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Heat transfer mechanisms in horizontal flame spread over wood and extruded polystyrene surfaces

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ABSTRACT

The heat transfer in horizontal flame spreading over the surface of construction materials was experimentally investigated at two different altitude conditions (the Lhasa plateau 3658 m, and the Hefei Plain, 50 m). The experiments were carried out with the charring material Whitewood and the thermoplastic material the extruded polystyrene (XPS) over a wide range of sample widths. The temperature profile in solid phase was measured. Different flame spread behaviors were found from the temperature profiles of the XPS and Whitewood. The XPS undergoes the melting stage in the preheated stage while the Whitewood undergoes the char burning stage after the pyrolysis stage. The heat transfer analysis suggests that the gas phase heat transfer is dominant for whitewood and XPS, even though the XPS is thermally thick. The flame spread rate and the surface heat flux with various sample widths were measured. They both dropped firstly and then rose with the increasing sample width. Furthermore, the spread rate was correlated with a pseudo-property Φ, which is the product of the surface heat flux and the preheated length. A good linear relationship was found between the spread rate and Φ, which agrees well with Quintiere's model. Moreover, the sample width effects on flame spread rate were well explained by the effects on heat transfer. The horizontal flame spread behaviors with sample width were dominated by two different regimes: the spread rate drops for small sample width in convection regime but rises for large sample width in radiation regime.

1. Introduction

Flame spread over construction material surfaces is very common in building fires. It causes the increase of the combustion area as well as the fire scale, and brings more threats to building safety. Extruded polystyrene (XPS) foam is a very good thermal insulation material and the most common used in the industry for energy saving. XPS foam insulation is based on polystyrene resin and is considered to be closed cell rigid foams. XPS is manufactured as a code-compliant insulation material. Wood is a common structure and decoration material, especially in the historic buildings, such as the Potala Palace in the Tibetan Plateau of China. However, these two construction materials are combustible (Table 1). There is always a concern on the potential fire hazards in using them in buildings. Upon ignition, flame might spread rapidly over their surface, and result in fire growth and fire disaster, e.g. the TVCC (Television Central Culture) fire in China in 2009.

Presently, much attention has been given to the flame spread behaviors over solid surfaces [1–10]. However, few studies were conducted on the plateau, and very limited information on the surface flame spread in the plateau is available in previous researches. In recent years, some burning behavior tests of wood were conducted on plateau, and results showed that the combustion temperature of flame on plateau [11] might be higher than that in plain and the ignition time [12] might be shorter, which suggested that fire on plateau might be more potential hazardous. Therefore, experimental studies are necessary to be carried out on the flame spread behaviors in the plateau. That would provide some accurate experimental flame spread data for predicting the fire development in the plateau, and benefit fire control and fire prevention in the plateau.

The central process in surface flame spread is heat transfer from the burning region of the fuel to the virgin material, which includes conduction through the solid, convection through the gas ahead the flame and radiation from flame. An understanding of dominant heat transfer mode will facilitate the development of reasonable simplified and accurate model of flame spread. For thermally thick materials, the dominant mode is conduction through the solid [13]. Quintiere [14] indicated that the heat transfer through the gas is

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Table 1
Thermo-physical properties of whitewood and XPS.

Material	Density (kg/m^3)	Specific heat (J/kg K)	Conductivity (W/m K)	Ignition temperature (°C)
XPS	36	1400	0.028	360
Whitewood	510	1380	0.12	385

Table 3
Summary of experimental scenarios.

Test series	Sample material	Location	Sample width (cm)
1	Whitewood	Lhasa	2, 3, 4, 5, 7, 9, 11
2	Whitewood	Hefei	2, 3, 4, 5, 7, 9, 11
3	XPS	Lhasa	4, 8, 12, 16
4	XPS	Hefei	4, 8, 12, 16

dominant in flame spread over thermally thin material, and proposed a simplified model. However, the conduction through the thermal insulation materials is very small, even though it is thermally thick. Thus, it is valid to presume Quintiere's model might be applicable for the thermal insulation materials rather than a thermally thick model.

In this paper, comparative experiments were conducted in the Lhasa plateau and in Hefei plain with flat sheets of Whitewood 3 mm thick (thermally thin fuel) and XPS 40 mm thick (thermally thick fuel) over a range of sample widths. The rate of spread, surface heat flux and especially the solid temperature profile were investigated. The dominant mode of heat transfer was discussed for flame spreading over the two materials, and the flame spread rate were correlated with the product of surface heat flux and the preheated length. The results agree well with the results predicted by Quintiere's model. Moreover, the altitude effects and the sample effects on flame spread behaviors were well explained by the heat transfer. These results are very useful for better understanding the scale effects and predicting the flame spread behaviors in real fires in the plateau.

2. Experimental apparatus and methods

Flame spread behaviors over Whitewood and XPS surfaces were experimentally investigated in the Lhasa plateau and the Hefei plain. Lhasa is the capital city of China's Tibet Autonomous Region, and its altitude is 3658 m. Hefei is the capital city of Anhui Province with an altitude of 50 m. Their ambient conditions are listed in Table 2.

Fig. 1 shows schematically the flame spread behaviors over Whitewood and XPS Surfaces. The Whitewood sample is 400 mm long and 3 mm thick (thermally thin), and the XPS is (800 mm long and 40 mm thick (thermally thick). Samples with various widths were tested in the Lhasa plateau and the Hefei Plain. A summary of these test conditions including the location and the sample width is presented in Table 3. Each test at the same condition was repeated 2–3 times to minimize experimental errors. 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. For the simulation of insulation boundary condition at the rear surface, a thermal insulation board was installed at the bottom of sample.

Flame spread behavior was monitored and recorded by a digital video camera (Sony, HDR-XR200V) with a data acquisition frequency of 25 frames per second. The rate of flame spread could be obtained from the video information. A sheathed k-type thermocouple was mounted in the interiors of the whitewood and XPS samples to measure the temperature profile in the solid phase. Its diameter is only 0.5 mm and it has an excellent performance on response, with a response time of 0.03 s. The temperatue measuring range is −200–600 °C, with an accurary rating of 2.2 °C. For whitewood, the thermocouple located 30 cm far away from the ignited end and 1 mm underneath the upper surface (Fig. 1a); for XPS, the thermocouple located 40 cm far away from the ignited end and 10 mm underneath its upper surface (Fig. 1b).

A heat flux meter (TS30), whose depth is 0.4 mm, is mounted at the upper surface to measure the surface heat flux from flame. Its measuring range is from 0 to 200 kW/m^2, and its uncertainty is less than 3%. To minimize its disturbing to flame spreading, the heat flux meter located at the other end far away from the ignited end and was removed away when the flame front reached it, because it cannot work at the temperature higher than 200 °C. The XPS at the location of the meter would be soften and melted when the flame propagates closed to it, and it might drop into the pool fire, which is fatal to the meter. Therefore, the XPS surface heat flux was not monitored.

3. Reslults and discussions

3.1. The behaviors of flame spread

Fig. 2 shows the flame spread behaviors over whitewood and XPS surfaces under W = 40 mm. Some different behaviors of flame

Table 2
Ambient conditions of experiments at the two locations.

Location	Altitude (m)	Atmospheric pressure (kPa)	Absolute oxygen concentration (kg/m^3)	Relative humidity (%)	Ambient temperature (°C)
Lhasa plateau	3658	65.5	0.25	27–30	25–30
Hefei plain	50	100.8	0.39	36–39	23–26

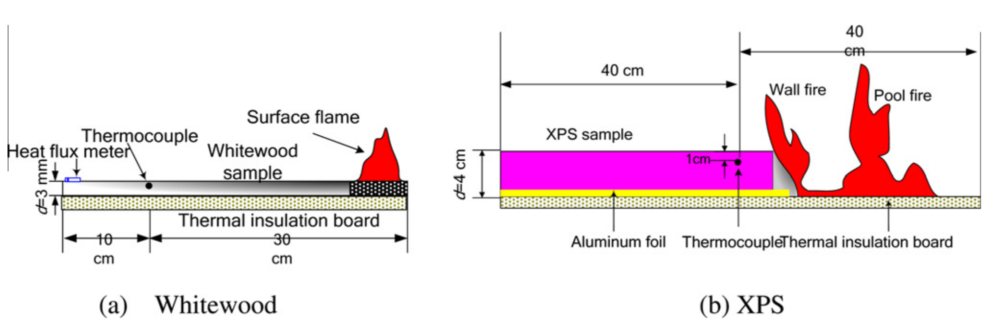

Fig. 1. Illustrations of flame spread over solid surfaces.