Aluminum Combustion under Different Condition: A Review

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Abstract

This paper reviews the collection of literature on aluminum combustion, with an emphasis on various parameters used. These parameters which affect combustion of aluminum are particles size and oxygen content. Aluminum is a material that is often used in combustion processes due to its effortless reactive material and explosive. A large amount of research has been published about combustion in aluminum materials where aluminum can be used as a way to increase propulsion in combustion. The purpose of this paper is to review some aspects that affect combustion in aluminum. It goes on to discuss the particles size differences and the different oxygen content mixture with gas in used. The results of various existing studies show that there is a difference in ignition temperature and burning time effect in aluminum combustion due to the size and oxygen content. Where, decreasing particles size can decrease ignition temperature and burning time. The review paper is intended to outline a parameter range for aluminum combustion.

Keywords: Aluminum Combustion; Burning rate; Particles Size Effect Temperature

1. INTRODUCTION

Aluminum is a reactive material that can be used as fuel added for propellant, ethanol, CH4 and solid-fuel [1-4]. Aluminum also has a high energy density and is also low in cost [5]. Various gases are used by researchers to be used as a mixture of combustion processes such as O_2, CO_2, Ar, N_2 [6-8]. Aluminum combustion with H_2O has also been studied and produced an exogenous H_2 gas content [9]. So that various studies on aluminum burning still continue to this day. Aluminum induction and combustion occurs starting when entering the melting process to the boiling point and continued with oxidation.

Sundaram et al. [10] the process of induction and combustion on aluminum particles with nanometer size has fewer steps when compared to aluminum with a micrometer size, namely at the nanometer size there are 3 stages while the micrometer size has 4 stages until combustion occurs. Melting behavior of aluminum powder was conducted using aluminum particle produced by milling process. Particle synthesis was carried out with the size of 13 to 40 nm using mechanical attrition under different atmospheres, and differential calorimetry scanning was carried out to determine the behavior of aluminum melting. Melting behavior studies have also been carried out using molecular-dynamics (MD) with a size of 1.0-2.9 nm [11, 12]. This shows the behavior of particles towards the ignition process in aluminum, where the smaller the particle size, the faster the ignition process in aluminum.

AlO emissions were observed in different particles, 2.8 and 10 μm in the aluminum combustion process with a temperature of 2650 K and a pressure of 8 atm [6]. From various starting point variations of ignition temperatures 1500, 2000, 2300, and 2800 K there is a decrease in ignition time from 25 μs for T = 1500 K to 0.5 μs for T = 2800 K with final equilibrium temperature 3742-3833 K[13]. Combustion of aluminum particles in oxygen

with a size of 10 μm, temperature 2650 K with a pressure of 3–30 atm, showing that the reaction process of the particle surface has a significant influence on the combustion behavior of aluminum particles[14]. The reaction enthalpy for particles from 2-10 nm decreases with increasing particle size and can reduce the surface fraction of atoms by hanging bonds. Also, when the particle size decreases, it gives the effect of increasing the rate of agglomeration [15].

From the background above, this paper aims to provide an overview of several things related to the effect of particle size on ignition temperature, burning time and also the effect of oxygen content on aluminum combustion under various conditions. It focused on the recent progress of aluminum combustion and use narrative approach in reviewing the related papers.

2. MECHANISM OF ALUMINUM COMBUSTION

When aluminum particles burn as depicted in Figure 1, a small portion of the product remains as vapor and a small portion condenses. Oxide vapor in the flame region can diffuse to the surface or the environment. The oxide vapor diffuses to the surface of the particles to condense, the increase in aluminum vapor increases. Steam that diffuses into the environment may or may not condense. The condensed phase is kept away from the fire zone based on the bulk gas movement. The vapors that diffuse into the environment and the condensed phase do not significantly affect the rate of combustion of particles.
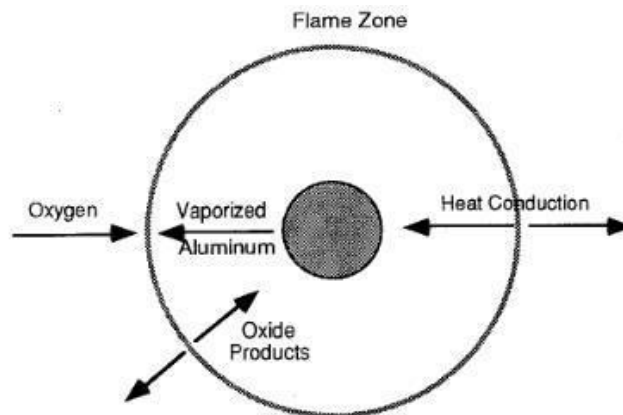

Figure 1. Model diagram of aluminum combustion [16]

At oxidizing concentrations or low gas temperatures, the gas moves towards the fire and the temperature of the fire is below the boiling point of the oxide. When the concentration of the oxidizer or the temperature of the gas increases, the temperature of the flame reaches the boiling point of the oxide and the evaporated oxide fraction begins to increase. The amount of the evaporated oxide is higher which results in an increase in diffusion of matter so that it moves away from the flame and the gas flow between the flame and infinity changes direction. At oxidizing concentrations or high gas temperatures, all oxides are evaporated and the temperature of the flame also rises [16].

When aluminum particles are heated, the weight of the particles is reduced due to moisture evaporation. As the temperature increases, the oxidation reaction of the aluminum surface with oxygen is greatly strengthened. At the peak oxidation temperature, the rate of the oxidation reaction reaches a peak value. However, as the thickness of the oxide layer increases on the surface of aluminum particles, the resistance of oxygen diffusion to the surface of simple aluminum material will greatly increase. To some extent, surface oxidation on aluminum particles will be hindered because of the alumina shell. As the temperature rises higher than the melting point of aluminum material, the core of aluminum particles wrapped in alumina skin will melt. Even at high temperature conditions, melted aluminum will evaporate and cause alumina skin to be damaged. In this case, liquid and aluminum will cause combustion reactions [17] as in Figure 2.
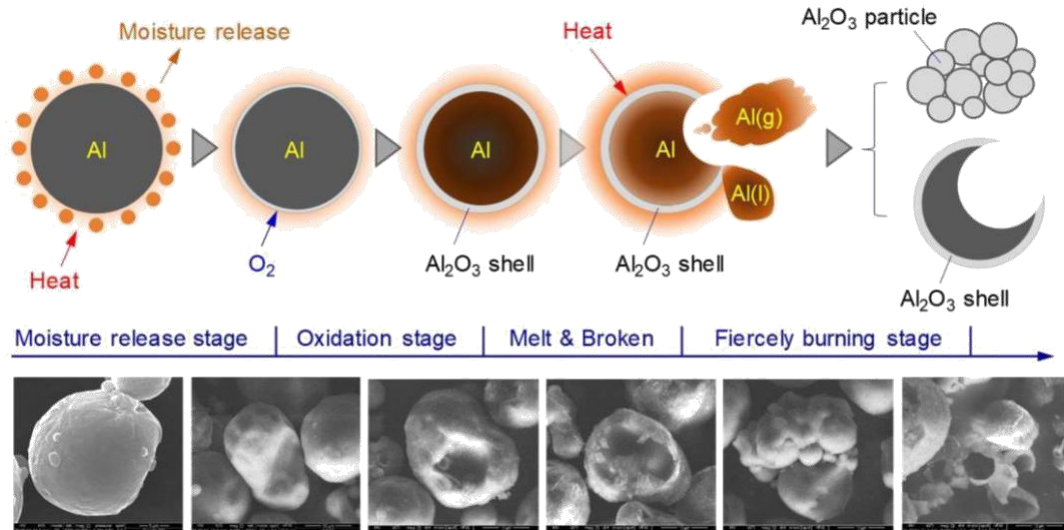
Figure 2. Oxidation diagram on aluminum [17]

This oxidation process is also explained by several researchers through TGA testing [18-20] so that the oxidation behavior can be known. This oxidation process is accompanied by an energy release [10, 13-15, 21] by being influenced by particle size, gas pressure, and oxygen content. Table 1 is a sub-mechanism of Al's reaction to O where each reaction has a different energy. Limiting dust to aluminum particles may be achieved in the air. The kinetic mechanism of the Al / O gas phase, consisting of 8 species and 10 reactions, as listed in Table 1, is used to simulate chemical processes [13].

Table 1. Al/O sub-mechanisms [13]

No.	Reactions	A (cm^3/mol s)	n	E (cal/mol)
1	$Al + O_2 = AlO + O$	9.72E13	0.	159.95
2	$Al + O + M = AlO + M$	3.0E17	−1.0	0.
3	$AlO + O_2 = OAlO + O$	4.62E14	0.	19885.9
4	$Al_2O_3 = AlOAlO + O$	3.0E15	0.	97649.99
5	$Al2O3 = OAlO + AlO$	3.0E15	0.	126999.89
6	$AlOAlO = AlO + AlO$	1.0E15	0.	117900.
7	$AlOAlO = Al + OAlO$	1.0E15	0.	148900.
8	$AlOAlO = AlOAl + O$	1.0E15	0.	104249.94
9	$OAlO = AlO + O$	1.0E15	0.	88549.86
10	$AlOAl = AlO + Al$	1.0E15	0.	133199.94
11	$Al = Al(l)$	1.0E14	0.	0.
12	$Al_2O_3 = Al_2O_3(l)$	1.0E14	0.	0.

3. PARTICLES SIZE EFFECT

Particle size is one of the important parameters in the generation and combustion of aluminum, various researchers examine using various sizes ranging from nanometers to μm [12, 22]. As part of this research, as much data as possible is collected, documented, and collected in the general format in Table 1. Only sources are used where variations in the data are sufficient to show trends. Many other sources where data were obtained in a set of test conditions are not included. A database of about 400 datum points was compiled

and analyzed to evaluate the effects of various parameters on the burning time of aluminum. The results of the study are presented below.

Table 1. Available Aluminum combustion data [23]

D$_0$, µm	T$_0$, K	p, atm	Gas Concentration %					reff
			H$_2$O	O$_2$	CO$_2$	CO	N$_2$	
10-42	150	9-20	0	20-50	20-50	0	0	[6]
60–96	2200–3200	1–204	0.5–50	0–27	9–50	9–41	9–41	[24]
300–760	1809–1827	1	29–31	10–25	27–30	15–49	46–64	[25, 26]
20	2225–2775	85–34	0	99	0	0	1	[27]
35–40	298	1–39	0	21	0	0	79	[28, 29]
40–70	3000	1	66–89	11–16	0–18	0	0	[30]
40-170	300	1	31.1	10.7	15.6	0	42.6	[31]

This brief summary is not necessarily comprehensive but is intended to identify the main research contributions, especially where aluminum burning time data is available which can be correlated with other researchers. A brief description of their technique is included along with a discussion of their results and conclusions. For simplicity, research has been separated by techniques used to ignite aluminum particles: propellant, gas burners, lasers, ash, and shock.
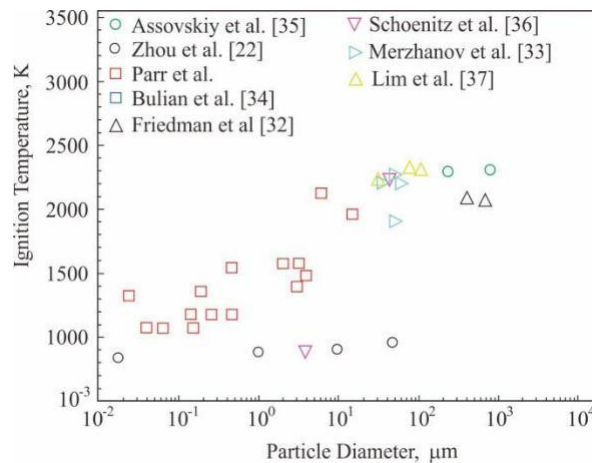

Figure 3. Ignition temperature of aluminum particle as a function of particle diameter.

The particle ignition temperature and combustion rate must be determined as input parameters in this analysis. Picture. 2 shows the ignition temperature of aluminum particles observed experimentally as a function of particle size in an oxygen-containing environment [22, 32-37]. For particles with diameters greater than 100 µm, most experimental studies have shown that ignition takes place at temperatures near the melting point of aluminum oxide (eg, 2350 K). Because each aluminum particle is covered by a resistant oxide shell, he argues that the particle does not ignite until the oxide shell melts or breaks near its melting temperature under the influence of aluminum thermal expansion. For particles with diameters of 1-100 µm, however, ignition can be achieved over a wide temperature range from 1300 to 2300 K. For nano-sized particles, ignition has been reported to occur at temperatures as low as 900 K [34, 38]. The low ignition temperature can be attributed to aluminum oxidation and polymorphic phase transformation of the alumina shell [18, 39], or cap of the oxide layer due to thermal expansion [40]. In this study, the results of the experimental data curve, as shown by the dotted line in Fig. 2, used for particle ignition temperature.
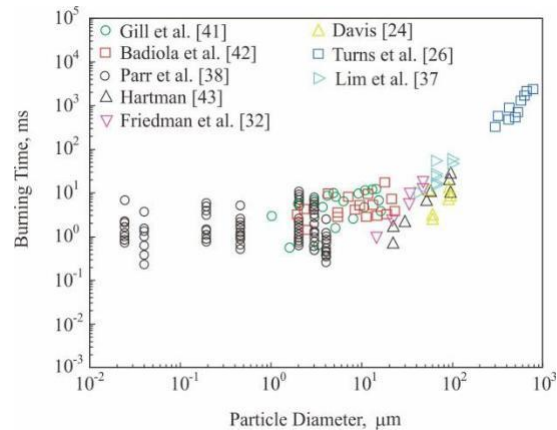
Figure 4. Comparison of measured burning times of aluminum as a function of particle diameter

The mechanism of combustion of nanoaluminum particles can be determined by comparing the measured and calculated combustion time. The combustion time dependence on particle size, pressure, and temperature can be used to gain insight into the mechanism of combustion. Figure 4 shows a comparison of the measured combustion time with theoretical counterparts under diffusion controlled conditions. Experimental data on the measured combustion time of aluminum particles are available in reference.[24, 26, 32, 37, 38, 41-43].

For nanoaluminum particles, the calculated gas phase diffusion time is some order of magnitude lower than the combustion time measured for nano-aluminum particles. As a result, mass diffusion through a gas phase mixture does not control the rate of combustion of nanoaluminum particles. Because the chemical rate constants and the mass diffusion coefficient in the oxide layer are less well known parameters, a comparison of the time scale of the characteristics of mass diffusion and chemical kinetics is not possible. Particle size gives a weak effect on the combustion of nano-aluminum particles. The burning time has a size dependence of the form $\tau b = aDp^n$, where the exponent n is ~0.3 [44]. The diameter exponents are lower than the unit due to cracks in the oxide layer and / or sintering and agglomeration of particles [45]. Cracks in the oxide layer increase the fractal dimension of the particle surface, while the particle volume is negatively affected. The resulting diameter exponents are significantly lower than the unit in kinetic controlled conditions. In addition, particles tend to aggregate during combustion and the resulting combustion time may not match the initial particle size. Furthermore, gas pressure and temperature have a strong effect on the combustion time of nanoaluminum particles.

The combustion time is an exponential function of temperature, with activation energy in the range of 50–144 kJ/mol [44]. This decreases by a factor of four when the pressure increases from 8 to 32 atm [46]. Note that, in the free molecular regime, the diffusion time scale of the gas phase is proportional to the square root of temperature, whereas the time scale of diffusion of mass through the oxide layer and chemical kinetics is an exponential function of temperature. This, together with the observed time dependence of the observed size, not only proves the fact that mass diffusion through a gas phase mixture is not a rate control process, but also shows the rate of combustion of aluminum nanoparticles controlled by chemical kinetics. Note that chemical rate constants are less well known parameters and need further investigation. In addition, several important phenomena such as sintering and agglomeration of particles and cracking of the oxide layer must be considered before a comparison can be drawn between predictions and experimental data. This phenomenon can be considered in future work to develop a rigorous aluminum nanoparticle combustion model [10].

4. OXYGEN CONTENT EFFECT

Measurement of wavelength dispersive spectroscopy in the study of Dreizin (1999) showed the presence of oxygen in the interior of the particle, confirming our previous measurements made for particles burning in the air. Oxygen is not distributed uniformly in particles. Instead, areas with high oxygen content (up to 11% atoms) are mixed with areas of pure aluminum. Backscattering electron (BSE) images were collected for several cross sections of particles to visualize phases with different oxygen contents. The strength of the BSE signal is proportional to the average number of atoms of the material and provides good contrast for the oxygen-rich (dark) and oxygen (bright) zones as shown in Fig. 5 [47].
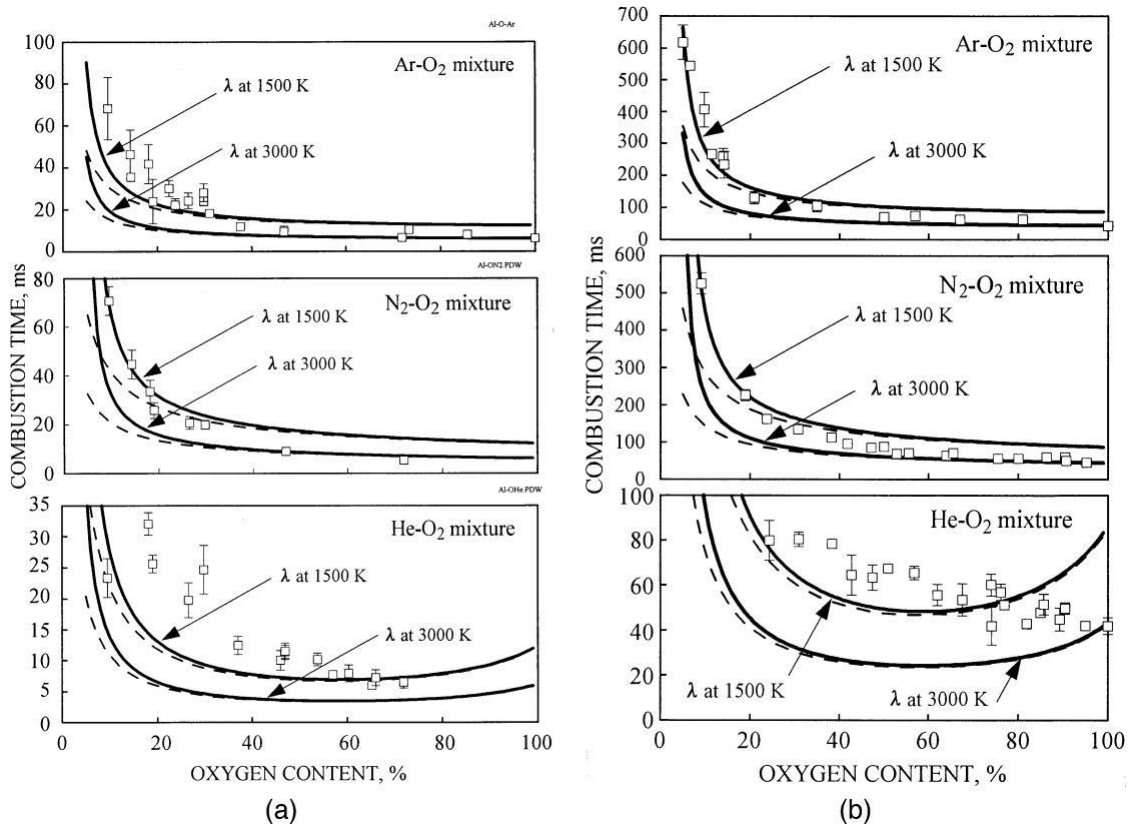

Figure 5. The experimental and estimated from the "d^2 law" times of combustion for 90 mm (a) and 250 mm (b) diameter aluminum particles in different gas mixtures [47].

The measured combustion time is plotted against the oxygen content for each diluting mixture in FIG. 6. Each data point is an average of six or more measurements. In comparison, curves showing combustion time, t, calculated using "d2-law" for burning droplets are also plotted. Details and comparisons of experimental and computational combustion times are discussed below.

5. SUMMARY

Particle size is very influential in various conditions in the combustion of aluminum in this case, namely aluminum particle size and oxygen content used in combustion, the smaller the aluminum particle size, the ignition temperature will be lower while the burning time will be faster as the particle size decreases. Oxygen content also greatly influences the process of combustion of aluminum where the richer the oxygen, the faster burning time and higher temperatures

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