Study on heating process of micro-sized aluminum particles in planar flame

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Introduction

Aluminum powders are widely used as fuel additives in various solid propellants. The advantages of aluminum are its relatively high volumetric combustion enthalpy, high combustion temperature and relatively low cost[1,2]. Studying heating and ignition process and combustion characteristics of aluminum particles are great significance for optimization of new solid propellants.

Feng[3] established a single-particle ignition apparatus to record the entire process of heating, ignition and combustion by using high-speed camera. However, there is no systematic model for the heating process, and it can't obtain characteristics of the heating process in a larger size range. Meanwhile, D.S.Sundaram[4] established a full-stage heating process model, and the model can obtain parameters such as preheating time and ignition delay time. However, the preheating time obtained in this paper is a steady-state approximation. The heating process of aluminum particles can't be obtained, and the model isn't verified by experiments. When Feng's experimental conditions were substituted into the heating model established by D.S.Sundaram, the preheat time obtained by the model was greatly different from Feng's experimental results. So D.S.Sundaram's model can't be used to estimate the heating time. Therefore, it is necessary to re-establish a heating model that can be used to predict the heating process during the preheating stage.

1. Single-particle heating model

In order to understand heating process of aluminum powders in high temperature gas and heating time from starting falling to ignite, this paper will establish a theoretical heating model for predicting heating process of aluminum particles and analyze the factors affecting heating time. To simplify heating model, it is considered that aluminum particles are quickly placed in heated gas stream, and heating time starts from introduction of aluminum particles into gas stream. During particles heated, aluminum particles' heating by porous medium is ignored.

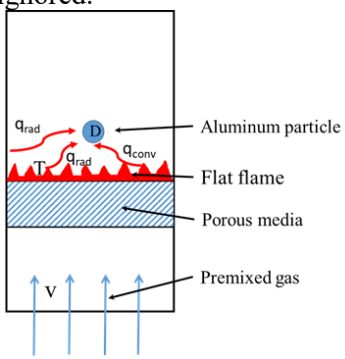

Figure 1 Diagram of single particle heating

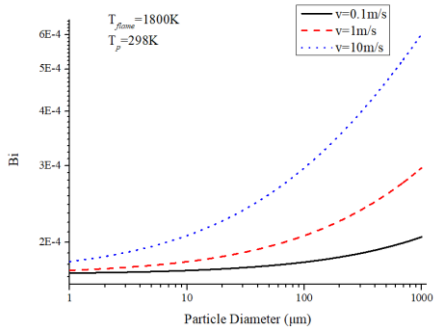

Figure 2 Effect of particle size on Biot number

The heating model of single aluminum particle is shown in Figure 1. As shown in Figure 1, aluminum

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particles heated in planar flame are mainly effected by three heating sources:(1) radiant heating of flame;(2) convective heating of high temperature gas;(3) radiant heating of burner wall. During the heating process, aluminum particles are heated in two steps:(1) heat transferred from three heating sources to the surface of particles;(2) heat transferred from particle surface to interior.

In order to calculate time that heat transferred from heating sources to particle surface and time that heat transferred from particle surface to interior, it is necessary to calculate Biot number(*Bi*) of the particle and convective heat transfer coefficient *h* between high temperature gas and the particle[5].

$$Bi = \frac{hD_p}{6\lambda_p} \tag{1}$$

$$h = \frac{\lambda_a}{D_p}\left[2 + \left(0.4\,\mathrm{Re}_{D_p}^{1/2} + 0.06\,\mathrm{Re}_{D_p}^{2/3}\right)\mathrm{Pr}^{0.4}\left(\nu_{T_a}/\nu_{T_p}\right)^{1/4}\right] \tag{2}$$

In equation(1), D_p is diameter of aluminum particles, and λ_p is thermal conductivity of aluminum particles. The Biot number(*Bi*) characterizes the ratio of thermal resistance of heat transfer per unit area to external thermal resistance per unit area. When $Bi \ll 1$, it can be considered that temperature gradient inside aluminum particles is small, and internal temperature is consistent with surface temperature of particles. In equation(2), h is convective heat transfer coefficient between gas and aluminum particles, λ_a is thermal conductivity of high temperature gas, Re_{Dp} is Reynolds number of aluminum particles, Pr is Prandtl constant, ν is kinematic viscosity, subscripts of T_a and T_p in equation(2) indicate temperature of high temperature gas and the initial temperature of particles, respectively.

Figure 2 shows the relationship between *Bi* and particle size at three flow rates. The Biot number is calculated at a flame temperature of 1800K and an initial particle temperature of 298K. When flame temperature is 1800K, thermal conductivity of ambient gas is 120×10^{-3}W/(m×K). As shown in Figure 2, for aluminum particles in the range of 1μm to 1000μm, the Biot numbers are much smaller than 1, so that temperature gradient inside particles can be ignored. In this case, heating process of aluminum particles can be analyzed by the lumped parameter method[5].

The heating process of aluminum particles depends on heat transfer between external heat sources and particle surface. Based on the law of conservation of energy, heating process of aluminum particles can be expressed by the following formula[5]:

$$m_p C_p \frac{dT_p}{dt} = \dot{q}_{cond} + \dot{q}_{rad(\,flame)} + \dot{q}_{rad(wall)} \tag{3}$$

In equation (3), m_p is mass of a single aluminum particle, C_p is the specific heat of aluminum particle and t is heating time. $\dot{q}_{cond}$ is convective heating amount of gas to particle, $\dot{q}_{rad(\,flame)}$ is radiant heating amount of flame to particle and $\dot{q}_{rad(wall)}$ is radiant heating amount of wall of burner to particle. These three heating amounts are:

$$\dot{q}_{cond} = h\left(T_{flame} - T_p\right)A_p \tag{4}$$

$$\dot{q}_{rad(\,flame)} = \varepsilon_{flame}\sigma\left(T_{flame}^4 - T_p{}^4\right)A_p \tag{5}$$

$$\dot{q}_{rad(wall)} = \varepsilon_{wall}\sigma\left(T_{wall}^4 - T_p{}^4\right)A_p \tag{6}$$

In equations(4)~(6), h is convective heat transfer coefficient between gas and particle surface, A_p is the surface area of particle, ε_{flame} is flame emissivity, ε_{wall} is wall emissivity and σ is Stefan-Boltzmann constant.

Flame emissivity ε_{flame} depends on flame temperature(T_{flame}), the fuel C/H mass ratio, and effective gas layer thickness(L). The calculation formula[6] is shown in equation(7).

$$\varepsilon = 1 - \exp\left(-K \frac{L}{T \cdot n^B} \right) \tag{7}$$

In equation(7), the K value and the B value are related to fuel type. For commonly used methane gas, K=300, B=0.2; n is weight ratio of C/H, for methane fuel, n=3; L is effective gas layer thickness, different gas volume shapes have different expression patterns.

Substituting equations(4)~(6) into equation (3) and simplifying equation (3), equation of dynamic heating process of aluminum particles can be obtained, and heating time can also be obtained.

$$\frac{\rho_p D_p C_p}{6} \frac{dT}{dt} = h\left(T_{flame} - T\right) + \varepsilon_{flame}\sigma\left(T_{flame}^4 - T^4\right) + \varepsilon_{wall}\sigma\left(T_{wall}^4 - T^4\right) \tag{8}$$

There may be some deviations between calculated results and actual results using equation(8), because there are two premise assumptions in energy conservation equation(3):(1)Ignore heat loss of $\dot{q}_{cond}$, $\dot{q}_{rad(flame)}$ and $\dot{q}_{rad(wall)}$ during heating;(2) Ignore heat generated by chemical reactions that may occur on the surface of particles

2. Calculation results and analysis

2.1 Comparison with other models

D.S. Sundaram established a heating model during preheat, heat transfer and ignition stage of micron-sized aluminum particles. He divided ignition stage into three main steps:(1) Heat transfer from external heat source to particles causes aluminum particles to reach the melting point;(2) Internal active aluminum melts, and oxide layer undergoes phase transformation and then rupture. Internal molten aluminum diffuses outward;(3) Finally, aluminum particles ignite. D.S. Sundaram define the heating time as heat transfer from gas to particle which is shown in equation(9). Meanwhile, the model that heat transfer from gas to particle is the steady-state model, which can't characterize the relationship between temperature and time during heating.

$$\tau_{heat} \approx \frac{\rho_p C_p D_p^2}{45\lambda_a} \tag{9}$$

2.2 Comparison with experiments

For single-particle aluminum ignition, many devices have been designed for researches. Ignition delay and combustion process of aluminum particles were studied by conducting ignition experiments to explore ignition mechanism. In Y Feng's study, single-particle aluminum is heated under a planar flame formed by methane-oxygen, and morphological changes of aluminum particles after heating is recorded by camera system[3].

According to physical conditions of Y Feng's study, heating time is calculated in equation(3) and compared with Y Feng's experimental results. Physical parameters of aluminum particles and flame gas in the experiment are shown in Table 1.

Table 1 Parameters of aluminum particles and flame gas

Parameters	Values	Units	Reference	Parameters	Values	Units	Reference
D_p	68.3/84/121.6	μm	[3]	v	329×10^{-6}	m^2/s	[5]
ρ_{Al}	2700	kg/m^3	[5]	Pr	0.683		[5]
C_p	C_p=0.48T+755 (T>300K)	J/(kg×K)	fitting in [5]	λ_a	120×10^{-3}	W/(m×K)	[5]
λ_p	903	W/(m×K)	[5]	v_p	15.71×10^{-6} (T=298K)	m^2/s	[5]
T_{flame}	1800	K	[3]	V	0.0926	m/s	[3]

When considering the wall radiation, due to radiation inside the burner mainly comes from the inner

wall, the boundary conditions are taken $T_{wall}=T_{flame}$.

In Y Feng's research, by distinguishing change rates of spot size and spot size of aluminum particles during heating, it can be determined different stages of aluminum particles[3]. The heat time can be obtained by Y Feng's results[3].

Submitting parameters in Table 1 into heating models in Equations(8) and heat transfer model in equation(9), the time required to heat from room temperature 298 K to melting point of 933 K can be calculated. Deviation between the two models and the Y Feng' experiments is compared. Results are shown in Table 2.

Table 2 Comparison between heating models and experimental results

Particle size（μm）	Heating model（ms）	Y Feng's preheat time（ms）	D.S.Sundaram's model (ms)
68.3	4.7(34.5%)	7.18	2.1(70.8%)
84	7(12.5%)	8	3.19(60.1%)
121.6	14.4(3.7%)	14.96	6.68(55.3%)

From comparison results in Table 2, it can be seen that D.S.Sundaram's heating model's results ares very different from Y Feng's experimental result. The model can't be used to predict heating time. While the deviation of heating model of this paper is much smaller than D.S.Sundaram's. As particle size is 121.6μm, the deviation is only 3.7%.

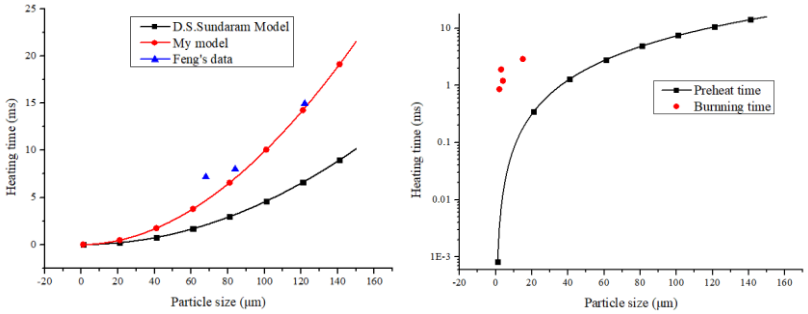


Figure 3 (a)Relationship between heating time of the two models and particle size (b)Comparision with burning time

When particle size range was extended to 1μm to 150μm, heating time between the two models was compared. As shown in Figure 3(a), the heating time obtained by this paper is more consistent with experimental results.. And in Figure 3(b), it can be seen that the preheat time is close to the burning time[7]. So the heating model is more reliable

3. Factors affecting preheat time

In most solid propellants, due to a long ignition delay time, molten particles agglomerate larger aluminum droplets. Most of the agglomerated aluminum particles will continue to burn in the oxidizing environment after leaving the propellant surface. According to equation(8), the most critical factors affecting these aluminum particles during heating are the convective heat transfer coefficient h between flame and aluminum particles and particle size D_p.

3.1 Effects of flame temperature

Effects of flame temperature are mainly reflected in: (1)Influences of flame temperature on high temperature gas parameters, such as gas thermal conductivity λ_a, gas kinematic viscosity v, etc., and further affecting convective heat transfer coefficient h; (2) Flame temperature directly affects convective heat transfer and heat radiation between gas and aluminum particles. Influences of flame temperature on convective heat transfer coefficient h are shown in Figure 4.

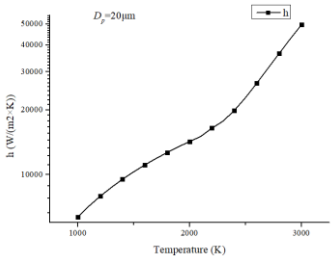
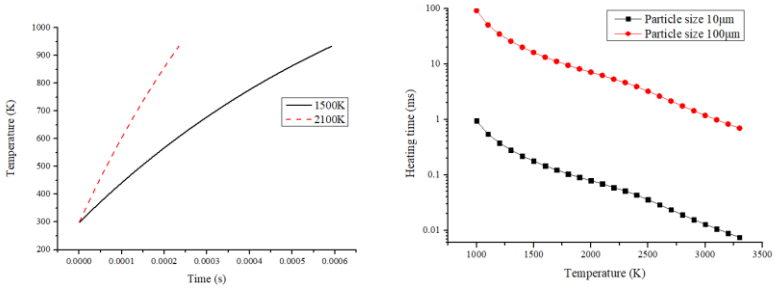


Figure 4 Relationship between flame temperature and *h*

As shown in Figure 4, when flame temperature increases from 1000K to 3000K, convective heat transfer coefficient *h* increases from 6365W/(m^2×K) to 49671W/(m^2×K). The convective heat transfer coefficient increases by about 8 times. So that flame temperature has great effects on heating time during preheating stage.



(a) (b)

Figure 5 (a) Particle temperature changes with time (b)Variations of preheating time with temperature

Figure 5(a) shows heating process during preheat stage under different flame temperature. It can be seen that different flame temperatures have different processes. Figure 5(b) shows that for different sizes of aluminum particles, variations of preheating time with flame temperature increasing using single-particle heating model. It can be seen from the figure, as gas temperature increases, the required preheating time of aluminum particles at all particle sizes is reduced. For 10μm particle size, when gas temperature increases from 1000K to 3300K, preheat time reduces from 9.4×10^{-4}s to 7.5×10^{-6}s. Preheat time reduces by about 1/100. Therefore, flame temperature has a great influence on aluminum particles' heating.

3.2 Effect of aluminum particle size

Effects of particle size are mainly reflected in: (1)Particle size has an influence on the Reynolds number, thereby affecting the Nusselt number; (2)Particle size can directly affect convective heat transfer coefficient; (3)It can be seen from equation(8) that particle size directly affects heating time. Effects on convective heat transfer coefficient *h* are shown in Figure 6.

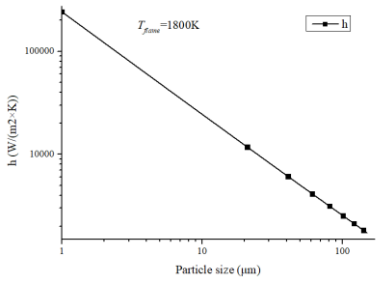


Figure 6 Particle size affects on Convective heat transfer coefficient

As shown in Figure 6, when particle size increases from 1μm to 100μm, convective heat transfer coefficient *h* decreases from 2.4×10^{5}W/(m^2×K) to 2.6×10^{3}W/(m^2×K). Convective heat transfer coefficient reduces by about 1/100. It means that convective heat transfer coefficient is mainly affected by particle size.

It can be seen from above that particle size has great effects on heating time during preheating stage.

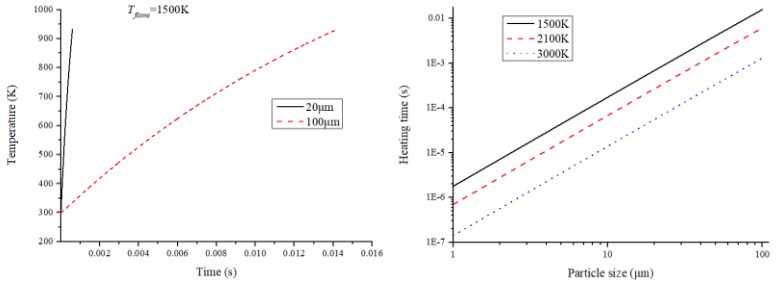


Figure 7 (a) Particle temperature changes with time (b)Variations of preheating time with particle size increasing

Figure 7(a) shows heating process during preheat stage under different particle size. It can be seen that different particle sizes have different processes. Figure 7(b) shows relationship between preheat time and different particle size of aluminum particles during the preheat stage in range of 1μm to 100μm. It can be seen that as particle size increases, preheat time of aluminum particles increases at all flame temperatures. At flame temperature of 1500K, when particle size increases from 1μm to 100μm, heating time increases from 1.8×10^{-6}s to 1.6×10^{-2}s. From equations(2) and (8), it can be seen that when particle size increases from 1μm to 100μm increasing by 100 times, heat transfer coefficient is correspondingly reduced to about 1/100. At the same time, energy required to heat particles also increases by 100 times, so heating time needs to be increased by about 10^4 times. It can be seen that, the convective heat transfer between flame and particles is the main heating source.

4. Conclusion

In this paper, heating process of aluminum particles is analyzed by establishing single-particle heating model. According to the calculation model, factors affecting aluminum particles' heating are analyzed, and the following conclusions are obtained:

(1) Correctness of the calculation model is verified by comparing theoretical results and experimental results. The calculation model can better predict dynamic process of single-particle heating and combustion;

(2) During heating process in preheating stage, factors affecting preheat time are mainly flame temperature and particle size. Heating time of particles decreases with increase of flame temperature. When flame temperature increases from 1000K to 3300K, preheat time reduces from 9.4×10^{-4}s to 7.5×10^{-6}s, reduced by about 1/100. As particle size increases, preheat time of particles increases significantly. At 1500K, when particle size increases from 1μm to 100μm, preheat time increases from 1.8×10^{-6}s to 1.6×10^{-2}, increased by about 10^4 times.

(3) During heating process of aluminum particles, convective heat transfer between flame and particles is the main heating source.

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