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Experimental study on the characteristics of horizontal flame spread over XPS surface on plateau

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ABSTRACT

A series of comparative laboratory-scale experiments were carried out in the Lhasa plateau and the Hefei plain respectively to investigate the characteristics of flame spread over the extruded polystyrene (XPS) foam, a typical thermal insulation material. Flame shape and the temperature profile in solid phase were monitored, and the effects of altitude on the heat transfer process were analyzed. The results show that the temperature rise with time undergoes three stages: the preheating stage, the melting stage and the pyrolysis stage. The durations of the melting and pyrolysis stages on plateau are longer than that in plain, which sequentially results in a lower flame spread rate on plateau. Comparing of the temperature change rate curve on plateau with that in plain, it is found that the peak characteristics of the curves in the pyrolysis stage changed from single peak to multi-peaks, which suggests that the altitude difference might change the pyrolysis mechanisms of XPS material. Moreover, the sample scale effects on flame spread are also explored. Two different regimes are found in flame spread behavior with sample scale at the both altitudes. The spread rate drops with sample scale in convection regime and rises in radiation regime.

1. Introduction

The extruded polystyrene (XPS) foam is a typical thermoplastic material with good thermal insulation performance. Couple with its beauty and light weight, XPS material is widely used in dwellings and office buildings, its thermo-physical properties are listed in Table 1. However, XPS material is easy to melt and be ignited, when exposing any heat. Once ignited, the fire would spread quickly and release lots of heat and toxic smoke. The buildings with XPS material are exposed to fire threat. For instance, a fire disaster happened in the Television Central Culture in February 2009. The fire started from the XPS material ignited by fireworks and it quick spread to the whole building.

Recently, more and more attentions were given to the fire safety of the thermal insulation materials [1–8]. Doroudian and Omidian [1] studied the hazards of expanded polystyrene (EPS) material in building fires, and proposed that the most dangerous factors are its toxic smoke and quick flame spread. The combustion products of polystyrene (PS) and its smoke generation characteristics were explored by Rossi and Camino [2] and Ergut and Levendis [3]. The methods of flammability resistance and flame retardant of PS were explored by Wang et al. [4], Morgan et al. [5,6] and Cipiriano et al. [7], in order to restrict the flame spread over PS surface.

The previous researches mainly focused on the smoke generation characteristics and the flame retardant method. Few researches about flame spread characteristics of thermoplastic were reported. Actually, flame spread over solid surface is a very common and important phenomenon in fires. Its development would result in the increasing of fire scale, and consequently bring more fire hazards. XPS material would not contribute a continue fire, because of its low density and insufficient available mass. Nevertheless, it is easily heated to melt and ignited. The melting and flowing behaviors would benefit to the flame spread [8] and ignite the surrounding inflammable materials, e.g., wood furniture and curtains. Moreover, the rate of horizontal flame spread is an important parameter to classify the flammability of materials. Therefore to carry out the studies on horizontal flame spread over XPS surface is helpful to understand its flammability and predict the development of flame spread.

Wang et al. [9] and Li et al. [10] experimentally studied the fire behaviors of charring material wood on plateau. They suggested that the ignition time of wood on plateau would be shorter and its flame temperature is lower, which means that fires on plateau might be easier to occur and more dangerous. However, experimentally study on the flame spread over thermoplastic materials on plateau is still very scarce. Therefore, to carry out experimental study on flame spread over XPS surface at high altitude can provide basic data and benefit to fire control and fighting on plateau.

A series of laboratory-scale experiments were carried out in the Lhasa plateau (in China, at the altitude of 3658 m) in this study, and

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Table 1
Thermophysical properties of XPS material.

Material	Density (kg/m^3)	Specific heat (J/kg K)	Conductivity (W/m K)	Melting temperature (°C)	Pyrolysis temperature (°C)
XPS	36	1400	0.028	200	350–400

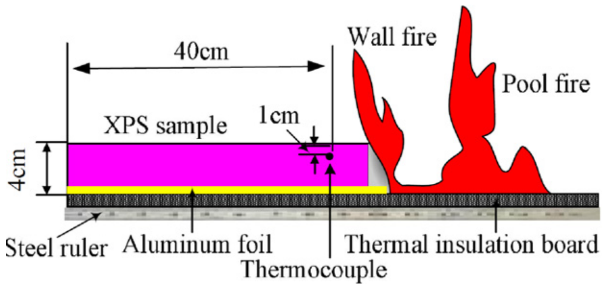

Fig. 1. Schematic of flame spread over XPS surface.

comparison experiments were also carried out in the Hefei plain (in China, at the altitude of 50 m) to investigate the altitude effects on the characteristics of flame spread over XPS surface. In order to apply experimental results in laboratory scale for the control of actual fires in full scale, flame spread experiments with various sample width were also performed in this paper to study the scale effects.

2. Experimental apparatus and methods

Comparative experiments in laboratory scale were carried out in the Lhasa plateau and the Hefei plain respectively. The experimental ambient conditions of two locations are listed in Table 2.

In order to investigate the scale effects on flame spread, a series of experiments with various sample width were also conducted. The XPS samples are 80 cm in length, 4 cm in thickness, and their width varies from 4 cm to 16 cm with 4 cm intervals. Considering the melting and flowing properties of XPS material in flame spread, the rear surface of XPS sample was wrapped by very thin aluminum foil. An aluminum foil trough was formed to hold the melted XPS. The sidewall of the trough is 5 mm high, as shown in Fig. 1. For the simulation of insulation boundary condition at the rear surface, a thermal insulation board was installed at the bottom of XPS sample.

Flame behaviors were monitored from the side view by a digital camera (DV) with a frequency of 25 frames per second. The characteristic parameters of flame shape (e.g. flame front position, pool fire length) could be obtained by image processing. A horizontal steel ruler was fixed on the thermal insulation board. The ruler is used to locate the positon of flame front, and determine the scale of pictures. A sheathed k-type thermocouple was mounted in the interior of XPS sample to measure the temperature profile in solid phase. Its diameter is only 0.5 mm and it have an excellent performance on response, with a response time of 0.03 s. The temperatue measure range is −200–600 °C, with an accurary rating of 2.2 °C. The thermocouple locates at the center line of sample, and 1 cm far away from the upper surface. At the beginning of each test, one end of the XPS sample was ignited by a linear ignitor, and then remove the ignitor. The linear ignitor is cast iron and drilled port continuous line burners with alloy side rails, which could produce a line flame. The side rails could improve flame retention. The ignitor is corrected with a natural gas cylinder in our study. The ignition duration is about 15–20 s.

3. Results and discussion

3.1. The behaviors of flame spread

Fig. 2 shows the behaviors of flame spread over XPS surface with different sample width on plateau. XPS sample in flame spread includes two zones: flame zone and unburned zone. The flame zone consists of wall fire and pool fire. At the initial stage (10 s after ignition), the scale of fire is small, and only wall fire was observed. There is no flame except at the surface in the sample depth direction. With time going on, more XPS material is heated, softened, melted and changed into liquid. One part of the liquid XPS adheres to the wall surface due to the viscosity effects. Most of them drop or flow down into the aluminum foil trough because of the gravity effects. The liquid XPS material continues to be heated to degrade and burn, and eventually a pool fire come into being. The heat released from the pool fire fed back to the unburned XPS material, and caused more XPS melt and feed into the pool fire zone. The loop mechanism between them maintained the flame spread forward.

It could be obviously observed that the length of pool fire increased with time in Fig. 2. In addition, it should be given attention to the generation of toxic smoke. For the XPS fire with larger scale ($W = 12$ cm and 16 cm), the visibility in the room decreased with time. At $t = 180$ s after ignition, nothing in the room can be seen except the flame. The flame color changes from the bright white to faint yellow, which is the result of more flame radiation heat loss due to lots of soot generation.

Comparing the flame spread behaviors over XPS surface under different sample width at the same time, it is found that flame front propagated farther and the pool fire is longer with wider sample on the whole. However, the flame spread behavior at $W = 8$ cm does not follow this change law. Compared with that under $W = 4$ cm, the flame front under $W = 8$ cm located behind at the same time, and the pool fire length is also smaller.

Similar flame spread behaviors over XPS surface were also observed in plain. In order to quantitatively analyze flame spread behaviors, the position of flame front and the length of pool fire were obtained by image processing to the picture sequences of flame spread. The results at $W = 12$ cm are shown in Fig. 3, taken as an example.

It was found in Fig. 3a that the positions of flame front on plateau and in plain both increase with time in a linear way. The increase rate on plateau is smaller than that in plain. That is, flame spread slower on plateau, on account of the change rate of flame front position represents the rate of flame spread.

As Fig. 3b shows, the length of pool fire increases with time. The change rate of pool fire length on plateau is lower than that in plain, which could be directly explained with the flame spread rate. The pool fire length $l_p = (v_f - v_b)t$, where v_f is flame spread rate, and

Table 2
Ambient conditions of experiments on plateau and in plain.

Location	Altitude (m)	Atmospheric pressure (kPa)	Absolute oxygen concentration (kg/m^3)	Relative humidity (%)	Ambient temperature (°C)
Lhasa plateau	3658	65.5	0.175	27–30	25–30
Hefei plain	50	100.8	0.269	36–39	23–26

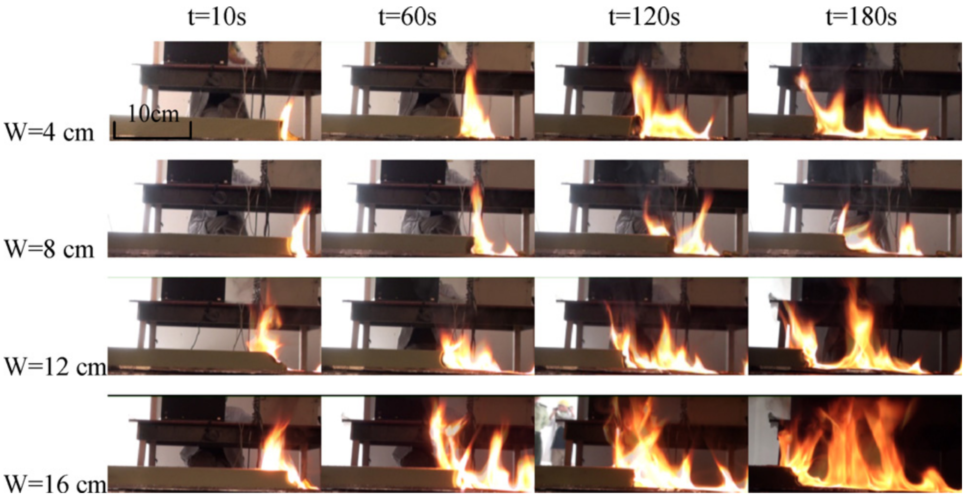

Fig. 2. Typical sequences of flame spread with different sample widths on plateau.

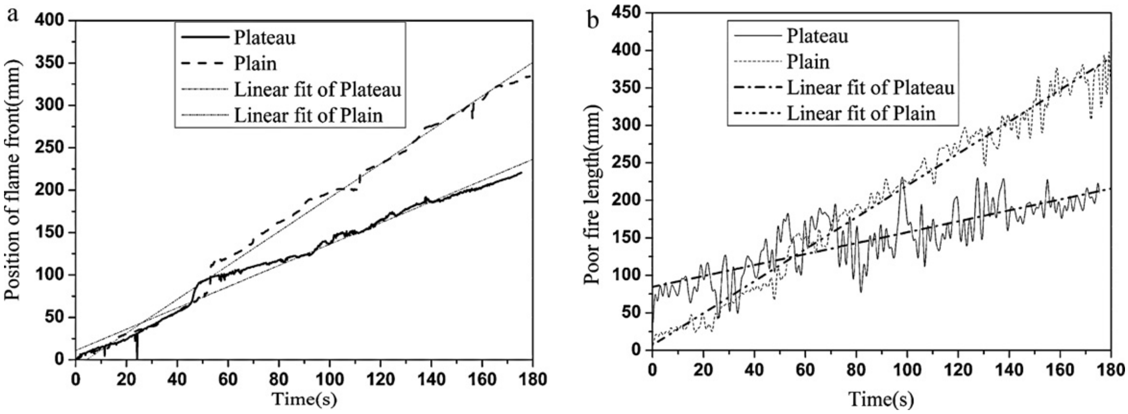

Fig. 3. Time evolutions of flame spread characteristics at $W = 12$ cm on plateau and in plain: (a) the positon of flame front; (b) the length of pool fire.

v_b is the burn out rate. Since the rate of flame spread on plateau is lower, the change rate of l_p is smaller too.

The rates of flame spread on plateau and in plain with other sample width were also obtained using the above method, and the results are presented in Fig. 4.

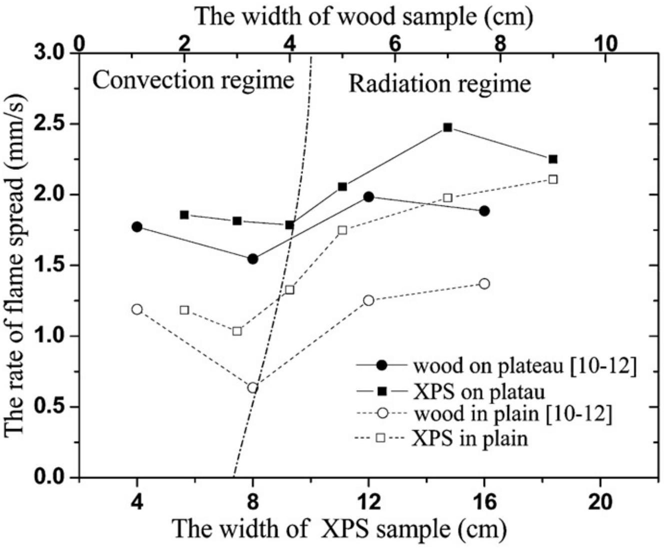

Fig. 4. The behaviors of flame spread rate with sample width on plateau and in plain.

It was found that flame spread rate on plateau is lower than that in plain at the same sample width. The altitude effects on flame spread over charring material (wood) surface were explored by Li and Zhang et al. [10–12], and their results were presented in Fig. 4 too. The results also showed that the flame spread rate on plateau is lower than that in plain under the same sample width. This agreement with our results suggested that the lower pressure and absolute oxygen on plateau restricts the flame spread over thermoplastic material (XPS) as well as charring material (wood).

According to the pressure scaling rule proposed by Corlett and Luketa-Hanlin [13], the burning rate of a solid fuel can be correlated to the ambient pressure p by

$$\frac{\dot{m}''_{\text{plateau}}}{\dot{m}''_{\text{plain}}} = \left(\frac{p_{\text{plateau}}}{p_{\text{plain}}}\right)^{2/3} \tag{1}$$

where $\dot{m}''_{\text{plateau}}$ and $\dot{m}''_{\text{plain}}$ are the burning rates on the plateau and plain respectively, and p_{plateau} and p_{plain} are the ambient pressures on the plateau and plain respectively. The burning rate on the plateau is smaller corresponding to the lower ambient pressure. Since the larger burning rate means the larger energy release rate and flame spread rate is positive related to the burning rate generally, so the flame on the plateau would spread slower.

As sample width increases, flame spread rate drops firstly and then rises at both altitudes, which is in agreement with the behaviors of flame spread shown by the picture sequences in Fig. 2. Below a sample width of 8 cm, flame spread rate decreases with sample

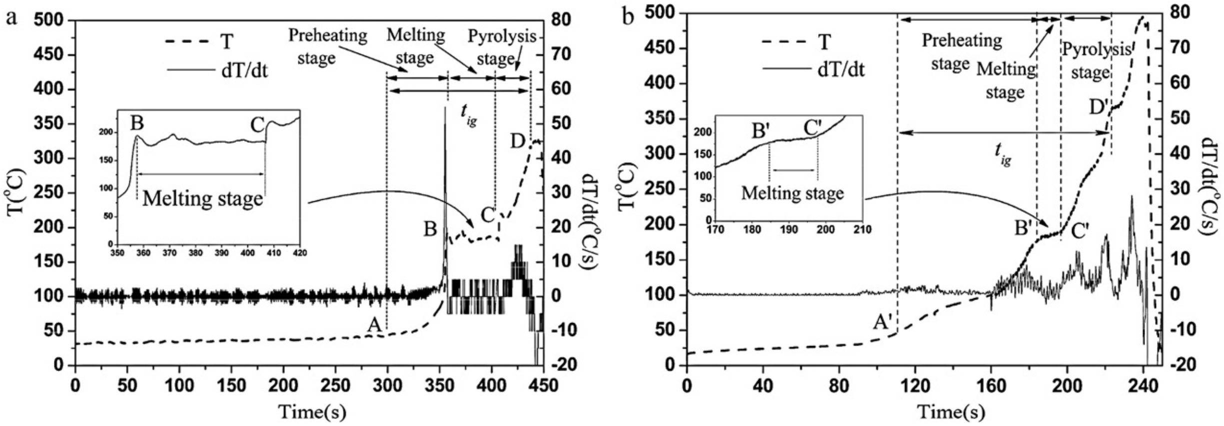

Fig. 5. Comparion of temperature profiles in solid phase at W = 12 cm for: (a) on plateau and (b) in plain.

width. Further increase in sample width would raise the rate of flame spread rate. The change of flame spread rate becomes slowly when sample width increases from 12 cm to 16 cm. The similar flame spread behaviors with sample width were also found by Li and Zhang et al. [10–12] in the experiments over charring material. As Fig. 4 shows, the turning point at which the flame spread rate is smallest was also observed in the curves of wood on plateau as well as in plain. This turning point for wood case occurs around the width of 3–4 cm, rather than 8 cm for XPS case.

3.2. The analysis on temperature profile

Flame spread over XPS surface is the processes that the unburned materials are heated by the energy from the combustion zone and ignited in essential. Analysis on the temperature profile of XPS in solid phase and the heat transfer process is useful to understand the flame spread.

Fig. 5a shows the typical change curves of temperature in solid phase and its change rate with time on plateau. The rise stage of temperature includes three stages: the preheating stage (AB stage), the melting stage (BC stage) and the pyrolysis stage (CD stage). As the flame propagates forward and the pyrolysis front gets closer to the thermocouple, the temperature at the measuring point rises slowly. After the pyrolysis front closed to the measuring point sufficiently (Point A), the temperature rises sharply until the melting temperature (about 200 °C) of XPS is reached (Point B). This stage (AB stage) lasts 58 s, corresponding to the preheating stage. Beyond Point B, a little temperature drop happens, and then the temperature retains in the range of 190–200 °C. This temperature platform lasts 38 s. This stage corresponds to the melting stage. After the temperature of XPS reaches the melting temperature, XPS melts and the temperature would drops slightly due to the endotherm of phase change, and then retains in the range of 190–200 °C until the end of the melting process (Point C). After Point C, the liquid XPS is still heated by the combustion zone and degraded, and the temperature continues to rise. This stage (CD stage) is the pyrolysis stage, which lasts 33 s.

Fig. 5b shows the curves of temperature profile and its change rate in plain. Similar with that on plateau, the temperature rise process in plain also undergoes three stages: the preheating stage (A′B′ stage), the melting stage (B′C′) and the pyrolysis stage (C′D′). Comparing with the temperature curve on plateau, the temperature drop is because that melting stage does not show obvious melting endotherm in plain. In addition, the duration of the melting stage t_m = 15 s in plain is much smaller than the value of 38 s on plateau, and the duration of the pyrolysis stage t_{py} = 27 s is also smaller than the value of 33 s on plateau. However, the duration of the preheating stage t_{ph} = 70 s is larger than the value of 58 s on plateau, which could be directly explained by the change rate of temperature in preheating stage. A very sharp peak was observed in the curve of temperature change rate on plateau, while the peak in plain is much gentler.

In addition, it could be deduced that the difference of ambient condition on plateau and in plain might have changed the mechanisms of XPS pyrolysis from the curve of temperature change rate. There is only a single peak in the pyrolysis stage on plateau and the temperature rise continually. For the pyrolysis of XPS in plain, two peaks were found in the pyrolysis stage, and the temperature in pyrolysis process shows a multi-sections rise behavior.

The analysis above suggests that the change of altitudes exerts major influences on the melting and pyrolysis of XPS material in flame spread. More time would be paid for the melting and pyrolysis processes. Therefore, the ignition time t_{ig} (the overall duration of the preheating, the melting and the pyrolysis stages) in flame spread on plateau is larger than that in plain. This might be the reason of that flame spread rate on plateau is lower.

Similar temperature profiles were also found with other sample width. The same processing was also used to them, and some key characteristics parameters of flame spread with different sample widths were obtained. The results are listed in Table 3.

Comparing the data at the same sample width on plateau with in plain, it was found that the maximum change rate of temperature $(\mathrm{d}T/\mathrm{d}t)_{\max}$ on plateau is larger. The duration of the preheating stage is shorter on plateau correspondingly. However, the ignition time is larger on plateau than that in plain, which results from that the

Table 3
Some key characteristic parameters of flame spread with different sample widths.

W (cm)	Plain	Plateau									
	t_{ig} (s)	t_{ph} (s)	t_m (s)	t_{py} (s)	δ_{ph} (cm)	$(\mathrm{d}T/\mathrm{d}t)_{\max}$ (°C/s)	t_{ig} (s)	t_{ph} (s)	t_m (s)	t_{py} (s)	δ_{ph} (cm)	$(\mathrm{d}T/\mathrm{d}t)_{\max}$ (°C/s)
4	80	45	13	22	7.97	50	87	40	24	23	4.76	60
8	91	48	17	26	7.42	37.8	100	44	29	27	2.8	53
12	112	70	15	27	13.89	26.9	129	58	38	33	7.26	50
16	119	76	14	29	14.33	21.4	138	66	36	36	9.04	47

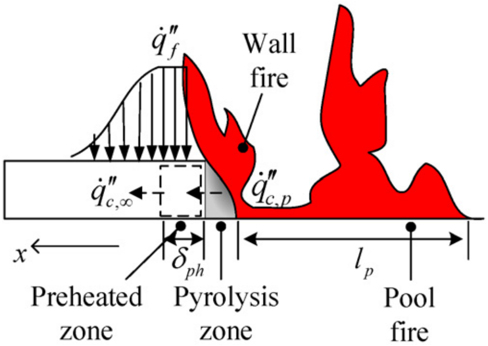

Fig. 6. Illustration of heat transfer processes in flame spread over XPS surface.

durations of the melting stage and the pyrolysis stage is much larger on plateau. The preheating length $\delta_{ph} = V_f t_{ph}$ on plateau is much smaller than that in plain, which results from the lower burning rate on plateau and the less heat feedback from the flame to the solid surface. It's known that the flame spread rate is directly related to the preheating length: a longer preheating length leads to a faster spread rate. Thus, the flame spread rate on plateau is lower than that in plain.

As sample width increases, the maximum temperature change rate shows a drop tendency at both altitudes, and the ignition time shows a rise tendency correspondingly. This might be explained by that the increasing of sample scale means that more heat transfer from the combustion zone to the unburned zone should be provides to maintain the temperature rise. The development of the preheating length is in agreement with the rate of flame spread. They both drop firstly and then rise with sample width.

3.3. *The analysis on heat transfer process*

In order to study the sample scale effects on flame spread, it's necessary to analyze the heat transfer process. The heat transfer model in flame spread over XPS surface is illustrated in Fig. 6.

The preheated zone was chosen as the control volume, and the control volume was fixed at the position of the pyrolysis front. The heat transfer between the control volume and the surrounding mainly consists of: the heat flux of flame $\dot{q}''_f$ to the upper surface (including the convection component $\dot{q}''_{fc}$ and the radiation component $\dot{q}''_{fr}$), the heat flux $\dot{q}''_{c,p}$ of solid phase conduction from the pyrolysis zone, the conduction flux $\dot{q}''_{c,\infty}$ from the control volume to the further XPS material and the heat loss $\dot{q}''_{loss}$ from rear surface. Considering of the thermal insulation condition of rear surface, we can set $\dot{q}''_{\mathrm{loss}} = 0$. In addition, the temperature of XPS far away from the preheated zone changes slowly with x ($\partial T/\partial x \approx 0$), we can set $\dot{q}''_{c,\infty} \approx 0$. Based on the analysis above, the following energy balance equation could be established:

$$\rho c_p (T_m - T_\infty) d v_f = \dot{q}''_f \delta_{ph} + \dot{q}''_{c,p} d \qquad (2)$$

where ρ and c_p are the density and specific heat of XPS material respectively, T_m and T_∞ are the melting temperature of XPS material and the ambient temperature respectively, and d is the thickness of XPS sample. The heat conduction in solid phase can be obtained by the temperature change rate, as predicted in Eq. (3).

$$\dot{q}''_{c,p} d = k\left(\frac{\partial T}{\partial x}\right)_{\max} d = kd\frac{(\partial T/\partial t)_{\max}}{v_f} \qquad (3)$$

where k is the conductivity of XPS material. Typically, the heat flux of flame to the preheated zone is almost constant [14]. The heat flux to the surface of the preheated zone could be predicted by the following equation [15]:

$$\Delta T_s = (\dot{q}''_f/h)\{1 - \exp[h^2 t/(k\rho c)]erfc[h(t/(k\rho c))^{1/2}]\} \qquad (4)$$

where $h = 25$ W/m K [15], is the global heat transfer coefficient, which equals to the convection plus the linearized radiation. T_s is the solid phase temperature. t is the time, and $t = 0$ is set at the time the pyrolysis front reaches the measuring point. The temperature rise $\Delta T_s = T_m - T_\infty$, near the pyrolysis front. Therefore, Eq. (4) could be rewritten into the following form.

$$\dot{q}''_f \delta_{ph} = h(T_m - T_\infty)\delta_{ph} \qquad (5)$$

The thermal insulation performance of XPS material is very good, and its conductivity is very small. The heat transfer in solid phase is relatively small compared to the heat transfer in gas phase. This could be illustrated by the heat transfer at $W = 12$ cm on plateau, taken as an example. In this case, the heat transfer in solid phase is 15.2 W/m, which is much smaller than the value of 634 W/m in gas phase. Thus, the flame spread over XPS surface is dominated by the heat transfer process in gas phase.

The heat transfer in gas phase from flame to the preheated zone consists of two components: the convective component and the radiative component. The entrainment between flame and air is relatively stronger with smaller scale samples, and the convection effects are also stronger. Quintiere [14] suggested that the convection coefficient follows the relationship for the pool fire with the effective diameter $D < 25$ cm:

$$h_c \propto D^{-1/4} \qquad (6)$$

With sample scale increases, the scale of combustion zone and the flame size increase. On one hand, the view factor of flame to the unburned zone becomes larger because of the larger flame size. On the other hand, the emissivity of flame ε_f also increases with sample scale, as predicted by Eq. (7) [14]:

$$\varepsilon_f \approx 1 - \mathrm{e}^{-\kappa D} \qquad (7)$$

where κ is the emission coefficient. Thus, the flame radiation to the unburned zone would increase with sample scale.

As mentioned above, the radiative component rises with pool scale while the convective component drops. The same conclusion can also be deduced from the scaling laws theory [14]. Preserving the convection and radiation yields $\dot{q}''_f \sim D^{-1/4}$ in convection dominant regime and $\dot{q}''_f \sim D$ for the optically thin case (κD is small) or $\dot{q}''_f \sim D^0$ for the optically thick case (κD is large). Modak and Croce [16] measured the convective and radiative components in PMMA (plexiglass) pool fires with different scales, and indicated that convection drops with scale and radiation increases. Emori and Saito [17] experimentally studied pool fire under optically thick conditions, and their results follow $\dot{q}''_f \sim D^0$.

The different behaviors of flame spread rate with sample width (as shown in Fig. 4) suggest that the flame spread is dominated by two different heat transfer regimes. When sample is narrow ($W < 8$ cm), the convection is dominant. The heat flux to the unburned surface decreases with sample width, and correspondingly, flame spread rate drops with sample width. When sample is wider than 8 cm, the radiation is dominant. The heat flux increases with sample width, and correspondingly, flame spread rate rises with sample width, and the rise becomes more and more slowly.

4. Conclusions

In this work, the characteristics of flame spread over XPS surface were experimentally studied respectively on plateau and in plain. The flame shape and the temperature profile in solid phase were monitored. Further, the flame spread rate, the temperature change rate, the durations of the preheating stage, the melting stage and the pyrolysis stage were obtained. Based on these data, the effects of the altitude and sample scale on the flame spread and the heat transfer process were analyzed. The conclusions are summarized as follows:

(1) In the temperature rise process of flame spread over XPS surface, three stages are undergoing both on plateau and in plain. The three stages are the preheating stage, the melting stage and the pyrolysis stage. The ambient conditions difference between the two altitudes indeed exerts influences on the three stages.
    (a) The preheating stage: the maximum temperature change rate in the preheating stage on plateau is much larger than that in plain, and correspondingly the duration of the preheating stage on plateau is shorter.
    (b) The melting stage: a temperature drop near the melting point in the temperature profile curve was observed on plateau, because of the endotherm of melting. However, the temperature drop was not found in plain. The duration of the melting stage is much shorter than that on plateau.
    (c) The pyrolysis stage: different behaviors of temperature rise in the pyrolysis stage were found on plateau and in plain. The temperature rises continually on plateau, and only a single peak was found in the curve of temperature change rate in the pyrolysis stage. However, multi-peaks were found in the curve of temperature change rate in plain, and the temperature rises with multi-sections. The duration of the pyrolysis stage on plateau is longer.

(2) The rate of flame spread on plateau is lower than that in plain, since the lower pressure and absolute oxygen concentration on plateau obviously increases the durations of the melting stage and the pyrolysis stage.

(3) Base on the analysis of heat transfer, it is suggested that the teat transfer in gas phase is the dominant mechanism in flame spread over XPS surface. Different scale effects were found in the flame spread behaviors with sample width. It suggests that the flame spread at different widths is dominated by two different heat transfer regimes. Below a sample width of 8 cm, flame spread is dominated by convection regime. The rate of flame spread decreases with sample width. When sample is wider than 8 cm, the radiation heat transfer is dominant. The rate of flame spread rises with the increasing sample width, and the rise becomes more and more slowly.

Acknowledgments

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