in combustion applications due to its high heat of reaction. Aluminum particles are commonly used in solid rocket propellants because of the large amounts of heat released

* Corresponding author, e-mail: bidabadi@iust.ac.ir

during combustion, which results in increasing the specific impulse of the propellant [9]. These applications motivate the researchers to investigate the aluminum dust combustion and its characteristics. A number of experimental studies are conducted on aluminum powder combustion and ignition under different conditions. Mechanism and characteristics of flame propagation through combustible particle clouds is investigated by Chen *et al.* [10] and Seshadri *et al.* [11]. In order to understand fundamental behavior of flames propagating through aluminum dust clouds in air with more details Sun *et al.* [12] performed an extensive experimental study for pure aluminum cloud with diameters ranging from 1.5-18 μm for a variety of particle concentrations. Results of this study show that the flame propagating velocity is not constant but increases with time as ignition initiates. Wilson and Williams [13], Bucher *et al*. [14], and Dreizin [15], studied combustion phenomena of single aluminum particles in different conditions. Goroshin *et al*. [16] performed a set of experiments to investigate quenching distance for aluminum dust flames, in which fine atomized aluminum is dispersed via a piston-type dust feeding system in a vertical Pyrex tube and ignited at the open tube end. Flame velocity as a function of dust concentration is investigated and represented at different oxygen concentration in nitrogen and helium as neutralized gases in this study. Results of this research also show that quenching distance and flame speed are week functions of dust concentration in rich mixtures. In another study Boichuk *et al*. [17] investigated flame propagation in gas suspensions of Boron particles, boron-aluminum mixtures and aluminum particles experimentally. Experiments are performed under atmosphere pressure and ambient temperature by using aluminum with diameter of 6 μm in a vertical semi-open quartz tube 0.036 m in diameter and 1 m long. Ignition was made near the upper open end of the tube with an electric spark. Friedman and Macek [18] developed a technique for measuring 15-67 μm aluminum powders ignition temperature in a combustible gas mixture composing of propane, oxygen, and nitrogen. The ignition was observed to occur when the gas temperature exceeds 1940 °C. The combustion mechanism of superfine aluminum dust cloud is scrutinized by Kwon *et al*. [19]. The formation of aluminum nitride during the combustion of aluminum particles in air and the influence of combustion conditions on the structures and compositions of the final products are addressed in this study. Goroshin *et al*. [1] studied burning velocities in fuel rich aluminum dust clouds. They found that in rich Al-$O_2$-$N_2$ mixtures, the burning velocity is a weak function of dust concentration. At the same time, the dependence of the burning velocity on the oxygen concentration is considerably stronger in rich mixtures than that of fuel-lean aluminum dust clouds.

Effect of oxidizer and pressure on burning time of 10 micrometer aluminum particles is investigated experimentally by Bazyn *et al*. [20] in $CO_2$, $H_2O$, and oxygen environments. Results show that burning times in $CO_2$ and $H_2O$ increase weakly with increasing pressure, while burning times in oxygen decreased as pressure increased. Oxidizing environment effect on burning time and consequently flame characteristics can also be found in studies conducted by Gill *et al*. [21] and Bucher *et al*. [22]. Recently Julien *et al*. [23, 24] have conducted a series of experiments to determine speed and structure of freely propagating flames in aluminum dust clouds by direct optical observation of dust flames. The results are represented on isobaric flame propagation for an extensive range of setup scales. Findings of this research reveal that for stable flame propagation regime in fuel lean mixtures, the flame speed is quite insensitive to the oxygen concentration. For fuel rich suspensions, the flame speed is insensitive to an increase in aluminum concentration. Effect of scales on dust flame characteristics is also discussed in this work.

A set of experiments for determination of aluminum combustion characteristics in hybrid aluminum-methane-air mixtures performed by Soo *et al*. [25] reveals that the combustion

behavior of micron-sized aluminum particles in the combustion products of methane strongly depends on the aluminum mass concentration. In the case of stoichiometric methane-air mixtures, the transition from slow oxidation of the aluminum particles to rapid burning occurs in the particle concentration range of 140-220 g/m$^3$. The transitional concentration is shown to be lower in the case of lean methane-air mixtures. In addition to oxidizer type, the neutralize gas can also affect aluminum particles burning time and flame propagation speed [22]. Studies conducted by [1], represents that burning velocity of aluminum particles is a strong function of the molecular transport properties of the carrier gas. Goroshin *et al*. [26] studies on Bunsen-type flames stabilized in aluminum suspensions in air and oxygen-argon/helium mixtures also declares the effect of environment inert gas on flame characteristics. Studies on combustion characteristics of suspension of aluminum powder in oxygen mixed with nitrogen, argon, and helium with various concentrations of aluminum and oxygen by Julien *et al*. [23] indicate that the flame propagation speed is a strong function of the heat conductivity of the gas mixture. The results also show that for oxygen concentration of 60% the average flame propagation speed in the pulsating regime increases only with aluminum concentration and is weakly dependent of the heat and mass diffusivity of the mixture, which differs by a factor approximately two between helium and argon mixtures. This behavior is different from a stable flame propagation regime, where the flame speed strongly depends on the thermal diffusivity of the mixture increasing by almost factor of four when argon in the mixture is replaced by helium when oxygen concentration is 15%. Effect of environment gas on burning time is also accumulated by Beckstead [27].

Since most researches for predicting aluminum particle dust flame characteristics are performed in an experimental set-up and analytical and numerical efforts are rare specially for determination of the effect of environment inert gas on combustion parameters, therefore as a contribution the goal of the present work is to introduce a diffusion controlled model based on discrete heat source model to predict flame propagation speed and quenching distance of aluminum dust in oxygenated media with different neutralize gas. The inert gas mainly influences the transport properties in the medium and consequently affects the flame behavior. This model is an extension of our previous work, Bidabadi *et al*. [28]. The composition of the oxidizer in this work includes, $O_2/N_2$, $O_2$/Ar, and $O_2$/He. Particle temperatures are updated at each time step in the preheat zone until particle temperature reaches its ignition temperature and starts to burn.

## Modelling methodology

Aluminum particle of μm size combustion is a surface phenomenon and the combustion process is diffusion controlled. There are some complications with aluminum combustion which makes its simulation different from that of simple hydrocarbon droplet combustion models. In case of hydrocarbon fuels, droplet formation, vaporization and flow rate are dominant parameters. While in solid particle combustion surface conditions, pressure and temperature are the rolling factors. An efficient approach for modeling aluminum particle cloud combustion is to consider each particles burning time and superimpose the overall effects.

Different burning time models for aluminum particle combustion have been proposed in literature which are introduced briefly. Shoshin and Dreizin [29] suggested that the burning time of aluminum particles is a function of particle diameter:

$$\tau = 310 D_P \tag{1}$$

where $D_P$ is the particle diameter in meter and $\tau$ is the burning time in seconds. Glassman *at el*. [30] compered metal and droplet combustion and recognized that there is an analogy between them, so they suggested that $D^2$ law could also be applied for metallic dust combustion. One

of the equations widely used by researchers to anticipate the burning time of aluminum was reported by [31]:

$$\tau = 0.67 \frac{D_P^{1.5}}{a_K^{0.9}} \tag{2}$$

where $\tau$, $D_P$, and $a_K$ are the burning time [ms], the particle diameter [μm], and a constant parameter, respectively. Macek [32] and Friedman [33] recommended the same correlation with the exponent of 1.2-1.5 for the particle diameter. Moreover, Dreizien *et al*. [34] investigated the combustion of aluminum particle with the diameter of 150 μm. They reported a considerable reduction in the burning time with increase in the oxygen concentration.

To estimate the burning time of aluminum particles in various oxidizers including water vapor, $CO_2$, and oxygen at different temperature and pressures, Brooks and Beckstead [35] started working on the role of different oxidizer and could explore an equation for the effective oxidizer:

$$X_{\text{eff}} = C_{O_2} + a_{H_2O} C_{H_2O} + a_{CO_2} C_{CO_2} \tag{3}$$

Based on the previous consideration, the burning time equation is formulated:

$$\tau = \frac{m D_P^n}{X_{\text{eff}} P^{0.1} T_0^{0.2}} \tag{4}$$

where $m = 0.00244$ for $n = 1.5$ and $m = 0.00735$ for $n = 1.8$.

Beckstead [27] has suggested the coefficients of $a_{H_2O}$ and $a_{CO_2}$ equal to 0.6 and 0.22, respectively, by review of some experimental results for burning time of aluminum particles in oxygenated environments with different neutralized gases including nitrogen, helium, and argon. The pressure is measured in atmospheres, the temperature in kelvins, the diameter [μm], and the time [ms]. These values are also used in this research.

Some other researchers have worked on the same issue and among them, Brzustowski and Brzustowski and Glassman [36] investigated the combustion of aluminum in the vapor phase and Bidabadi *et al*. [37] studied the combustion of μm-sized aluminum dust cloud in a quiescent reaction medium with spatially discrete sources in order to estimate the flame front speed in a lean reaction environment under different oxidizer concentrations. The heat transfer mechanism plays a significant role in dust combustion phenomena. Bidabadi *et al*. [28] calculated the ratio of heat transfer caused by conduction to the heat transfer caused by radiation for different dust clouds. This ratio is also known as Stark number. This number is 501 for aluminum and therefore radiation heat transfer is considered negligible with respect to conductive heat transfer. Julian [24] has announced by means of experimental tests that the flame speed of stable dust flames is a strong function of surrounding gas thermal conductivity.

## Governing equations

In the present research it is assumed that aluminum particles are uniformly dispersed on virtual parallel flat plates with uniform sizes. Combustion heat diffuse from the flame zone to particles located in the preheating zone until their temperature reach the ignition temperature. As a result the flame propagates by this mechanism in the whole domain. In order to model the single aluminum particle combustion and the time-space temperature distribution in each particle domain, the energy equation in spherical coordinates is used:

$$\frac{\partial T_a(r,t)}{\partial t} = \frac{\alpha}{r^2} \frac{\partial}{\partial r} \left[ r^2 \frac{\partial T_a(r,t)}{\partial r} \right] \tag{5}$$

where is $T_a(r, t)$ is $T(r, t) - T_\infty$ where $T_\infty$ is and is the ambient temperature. The boundary and initial conditions of the equation:

$$k_p A\frac{\partial T_a}{\partial r} = \dot{q}\,\text{Heaviside}(\tau_b - t):\ T_a(\infty,t) = 0,\quad T_a(r,0) = 0 \tag{6}$$

Here $\dot{q}$ is rate of heat release from a single particle surface during its burning time, which is defined [30]:

$$\dot{q} = \frac{Ak_p(T_f - T_c)}{r_p} \tag{7}$$

The space-time temperature distribution of single particles has been obtained through the whole domain:

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

where $H$ is Heaviside function. The temperature distribution in the domain can be calculaed by superposition principle by superimposing effect of all burning and burned particles.

$$T_s = \sum_i\sum_j\sum_k T_{a(i,j,k)}(r_{i,j,k}, t_{ig,i}) \tag{9}$$

where $T_a$ is the space-time distribution of temperature around a single burning particle and beyond, and $T_s$ is the total effect of burning and burned particles which is indicative of the temperature of medium fluid around a particle in the preheated zone. The $T_\infty$ = 300 K and $T_f$ = 3700 K are the considered values for ambient and flame temperature [31]. Table 1 shows other properties of aluminum particle.

**Table 1. Aluminum particle properties**

| Particle properties | Value | Unit |
|---|---|---|
| $\rho_v$ | 1350 | kgm$^{-3}$ |
| $C_{p,v}$ | 448.48 | Jkg$^{-1}$K$^{-1}$ |
| $T_{ia}$ | 1400 | K |

The space between the target particle and each particle placed at $i$, $j$, and $k$:

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

where $L$ is the space between two adjacent layers which is defined:

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

where $\rho_p$ is the particle density, $C_d$ – the dust cloud concentration, and $d_p$ – the particle diameter. The flame propagation speed is defined as the ratio of the space between two adjacent layers to the difference between their ignition times [33]:

$$S = \frac{L}{t_{ig,n+1} - t_{ig,n}} \tag{12}$$

Particle diameter also affects the ignition temperature. Marino [38] determined the ignition temperature of aluminum particles at different diameters. Results of this work revealed an equation for ignition temperature in terms of particle diameter that fits experimental data suitably, eq. (13):

$$T_{ig} = 34.5\,D_P + 789.1 \tag{13}$$

The ignition system which initiates the combustion and prepare initial required heat to ignite particles is modeled by eq. (14) and related boundary conditions, eq. (15). This equation is solved analytically to give the temperature around the ignition system affecting the surrounding particles, eq. (16).

$$\frac{\partial^2 T_{a,ig}(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T_{a,ig}(x,t)}{\partial t} \tag{14}$$

$$T_{a,ig}(x,0) = 0$$

$$K\frac{\partial}{\partial r}T_{a,ig}(x,t) = \frac{1}{2}Q\delta(t) \xrightarrow{at} x = 0 \tag{15}$$

$$T_{a,ig}(x,t) = \frac{Q\alpha}{K}\frac{1}{\sqrt{\pi\alpha t}}\exp\left(\frac{-x^2}{4\alpha t}\right) \tag{16}$$

An algorithm illustrating of how the ignition times are obtained is shown in fig. 1.

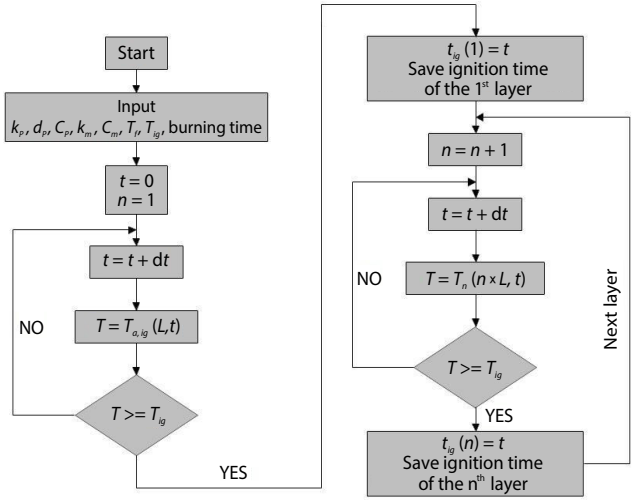


**Figure 1. Flowchart for calculating the ignition time of aluminum particles**

According to the flowchart after the energy release by the ignition system, the temperature of the first layer at the considered location is calculated. When the temperature of particles in the first layer reaches the ignition temperature, it is recorded as the ignition time of the first layer, and the calculations continues to find the ignition times of other layers. Beyond the first layer ($n > 1$), preheating of unburned layers is influenced by burning of the preceding layers, in addition to the ignition system. The flame propagation speed might be calculated from eq. (13) by knowing ignition time of all layers.

## Results and discussion

In the current study, flame propagation of aluminum dust cloud in a medium with different neutralized gas is analytically investigated. An in-house computer code is generated in order to study the effects of aluminum dust concentration and particle size on flame propagation speed in different oxygenated environments including helium, nitrogen, and argon. Additionally, variation of quenching distance is calculated as functions of the same variables. This model based on uniform distribution of aluminum dust particles is presented and solved analytically. In order to demonstrate the accuracy of the present method, the obtained values for flame propagation speed are compared with the experimental results obtained by Goroshin *et al*. [1], Boichuk *et al.* [17], and Goroshin *et al*. [16]. Goroshin *et al* [1] performed the experiments un-

der atmospheric pressure and ambient temperature by using aluminum particles with diameter of 5.4 μm in a flame tube 1.2 m long and diameter of 0.05 m. The ignition system is a tungsten wire installed in the top of the tube, and the dust was ignited at the upper open end of the tube. Boichuk *et al*. [17] conducted the experiments under the same condition by using aluminum with diameter of 6 μm in a vertical semi-open quartz tube 0.036 m in diameter and 1 m long. Ignition was made near the upper open end of the tube with an electric spark. Goroshin *et al*. [16] has performed the set of experiments under atmospheric pressure and ambient temperature by using aluminum particles with diameter of 5.4 μm in a long, stainless steel tube of 7 m length and inner diameter of 0.025 m which is connected to a dispersion chamber with a small-angle conical diffuser. Ignition was made by a small, remotely operated propane-air torch. The torch is immediately turned off after a stabilized dust flame is achieved.

Figures 2-4 describe the flame propagation speed in a quiescent reaction medium with 21% oxygen and 79% of different neutralized gases including nitrogen, argon and helium under atmospheric pressure with particle diameter of 5.4 μm. The initial temperature is considered to be at room temperature and equal to 300 K. The flame propagation speed predicted by the present model is laminar burning velocity of a planar front because of the fact that the laminar burning velocity is the speed at which a plane flame front will propagate into a stationary, quiescent flammable mixture. According to fig. 2, with the increase in dust concentration, the value of flame speed tends to rise. The reason is that in case of higher value of fuel dust concentration, more amount of fuel particles are available for the combustion process, consequently unburned particles would receive more energy and preheat faster due to higher amount of heat released during the combustion. As a result the value of flame speed increases significantly with increase in alu-

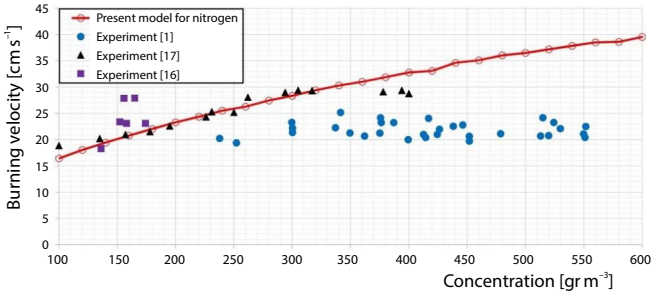


**Figure 2. Flame propagation speed as function of dust concentration with particle diameter of 5.4 μm in oxygenated environment with 79% nitrogen ($T$ = 300 K, $P$ = 1 atm)**

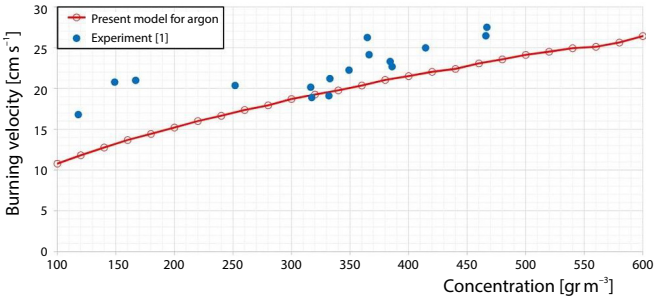


**Figure 3. Flame propagation speed as function of dust concentration with particle diameter of 5.4 μm in oxygenated environment with 79% argon ($T$ = 300 K, $P$ = 1 atm)**

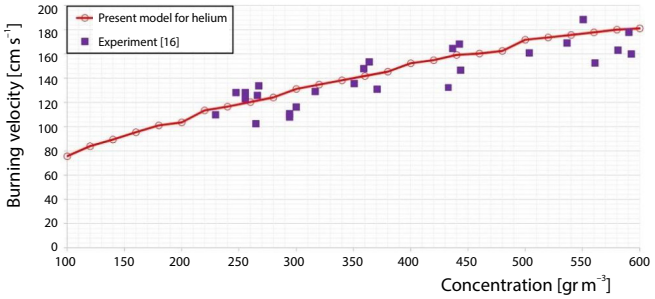


**Figure 4. Flame propagation speed as function of dust concentration with particle diameter of 5.4 μm in oxygenated environment with 79% helium ($T$ = 300 K, $P$ = 1 atm)**

minum dust concentration. This trend can be observable in both fuel lean and rich regions. The stoichiometric aluminum powder concentration in an oxygenated medium is about 340 g/m$^3$. A more precise investigation of the results also reveals that the sensitivity of flame velocity to particle concentration for lean mixtures is higher than rich suspensions. In order to check the validity of the present model with previous experimental data, results are compared with [1, 17, 16] in case of 21% oxygen and 79% nitrogen in fig. 2, and reasonable agreements are obtained. Additionally in case of 21% oxygen and 79% argon and 21% oxygen and 79% helium results are validated by works of [1, 16], respectively, in figs. 3 and 4. In addition, by comparing aluminum burning velocity in different neutralized gases for a specific dust concentration in figs. 2-4, it is realized that the flame speed in helium is much higher than nitrogen and nitrogen higher than argon. This significant difference in the amount of obtained flame propagation speed can be explained by the fact that the heat transfer characteristics of helium is much better than nitrogen and nitrogen better than argon. In other words thermal conductivity and thermal diffusivity for an oxygenated helium is stronger rather than oxygenated nitrogen and argon. As a result diffusion heat transfer rate to the preheating zone which preheats the unburned particles is higher in helium than nitrogen and nitrogen higher than argon. Comparison between figs. 2-4 also indicate that effect of neutralize gas finds a more important role for rich suspensions. For instance the simulation predicts values of 21, 13, and 95 cm/s for the flame speed in 150 g/m$^3$ aluminum suspensions in oxygenated nitrogen, argon and helium, respectively. When the aluminum particle concentration in the mixture increases to 400 g/m$^3$ in the rich region, the flame speed changes to 33, 22, and 154 cm/s for nitrogen, argon and helium. That is to say, good thermal transport properties of helium make 59 cm/s improvement in the flame propagation speed when the aluminum concentration increases from 150-400 g/m$^3$, while this value is 9 cm/s and 12 cm/s for nitrogen and argon, respectively. This behavior can be explained in the way that, for rich fuels larger number of particles exist and a medium with appropriate thermal properties can extensively accelerate the high amount of energy transfer between burning and unburned particles.

Quenching distance is defined as the critical distance between flat plates, below which the flame cannot propagate. Flame quenching by the wall is important for understanding the combustion process in safety purposes. Every flame can be quenched if the walls of the duct are placed close enough. The heat loss from the flame region to the walls is responsible for this phenomenon and each flame under its specific condition has its unique quenching distance. Figure 5 demonstrates how an increase in dust concentration results in reduction in quenching distance for aluminum dust dispersed in air (21% oxygen and 79% nitrogen) for particle diameter of 5.4 μm. The same results are expected for other particle sizes in order of micron. The results of this work are also compared with results obtained by [16] in this figure, where good agreement can be observable. As mentioned the figure illustrates that for a considered particle diameter the value of quenching distance is lower for higher dust concentrations. The reason is that at higher dust concentration the flame tem-

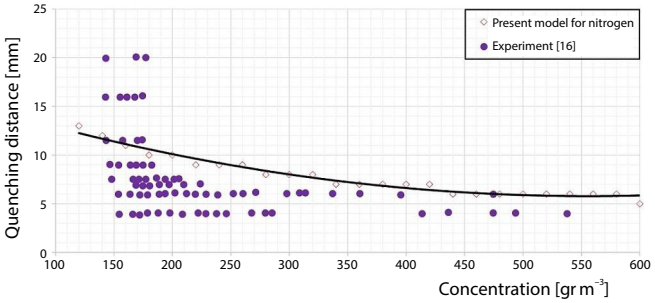


**Figure 5. Quenching distance of aluminum dust cloud as a function of dust concentration for particle diameter of 5.4 μm in oxygenated environment with 79% nitrogen ($T$ = 300 K, $P$ = 1 atm)**

perature is higher and more heat loss is needed for the flame to be quenched. Additionally the flame speed increases with dust concentration and narrower channels are needed to quench fast propagating flames. Consequently quenching distance reduce in case of rich mixtures with respect to lean suspensions.

The same trends for variation of quenching distance in terms of dust concentration is depicted in figs. 6 and 7 for argon and helium as the neutralize gas, respectively. Comparing figs. 5-7 reveals that, flame propagation through aluminum micron-sized powder suspensions in helium has the minimum quenching distance with respect to air and oxygenated argon. In other words the biggest distance between two parallel plates for which no flame can propagate, is smaller for helium. As previosly discussed due to faster heat transfer rates between particles in burning of aluminum dust at oxygenated helium, the flame propagation velocity is high. The fast flame propagation restricts the heat loss from the flame to the quenching channel walls because there exist less time for the heat transfer process. Therefore narrower channels are required to increase the heat loss and as a result the quenching distance is smaller for aluminum dust combustion in oxygenated helium.

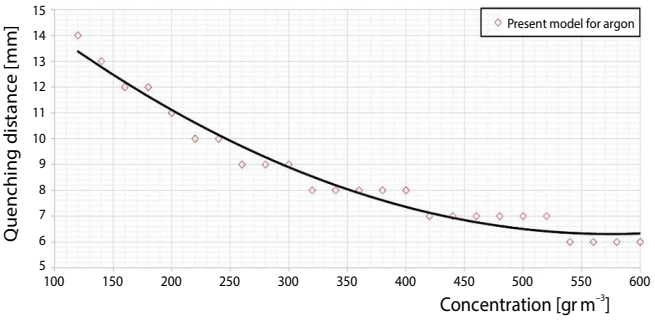


**Figure 6. Quenching distance of aluminum dust cloud as a function of dust concentration for particle diameter of 5.4 µm in oxygenated environment with 79% argon ($T$ = 300 K, $P$ = 1 atm)**

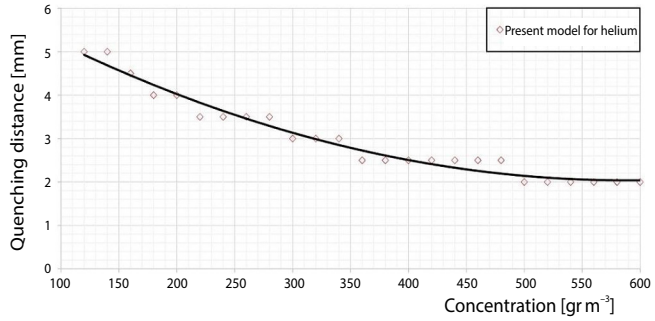


**Figure 7. Quenching distance of aluminum dust cloud as a function of dust concentration for particle diameter of 5.4 µm in oxygenated environment with 79% helium ($T$ = 300 K, $P$ = 1atm)**

## Conclusions

In the present study, flame propagation of mono-dispersed aluminum dust cloud in medium with different neutralized gas including nitrogen, argon, and helium is analytically investigated. An in-house computer code based on discrete heat source model is generated in order to study the effects of dust concentration and particle size on flame propagation speed in different oxygenated environments. Additionally, the variation of quenching distance is also considered as a function of the same variables.

The results indicate that with an increase in the value of aluminum dust concentration, the flame propagation speed increases for all oxygenated environments investigated. By comparing aluminum dust cloud burning velocity in different neutralized gases for a considered dust concentration, results revealed that the flame speed in helium is much higher than nitrogen and in nitrogen higher than argon due to better diffusive heat transfer characteristics of helium

rather than argon and nitrogen. Results also indicate that the neutralize gas plays a more important role for rich mixtures rather than lean mixtures due to larger amount of energy released by burning particles. For rich suspensions an inert gas with appropriate thermal diffusivity can broadly improve the flame speed.

Values of quenching distance in terms of aluminum dust concentration in oxygenated nitrogen, argon, and helium are also discussed. Results show that flame quenching distance reduce as fuel concentration increase and quenching distance has the least value when helium acts as the mixture neutralize gas.

## References

[1] Goroshin, S., *et al*., Burning Velocities in Fuel-Rich Aluminum Dust Clouds, *Proceedings*, 26th Symposium (International) on Combustion/The Combustion Institute, Napoli, Italy, 1996, pp. 1961-1967
[2] Eckhoff, R., *Dust Explosions in the Process Industries*: *Identification, Assessment and Control of Dust Hazards*, Gulf Professional Publishing, Houston, Tex., USA, 2003
[3] Myers, J. T., Reducing Aluminum Dust Explosion Hazards: Case Study of Dust Inerting in an Aluminum Buffing Operation, *Journal of Hazardous Materials*, *159* (2008), 1, pp. 72-80
[4] Li, Q., *et al*., Explosion Characteristics of Nano-Aluminum Powder-Air Mixtures in 20 L Spherical Vessels, *Powder Technol*, *212* (2011), 2, pp. 303-309
[5] Yang, V., *et al*., *Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics*, in: Progress in Aeronautics and Astronautics, (Ed. Zarchan, P.) AIAA Inc. New York, USA, Vol. 165, 2000
[6] Price, E. W., *Combustion of Metalized Propellants*, in: Progres Astronauties Aero 90, Am. Inst. Aeronaut Astronaut, (Eds. K. K. Kuo, M. Summerfield), New York, USA, 1984, pp. 479-514
[7] Washburn, E. B., *et al*., The Simulation of the Combustion of Micrometer-Sized Aluminum Particles with Steam, *Combust. Sci. and Tech*., *180* (2008), 8, pp. 152-1517
[8] Kim, C. K., *et al*., Afterburning of TNT Explosive Products in Air with Aluminum Particles, *Proceedings*, 46th AIAA Aerospace Sciences Meeting, Reno, Nev., USA, 2008
[9] Price, E. W., *Fundamentals of Solid-Propellant Combustion*, in: Progress in Astronautics and Aeronautics, (Ed. M. Summerfield), AIAA Inc., New York, USA, Vol. 90, 1984
[10] Chen, J. L., *et al*., Mechanisms of Flame Propagation through Combustible Particle Clouds, *Journal of Loss Prevention in the Process Industries*, *9* (1996), 3, pp. 225-229
[11] Seshadri, K., *et al*., The Structure of Premixed Particle-Cloud Flames, *Combustion and Flame, 89* (1992), 3-4, pp. 333-342
[12] Sun, J., *et al*., Structure of Flames Propagating through Aluminum Particles Cloud and Combustion Process of Particles, *Journal of Loss Prevention in the Process Industries, 19* (2006), 6, pp. 769-773
[13] Wilson, Jr R. P., Williams, F. A., Experimental Study of the Combustion of Single Aluminum Particles in $O_2$/Ar, *Proceedings*, 13th Symposium (International) on Combustion, Salt Lake City, Ut., USA, 1971, Vol. 1, pp. 833-845
[14] Bucher, P., *et al*., Flame Structure Measurements of Single, Isolated Aluminum Particles Burning in Air, *Proceedings*, 26th Symposium (International) on Combustion/The Combustion Institute, Napoli, Italy, 1996, pp. 1899-1908
[15] Dreizin, E. L., Experimental Study of Aluminum Particle Flame Evolution in Normal and Micro-Gravity, *Combustion and Flame*, *116* (1999), 3, pp. 323-333
[16] Goroshin, S., *et al*., Quenching Distance of Laminar Flame in Aluminum Dust Clouds, *Combustion and Flame, 105* (1996), 1-2, pp. 147-160
[17] Boichuk, L., *et al*., Flame Propagation in Two-Component Aluminum-Boron Gas Suspensions, *Combustion, Explosion and Shock Waves*, *38* (2002), 6, pp. 651-654
[18] Friedman, R., Macek, A., Ignition and Combustion of Aluminum Particles in Hot Ambient Gases, *Combust. Flame, 6* (1962), pp. 9-19
[19] Kwon, Y. S., *et al*., The Mechanism of Combustion of Superfine Aluminum Powders, *Combustion and Flame, 133* (2003), 4, pp. 385-391
[20] Bazyn, T., Oxidizer and Pressure Effects on the Combustion of 10-μm Aluminum Particles, *Journal of Propulsion and Power*, *21* (2005), 4, pp. 577-582
[21] Gill, J. R., Combustion Times and Emission Profiles of Micron-Sized Aluminum Particles Burning in Different Environments, *Combustion and Flame*, 157 (2010), 11, pp. 2015-2023

[22] Bucher, P., *et al*., Condensed-Phase Species Distributions about Al Particles Reacting in Various Oxidizers, *Combustion and Flame*, *117* (1999), 1-2, pp. 351-361
[23] Julien, P., *et al*., Freely-Propagating Flames in Aluminum Dust Clouds, *Combustion and Flame*, *162* (2015), 11, pp. 4241-4253
[24] Julien, P., *et al*., Effect of Scale on Freely Propagating Flames in Aluminum Dust Clouds, *Journal of Loss Prevention in the Process Industries*, *36* (2015), July, pp. 230-236
[25] Soo, M., Stabilized Flames in Hybrid Aluminum-Methane-Air Mixtures, *Proceedings of the Combustion Institute*, *34* (2013), 2, pp. 2213-2220
[26] Goroshin, S., *et al*., Emission Spectroscopy of Flame Fronts in Aluminum Suspensions, *Proceedings of the Combustion Institute, 31* (2007), 2, pp. 2011-2019
[27] Beckstead, M. W., Correlating Aluminum Burning Times, *Combustion, Explosion, and Shock Waves*, *41* (2005), 5, pp. 533-546
[28] Bidabadi, M., *et al*., Modeling Combustion of Aluminum Dust Cloud in Media with Spatially Discrete Sources, *Heat Mass Transfer*, *5* (2015), 6, pp. 837-845
[29] Shoshin, Y. L., Dreizin, E. L., Particle Combustion Rates for Mechanically Alloyed Al-Ti and Aluminum Powders Burning in Air, *Combustion and Flame*, *145* (2006), 4, pp. 714-722
[30] Glassman, I., Metal Combustion Processes, *Proceedings*, 14th Annual Meeting of the American Rocket Society, Washington DC, 1959, pp. 938-959
[31] Belyaev, A. F., *et al*., Combustion and Ignition of Particles of Finely Dispersed Aluminum, *Combustion, Explosion and Shock Waves*, *4* (1968), 3, pp. 323-329
[32] Macek, A., Fundamentals of Combustion of Single Aluminum and Beryllium Particles, *Proceedings*, 11th Symposium (International) on Combustion, Berkeley, Cal., USA, 1967, Vol. 11, pp. 203-217
[33] Friedman, R., Macek, A., Combustion Studies of Single Aluminum Particles, *Proceedings*, 9th Symposium (International) on Combustion, Ithaca, N. Y., USA, Vol. 9, 1963, pp. 703-709
[34] Dreizin, E. L., Trunov, M. A., Surface Phenomena in Aluminum Combustion, *Combustion and Flame, 101* (1995), 3, pp. 378-382
[35] Brooks, K. P., Beckstead, M. W., Dynamics of Aluminum Combustion, *Journal of Propulsion and Power*, *11* (1995), 4, pp. 769-780
[36] Brzustowski, T. A., Glassman, I., *Spectroscopic Investigation of Metal Combustion*, Heterogeneous Combustion, Academic Press, New York, USA, 1964, pp. 41-74
[37] Bidabadi, M., *et al*., A Comparative Study of Different Burning Time Models for the Combustion of Aluminum Dust Particles, *Applied Thermal Engineering*, *105* (2016), July, pp. 474-482
[38] Marino, T. A., Numerical Analysis to Study the Effects of Solid Fuel Particle Characteristics on Ignition, Burning, and Radiative Emission, ProQuest Dissertations Publishing, The George Washington University, Washington DC, 2008, 3304086

Paper submitted: July 22, 2017
Paper revised: October 1, 2017
Paper accepted: October 1, 2017