Journal of Hazardous Materials 283 (2015) 536–543

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Ignition of expandable polystyrene foam by a hot particle: An experimental and numerical study

Supan Wang, Haixiang Chen*, Naian Liu**

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China

HIGHLIGHTS

- Ignition criteria of expandable polystyrene foam by a hot particle were studied.
- The flaming ignition limits were determined from the experiments.
- Three ignition regimes and two critical lines were revealed by the numerical model.
- The model describes the experimental critical ignition temperatures well.

ARTICLE INFO

Article history:
Received 16 April 2014
Received in revised form 2 September 2014
Accepted 5 September 2014
Available online 13 October 2014

Keywords:
Ignition
Expandable polystyrene foam
Hot particle
Building insulation materials

ABSTRACT

Many serious fires have occurred in recent years due to the ignition of external building insulation materials by hot metallic particles. This work studied the ignition of expandable polystyrene foam by hot metallic particles experimentally and numerically. In each experiment, a spherical steel particle was heated to a high temperature (within 1173–1373 K) and then dropped to the surface of an expandable polystyrene foam block. The particles used in experiments ranged from 3 mm to 7 mm in radius. The observed results for ignition were categorized into two types: "flaming ignition" and "no ignition", and the flaming ignition limit was determined by statistical analysis. According to the experimental observations, a numerical model was proposed, taking into account the reactant consumption and volatiles convection of expandable polystyrene decomposition in air. Three regimes, no ignition, unstable ignition and stable ignition, were identified, and two critical particle temperatures for separating the three regimes were determined. Comparison with the experimental data shows that the model can predict the range of critical ignition temperatures reasonably well.

1. Introduction

Because of low cost and superior adiabatic performance, organic insulation materials have been widely used for energy savings in buildings. However, the organic insulation materials are generally flammable. In recent years, the ignition of external building insulation materials by hot metallic particles (generally generated from fireworks or welding process) has caused several disastrous fires in China, such as China Center Television (CCTV) fire (2009) and the high-rise residential building fire in Shanghai Jing'an district (2010) [1]. Therefore, the critical conditions for ignition of insulation materials by hot metallic particles are of great importance for building fire safety management. Such ignition criteria can be used in determining the safe distance between fireworks display place and the building [2], and in improving the safety guidelines for welding operation.

In physics, when an insulation material is heated by contacting with a hot metallic particle, the material decomposes to release flammable gases, which then mix with the surrounding air to form a flammable mixture. If the mixture reaches the low flammability limit, the hot particle can act as a pilot ignition source to induce the gas-phase combustion of the mixture [3]. The mixture combustion in turn accelerates the material decomposition to produce more flammable gases. It can be seen that the ignition of insulation material is essentially induced by the ignition of the decomposed gases.

There have been some experimental studies which examined the ignition of fuel beds by metallic or wooden particles. Most of them used cellulose beds consisting of barley grasses, sawdust or pine needles [4–8], and the major purpose was to understand the mechanism of firebrand spotting in wildland fire or wildland–urban

---

* Corresponding author. Tel.: +86 551 63600275; fax: +86 551 63601669.
** Corresponding author. Tel.: +86 551 63601668; fax: +86 551 63601669.
E-mail addresses: hxchen@ustc.edu.cn (H. Chen), liunai@ustc.edu.cn (N. Liu).

http://dx.doi.org/10.1016/j.jhazmat.2014.09.033

interface (WUI) fires [5]. Some critical ignition conditions, including the critical particle temperature and radius required for ignition, have been experimentally determined to update fire prevention guidelines [4].

It is important to note that the hot-spot ignition theory [9–12], which is based on solid combustion rather than gas combustion, was often used to explain the experimental results [4]. Early studies based on the hot-spot ignition theory focused on the ignition of explosives in contact with hot inert objects or local reactive area. The local energy sources were often embedded inside the explosives, and the reaction of explosives released energy enormously and rapidly [13]. In comparison, for the ignition of building insulation materials by hot particles, the particles are often located at the surface of materials, and the insulation materials are of relatively low calorific values. The hot-spot ignition theory later considered solid reactant consumption, gas diffusion in solid, lower calorific values of material, multi-step reaction of solid, etc. [14–19]. However, the ignition considered was in the form of smoldering ignition (flameless ignition) rather than flaming ignition. For the smoldering ignition, the oxidation of reactant species occurs on the surface of the solid rather than in the gas phase. The characteristic temperature, spread rate and heat released during smoldering are lower than those in flaming combustion. Very importantly, gas convection plays a significant role in flaming ignition [20,21], however, a recent numerical study [22] on the flaming ignition of solid by a hot particle ignored the effect of gas convection.

The hot-spot ignition theory has also been used to examine the critical conditions for ignition of dust and bulk materials [14,23], a cotton bale [24] or low-rank coal [25,26] by localized hot spots which could be generated by devices such as blenders and mills screw feeders. The developed ignition criteria can help mitigate fire and explosion hazards in industries. It is noted that these studies were also based on solid combustion rather than gas combustion.

This work investigated the ignition of building insulation materials by hot metallic particles experimentally, and developed a numerical model to describe the heat and mass transfer processes. The numerical model considered the gas-phase combustion and convection. Ignition criteria were extracted by the numerical modeling and compared with the experimental results.

2. Experimental

Fig. 1 shows the experimental setup, the main part of which is a carbon resistance furnace. In each experiment, the ceramic tube of furnace was firstly heated to a pre-set temperature. A control unit integrated with a platinum-rhodium thermocouple (WRP-100) was used to adjust the heating power in order to control the tube temperature. When the tube temperature was steady, a metallic particle, held by a long-tail metal spoon, was placed into the center of the tube. In addition, a type K thermocouple (with a sheathed diameter of 2 mm) was inserted into the particle to record the temperature. Once the particle reached a stable temperature, it was released to slip along the ceramic tube to the fuel surface. The ignition phenomenon was recorded with a video camera (25 frames per second) and also a high-speed camera (SVSI, Inc., GigaView) with a frame size of 1280 × 720 pixels at 150 frames per second.

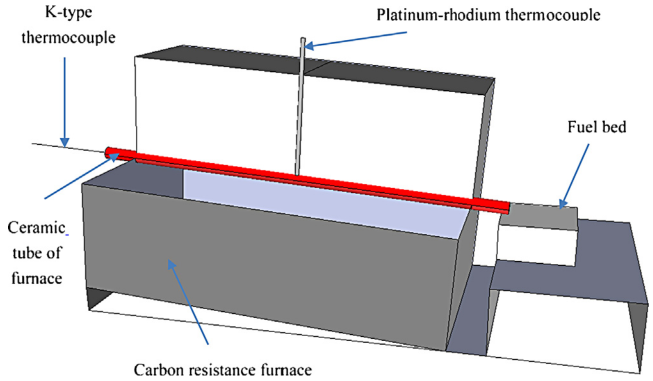

Fig. 1. Schematic of experimental setup.

The spherical steel particles with radii of 3, 4, 5, 6 and 7 mm were used in experiments, and the particle temperatures ranged within 1173–1373 K. The expandable polystyrene foam block samples used in this work were produced by Hefei Shuangxing Packing Co., Ltd. via catalytical polymerization of styrene with no flame retardant. The sample density was 18 kg/m^3, and the sample horizontal size was 100 mm × 100 mm. In tests different sample depths were used and it was found that the depth had no influence on the experimental results when it was higher than 20 mm. The observation results were categorized as two types: “no ignition” or “flaming ignition”. Flaming ignition denotes the presence of a visible flame that persisted for more than 1 s after the particle contacted the fuel block (see Figs. 2 and 3). For a given set of experimental conditions, 10–20 repeating runs were performed to obtain the probability of flaming ignition.

3. Formulation of the model

This section presents a numerical model for the ignition of expandable polystyrene foam by a small hot spherical particle, as outlined in Fig. 4. The penetration depth of the particle can be normally assumed to be 50% of the diameter, which is consistent with the experimental observations (see Figs. 2 and 3). Also 40% and 60% diameter penetrations are used to examine the effect of penetration depth on ignition. The problem is solved in a cylindrical coordinate system, whose origin coincides with the particle center.

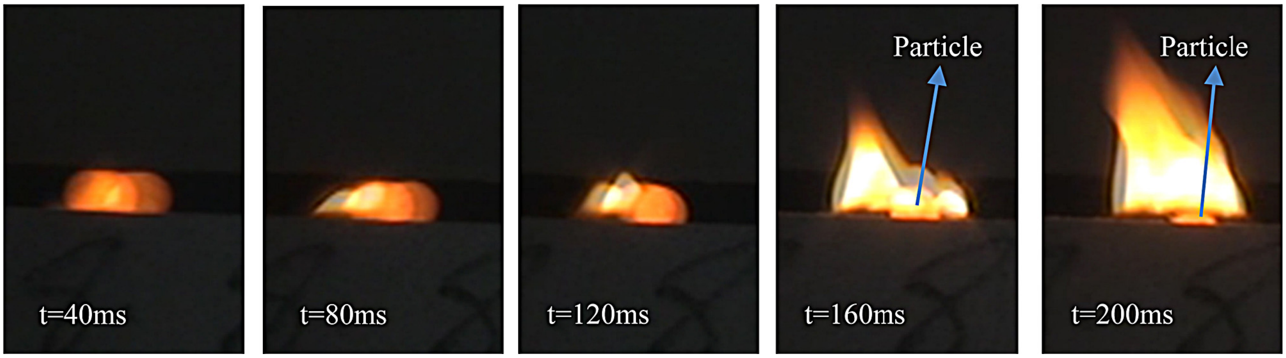

Fig. 2. Continuous experimental images (front view) recording the flaming ignition process (particle radius: 5 mm; particle temperature: 1238 K). The images were achieved by a normal video camera (25 frames per second). As can be seen, the particle was nearly half embedded in the foam, and after ignition, the flaming burning was sustained.