Construction and Building Materials 167 (2018) 449–456

Contents lists available at ScienceDirect

Construction and Building Materials

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

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

Xin Ma [a,*], Ran Tu [b], Chao Ding [c], Yi Zeng [d], Yang Wang [a], Tingyong Fang [a,*]

[a] College of Environment and Energy Engineering, Anhui Jianzhu University, Hefei, Anhui 230022, China
[b] College of Mechanical Engineering and Automation, Huaqiao University, Xiamen, Fujian 361021, China
[c] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China
[d] College of Tourism, Huaqiao University, Quanzhou, Fujian 362021, China

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.

ARTICLE INFO

Article history:
Received 9 October 2017
Received in revised form 18 January 2018
Accepted 5 February 2018
Available online 22 February 2018

Keywords:
Energy saving
Low air pressure
Flexible polyurethane
Heat feedback
Building facade

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

* Corresponding authors.
E-mail addresses: maxin@ustc.edu.cn (X. Ma), ftyong@mail.ustc.edu.cn (T. Fang).

https://doi.org/10.1016/j.conbuildmat.2018.02.027
0950-0618/

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.

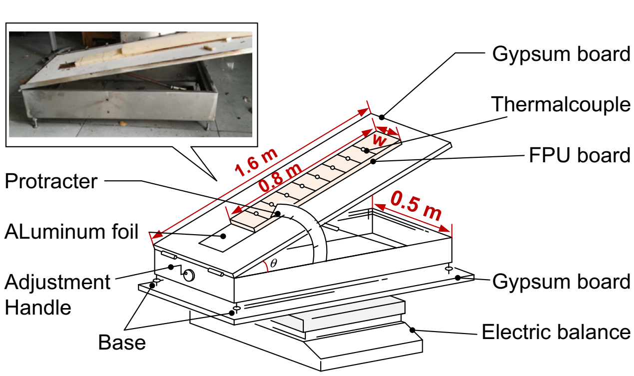

Fig. 1. Experimental setup modelling a building facade with varying incline angles.

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

Table 1
Physical properties of the FPU foam employed in experimental trials.

Average element structure	Density (kg/m^3)	Specific heat (kJ/kg·K)	Heat conductivity coefficient (W/m·K)	Pyrolysis temperature (K)	Heat of combustion (MJ/kg)
$CH_{1.8}O_{0.30}N_{0.05}$	41.5	1.5	0.037	440	30

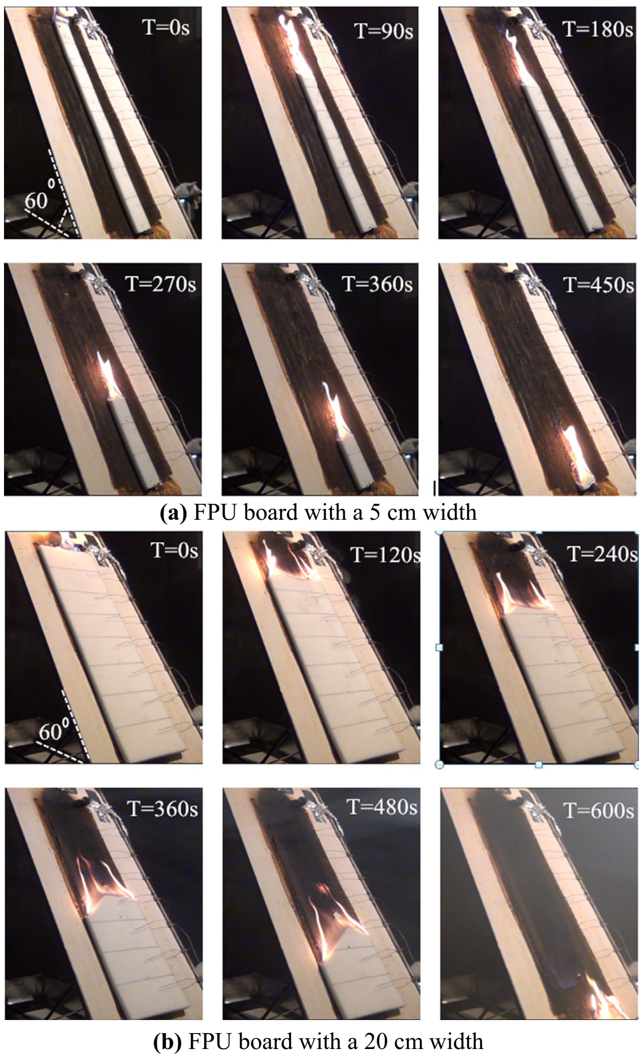

Fig. 2. Sequential images of the combustion behaviour of FPU boards with widths of (a) 5 cm and (b) 20 cm at 66.5 kPa (Lhasa).

evident that the wider board exhibits a transition from a linear pyrolysis front (Fig. 2(a)) to an irregular shape (Fig. 2(b)). The pyrolysis of the wider specimen can also be divided into two stages. Initially, the front has an inverted "U" shape (see t = 120 s in Fig. 2(b)) that later transitions to an inverted "V" shape (see t = 360 s). This phenomenon results from downward flame spreading caused by the molten fuel, and is similar to results reported from prior liquid pool fire studies [5,8,15,16,19]. The fluid effect of the thin molten layer at the flame front produces the initial "U" shape. However, as the fuel width increases, the proportion of air entrainment is also increased owing to the more vigorous combustion. The enhanced air flow from both sides and the ensuing enhancement of the gas movement in the pyrolysis region subsequently combine to move the flame base forward to generate the "V" shape.

A diagram summarizing the parameters affecting the burning behaviour during the tests is provided in Fig. 3. The downward burning of the FPU foam sheet can be considered as the result of the formation of a small, narrow pool fire on the upper surface of the solid foam. New liquid fuel will be provided to this pool as the foam near the moving flame front melts. Thus, the pool is not static but rather moves downward as new liquid is added. The above suggest that the formation and development of the pool plays a key role in downward combustion behaviour.

In addition, the liquid generated in the pool fire flame front drips downward. At a large inclination angle, the molten flow/dripping becomes significant, leading to leakage or overflow of the narrow pool fire, and increases the complexity of fire hazard prevention assessments.

3.2. Burning rate

Throughout this work, the average burning rates during the relative steady burning stage are used, as obtained by the linear fit depicted in Fig. 4 (taking a 20-cm-wide FPU board at a 30° inclination angle and under different pressure conditions as an example). A comparison of the resulting burning rate data is provided in Fig. 5, which demonstrates that the relationship between pressure and burning rate was affected by both the inclination angle and sample width. Within the data for each width, the burning rates at low pressure were always lower, particularly at larger inclination angles. This effect was also more pronounced for the 20 cm boards. The relationship between the burning rate and the inclination angle is also seen to be non-monotonic; with increases in the angle, the burning rate first decreases significantly and then increases. This phenomenon is thought to be due to variations in the degree of heat feedback, as discussed below.

The burning rate of FPU at various inclinations is largely dependent on heat transfer from the flame to the molten region, which in turn is controlled by the convective and radiative heat transfer mechanisms. Heat will be transferred via conduction from the fire through to the back of the board only at very high angles. The relationship between these heat transfers and the burning rate may be approximated by the equation [5]

$$\dot{m} \propto h(T_f - T_p) + \sigma(T_f^4 - T_p^4)(1 - \exp(-k_s l_f)) \quad (1)$$

where h, $\dot{m}$, T, σ, k_s and l_f are the convective heat transfer coefficient, total mass loss rate, temperature, Stefan-Boltzmann constant, absorption coefficient of soot, and characteristic flame mean beam length, respectively.

When using the 5-cm-wide boards, the pressure had a negligible impact on the horizontal flame spread. This lack of effect occurred because the heat feedback to the unburned region in the case of the narrow boards was primarily determined by conduction and convection, both of which are almost independent of ambient pressure in the case of small scale combustion, as reported by De Ris [1] and Tu [5,18]. At higher inclination angles, the angle between the flame and the board is increased, which in turn decreases the radiative heat feedback. This effect explains why the burning rates were reduced at an angle of 30°. However, with additional increases in the angle, the flame approaches the exposed surface of the gypsum board above the burning sample, such that the unburned portion of the FPU board receive a greater degree of conductive heat feedback through the gypsum, resulting in an increased burning rate.

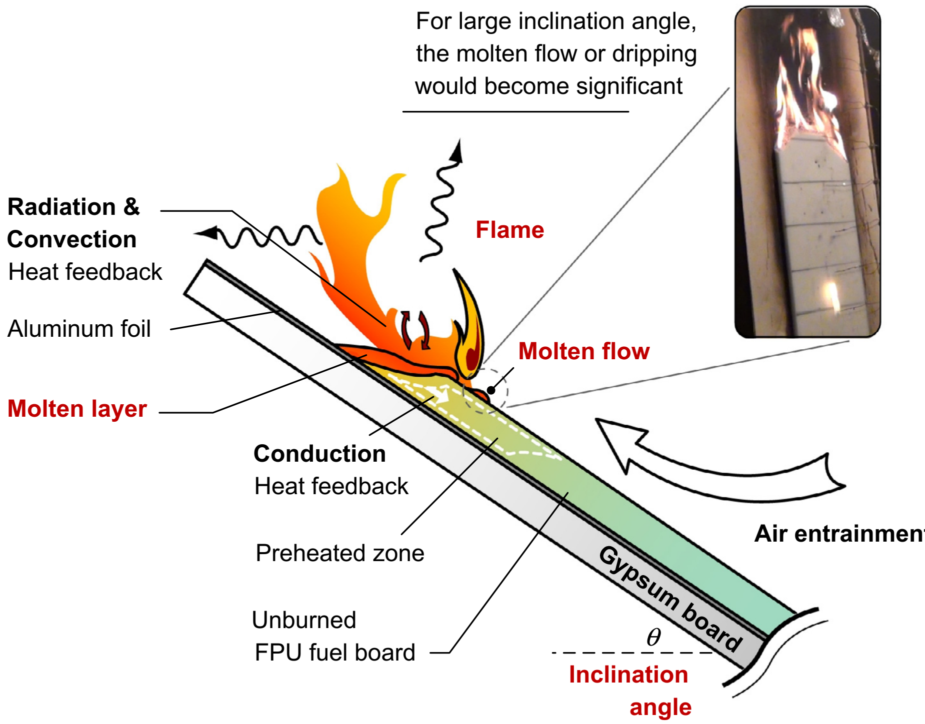

Fig. 3. Diagram showing the factors affecting combustion behaviour during the experimental trials.

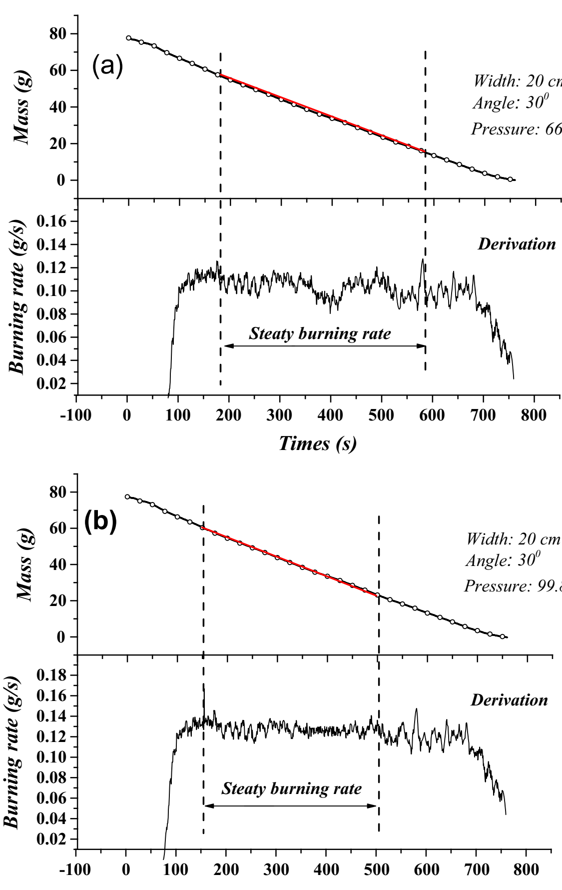

Fig. 4. Burning rate, m'' (calculated as the derivative of the mass loss), as a function of time during the steady burning stage.

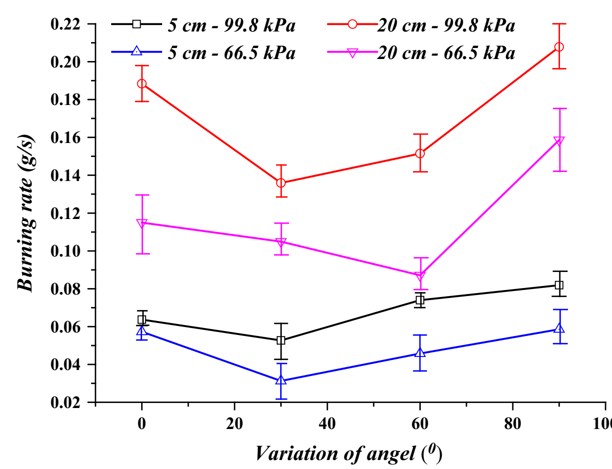

Fig. 5. Variations in the burning rates of FPU boards having different widths and inclination angles in Hefei (99.8 kPa) and Lhasa (66.5 kPa).

In contrast, in the case of the wider board, the effect of pressure becomes more significant owing to the onset of radiation-controlled burning. In a previous study, Gong [8] examined the correlation between pressure and the burning rates of 20-cm-wide PMMA samples.

$$\dot{m} \propto C_h \cdot P^{2n} + C_r \cdot P^2 \tag{2}$$

According to Gong, the relationship between burning rate and ambient pressure can be summarized as $\dot{m} \propto p^{1.8}$. Quintiere [14] also included the angle effect and reported that gravity-assisted flame spreading could be predicted using the equations

$$\dot{m}' x_p = 116(\sin\theta)^{1/2} x_{f,T}^{2/3} / \Delta H_c \tag{3}$$

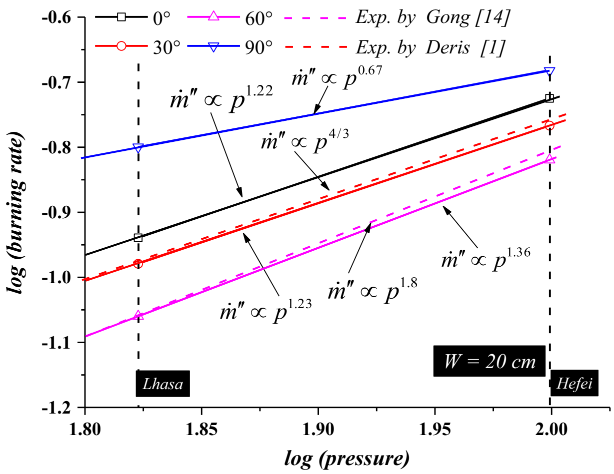

Fig. 6. Plots of experimental $\log(\dot{m})$ and $\log(p)$ data with theoretical fits.

and

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

where $\dot{q}_f''$ is the total heat flux generated by both radiative and convective heat feedback from the flame to the molten region. However, this model underestimates the effect of the heat flux on flame spreading in the case of a horizontal board and $\dot{q}_f'' = 0$.

As noted, the effect of pressure on the burning rate can be summarized as $\dot{m} \propto p^{\alpha}$. Thus, a linear relationship can be obtained by plotting $\log(\dot{m})$ against $\log(p)$, as illustrated in Fig. 6, in which case the slopes of the lines represent the indexes. In this figure, the dotted lines were generated using an index of 4/3. If we consider the data obtained at an angle of 90° as the result of pool fire combustion, the relationship $\dot{m}'' \propto p^{0.67}$ in Fig. 6 is consistent with the results reported by Tu [18]. Tu proposed that the general relationship between pressure and pool fire burning rates can theoretically be expressed by a series of exponential relationships in four regions, written as below.

$$\dot{m}'' \propto p^n, n \approx \begin{cases} <0, (conduction - controlled) \\ 0 \sim 1, (transition) \\ 1 \sim 2, (convection - controlled) \\ 1 \sim 1.7, (radiation - controlled) \end{cases} \tag{5}$$

Furthermore, based on dimensional analysis, De Ris determined that the relationship between pressure and burning rate is $\dot{m}'' \propto p^{4/3}, n = 4/3$. Using the wider board at an angle of 0°, the heat feedback is primarily radiative and the index is 1.22 (and thus in the range of 1–1.7). As the angle is increased, the heat feedback mechanism transitions to conduction-controlled owing to the significant heat conduction through the gypsum board. The relative effects of both conduction and convection are increased, such that n is 0.63 at 90°. In the present study, the data acquired as below.

$$\dot{m}'' \propto p^n, n \approx \begin{cases} 1.22, \theta = 0^\circ \\ 1.23, \theta = 30^\circ \\ 1.36, \theta = 60^\circ \\ 0.63, \theta = 90^\circ \end{cases} \tag{6}$$

3.3. Flame temperature and flame spreading velocity

Flame spreading velocity is a vital factor in assessing fire risks. In this study, the flame velocity was determined by video camera and by thermocouples, which assisted in following thick or unsteady flames in the later stages of combustion. The proportional contribution of radiative heating will be affected by pressure, soot formation in the diffusion flame and increases in the flame velocity at the flame front, and this will ultimately affect the flame spreading rate. The ambient pressure affects the flame spreading rate over the FPU by modifying the thermal diffusivity,α_g. Assuming an infinitely wide specimen, the flame spreading velocity can be written as

$$V_f = C_{V,\inf}P^{2/3} \tag{7}$$

where $C_{V,\inf}$ is an indented pressure constant.

Gong [8] determined the downward flame spreading rate for a sample with a finite width without including the angle effect, and reported the relationship

$$V_f \propto C_{v,fini}P^2 \tag{8}$$

where

$$C_{v,fini} = C_r/w \cdot d \cdot \rho_s \tag{9}$$

De Ris [1] used complex mathematical methods with dimensional arguments to predict that the spreading velocity will increase according to the pressure raised to an exponent of 2/3. This was confirmed by experimental data collected by Mc Alevy and Magee [19], who found that the flame velocity over cellulose and various plastics on thermally thick solids increased relative to the pressure raised to an exponent ranging from 0.63 to 0.78. This prior work also found that changing the inclination angle modified the burning rate by affecting the heat feedback mechanism. Therefore, the correlation between the average flame spreading velocity and the angle and pressure can be approximated by the equation

$$V_f = C_{V,\inf}P^nC(\theta) \tag{10}$$

Fig. 7 summarizes the average flame spread rates and demonstrates that a decrease in the ambient pressure reduces the flame spreading velocity while increases in the inclination angle enhance the velocity significantly. Fig. 8 plots $\log(V_a)$ as a function of $\log(p)$. In this figure, Eq. (7) is used to fit four sets of experiment results having different slopes and the dotted line represents a slope of 2/3. The relationships between average flame spreading velocity and pressure at angles of 0° and 30° were consistent with De Ris' results. At angles of 60° and 90°, the relationship between the flame spreading rate over the FPU board and pressure becomes $V_a \propto p^{0.89}, n = 0.89$ and $V_a \propto p^{0.91}, n = 0.91$, respectively, which is similar to the trend of burning rate vs.p. In the present study, the data acquired at inclination angles of 0°, 30°, 60° and 90°can be described by the relationships as below.

$$V_a \propto p^n, n \approx \begin{cases} c0.87, \theta = 0^\circ \\ 0.65, \theta = 30^\circ \\ 0.89, \theta = 60^\circ \\ 0.90, \theta = 90^\circ \end{cases} \tag{11}$$

Fig. 9 shows that the effect of pressure on $T_{f-\max}$ (the peak temperature that occurs when the core reaction zone in the fire plume reaches each thermocouple location) is not clear. The $T_{f-\max}$ values at 99.8 and 66.5 kPa were approximately 1103 and 1163 K when the angle is 30°, respectively, when the flame front reached the fourth thermocouple. This result indicates steady flame spreading, with a maximum temperature difference of <10% ($T_{f-\max}(99.8kPa) \leqslant T_{f-\max}(66.5kPa)$). This result is attributed to decreases in both ρ_∞ and $\dot{Q}$ under low pressure conditions. However, ρ_∞ decreases faster than $\dot{Q}$ in the case of small and mid-scale combustion, as expressed in the equation

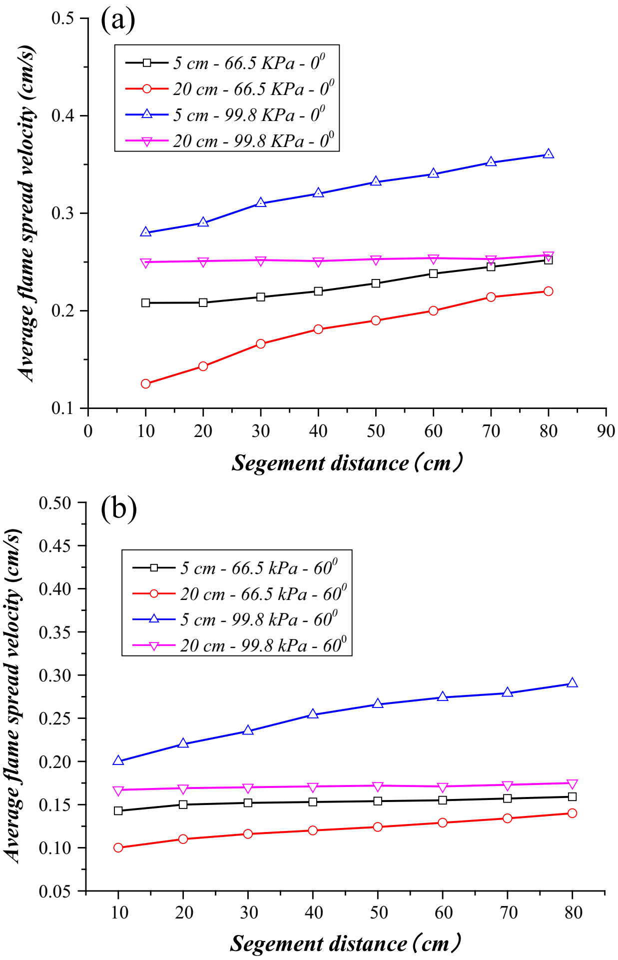

Fig. 7. Average flame spreading rate over 5 and 20 cm boards at 99.8 kPa (equivalent to Hefei) and 66.5 kPa (equivalent to Lhasa) at inclination angles of (a) 0° and (b) 60°.

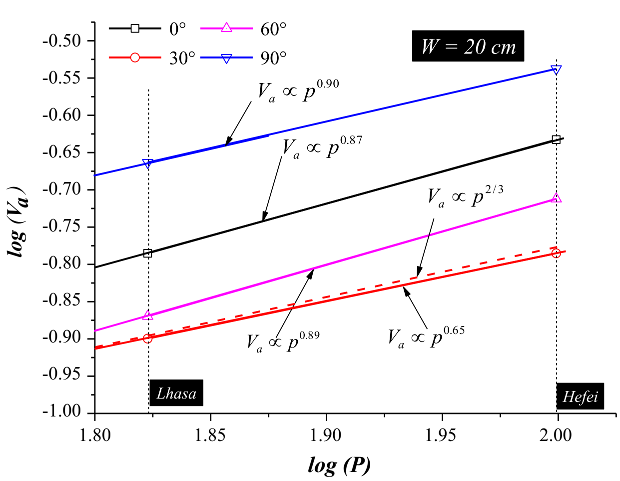

Fig. 8. Plots of $\log(V_a)$ as a function of $\log(p)$ based on experimental data, with theoretical line fits.

$$\Delta T \propto \left(\frac{T_\infty}{g c_p^2 \rho_\infty^2}\right)^{1/3} \dot{Q}^{2/3} \cdot (Z - Z_0)^{-5/3} \tag{12}$$

The errors associated with temperature measurements were primarily associated with radiative effects, and so we analysed errors using Luo's [20] method. Based on this method, the error of flame could be <3% for our test.

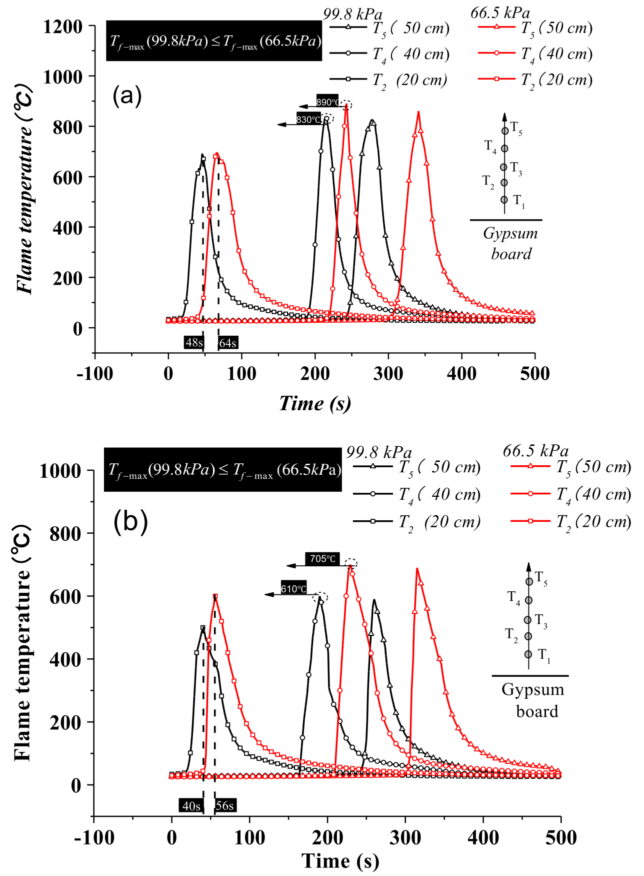

Fig. 9. Axial temperatures in the plume region at 99.8 kPa (Hefei) and 66.5 kPa (Lhasa) obtained using 5-cm-wide boards at inclination angles of (a) 30° and (b) 60°.

3.4. Flame length

The flame length (L), was defined as the distance between the flame root and tip, and was affected by the fuel supply rate, pressure and inclination. In general, increases in the flame length or height elevate the fire risk. Because the flame scale varies regularly with the flame pulsation, digital image processing using the MATLAB program [9], with a scale error <5%, was utilised to calculate the flame length based on 20 s sequences of flame images acquired during the steady burning state (the region indicated in Fig. 3). Under these conditions, the classical relationship between flame height and inclination based on nonlinear burning developed by Zukoski [21,22] is not suitable. This relationship is summarized by the equation

$$H/D = 3.7\dot{Q}^{*2/5} - 1.02 \tag{13}$$

where H, D and $\dot{Q}^*$ are the flame height and diameter, and the non-dimensional heat release rate, respectively. Delichatsios et al. [23] proposed a correlation to predict the flame height, $H = k \cdot \dot{Q}^{n_0}$, where H is the flame height, $\dot{Q} = \dot{m}\Delta h$ is the heat release rate, and k and n_0 (the latter having a value of 2/3) are constants. Similar correlations having the form $H = a \cdot x_p^n$ have also been reported by other researchers. The flame length can be expressed as

$$L \propto Q^{n_0} \sim (m\Delta H)^{n_0} \sim p^j \tag{14}$$

Eq. (14) demonstrates that the flame height is proportional to the pressure raised to an index, which might explain the experimental data. Fig. 10 plots the relationship between flame length

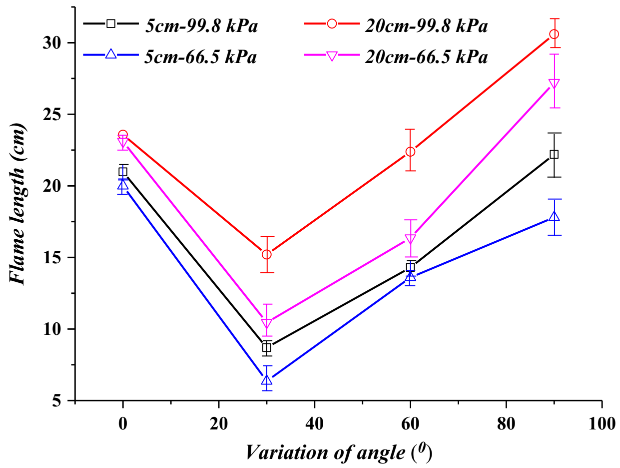

Fig. 10. Flame lengths as functions of inclination angle at 99.8 kPa (Hefei) and 66.5 kPa (Lhasa) for 5- and 20-cm-wide FPU boards.

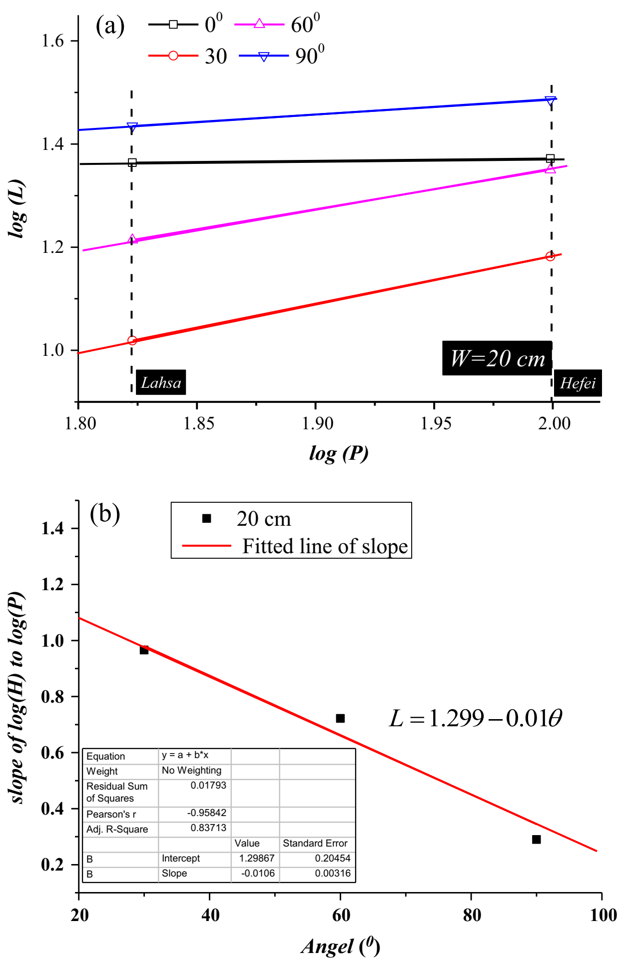

Fig. 11. Relationships between flame height and pressure: (a) log(H) as a function of log(p) with linear fits, and (b) the relationship between the pressure indexes from (a) and the inclination of FPU samples.

and pressure and demonstrates that the flame length increases with increases in pressure. It should be noted that there is also an obvious decrease at a 30° inclination angle at all pressure conditions, which mirrors the trend observed in the burning rate data in Fig. 5. Increasing either the angle or the width increases the flame length. The reduced flame length at low pressure is due to the differences in the burning rate and burning area. These results are in some ways different from previous pool fire flame height data [24].

Further comparisons between experimental flame lengths at different inclination angles and pressures are shown in Fig. 11. With increases in the angle, a linear correlation is realised between slopes obtained in Fig. 11(a) and the inclination angle, as illustrated in Fig. 11(b). The flame height can be expressed as

$$H \propto P^{1.299-0.01\theta} \tag{15}$$

4. Conclusion

The effects of atmospheric pressure and building facade inclination on the downward burning characteristics of FPU foam board (including burning rate, flame temperature, spreading velocity and flame length) were examined. The results are expected to support the safe design of buildings with external thermal insulation systems. The downward burning behaviours of various FPU samples were analysed and the results can be summarized as follows.

(1) Compared with solid fuels such as PMMA, XPS and EPS, which are commonly employed in building façade construction and which produce dripping and melting, FPU exhibits more complex "melting-flowing" behaviour that complicates safe building design.
(2) Both pressure and inclination are key factors affects the burning rate of FPU. The relationship between pressure and burning rate can be summarized as $\dot{m} \propto p^{n} (0.67 < n < 1.36)$. At an angle of 90°, the experimentally-derived relationship is$\dot{m}'' \propto p^{0.67}, n = 0.67$, which is consistent with pool fire theory. At 0°, 30° and 60°, the experimental data result in the same relationship but with n values of 1.22, 1.23 and 1.36, owing to the onset of a radiative feedback regime.
(3) The flame spreading velocity over the FPU increases with increases in the ambient pressure. The relationship between pressure and the average flame spreading rate at various angles can be expressed as $V_a \propto p^{n}, 0.65 < n < 0.89$. However, greater inclination angles lead to complex variations in the flame spreading velocity owing to transitions between different heat feedback mechanisms.
(4) Flame length is determined by both the heat release rate and consequent burning rate. A non-monotonic tendency was found with increases in the inclination angle, similar to the behaviour of the burning rate. On the basis of the experimental findings, at sub-atmospheric pressure, the flame height and pressure are proportional according to $H \propto P^{1.299-0.01\theta}$.

Acknowledgements

This work was supported by the National Key Research and Development Program of China (No. 2017YFC0803300), the National Natural Science Foundation of China (No. 51506059), the Educational Commission of Anhui Province of China (KJ2017A499), and the Huaqiao University Scientific Research Foundation of China (No. 16BS801). The authors gratefully acknowledge all these supports.

References

[1] J.L. De Ris, A.M. Kanury, M.C. Yuen, Pressure modeling of fires, Proc. Combust. Inst. 14 (1973) 1033–1042.

[2] J.L. De Ris, P.K. Wu, G. Heskestad, Radiation fire modeling, Proc. Combust. Inst. 28 (2000) 2751–2759.
[3] J.M. Most, P. Mandin, J. Chen, P. Joulain, D. Durox, A.C. Fernandez-Pello, Influence of gravity and pressure on pool fire-type diffusion flames, Proc. Combust. Inst. 26 (1996) 1311–1317.
[4] D. Wieser, P. Jauch, U. Willi, The influence of high altitude on fire detector test fires, Fire Safety J. 29 (1997) 195–204.
[5] R. Tu, Y. Zeng, J. Fang, Y.M. Zhang, The influence of low air pressure on horizontal flame spread over flexible polyurethane foam and correlative smoke productions, Appl. Therm. Eng. 94 (2016) 133–140.
[6] X. Ma, R. Tu, Q.Y Xie, Study on downward flame spread behavior of flexible polyurethane board in external heat flux. J. Thermoplast. Compos. 28 (2015) 1693–1707.
[7] Q.Y. Xie, S.F. Luo, A quantitative model and the experimental evaluation of the liquid fuel layer for the downward flame spread of XPS foam, J. Hazard. Mater. 329 (2017) 30–37.
[8] J.H. Gong, Influences of low atmospheric pressure on downward flame spread over thick PMMA slabs at different altitudes, J. Heat Mass Tran. 61 (2013) 191–200.
[9] J. Kleinhenz, I.I. Feier, S. Hsu, et al., Pressure modeling of upward flame spread and burning rates over solids in partial gravity, Combust Flame. 154 (2008) 637–643.
[10] F. Tang, L.H. Hu, Heat flux profile upon building facade due to ejected thermal plume from window in a subatmospheric pressure at high altitude, Energ. Building. 92 (2015) 331–337.
[11] F. Tang, Mean flame height and radiative heat flux characteristic of medium scale rectangular thermal buoyancy source with different aspect ratios in a sub-atmospheric pressure, J. Heat Mass Tran. 84 (2015) 427–432.
[12] W. Mell, T. Kashiwagi, Dimensional effects on the transition from ignition to flame spread in microgravity, in: 27th Symposium (International) on Combustion, Boulder, CO, 2–7 August 1998, pp. 2635–2641. Amsterdam, The Netherlands: Elsevier Inc.
[13] L. J, J. J, Y. Zhang, et al. Characteristics of flame spread over the surface of charring solid combustibles at high altitude, Chin. Sci. Bull. 54 (2009) 1957–1961.
[14] J. Quintiere, M. Harkleroad, Y. Hasemi, Wall flames and implications of upward flame spread, Combust. Sci. Technol. 48 (1986) 191–222.
[15] W.G. An, Effects of sample width and inclined angle on flame spread across expanded polystyrene surface in plateau and plain environments, J. Thermoplast. Compos. 28 (2015) 111–127.
[16] W.G. An, Thermal and fire risk analysis of typical insulation material in a high elevation area: Influence of sidewalls, dimension and pressure, Energ Convers Manage. 88 (2014) 516–524.
[17] British Standard EN54-7, Fire Detection and Fire Alarm Systems, Part 7: Smoke detectors – Point detectors using scattered light, transmitted light or ionization, 2001.
[18] R. Tu, Low air pressure effects on burning rates of ethanol and n-heptane pool fires under various feedback mechanisms of heat, Appl. Therm. Eng. 99 (2016) 545–549.
[19] Magee Mc alevy, Flame spread over fuel beds: solid-phase energy considerations, Proc. Combust. Inst. 17(1971) 935–948.
[20] M. Luo, Effects of Radiation on temperature measurement in a fire environment, J Fire Sci. 15 (1997) 443–461.
[21] E. Zukoski et al., Entrainment in fire plumes, Fire Safety J. 3 (1983) 107–114.
[22] E. Zukoski, et.al. Mass Flux. IAFSS[M]. Fire Safety Science, in: Proceedings of the 4th International Symposium, Ottawa, 1994.
[23] M. Delichatsios, B. Paroz, A. Bhargava, Flammability properties for charring materials, Fire Safety J. 38 (2003) 219–228.
[24] B.M. Cetegen, T.A. Ahmed, Experiments on the periodic instability of buoyant plumes and pool fires, Combust Flame. 93 (1993) 157–184.