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Effects of Bulk Densities and Inlet Airflow Velocities on Forward Smoldering Propagation Properties of Flexible Polyurethane Foam

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Abstract

Smoldering processes of flexible polyurethane foam (FPUF) with densities of 20.0, 30.0 and 35.0 kg/m^3 were simulated in a self-designed mesoscale generator with dimensions of 60.0 cm × 25.0 cm × 25.0 cm. Characteristic parameters like smoldering establishment time, average smoldering rate, smoldering temperature, and high temperature duration were proposed and analyzed at five different air flow rates of 1.0, 2.0, 3.0, 5.0 and 7.0 L/min. Scanning Electron Microscopy (SEM) was used to investigate the morphological evolution of bulk materials before establishment and propagation of smoldering. Air was forced in the direction of approximately one-dimensional forward propagation. Results show that FPUF (20.0 kg/m^3) has the shortest average smoldering establishment time of 1828.0 s at five airflow rates, FPUF (30.0 kg/m^3) has the longest average smoldering establishment time of 2646.0 s. The average smoldering rate of FPUF (35.0 kg/m^3) is higher than that of FPUF (30.0 kg/m). Smoldering of FPUF (20.0 kg/m^3) cannot be self-sustained, due to largest porosity and insufficient heat accumulation. The average smoldering temperature and duration of high temperature values of FPUF (30.0 kg/m^3) are higher than those of FPUF (35.0 kg/m^3), and the highest average smoldering temperature of FPUF (30.0 kg/m^3) is 410.0 ℃. Since smoldering is derived from chemical reactions of oxygen transported and pyrolyzed products, the bulk material with low density shows higher porosity and contains more oxygen, it burns more fully and thus smoldering establishment time is less. In the process of smoldering, the oxidation and exothermic effects of porous carbon-based chars and oxygen is the main source of energy for the self-sustaining propagation of smoldering. The porosity of FPUF with high density (35.0 kg/m^3) is lower, the burning produces a porous carbonate residue and limits the heat loss on the surface, so the smoldering rate of FPUF (35.0 kg/m^3) is faster.

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Keywords: flexible polyurethane foam, smoldering, mesoscale smoldering generator, smolder propagation.

1. Introduction

Smoldering combustion is a non-flaming, self-sustaining and exothermic process that is propagating and undergoing heterogeneous reaction on the surface in the porous combustible materials [1]. Smolder produces a large amount of toxic gases and leads to flaming fire which poses greater damages. One-dimensional smoldering has two distinctive modes, forward and opposed smoldering. The forward smoldering is defined as the oxidizer flow moves in the same direction as the reaction zone, while the opposed smoldering moves in the opposite direction. Examples of materials that can induce smoldering combustion are polyurethane foams, cotton, cigarettes, wood chips, dusts, coal and etc. FPUF has a broad prospect in the building insulation and home decoration because of its excellent thermal conductivity and mechanical properties. However, as a typical

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smoldering material, FPUF has caused a lot of death, injury and disability accidents. From the social and economic point of view, the study of FPUF is a very important issue. The research of this paper is helpful to discuss the establishment and propagation mechanisms of FPUF smoldering and thus to figure out the root causes of such fire disasters.

Smoldering combustion contains complex physical and chemical processes. Domestic and foreign scholars have done considerable experimental simulations to explore the propagation of smoldering combustion of diverse porous materials. Amanda [2] studied spontaneous transition from smoldering to flaming in polyurethane foams and found that as the porosity of the foam increases oxygen and gas fuel mixtures can produce more combustible products and spontaneous combustion become easier. Lei [3] conducted experimental and theoretical studies on smoldering propagation of the flexible polyurethane foam with controlled air supply (0.06 m^3/h) to show that increasing air supply both enhances the oxidation reaction and increases the heat loss. Leach [4] presented a one-dimensional transient model of forward smoldering to explain that at low gas velocities of 0.09 cm/s the smolder process is oxygen limited and oxidation frequency factor has little effects on smolder velocity. However, at higher inlet gas velocities of 0.78 cm/s, the smolder process becomes kinetically limited and the smolder velocity is therefore highly dependent on the oxidizing frequency factor of fuel. Garrido [5] has explored thermal degradation of polyurethane foam with three consecutive reactions, say, fracture of urethane bonds, decomposition of ether polyols and formation of coke burning occurs in the first, second and third reaction, respectively. Torero and Fernandez-Pello [6] used air as an oxidizer and forced it in the direction of a forward smolder propagation of polyurethane foam, and calculated the smolder propagation velocity as a function of the air flow velocity. Tse et al. [6] proved that char is not totally consumed by flowing oxidizer and has a different reaction level from that of the virgin foam in air supply or temperature requirements for its oxidation.

Previous literature show that air supply rate plays a crucial role in the propagation of forward smoldering. In this paper, behaviors and properties of forward smoldering combustion of open-celled flexible polyurethane foam with controlled air supply rates of 1.0, 2.0, 3.0, 5.0, 7.0 L/min and different bulk densities of 20.0, 30.0 and 35.0 kg/m^3, are further examined by analyzing newly proposed smoldering parameters like smoldering establishment time, average smoldering rate, smoldering temperature, and high temperature duration.

2. Experimental equipment and methods

2.1. Experimental materials and instrument

The experimental samples are polyether-type open-celled flexible polyurethane foams with a density of 20.0, 30.0, 35.0 kg/m^3. JSM ~ 5900 Scanning Electron Microscope (SEM) was used for scanning surface micromorphologies. Self-designed mesoscale smoldering generator was used to simulate forward smoldering processes, as shown in Fig.1. The smoldering set-up consists of a gas control module, smoldering generator module, temperature acquisition module and data processing module. The container has a dimension of 60.0 cm × 25.0 cm × 25.0 cm and is filled with foams. The electric heater is located on the left side of the box. 15 thermocouples (numbered as $A_{1\sim3}$-$E_{1\sim3}$, see Fig. 1) were inserted into smoldering material from above with a depth of 10.0 cm each.

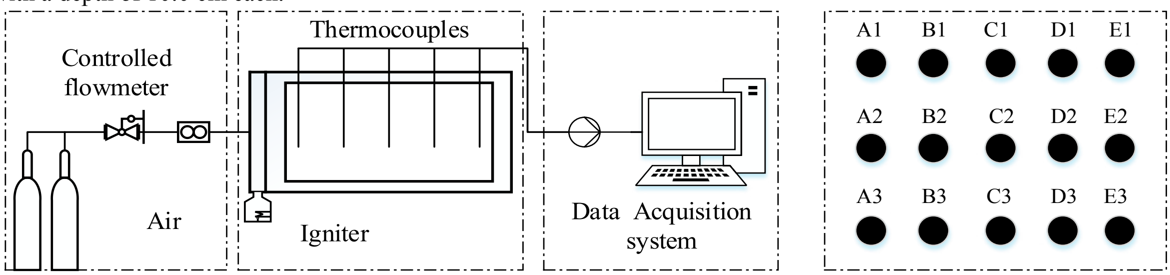

Fig. 1. Self-developed mesoscale smoldering simulation device and arrangement scheme of thermocouples

2.2. Experimental methods

In the smoldering generator (chamber), effects of three density of materials on the smoldering were investigated at five airflow rates (1.0, 2.0, 3.0, 5.0, 7.0 L/min). External heating power was 8.0 kW. Atmosphere inside smoldering generator was air. During the experiment, it stopped heating when Thermocouple A2 reached 350.0 ℃, so that the smoldering could be established and propagated further. The microstructure of FPUF before and after simulated smoldering were characterized by using SEM.