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Experimental study on thermal safety analysis of flexible polyurethane at various facade inclined structures under low ambient pressure condition

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ABSTRACT

Experimental and theoretical investigations are conducted to analyze the influences of low atmospheric pressure on burning behavior of building facade insulation material flexible polyurethane (FPU). Comparison experiments for downward flame spread process over FPU under various facade inclined structures were performed at Hefei (99.8 kPa) and Lhasa (66.5 kPa), respectively. Characteristic parameters including burning rate (i.e. mass loss rate), flame spread velocity and flame height were studied in this paper. Firstly, morphological experimental results exhibited that the combustion was slower in reduced pressure condition and wider specimens showed more gradual flame spreading. Secondly, an inverted V-shaped spreading pyrolysis front was observed, and a "two-terminal" combustion behavior was found for narrow FPU board by partial molten flow combustion, which is critical to practical fire rescue techniques. Thirdly, power-law progressions of burning rate vs. pressure was proposed with an exponent ranging from 0.61 to 1.39, which can be illustrated by utilizing classical theory for sub-atmospheric pressure pool fire. Further, the increasing facade inclination angle significantly enhanced the flame spreading velocity, which suppressed the effect of pressure at high inclination angles. The flame temperature was measured to be increased at the lower pressure causing faster flame puffing. Finally, a linear relationship was determined between the pressure index values obtained by flame height vs. pressure and the inclination angle.

1. Introduction

Interest in energy conservation has increased in the last few decades, especially in developing countries such as China [1,2]. Energy-saving technologies could also substantially reduce carbon emissions, thus reducing climate change [3,4]. For these reasons, flexible polyurethane (FPU) foam has been widely used in the construction industry as insulation material, owing to its excellent thermal insulation properties and relatively low cost. Many FPU foams have some thermoplastic properties and thus can be considered as thermoplastic-like materials, especially when compared to rigid polyurethane (RPU), which is a thermoset [5]. On the other hand, there happened several large fires concerning the thermoplastic thermal insulation materials on the exterior wall of the building, such as the London Grenfell Tower fire in 2017 [6], ShenyangWanxin Hotel fire in 2011 [7] and Beijing Television Cultural Center fire in 2009 [8]. The combustion began from the bottom of the building, fire spread rates are amazingly fast when some exposed foam was ignited by the ignition source. Previous research has demonstrated that the unique "melting-flowing" behavior of FPU during combustion results in various challenges when designing fire protection systems for buildings. In addition, reduced pressure can lead to completely different burning dynamics and burning characteristics for FPU, including changes in burning rate, flame spreading, flame morphology, and flame temperature [5,9–11]. Tu et al. [5] predicted the effects of pressure on quasi-two-dimensional FPU foam burning behavior and conducted a quantitative analysis of the relationship between burning rate, soot number concentration, and pressure. Ma et al. [9–11] carried out a study of the flame height and flame pulsation during the downward burning of FPU based on an empirical relationship, and discovered that values predicted using the pool fire theory were consistent with experimental results. Thus, the experimental analysis of combustion behavior of FPU at high altitudes can provide

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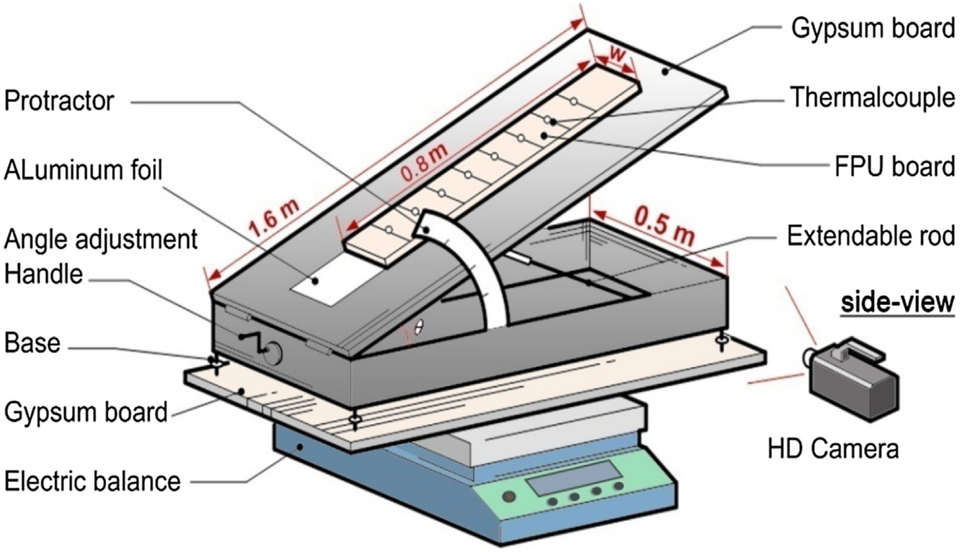

Fig. 1. Experimental setup used to study FPU board burning behavior while mimicking various facade inclinations.

data to assist in developing fire-fighting strategies for use at elevated altitudes.

Both theoretical modelling and experimental studies have demonstrated that ambient pressure has an effect on solid fuel combustion [1,2,5,9–11]. The empirically-derived correlation $\dot{m}'' \sim p^n$ describes this relationship [5], where n has been shown to vary over three ranges based on whether heat feedback is controlled by

$$\dot{m}'' \propto p^n,\ n \approx \begin{cases} <0,\ (conduction-controlled) \\ 0 \sim 1,\ (transition) \\ 1 \sim 2,\ (convection-controlled) \\ 1 \sim 1.7,\ (radiation-controlled) \end{cases} \tag{1}$$

Quintiere [12] reported that the flame spreading velocity (V_f) under reduced pressure is significantly reduced, and deduced the flame spread rate is proportional to $P^{2/3}$. The pressure–gravity model developed by Kleinhenz et al. [13] proposes that the upward flame spreading rate as well as the actual burning rate is proportional to $P^{1.8}g$. Deris [1] characterized radiation-controlled, low pressure, one-dimensional solid-phase flame spreading based on dimensional analysis as

$$\dot{m} \sim \dot{m}''{\cdot}v \sim p^{2/3} \tag{2}$$

In addition, Tu [5] determined a simplified relationship between pressure and burning rate for horizontal flame spreading over two-dimensional FPU boards, and proposed that the burning rate is proportional to $p^{4/3}$. Gong et al. [14] explored the effect of low atmospheric pressure on downward flame spreading over thick polymethyl methacrylate (PMMA) slabs at different heights and found that the burning rate is proportional to $p^{1.8}$.

Previous research has also examined the effects of angular orientation and width of the fuel source on flame spreading. Tsai [15] analyzed the effect of fuel width on upward turbulent diffusion flames produced by the combustion of thermally-dense substances. The results showed that the flame spreading rate and fuel width that could be summarized as $V_f \sim w^{0.35}$. Studies by An [16,17] also developed an expression for the relationship between specimen width and the dimensionless flame height:

$$H/w \sim w^n \tag{3}$$

Quintiere [12] predicted that a gravity-assisted flame will spread in accordance with the angular orientation, and also determined the relationship between total flame heat flux and sample inclination, expressed as:

$$\dot{q}_f'' = C_{q,L}BL(\sin\theta L)^{2/5}x_p^{1/5} \tag{4}$$

An [16,17] examined the effects of both specimen width and inclination angle on the dispersion of flames over an expanded polystyrene (EPS) surface under low pressure, and found that the dimensionless maximum flame height varied with the specimen width according to the relationship

$$H \sim w^n (0.7 < n < 0.9) \tag{5}$$

In addition, a non-linear correlation was observed between the flame spreading rate and the inclination angle:

$$V_f = ce^{-p\sin^q(\alpha/2)} \tag{6}$$

Despite the above work, existing models are impractical with regard to estimating upward flame spreading rates over FPU in cases where the fuel width is constrained, the ambient air pressure is low (due to altitude), or the building has been constructed with different facade inclinations. In the present study, comparative experiments were performed to investigate the burning behavior of FPU foam board in conjunction with upward flame spreading under various conditions. These experiments were conducted in Hefei, the capital of Anhui province, China (altitude: 40 m, air pressure: 99.8 kPa), and Lhasa, the capital of Tibet (altitude: 3650 m, air pressure: 66.5 kPa), thus representing natural variations in ambient air pressure within China. This study examined the effects of air pressure on FPU foam board burning rates, flame spread characteristics, flame temperature, spreading velocity, vertical flame height, and puffing frequency. An analysis of the associated heat transfer mechanism was also performed.

2. Materials and methods

The comparative burning tests were performed in two similar EN54 [18] fire test rooms, in Hefei and Lhasa. Each room was 7 m wide, 10 m long, and 4 m high. This room size was sufficient to allow the reduction of oxygen inside the room during the burning tests to be neglected. The experimental apparatus consisted of an electric balance, an FPU board holder, sensors, and a measurement system (Fig. 1). A sample of FPU foam board (2 cm thick, 80 cm long, 5 or 20 cm wide) was mounted on an insulating gypsum board on the FPU board holder. The FPU board was ignited by a ethanol-soaked wick at the bottom to achieve linear ignition and provide an unrestricted upward spreading flame. As illustrated in Fig. 1, the inclination angle of the board could be adjusted, allowing only the upper surface of the FPU foam board to be burned.