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Safety distance for preventing hot particle ignition of building insulation materials

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Abstract Trajectories of flying hot particles were predicted in this work, and the temperatures during the movement were also calculated. Once the particle temperature decreased to the critical temperature for a hot particle to ignite building insulation materials, which was predicted by hot-spot ignition theory, the distance particle traveled was determined as the minimum safety distance for preventing the ignition of building insulation materials by hot particles. The results showed that for sphere aluminum particles with the same initial velocities and diameters, the horizontal and vertical distances traveled by particles with higher initial temperatures were higher. Smaller particles traveled farther when other conditions were the same. The critical temperature for an aluminum particle to ignite rigid polyurethane foam increased rapidly with the decrease of particle diameter. The horizontal and vertical safety distances were closely related to the initial temperature, diameter and initial velocity of particles. These results could help update the safety provision of firework display.
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Keywords safety distance, hot metallic particle, critical ignition temperature, particle trajectory

Chinese has a tradition to enjoy watching aerial firework display in important festivals. However, firework display has caused some disastrous building fires in recent years. The infamous one is China Center Television (CCTV) fire in 2009, which caused a great economic loss and one firefighter's death.[1] The investigation reported that some hot metallic particles produced by firework display contacted and ignited the organic building insulation materials, and subsequently induced a violent burning. Reviewing of these fires reveals that safety provision of firework display can not meet the rapid development of buildings in China. On one hand, the newly constructed high-rise buildings make the distance between firework explosion point and the building too short to be safe. Therefore, the aerial firework display place should be farther away from the high-rise buildings. On the other hand, the envelope of many buildings is covered by building insulation layer for energy saving in China. Due to the low cost and superior adiabatic performance, the organic building insulation materials, such as rigid polyurethane foam and expanded polystyrene foam, are wildly used. However, these organic building insulation materials are flammable and prone to be ignited and burn violently. In order to make firework display safer, the mechanism of hot

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metallic particle movement and the ignition of building insulation materials should be understood.

Fireworks are a class of explosive pyrotechnic devices and the colors in fireworks are usually generated by pyrotechnic stars (usually just called stars) which produce intense light when ignited. The brightest stars are fueled by aluminum. Aluminum is used to produce silver and white flames and sparks and is a common component of fireworks. In this work, the hot metallic particles produced by fireworks are represented by aluminum particles. However, the analysis in this work is also valid for other metallic particles.

When the hot metallic particles are released from the explosion point of pyrotechnic stars, the particles obtain their initial velocity and temperature. When they fall, the trajectory and temperature history can be calculated. There are some articles about the ignition of wildland fuels by hot particles ejected from clashing/short-circuit overhead transmission lines.[2–5] In these studies, the metal particles were created by clashing or short-circuit of lines with given temperature and height and then the particle temperature at landing was predicted. If the temperature at landing exceeds the assumed ignition temperature of wildland fuels, ignition and fire will happen. Whether ignition occurs is only judged by the relative magnitude of the particle temperature at landing and ignition temperature of fuels. However, the ignition process depends on the interactive heat transfer of particle and fuel, and the constant ignition temperature assumption may not be valid. For the condensed materials contacted with hot particles with different diameters, the ignition process occurs at different temperature.[6–10]

This work addresses the safety distance for preventing hot particle ignition of building insulation materials. The trajectories of flying hot particles with different initial sizes, temperature, and velocities are predicted and the temperatures during the movement are calculated too. Once the particle temperature decreases to the critical temperature for a hot particle to ignite building insulation materials, which is predicted by the hot-spot ignition theory, the travelled distance is considered as the minimum safety distance.

When a hot metallic particle is ejected from a firework explosion point, it gets its initial velocity and temperature. Then the particle moves horizontally when it falls and the movement can be described by Newton's second law. The initial velocity is assumed to be U_0 in the X-direction (horizontally) and $V_0 = 0$ in the Y-direction. Under this assumption, the horizontal distance that particle travels is the longest for the same initial velocity and hence the corresponding safety distance will be more reasonable for all cases. For simplicity, the particle is assumed to be spherical with diameter d and density $\rho_{\rm P}$, and is not burning (the initial temperature is below the ignition temperature of aluminum 2 327.15 K).[3] The particle mass $m = \rho_{\rm P}\pi d^3/6$ is constant during flying.[5] The ambient wind is not considered.

The motion equation in the X-direction is

$$m\,\mathrm{d}U_{\rm P}/\,\mathrm{d}t = -A_{\rm P}C_{\rm D}\rho U_{\rm P}^2/2, \tag{1}$$

then we have

$$\mathrm{d}U_{\rm P}/\,\mathrm{d}t = -3C_{\rm D}(\rho/\rho_{\rm P})U_{\rm P}^2(4d)^{-1}. \tag{2}$$

The motion equation in the Y-direction is $m\,\mathrm{d}V_\mathrm{P}/\mathrm{d}t = -A_\mathrm{P}C_\mathrm{D}\rho V_\mathrm{P}^2/2 + mg$, then we have

$$\mathrm{d}V_\mathrm{P}/\mathrm{d}t = -3C_\mathrm{D}(\rho/\rho_\mathrm{P})V_\mathrm{P}^2(4d)^{-1} + g. \tag{3}$$

A good fit to the standard drag coefficient of a spherical object is given by $C_\mathrm{D} = (24/Re)(1 + Re^{2/3}/6)$.[11] The Reynolds number, based on the velocity of particle, is given by $Re = (\rho d/\mu)\cdot\left(U_\mathrm{P}^2 + V_\mathrm{P}^2\right)^{1/2}$.

In the above equations, ρ is air density (kg·m^{-3}) near the particle, μ is the dynamic viscosity (kg·m^{-1}·s^{-1}) of air, U_P and V_P are respectively the horizontal and vertical components of particle velocity (m·s^{-1}), and A_P is the projected area (m^2) of the particle.

Air density ρ can be expressed by the state equation of ideal gas $\rho/\rho_0 = T_0/T$. Reference density is $\rho_0 = 1.293$ kg/m^3 ($T_0 = 273.15$ K). Dynamic viscosity of air is expressed by Sutherland's formula of viscosity $\mu/\mu_0 = (T/T_0)^{3/2}(T_0 + B)(T + B)^{-1}$ with $B = 110.4$ K and $\mu_0 = 17.9$ mg·m^{-1}·s^{-1} ($T_0 = 293.15$ K).[12] Air temperature near the particle is approximated by $T = (T_\mathrm{P} + T_\infty)/2$.[13]

During the flying, the hot particle is cooled down by the ambient air, and the temperature decreases accordingly. For aluminum particles, Biot number is very low ($Bi \ll 0.1$) and the lumped thermal capacity model can be used, that is, the temperature gradient inside the particle is not considered.[2] So the energy conservation of the particle can be defined as $-m_\mathrm{P}C_\mathrm{P}\,\mathrm{d}T_\mathrm{P}/\mathrm{d}t = q_\mathrm{conv} + q_\mathrm{rad}$, with $q_\mathrm{conv} = h_\mathrm{c}A_\mathrm{S}(T_\mathrm{P} - T_\infty)$ and $q_\mathrm{rad} = \varepsilon\sigma A_\mathrm{S}(T_\mathrm{P}^4 - T_\infty^4)$.[2] Then we have

$$\mathrm{d}T_\mathrm{P}/\mathrm{d}t = -[6/(\rho_\mathrm{P}C_\mathrm{P}\,\mathrm{d})]\left[h_\mathrm{c}(T_\mathrm{P} - T_\infty) + \varepsilon\sigma(T_\mathrm{P}^4 - T_\infty^4)\right]. \tag{4}$$

Here h_c is convective heat transfer coefficient (J·m^{-1}·K^{-1}) under the prevailing conditions, C_P is specific heat capacity (J·kg^{-1}·K^{-1}) of particle material, T_P is particle temperature (K), T_∞ is ambient temperature (K), A_S is the surface area (m^2) of the particle, $\sigma = 5.67\times10^{-8}$ W·m^{-2}·K^{-4} is Stefan–Boltzman constant , and $\varepsilon \sim 0.3$ is emissivity of the particle.[4] The convective coefficient is calculated by the Nusselt number $Nu = h_\mathrm{C}d/k_\mathrm{a} = 2 + 0.6Re^{1/2}Pr^{1/3}$. The Prandtl number is $Pr = C_\mathrm{a}\mu/k_\mathrm{a}$. Here k_a is thermal conductivity (J·m^{-1}·K^{-1}) of air under prevailing conditions.

There is a thermal requirement for a hot particle to ignite the organic building insulation materials, that is, heat reserve of the particle should exceed a critical value to initiate the combustion reaction of the materials. For a given initial temperature of a hot particle (T_P), the minimum particle size (r_crit) for ignition of the organic building insulation materials, here taken polyurethane foam as an example, can be obtained by the Frank–Kamenetskii parameter δ_cr

$$r_\mathrm{crit} = \delta_\mathrm{cr}\sqrt{[\lambda_0/(\rho_0 A\overline{H}_\mathrm{P})](RT_\mathrm{P}^2/E)\exp\left(E/(RT_\mathrm{P}^2)\right)}, \tag{5}$$

where λ is thermal conductivity and ρ is the density. The subscript "P" corresponds to the particle and the subscript "0" corresponds to polyurethane foam. The critical Frank–Kamenetskii parameter for the ignition of solid combustibles by a hot particle was proposed by Goldshleger et al.[14] as $\delta_\mathrm{cr}^* = 0.4\sqrt{b^2 + 0.25n(n+1)(b + 0.1b^3)}\left[\theta_\mathrm{p} + 2.25(n-1)\right]^2(1 + 0.5\beta\theta_\mathrm{p})$, $\delta_\mathrm{cr} = \delta_\mathrm{cr}^*\{1 + (\theta_\mathrm{p} - 3)^2 b(n+1)/[30\lambda_\mathrm{r}^{2/3}(1 + 3b^{2/3})]\}$, where $\theta_\mathrm{p} = [E/(RT_\mathrm{P}^2)](T_\mathrm{P} - T_0)$, $b = (\rho_0 C_0)/(\rho_\mathrm{P}C_\mathrm{P})$, $\lambda_\mathrm{r} = \lambda_\mathrm{P}/\lambda_0$, $\beta = RT_\mathrm{P}/E$. Here n is a factor whose value depends on the shape of

Table 1. Parameters for polyurethane foam (with subscript "0") and duminum particles (with subscript "P").

λ_0, λ_P/ $(W \cdot m^{-1} \cdot K^{-1})$	ρ_0, ρ_P/ $(kg \cdot m^{-3})$	C_0, C_P[3]/ $(J \cdot kg^{-1} \cdot K^{-1})$	Activation energy[15] $E_0/(kJ \cdot mol^{-1})$	Pre-exponential factor[15] A_0/s^{-1}	Reaction heat[15] $Q_0/(kJ \cdot kg^{-1})$
0.03 250	100 2 702	1 460 1 045	142	$10^{10.456}$	5 443

Table 2. The height and horizontal distance of the particle travelled when its temperature decreases to the critical ignition temperature (with same initial velocity and initial temperature).

d_0/mm	1	2	3	4	5
T_i/K	789	740	715	696	683
Height/m	2.7	19.8	55.0	109.8	183.4
Distance/m	7.1	20.8	37.5	56.6	77.4

the hot particle ($n = 2$ for a sphere particle). The parameters for polyurethane foam and aluminum particles are listed in Table 1.

Equation (5) can be used inversely to calculate the critical ignition temperature for a particle with the given diameter. Numerical results of accidental ignition of polyurethane foam by a hot aluminum particle are shown in Fig. 1 by plotting r_{crit} vs. T based on Eq. (5). It is seen that the critical diameter decreases with the increase of particle temperature. For a spherical aluminum particle with a specific diameter, the critical ignition temperature is listed in Table 2. The critical ignition temperature is about 683 K for a 5 mm-diameter particle while it is 789 K for a 1 mm-diameter particle. It is obvious that the constant ignition temperature assumption is not valid here.

According to Eqs. (3) and (4), the safety distances can be obtained for various initial particle sizes, initial particle temperatures, and initial particle velocities. When the particle temperature decreases to the critical ignition temperature, the distance that particle travelled is considered as the minimum safety distance for preventing ignition. The values of initial particle sizes, initial particle temperatures, and initial particle velocities are listed in Table 3. Control variate method is used in different numerical cases.

Figure 2 presents the trajectories and temperature of hot particles with initial temperature ranging from 900 to 2 000 K. It is shown that the particle with the initial temperate of 2 000 K travels the farthest. As μ and ρ increase with the increase of temperature and then cause Re to increase, which have an effect on horizontal distance according to Eq. (1). It is obvious that the horizontal and vertical distances are in direct proportion to the initial particle temperatures. Since

Table 3. The initial values of numerical cases with $T_\infty = 298.15$ K.

T_{P0}/K	900	1 200	1 500	1 800	2 000
$\rho_P/(kg \cdot m^{-3})$	2 702	2 380	2 380	2 380	2 380
d_0/mm	1	2	3	4	5
$U_{p0}/(m \cdot s^{-1})$	5	10	15	20	25

Table 4. The height and horizontal distance of a 3 mm-diameter particle travelled when its temperature decreases to the critical ignition temperature (with same initial velocity) with $T_3 = 715\,\mathrm{K}$.

T_{P0}/K	900	1 200	1 500	1 800	2 000
Height/m	14.8	36.9	55.0	68.0	74.5
Distance/m	21.0	30.9	37.5	41.8	43.9

the critical ignition temperature of 3 mm-diameter aluminum particles is 713 K obtained from Fig. 1, the horizontal and vertical safety distances are determined when the particle temperature decreases to 713 K, as presented in Table 4. So the horizontal and vertical safe distances should be longer than the maximum values which are 43.9 and 74.5 m, respectively.

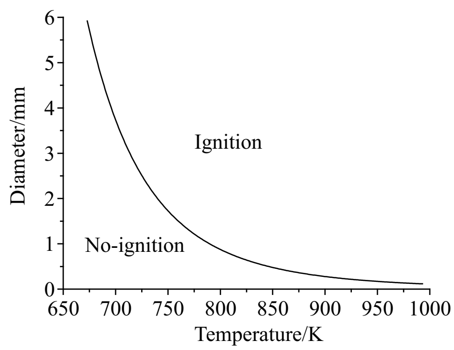

Fig. 1. Criterion for a hot aluminum spherical particle to ignite polyurethane foam.

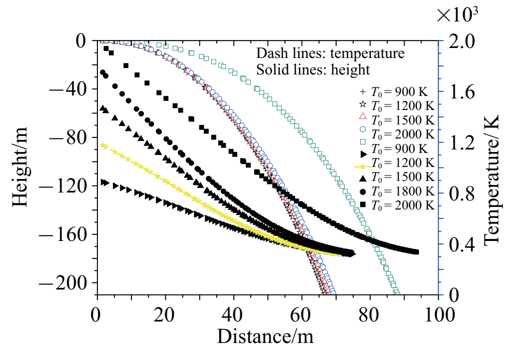

Fig. 2. Trajectories and temperatures of a 3 mm-diameter aluminum particles with different initial temperature. (The initial velocity is 15 m/s).

Figure 3 shows the results for particles with diameters of 1, 2, 3, 4, 5 mm with an initial particle velocity of 15 m/s and an initial particle temperature of 1 500 K. The horizontal distance and vertical distance increase with the increase of diameter. According to Eqs. (1) and (2), acceleration increases with the increase of diameter. The aluminum particles cool down along their flight path and the decrease rate of temperature is in inverse proportion to the diameter. For given initial particle velocity and vertical distance, smaller diameter particles always travel farther than the larger ones. At the same time, however, smaller diameter particles land with lower temperatures, and their smaller masses result in smaller amounts of heat brought to fuels. Table 2 shows the horizontal distances and vertical distances which are in correspondence to the critical ignition temperature for particles with different diameters. The most dangerous case is the 5 mm-diameter particle. It travels horizontally 77.4 m and falls 183.4 m when its temperature decreases to the critical ignition temperature. So the horizontal and vertical safe distances should be longer than 77.4 and 183.4 m, respectively.

Figure 4 presents the results for particles with initial velocity of 5, 10, 15, 20, 25 m·s^{-1} with a diameter of 3 mm and an initial temperature of 1 500 K. The horizontal distances and vertical distances increase with the increase of initial velocity. The critical horizontal distance is in direct proportion to the initial velocity, while the critical vertical distance is in inverse proportion to the initial velocity. This tendency may be attributed to the competing effect, that is, particle with higher initial velocity travels faster but the temperature decreases more rapidly to the critical ignition temperature due to enhanced convection. Table 5 shows the horizontal and vertical distances when the particle temperature decreases to 713 K. The maximum of horizontal and vertical distances are 51.6 and 60.3 m. The vertical distance decreases with the increase of initial particle velocity, while the horizontal distance increase with it. As the maximum value of vertical distance and horizontal distances can not reach at the same time, the maximum value of horizontal distance is used as critical safe distance. The horizontal and vertical safe distances should be longer than 51.6 and 50.8 m, respectively.

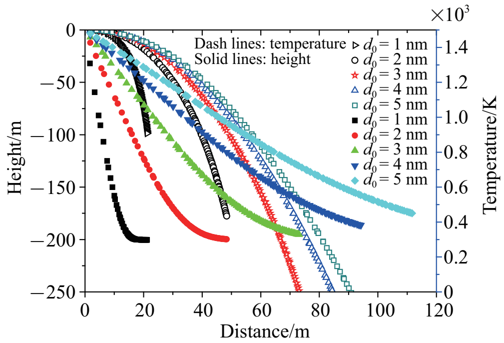

Fig. 3. Trajectories and temperatures of aluminum particles with different diameter.

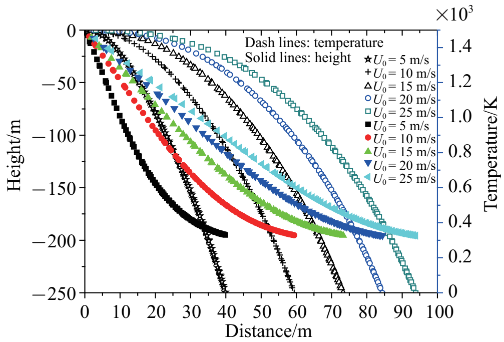

Fig. 4. Trajectories and temperatures of aluminum particles with different initial velocity.

From Figs. 2–4, we can see that diameter has the largest influence on trajectories of particles. According to Fig. 3, the horizontal distance varies from 22 to 92 m. The second one is initial particle velocity. The horizontal distances change from 40 to 94 m for different initial particle velocities. The initial temperature has least effect on trajectories, whose horizontal distances vary from 67 to 88 m. The changes of temperatures in these three situations are approximately the same.

Comparison of Tables 4 and 5, which has the same particle diameter and the same critical ignition temperature, shows that the horizontal distances and vertical distances in Table 4 change quicker than those in Table 5, which means that change of diameter has larger influence on safe distances. For all the numerical cases, the maximum horizontal distance was 77.4 m and the vertical distance was 183.4 m.

This work studied the safety distance for preventing the ignition of external building insulation materials by hot metallic particles. The safety distances were regarded as the horizontal and vertical distances particle travelled until the particle temperature decreased to the critical ignition temperature.

The effects of particle diameter, initial temperature and initial velocity on the horizontal and vertical distances were discussed. The results showed that the horizontal and vertical distances were in direct proportion to the initial temperature and initial diameter. However, the horizontal distance was in direct proportion to while the vertical distance was in inverse proportion to the initial velocity when other parameters remained the same. For a given vertical distance, the par-

Table 5. The height and horizontal distance of the particle travelled when its temperature decreases to the critical ignition temperature with $d_0 = 3$ mm and $T_3 = 715$ K.

$U_{p0}/(m{\cdot}s^{-1})$	5	10	15	20	25
Height/m	60.3	59.5	55.0	52.8	50.8
Distance/m	17.1	28.6	37.5	45	51.6

ticles with higher initial temperatures could travel farther, since higher temperatures resulted in lower *Re* and larger C_D. From comparison of the trajectories for different diameter particles, the smaller ones traveled farther. At the same time, however, smaller diameter particles landed with lower temperatures and hence the ignition risk was lower.

For all the numerical cases, the maximum horizontal distance was 77.4 m and the vertical distance was 183.4 m, which indicated that the explosion point of fireworks should be 77.4 m away and 183.4 m higher from the building. Otherwise, the risk for building insulation materials to be ignited by hot particles would be very high. This study can be extended and generalized to other similar situation cases of hot-spot ignition and help design more reasonable safety guidance for firework display.

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