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Experimental investigation on downward flame spread over rigid polyurethane and extruded polystyrene foams

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ABSTRACT

With the development of social economy and architectural aesthetics, flame spread over exterior thermal insulation system in real high-rise building fire disasters often features inclined downward or upward propagation, however most developed models for flame behavior prediction only assume absolute vertical or horizontal direction. Some researchers have explored the behavior of inclined upward flame spread for its quick development and hazardous characteristics. However, for downward flame spread over plastic polymers, theirs flame spread characteristics can also feature a special hazardous configuration, especially for porous and thermoplastic polymers. In this study, the orientation effects during inclined downward flame spread processes were thoroughly investigated by experimental and theoretical methods. Two kinds of typical thermal insulation materials were selected, rigid polyurethane (RPU) and extruded polystyrene (XPS) foams. The mass flow rate and flame spread rate at different inclination angles were obtained and analyzed. The different flame spread behaviors of RPU and XPS foams were scrutinized. Experimental results show that a linear relationship exists between flame spread rate and cube root of sine of sample inclination angle of RPU and XPS foams when the slope is smaller than a transition angle. The mechanism of orientation effect during the flame spread process was qualitatively analyzed in detail, and simplified expressions of flame spread rate of the two insulation materials with different orientations were deduced. The results of this study have implications concerning the fire safety design of exterior thermal insulation wall.

1. Introduction

With the rapid development of social economy and environmental consciousness in China, many organic polymer materials such as rigid polyurethane (RPU) and extruded polystyrene (XPS) foams are usually utilized as thermal insulation material for building energy conservation due to their low thermal conductivity and density. However, for such kind of organic polymers, there are many fire risks during constructions and applications. For example, the severe building fire accident in China Central Television (CCTV) of Beijing, China, in 2009, which led to a significant damage, was caused by PS foam, and the fire spread from top to bottom made the whole building on fire. Therefore, downward flame spread can also lead to a severe damage in certain circumstance. In many high-rise buildings, the exterior facades are usually inclined or even curved to meet the demands of lighting and beauty, as shown in Fig. 1, and then there must be an inclined flame spread process in the real fire scenarios.

Flame spread over combustible surface plays an important role during the occurrence and propagation of compartment fire. Many aspects of flame spread have attracted extensive attentions, e.g. the issues of upward [1–7] and horizontal [8] flame spread, and the leading edge length problem [9,10]. For downward flame spread over a solid surface with natural convection, it is usually classified as opposed-flow flame spread [11]. Since 1970 s, many researches have been carried out to study this process after de Ris [12], and most of the objects in the studies were cellulose sheets and PMMA slabs [13–16]. Many researchers have also studied the influence of sample thickness on downward flame spread rate. The experimental data of Fernandez-Pello et al. [13], Sibulkin et al. [14], and Bhattacharjee et al. [16] showed that the downward flame spread rate increased first and then kept constant with the thickness increasing. Ayani et al. [17] and Mamourian et al. [18] analyzed the vertical-settled downward flame spread of PMMA experimentally and theoretically. Ayani et al. [17] deduced a relationship between downward flame spread rate and sample depth δ on the basis of Suzuki et al.'s theoretical analysis [19]: Mamourian et al. [18] obtained the conclusions that the solid-phase

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Nomenclature

B	Spalding mass transfer number
c	charring constant
c_p	specific heat (kJ/kg K)
h	heat transfer coefficient (W/m^2 k)
k	thermal conductivity (W/m k)
L	latent heat (kJ/kg)
l_1	length scale for upstream of flame front
$\dot{m}_p$	mass loss rate (g/s)
$\dot{q}_1''$	upstream heat flux (kW/m^2)
$\dot{q}_2''$	external heat flux (kW/m^2)
$\dot{q}_f''$	heat flux of flame (kW/m^2)
r	stoichiometric fuel-to-air-mass ratio
S	fuel area (m^2)
T	temperature (K)
T_s	ambient temperature (K)
v_f	flame spread rate (mm/s)
$\vec{v}_{shrink}$	velocity vector of sample shrinkage
$\vec{v}_{flame}$	velocity vector of flame front
$\vec{v}_{flow}$	velocity vector of flowing molten mass

Greek

α	thermal diffusivity (m^2/s)
δ_c	ratio of pristine solid to thermal diffusivities of char
δ_f	length of preheating zone (m)
δ_g	gaseous heat transfer length (m)
$\delta_{v,s}$	thermal length of solid (m)
$\delta_{v,l}$	thermal length of liquid (m)
ε_s	surface emissivity
θ	inclined angle (°)
ρ	density (kg/m^3)

Subscripts

BL	boundary layer
f	flame
g	gas
l	liquid
m	melting
p	pyrolysis
s	solid
tr	transition
v	vaporization

Fig. 1. High-rise buildings with inclined and curved exterior facades.

temperature gradient decreases with the increasing thickness. The downward flame spread rate they obtained presents the same variation tendency as the research results of [13,14,16].

Besides sample thickness, there are many other factors that might influence the downward flame spread over solid fuels, such as environmental oxygen concentration, external radiative heat flux, airflow rate, sample width and inclination angle. Wu et al. [20] studied the downward flame spread of thermally-thick PMMA slabs under various velocities and temperatures of airflow, and found that the flame spread rate decreases with the increase of additional airflow velocity and airflow temperature. Comas and Pujol [21–23] researched the impacts of various elements on thermally-thin cellulose sheets in detail, such as sample width, thickness, inclination angle, relative oxygen volume fraction, and lateral blockage, and mainly discussed the hydrodynamic instability during downward flame spread with various inclination angles. They also developed a determinate criterion based on Nusselt number and compared it with experimental data. Gong et al. [24] studied the vertically downward flame spread process of PMMA with various thicknesses (3, 4, 5, 6 mm) and atmospheric pressures (1.0, 0.77, 0.67 atm) through corresponding heat transfer analysis, and obtained empirical correlations between flame height, flame spread rate, mass loss rate, environmental pressure, and specimen thickness. Moreover, some scholars [25–29] investigated a number of new factors such as slope and obstruction on flame propagation recently.

This research will seek to find sample sheet orientation effects on inclined downward flame spread predictions, including flame spread rate and mass loss rate during this process. For this investigation, inclined downward flame spread experiments are designed to perform on two kinds of typical thermal insulation materials, rigid polyurethane and extruded polystyrene. The former is thermal-setting porous polymer, and the latter is thermal plastic materials with high flowability, which characteristics are usually ignored in traditional flame spread models but really matter in real fire disasters. Results of this study can provide a systematic approach to evaluate fire hazards of