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Ignition of low-density expandable polystyrene foam by a hot particle

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ABSTRACT

Insulating materials are ubiquitous in modern buildings for improving energy efficiency, but their high flammability becomes a significant fire safety issue. Many large fires in high-rise buildings were caused by the ignition of insulating materials by hot particles from fireworks and welding processes. Such ignition event is fundamentally different from the traditional flame or radiation driven ignition assumed in the literature, and still presents significant knowledge gaps. In this work, we study experimentally the ignition of a widely used insulation materials, expandable polystyrene (EPS) foam, by a hot steel particle under different conditions. In the experiments, a small spherical particle (6∼14 mm in diameter) was heated to a high temperature (>900 °C), and then placed on a bench-scale low-density (18 or 27 kg/m^3) foam sample. It was observed that flaming ignition could only occur on the foam surface during its rolling process (rolling ignition) or before it was fully embedded (embedding ignition). The measurements suggested that larger particles held lower critical temperatures for ignition, which decreased from 1030 to 935 °C for diameters increasing from 6 to 14 mm. Compared to higher-density forest fuels in the literature, the critical particle temperature of EPS foam is much higher, with a narrower transition region for ignition probability of 5–95% and has a weaker dependence on the particle size. Results also show that both the sample density and thickness have a negligible influence on the ignition probability and mass-loss ratio. Theoretical analysis suggested that the hot particle acts as both heating and pilot sources, and the ignition of EPS foam is controlled by the competition between the gas mixing time and the particle residence time.

1. Introduction

For improving energy efficiency, the use of plastic insulation materials such as polystyrene, polyisocyanurate and polyurethane is increasing in buildings and industrial sites because of the low cost and the superior insulating performance. However, these organic insulation materials are flammable [1,2], and their fire safety becomes a serious public concern. In the last decade, the ignition of external wall insulation by hot metallic particles (mainly generated from fireworks display and welding processes) has caused several disastrous fires, such as the Germany Düsseldorf Airport fire (1996), the China Centre Television fire (2009), and the high-rise residential hall fire in Shanghai Jing'an district (2010) [3]. More importantly, the process of hot-particle ignition is a fundamentally different ignition event, compared to the traditional flame or radiation driven ignition assumed in the fire science literature [1,2]. Significant knowledge gaps present on this complex ignition phenomenon. Therefore, a better understanding of the conditions for igniting insulation materials by hot metal particles is of great importance for the building fire safety. These ignition conditions, such as the critical temperature for particle size, can help determine the safe distance between the fireworks display space and high-rise buildings [4], and optimize the safety of welding operations [5].

Most building insulation materials are polymeric and porous fuels, such as expandable polystyrene (EPS) foam (close-cell) and polyurethane (PU) spray foam (open-cell) [6]. Most of these insulation materials have a low density (<50 kg/m^3) to assure a superior insulation and weight performance. When the insulation materials are hit by a hot particle, it will be heated and pyrolysed locally. If the particle is hot and large enough, a flammable gaseous mixture can be generated and ignited into a flame [1]. Some fuels can also go through smouldering ignition [7]. In general, the ignition by a hot particle is a complex process, combining heat and mass transport, phase change, and chemical reactions. The ignition propensity depends on the fuel bed, particle, environment, and the landing conditions [2].

There are a limited number of studies on the ignition of fuel beds by hot metal particles in the literature (e.g., [8–19]). Wang et al. [8] numerically studied the ignition process on the low-density (18 kg/m^3) EPS foam by small steel particles, and found the ignition required an extremely high particle temperature (>1000 °C).

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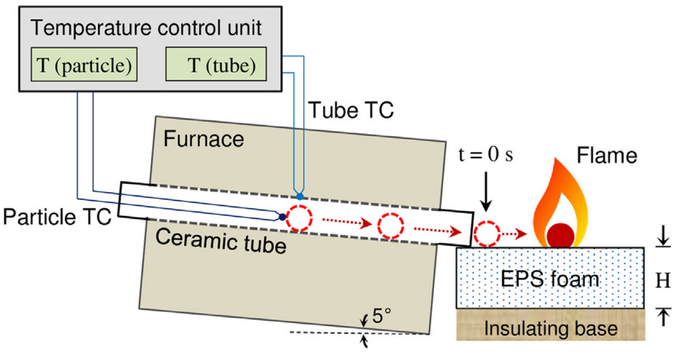

Fig. 1. Schematic of experimental setup for the hot-particle ignition of EPS form samples.

All other studies used the high-density forest fuel beds ($>$200 kg/m^3). Tanaka [9] conducted an experimental study to investigate the ignition condition of sawdust with various moisture contents by the welding spatters. Rowntree and Stokes [10–12] focused on the ignition of forest fuels, such as barley grass, hardwood forest litter and pine needle, exposed to incandescent particles from electrical arcing or frictional sparks. More recently, Fernandez-Pello and co-workers [13–16] have conducted a series of studies of the ignition of alpha-cellulose powder by steel, aluminium, copper and brass spheres over a range of initial temperatures and diameters (2 ∼ 19.1 mm). Their work simulated the ignition of forest fuels by the hot particles generated by power lines clashing, welding, grinding and various forms of hot work. Other studies focused on the ignition of forest fuels by firebrands (burning wooden particles) generated from wildfires and fires at wildland–urban interface (WUI) [17–19]. Compared with forest fuels, the insulation materials are of low density and melt when heated. Therefore, the ignition mechanism of insulation materials by a hot particle may be different from that of forest fuels. The aim of the present work is to study the ignition process of insulation materials by a hot particle and to provide a basic understanding of their ignition mechanism.

In this work, a well-controlled experiment was designed to reproduce the ignition process of insulation materials by a hot particle in the laboratory. Various flaming ignition phenomena are observed and described in detail. The ignition limit, relating to the critical size and temperature of particle, was measured through a statistical analysis of a series of experiments. Afterwards, the hot-particle ignition mechanism of insulation materials is analysed using heat and mass transport theories and compared with that of forest fuel bed found in the literature.

2. Experimental setup

A schematic of the experimental apparatus is illustrated in Fig. 1. A ceramic tube furnace was used to heat the hot particle up to a pre-set temperature. The tube temperature was monitored and adjusted based on the measurement of a Pt/Rh thermocouple. When the tube temperature was steady, a metal particle, held by a long-tail spoon, was placed into the centre of the tube. The particle temperature was monitored by a 0.5-mm K-type thermocouple which was in contact with the particle surface. The temperature difference between T(particle) and T(tube) was not constant for the full temperature range but less than 50 °C, and remained fairly constant for the given particle size and furnace temperature.

Under a steady tube temperature, the particle was quickly heated up and stabilized at a temperature (T_p). Since the B_i number of the particle was very small ($B_i \sim 0.02 < 0.1$ [20], see Appendix), the temperature inside the particle was uniform after reaching steady-state. Then, the particle was released to slip along the inclined tube (5° slope). The tube outlet rested on top of the sample to minimize the impact of the particle's vertical momentum. The fuel sample was placed above the insulating base. All experiments were conducted without forced air flow to minimize ambient cooling and avoid disturbance to the emitted pyrolysis gases. The whole process was recorded by a video camera (at 25 fps), placed horizontally to the sample top surface to image the front view.

Spherical steel particles with diameter of 6, 8, 10, 12 and 14 mm were tested, and the steady tube temperatures increased from 900 to 1100 °C in steps of 10 °C. Preliminary experiments found that 4-mm (or smaller) particles required a very high temperature for ignition ($>$ 1200 °C), close to the melting point of steel and beyond the furnace upper temperature limit. Therefore, particle temperatures above 1100 °C are not explored here. The EPS foam used in this work was produced by a local manufacturer via catalytic polymerization of styrene without flame retardant. For building insulation, the density of EPS foam is in the range of 15–40 kg/m^3, thus two typical foam densities of 18 and 27 (±0.5) kg/m^3 were tested. The foam was cut into small samples of 100 × 100 mm^2 cross section (A_o) and 20–100 mm thickness (H). For any given experimental condition, 10–20 repeats were performed to capture the full experimental uncertainty. The mass of the EPS foam sample in each run was measured before and after the experiment.

3. Experimental results

In the experiment, only flaming ignition or no-ignition was observed. Unlike some forest fuels [15,16], smouldering ignition by a hot particle was never observed. We define a successful ignition as the presence of a visible flame that persisted for more than 1 s. The outcome of each run was categorized as “ignition” or “no ignition”. We report the ignition probability as the ratio of ignition times (N_{ig}) to the number of total repeating runs (N_{tot}):

$$P_{ig} = \frac{N_{ig}}{N_{tot}} \times 100\% \tag{1}$$

Accordingly, we define the initial particle temperature with $P_{ig} =$ 50% as the critical temperature for ignition, and quantify a transition ignition region between $P_{ig} = 5\%$ and 95%.

3.1. Ignition phenomena

Flaming ignition occurred on the top surface of the sample during particle's rolling over the sample surface (called “rolling ignition”), or after the rolling has ceased while before the hot particle is fully embedded (called “embedding ignition”). Once ignition occurred, flame always lasted for more than 1 s, differing from the unstable flash. Figure 2 presents a group of snapshots to illustrate a typical case of

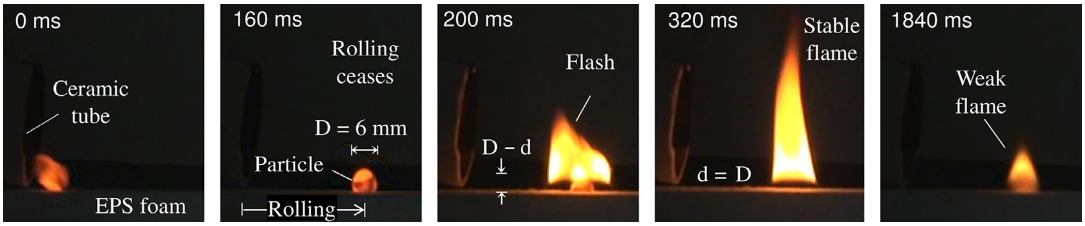

Fig. 2. Illustrative case of the embedding ignition for the EPS foam (18 kg/m^3 and 40 mm thick) by a hot steel particle ($D = 6$ mm and $T_p = 1022$ °C), recorded at 25 fps.

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