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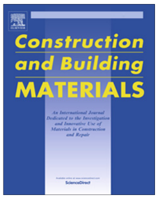

Thermal and fire risk analysis of low pressure on building energy conservation material flexible polyurethane with various inclined facade constructions

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HIGHLIGHTS

- Phenomenological analyses of flame spreading behavior of FPU were provided.
- Global burning rate was illustrated by theory of effect pressure and pool fire.
- The influence of pressure on flame height and temperatures was studied theoretically.
- Pressure effects on flame spread velocity were interpreted in mechanism.

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ABSTRACT

This study investigated the factors affecting the fire safety analysis of the common construction material flexible polyurethane foam, based on combustion at various inclination angles and the ambient pressures at the altitudes of the cities of Hefei (99.8 kPa) and Lhasa (66.5 kPa). The effects of ambient air pressure, specimen width and inclination angle on the burning rate (as determined by mass loss), average flame spreading velocity, flame temperature and flame length were examined. The combustion rate was lower at 66.5 kPa and the wider specimens exhibited gradual spreading of the flame front in conjunction with melting and dripping. The burning rates at various inclinations were found to correlate with the pressure according to the expression $\dot{m} \propto p^n, 0.67 < n < 1.36$, and this result can be explained based on pool fire theory. The average flame spreading velocity was found to correlate with pressure at various inclinations according to the relationship $V_a \propto p^n, 2/3 < n < 1$. The flame temperature was also observed to increase somewhat at the lower pressure, leading to an increase in the flame puffing frequency. Finally, a power law was used to describe the relationship between flame height and pressure, while a linear relationship was obtained between the index and the angle of inclination.

1. Introduction

In recent decades, there has been a growing interest in developing new methods of both generating and conserving energy to protect the environment [1–4]. Polyurethane (PU) foam, a common material with numerous applications, is often employed as insulation in buildings as a means of saving energy. Both Rigid and Flexible polyurethane (RPU and FPU) foams can be produced. RPU foams are typically thermoset polymers, while FPU foams tend to be thermoplastics [5,6]. Xie et al. developed a quantitative model based on experimental evaluations of downward flame spreading over a liquid fuel layer on Extruded polystyrene (XPS) foam, and proposed that the flame spreading is augmented by liquid fuel generated through melting of the XPS [7]. Many common building materials, including Polymethyl methacrylate (PMMA), XPS and Expanded polystyrene (EPS), will undergo dripping and melting during combustion and generate a large amount of liquid fuel. In contrast, a thermoplastic-like material such as FPU will form a thin molten layer at the flame front that generates what is essentially a narrow, downward-flowing pool fire, rather than the downward surface flame spreading more commonly exhibited

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by burning solids [5,6]. Ma et al. [6] studied flame heights and pulsations during downward flame spreading over FPU and developed an empirical relationship based on pool fire theory that produced results that coincided with the experimental data. This prior work demonstrated that the FPU combustion mechanism at high altitudes can be affected by changes in the pool fire combustion behaviour as well as by variations in the incline of the material. Thus, the factors determining the fire hazards presented by FPU are actually quite complicated, and the unique "melting-flowing" behaviour of FPU during combustion can represent a challenge when designing fire protection systems for buildings [6–10].

The effects of variations in atmospheric pressure on combustion are a significant aspect of assessing the safety of historic buildings at high altitudes, such as in western China, where thousands of Buddhist buildings are located. Prior research has demonstrated that the reduced pressures at higher altitudes could lead to changes in combustion characteristics such as burning rate, flame spreading velocity, the physical morphology of the fire and the flame temperature. De Ris [1,2] predicted that, in the case of one dimensional flame spreading, the flame spreading velocity at lower pressures will be considerably reduced. The effects of low atmospheric pressure on the burning behaviour of PMMA were also assessed by Gong et al., who formulated the expression $\dot{m} \propto P^{1.8}$ to describe these effects [8]. A pressure–gravity model was proposed by Kleinhenz et al. [9], in which the upward flame spreading velocity and burning rate are proportional to $P^{1.8}g$. Tang et al. [10,11] proposed a correlation to characterize the vertical profile of the heat flux upon external facade in the thermal plume region by accounting for relative pressure variation and entrainment change. However, studies analysing the combustion risks associated with FPU are rare. Tu et al. [5] investigated the effects of pressure on the burning behaviour of FPU, and found that the average global burning rate was proportional to the pressure to an exponent of 4/3, based on a hypothetical model.

Many other parameters, such as the width of the fuel, the angular orientation, gravitational effects and oxygen concentration, have also been studied. Mell et al. [12] confirmed that more intense convection increases the flame spreading velocity in the case of non-inclined narrow samples. Li et al. [13] reported that the flame height and flame spreading velocity on a wooden board increased with width at a 90° inclination angle, for widths ranging from 2 to 11 cm. Quintiere [14] researched the effects of the inclination angle on the flame spreading over thin substrates. This work determined that the flame spreading increases in the downward and upward directions at critical angles of −60° and 60°, respectively. An et al. [15,16] conducted experiments that examined the effects of the substrate thickness as well as the effects of sidewalls and pressure on the downward flame spreading over XPS and various thermoplastic materials and developed a three dimensional downward flame model. However, these existing simplified representations of combustion processes do not allow estimation of flame spreading rates on FPU specimens with finite widths or at reduced ambient pressure. Therefore, additional experimental studies concerning the combustion behaviour of FPU at high altitudes are required.

In the present work, comparative experiments were performed to assess the burning behaviour of FPU foam board in conjunction with gravity-assisted downward flame spreading at two locations having different atmospheric pressures. These were the cities of Hefei (altitude 40 m and pressure 99.8 kPa) and Lhasa (altitude 3650 m and pressure 66.5 kPa). The results provide basic information that should be useful in developing safety regulations for construction at elevated altitudes.

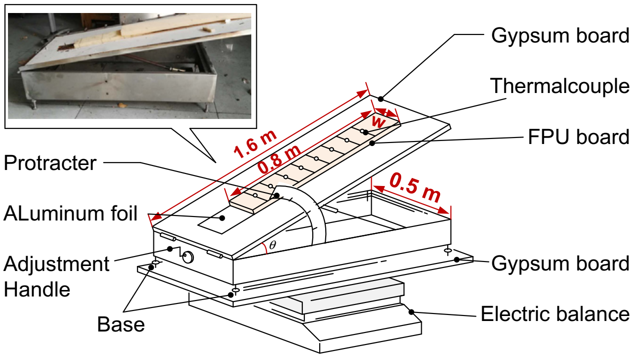

Fig. 1. Experimental setup modelling a building facade with varying incline angles.

2. Material and experiments

The experimental device employed in this study is illustrated in Fig. 1. The apparatus primarily consisted of an electric balance, an FPU board holder, sensors and a measurement system. The FPU foam board had a thickness 2 cm, a length of 80 cm and a width of 5 or 20 cm and was mounted on an insulating section of gypsum board. The FPU specimen could be ignited on its upper side to create a downward spreading flame. As shown in Fig. 1, the inclination angle of the underlying gypsum board that simulated a building facade could be adjusted and also ensured that only the upper surface of the FPU board burned. The angle of the specimen could be altered using a manually-operated adjustment system and was measured using a protractor on the side of the device. Four inclination angles (θ) were employed: 0°, 30°, 60° and 90°. The physical properties of the FPU foam board selected for the experiments are summarized in Table 1. Comparative trials were conducted using two identical testing rooms EN54 [17] with the following dimensions: 10 m in length, 7 m in width and 4 m in height. These areas were large enough to allow the reduction in oxygen concentration during combustion trials to be neglected.

The FPU board holder was situated on a second thick gypsum board, which in turn sat on an electronic scale with a precision of 0.01 g. This scale was used to track variations in the mass of the FPU over time. A wick soaked with ethanol positioned in an iron slot was employed as a linear ignition source. Two high definition digital cameras (30 frames per second) were used to monitor the flame spreading behaviour both overtop and from the side of the FPU board. Reference lines spaced 10 cm apart on the upper surface of the FPU board provided a means of assessing the flame spreading at specific time intervals. An array of seven thermocouples (T1–T7), were positioned along the centreline of the FPU specimen at a height of approximately 2 mm above the board surface, and could be relocated when the FPU board changed to a new inclination angle.

Temperature and humidity values similar to those typically encountered in the two cities were employed (Hefei: 23 ± 1.0 °C, 55 ± 3% relative humidity; Lhasa: 21 ± 1.0 °C, 50 ± 3% relative humidity) when assessing the effects of the ambient air pressure. All the mass and temperature data were recorded at a frequency of 1 Hz. Each trial was repeated several times and the data exhibited excellent reproducibility.

3. Results and analysis

3.1. Typical downward burning behaviour of FPU

Photographic images of a typical downward flame spreading sequence over FPU foam boards (5 or 20 cm wide) at a 60° inclination angle and a pressure of 66.5 kPa are provided in Fig. 2. It is