INFLUENCE OF MELTING ON MAGNESIUM PARTICLE IGNITION

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Abstract: The modified model of magnesium particle ignition in the oxidizer gas has been suggested. In addition to transient heat transfer between gas and particle and nonuniform temperature distribution in particle interior the model takes into account particle melting during the preignition period. The results of calculations indicate that metal melting can produce a significant effect on magnesium particle ignition.

Introduction

Small magnesium particles 15–46 μm in diameter are known to ignite in the oxygen containing gas at temperatures exceeding the magnesium melting temperature (≈ 923 K) [1]. As a rule, the existing mathematical models ignore the metal melting period. However the results presented in [2] unambiguously indicate that metal melting can affect significantly particle ignition delay. Note that in [2] a simple model based on the classical Newton heat transfer law was used for estimating the ignition delay.

In [1], a simple model of [2] was modified to take into account transient heat transfer and temperature nonuniformity in particle interior. The modified model of magnesium particle ignition provided better agreement between the predicted and measured ignition delays of magnesium particles. Moreover, model [1] made it possible to obtain a modified set of effective kinetic parameters in the magnesium oxidation law. However the model reported in [1] did not include the effect of metal melting. The objective of this paper was to further improve the model of [1] by taking into account metal melting.

1. Problem Formulation for Particle Ignition with Melting

1.1. MODEL [1]

The model of magnesium particle ignition in oxygen containing gas is formulated as follows [1]:

$$cm\frac{d\overline{T}}{dt} = \alpha_{eff} S(T_{g\infty} - T_i) + Sq\rho_{ox} K \overline{c}_{ox} e^{\left(-E/R_{Mg}T_i\right)}; \qquad \overline{T}(0) = T_0 \tag{1}$$

$$\Theta_i = \sum_{j=0}^{n} b_j \overline{\Theta}^j; \tag{2}$$

where c is the metal specific heat, m is the particle mass, $\overline{T}$ is the mean particle temperature, t is time, $\alpha_{eff} = \lambda_g\left(1 + \sqrt{R^2/\pi a_g t}\right)R^{-1}$ is the effective heat transfer coefficient, R is the particle radius, a_g and λ_g are the gas thermal diffusivity and conductivity, S is the particle surface area, $T_{g\infty}$ is the gas temperature at a large distance from the particle, T_i is the particle surface temperature, q is the reaction heat per unit mass of metal oxide, ρ_{ox} is the metal oxide density, $\bar{c}_{ox}$ is the mass concentration of oxygen (for pure oxygen $\bar{c}_{ox} = 1$), K and E are the effective kinetic parameters of metal oxidation rate, R_{Mg} is the magnesium gas constant, T_0 is the initial particle temperature, $\Theta_i = T_i / T_0$ is the dimensionless particle surface temperature, $\overline{\Theta} = \overline{T} / T_0$ is the dimensionless mean particle temperature, n is the polynomial order and b_j are the polynomial coefficients ($b_0 = 0.0469521$, $b_1 = 0.931$, $b_2 = 0.03682$, $b_3 = -6.129\text{e-}3$).

1.2. MODIFIED MODEL

The modified model differs from the model of Eqs. (1) and (2) by the additional term $d\eta/dt$ in the right-hand side of Eq. (1) which takes metal melting into account:

$$cm\frac{d\overline{T}}{dt} = \alpha_{eff}S(T_{g\infty} - T_i) + Sq\rho_{ox}K\bar{c}_{ox}e^{\left(-E/R_{Mg}T_i\right)} - mL_m\frac{d\eta}{dt}; \qquad \overline{T}(0) = T_0 \tag{3}$$

$$\frac{d\eta}{dt} = \frac{\delta_m}{mL_m}\left[\alpha_{eff}S(T_{g\infty} - T_m) + Sq\rho_{ox}K\bar{c}_{ox}e^{\left(-E/R_{Mg}T_m\right)}\right]; \qquad \eta(0) = \eta_0 \tag{4}$$

$$\Theta_i = \sum_{j=0}^{n} b_j\overline{\Theta}^j; \tag{5}$$

where η is the fraction of molten metal, L_m and T_m are the melting heat and temperature of magnesium, and δ_m is the coefficient defined as

$$\delta_m = \begin{cases} 0 & \text{if} \quad \overline{T} \neq T_m \\ 1 & \text{if} \quad \overline{T} = T_m \ \text{ and } \ 0 \le \eta \le 1 \end{cases} \tag{6}$$

The additional term $d\eta/dt$ is constructed in such a way that metal melting leads to temporal termination of particle heating.

2. Results

To evaluate the influence of metal melting on particle ignition, a set of calculations was made for magnesium particles with $R = 22$ μm and T_0 = 300 K using both models based on Eqs. (1), (2) and Eqs. (3)–(5). The thermophysical properties of magnesium and its oxide, as well as the effective kinetic parameters K and E were fixed (see Table 1).

The main characteristic of interest was the ignition delay of a particle suddenly placed into the hot air at a temperature ranging from 1023 to 1323 K and atmospheric pressure. The ignition delay was defined as a time taken for the rate of particle temperature rise dT/dt to attain the value of 10^7 K/s [1]. Figure 1 shows the predicted effect of metal melting on the particle ignition delay. As is seen, the account for metal melting (curve 2) results in increasing the ignition delay as compared to the model without melting (curve 1) by a factor of 1.4 to 1.5. Figure 2 demonstrates the corresponding changes in the particle temperature histories. Curve 2 in Fig. 2 relates to the case with metal melting. The reason for ignition delay increase is the appearance of the isothermal segment in curve 2.

Table 1: Thermophysical properties and kinetic parameters[1].

Material	λ, W/(m·K)	c, J/(kg·K)	ρ, kg/m^3	Reaction	q, MJ/kg	K, m/s	E, MJ/kg
Mg	100.0	1100.0	1700	$Mg+O_2$	49	1.391	4.345
MgO	58.0	803.0	3600				

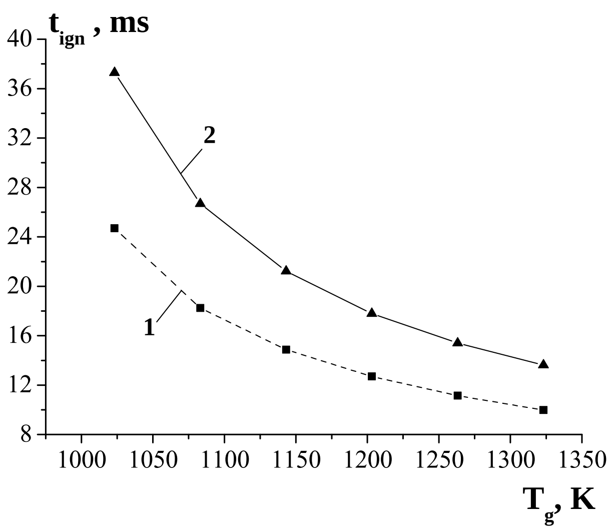

Figure 1: Predicted ignition delays of magnesium particles (R = 22 μm): 1 – model [1] without metal melting, 2 – modified model with metal melting

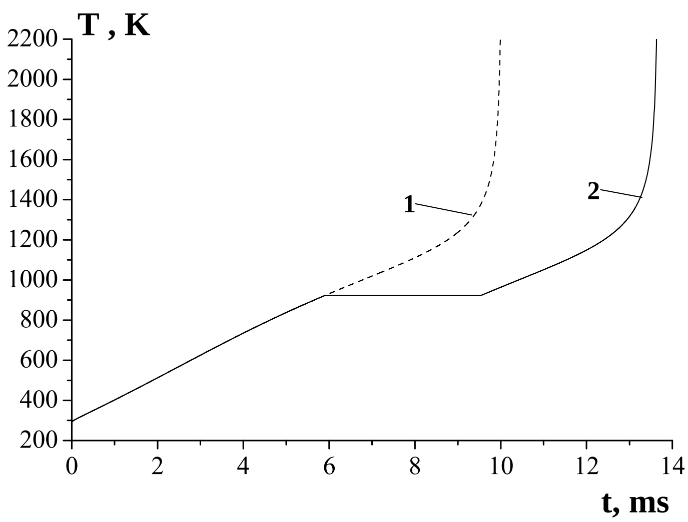

Figure 2: Predicted time histories of the mean temperature of magnesium particle (R = 22 μ m) at $T_{g\infty}$ =1323 K: 1 – model [1] without metal melting, 2 – modified model with metal melting

Conclusion

The modified model of magnesium particle ignition taking transient heating and metal melting into account has been developed. Metal melting in the preignition period was shown to increase the predicted ignition delay by 40% to 50% as compared with model [1] without melting. Thus, to fit the predicted ignition delays with available measurements one has to properly modify the effective kinetic parameters in the metal oxidation law. These parameters can be different for particles of different size.

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