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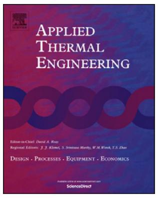

Research Paper

The influence of low air pressure on horizontal flame spread over flexible polyurethane foam and correlative smoke productions

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HIGHLIGHTS

- Quasi two-dimensional flame spreading behavior of flexible polyurethane (FPU) foam was investigated.
- Theoretical correlation of pressure effects on global burning rate was proposed.
- The influence of pressure on plume and ceiling jet temperatures was studied theoretically.
- Pressure effects on soot formation and CO concentration were analyzed.

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ABSTRACT

Pressure effects on quasi two-dimensional flexible polyurethane (FPU) foam flame spreading behavior, typical product concentrations, and smoke detector responses were investigated by comparative experiments under different ambient pressures of 99.8 kPa (in Hefei) and 66.5 kPa (in Lhasa), respectively. First, significant decreases of flame spreading velocity and burning rate were observed under low pressure condition. Averaged global burning rate was found to be dependent on pressure, with an exponential factor of 4/3 theoretically based on pressure modeling. Second, the maximum temperature at a given position in axial thermal plume showed insensitivity to pressure, yet the maximum temperature in ceiling jet was obviously higher. Third, the low pressure was shown to have no effect on soot particles size distribution by scan electron microscopy (SEM) imaging. However, the soot number concentration decreased with reduced pressure attributed to the much slower soot formation rate under low pressure. This result would further have an interesting influence on the response signals of photoelectric detector and ionization detector. Finally, the pressure effects on variation of CO and O_2 volume concentration were discussed. Considering the relatively small heat release rate for FPU foam selected, the CO concentration in the far-field ceiling jet low under low pressure was found to be lower for the enhanced diffusive effect.

1. Introduction

Fire research with regard to air pressure is important for safety design in aerospace industry and also for the protection of historic buildings, e.g., plateau area in West China where thousands of Buddhism buildings are located. The interest in burning behavior under low air pressure was based on the consensus that the reduced atmospheric pressure has significant influence on fire dynamics and burning characteristics [1–14], including burning rate, flame spreading velocity, temperature variation, and product concentration, etc.

Previous study on fire mass burning rate, with liquid fuel such as ethanol (C_2H_6O), acetone (C_3H_6O) and *n*-heptane (C_7H_{16}), showed that the pressure effects on burning rate were complicated and attributed to various heat feedback mechanisms, which could be described as $\dot{m} \propto p^n$, where n was reported to be $-0.4 \sim 0$ for conduction-controlled with pan diameter $D < 7$ cm [9,11], $1 \sim 1.45$ for convection-controlled ($10\text{ cm} < D < 20\text{ cm}$) [3,9,13], and 1 for radiation-controlled ($D > 20$ cm) [9,10,14]. Theoretical models including pressure modeling of fires (in 1973) and radiation fire modeling (in 2000) by De Ris et al. [1,4] and some other theoretical relationships (e.g. [5,9,10],) were developed for solving the issues of pressure effects on burning behavior, but there is still a lack of systematic model that is suitable for fuels with different materials.

The flexible polyurethane (FPU) foam, as a typical composite material with good thermal insulation performance, is widely used in the construction and furniture industry. Meanwhile, the combustibility of FPU material increases the potential risk of fire hazard, which could be dangerous and harmful to human and environment. Moreover, many kinds of FPU materials are able to show thermoplastic due to special preparation method. It is particularly

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challenging for fire protection of buildings with a large amount of thermoplastic FPU material because of the melting and flowing behavior of burning thermoplastics in fire [15,16].

Experimental results concerning the influence of air pressure on burning behavior of some typical thermoplastics, e.g., polystyrene, polymethyl methacrylate and extruded polystyrene, showed that the flame spreading velocity in reduced pressure is much lower as an approximate quantitative relationship of $v \propto p^{2/3}$ [1,7] for one-dimensional flame spread. It is interesting that this relationship for such a complex chemical process was surprisingly predicted with simple dimensional arguments by De Ris et al. in pressure modeling of fires [1].

Another threat of FPU fire is the heavy and toxic hot smoke gases in combustion, including CO, NO_x, HCN, etc., and the characteristics of these smoke gases or ceiling jet are critical for fire detection and thermal engineering researches [17–22]. Wieser et al. investigated the influence of low pressure on fire detector test fires (in 1997) [3], including polyurethane foam fire in 4 altitudes. It is shown that the smoke concentration by optical extinction measurement decreased with the reduced ambient pressure. Similar results and theoretical analysis were also reported in our previous study [5] using *n*-heptane pool fire with much larger heat release rate (HRR) in British standard EN54 test room [19].

In this work, comparative fire tests of FPU foam were conducted in Hefei (with an altitude of 40 m and pressure of 99.8 kPa) and Lhasa (with an altitude of 3650 m and pressure of 66.5 kPa), two representative locations with natural altitude difference in China. Theoretical and phenomenological analyses of low air pressure effects on FPU foam spreading behavior, burning rate, plume temperature, ceiling jet temperature and typical smoke product concentration were provided according to experimental results. Also, the response (i.e., output signals) of ordinary point-type smoke detectors including light scattering photoelectric smoke detector (photoelectric detector) and ionization smoke detector (ionization detector) in tests under 2 altitudes were studied.

2. Experimental

The experimental facility is shown in Fig. 1. All the experiments were carried out in EN54 fire test rooms with dimensions 7 m wide, 10 m long and 4 m high in Hefei and Lhasa, respectively. Similar ambient temperatures and humidities (Hefei: 21 ± 2.0 °C, 53 ± 4%; Lhasa: 20 ± 2.0 °C, 50 ± 4%) were applied in contrast to ambient air pressure. The parameters of FPU foam board selected for experiments are listed in Table 1.

As shown in Fig. 1a, FPU fuel source was set on the floor center of EN54 fire test room. Electronic balance (Excellence-Plus XP from Mettler Toledo, Switzerland) was used to record fuel mass loss with precision 0.01 g and uncertainty within 1.50%. Gypsum board and steel frame beneath the FPU foam board were used for heat insulation. Temperatures were measured by Type K armored thermocouple arrays A and B with each diameter 0.5 mm and uncertainty within 0.75%. Fire smoke detectors including photoelectric detector (GD-2000 from EI Fire, China) and ionization detector (M-2000 from EI Fire, China) were mounted under the ceiling around the 3 m ring [19]. HD digital cameras with frequency of 30 frames per second were used to monitor the burning and spreading behaviors of FPU foam board.

A more detailed arrangement of thermocouple arrays is shown in Fig. 1b. Thermocouple array A (T1–T4) showed ceiling jet or smoke layer temperature with height under ceiling 4 cm, 20 cm, 40 cm and 70 cm, respectively. Axial plume temperature was measured by thermocouple array B (T5–T9) with height above gypsum supporter 80 cm, 70 cm, 60 cm, 50 cm and 40 cm. A gas analyzer (VARIO plus from MRU, Germany) was set 20 cm under the 3 m ring to record the variation of O_2 and CO concentration in smoke, with uncertainty of 2.00% and 5.00%, respectively. Laser imaging was introduced for a better observation of the early smoke movement, which consists of 2 vertical laser beam generators and one laser sheet generator with a vertical optical cross section just through the center of test room. Scan electron microscopy (SEM) system (JSM-6700F from JEOL, Japan, with precision 1.0 nm) and soot thermophoretic sampling are used to obtain the soot particle structure and size distribution of FPU fire smoke in two altitudes. Any trade name mentioned is for descriptive purpose only.

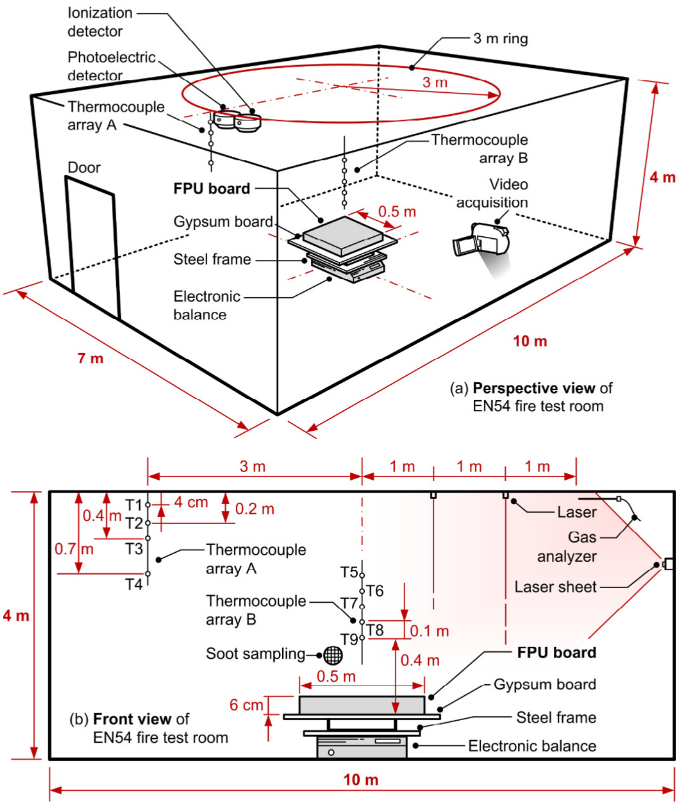

Fig. 1. Sketch of experimental facility with perspective view (a) and front view (b).

Table 1
Property of FPU foam for tests.

Fuel material: flexible polyurethane foam board	
Average element structure	$CH_{1.8}O_{0.30}N_{0.05}$
Density (kg/m^3)	41.5
Dimension	50 cm long, 50 cm wide, 6 cm thick
Initial mass (g)	623.0 ± 2.0
Soot yield (g/g)	~0.131 for normal pressure

FPU foam board was ignited from one upper corner by igniter, which showed actually a quasi two-dimensional flame spread for the large ratio of length (or width) to thickness. In addition, each test was repeated at least 3 times to ensure reproducible results within permitted error ranges.

3. Results and analysis

3.1. Horizontal flame spreading behavior of square FPU foam

The schematic thermodynamic process of horizontal flame spread over FPU foam in test is illustrated in Fig. 2. As the FPU foam selected is a thermoplastic-like material, a thin molten fuel layer, which mainly consisted of the short molecular chains with liquefied form