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Experimental study of the heat flux effect on combustion characteristics of commonly exterior thermal insulation materials

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Abstract

For the sake of examining the heat flux effect on combustion characteristics of commonly exterior thermal insulation materials, the six kinds of exterior thermal insulation materials were tested by the cone calorimeter in this paper included rock wool, adhesive polystyrene granule, phenolic resin, EPS, XPS and RPU. The experimental results showed that the fire risk of different thermoplastic insulation materials arrange in descending order was XPS>RPU>EPS> adhesive polystyrene granule> phenolic resin> rock wool; with the increase of radiation intensity, the heat release peak rate of PS increased and the ignition time and the peak time reduced, the heat release peak rate and the peak time points showed inverse proportion; the peak HRR value of B_2 RPU is 2 times of B_1 RPU and the efficiency of fire retardant of B_1 RPU increases by 37.53 % compared to B_2 RPU.

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Keywords: thermoplastic insulation materials; cone calorimeter; combustion characteristics; heat release rate; ignition time

1. Introduction

According to incomplete statistics[1], from 2007 to the end of 2012, the number of national fires caused by insulation materials and flammable fuels from buildings’ exterior decoration had reached more than 1300. More than 70 people were killed and more than 80 injured. Flammable and combustible building insulation materials have become a new class of fire hazard. Therefore, it is necessary to study the combustion performance of materials. In

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this case, we can not only understand the combustion properties of the material itself and prevent the occurrence of fire, but also provide data for the evaluation of the combustion performance of the insulation systems.

At present, domestic and foreign researchers carry out various studies of the combustion characteristics of insulation materials and fire hazards. In terms of foreign research, Quintiere and Tewarson[2-4] studied the characteristics of flame spreading over the surface of thermal insulation material. Their experiments show that the combustion performance of thermal insulation materials is affected by their own properties, thickness, surface area, fire size, fire location, and more. In regard to the thermal properties of materials, the size of the fixed position of the ignition source has great influences on the combustion characteristics of materials. Zhang[5] conducted a preliminary study on the flow behavior of molten thermoplastic materials and the open space for fire to spread upwards. Their research found that the upward flame spread of thermoplastic materials has significantly different rules compared to thermoset materials. Ohlemiller[6] found that the type of insulation materials, melt viscosity, pool fire position formed and the thermal conductivity of pool fire underneath materials will have an impact on the melt flow and combustion performance of insulation materials. Bakhtiyari[7] used the cone calorimeter to test fire response characteristics of EPS boards with different densities and different thickness. It was found that with increasing thickness, materials gained less energy and ignition time was reduce due to rapid melting on the one hand. When flammable vapors increased, the amount of heat release and smoke also increased.

Domestic research is mainly concentrated on the standard combustion performance test under the condition of thermal insulation material and the division of refractory performance levels, while it is rarely concerned with the combustion performance and fire risks of thermal insulation materials in building external walls. Xieqi-yuan[8], Xu Liang[9] and Chenxu-dong[10] made elementary studies of how the combustion behavior of thermoplastic insulation materials, the melt flow rate and the thickness of the material respectively impact the spread of the fire. However, scholars lack systematic research into the combustion performance and influential factors of insulation materials. Less attention has been paid to the influence of the heat flux intensity on fire response characteristics of heat preservation materials and comparisons and analyses of combustion performance differences between different heat preservation materials.

Among the fire response tests by the existing materials, cone calorimeter testing has become a more internationally recognized standard that can simulate the heat combustion behavior of materials under real fire conditions[11-13] to a certain extent. Therefore, this work systematically studies the combustion performance of six kinds of typical insulation materials by cone calorimeter. By analyzing changes in insulation materials, heat release rate, ignition time and other parameters of the external heat insulation materials, we derive the influence rule of combustion properties.

2. Test description

2.1. Test unit

Cone Calorimeter mainly consists of the combustion chamber, load units, oxygen analyzers, smoke measurement, ventilation systems and related auxiliary equipment, as shown in Fig. 1. Cone calorimeter can provide radiant heat flux intensity of 0-100 kW/m^2. In the testing process, we can choose reasonable radiation intensities based on simulated fire scenarios. Ventilation air duct oxygen percentage changes over time; according to the principle of oxygen, the oxygen concentration can be measured by the heat release rate for the combustion of the material and can be accurately detected by the oxygen analyzer.

2.2. Selection and preparation of test material

Our common insulation materials include three categories[14]: inorganic insulation material represented by mineral wool, organic-inorganic composite insulation materials represented by powder particles of polystyrene insulation mortar and organic insulation material represented by phenolic-based polystyrene foam (PS) and rigid polyurethane foam (RPU). According to different molding techniques, PS is divided into extruded polystyrene (XPS) and expanded polystyrene (EPS) [15]. The paper selects six kinds of typical insulation materials for experiment, which was prepared in a square sample sized at 100 mm×100 mm and thick at 35 mm. The specific performance parameters are shown in Table 1.

2.3. Design test conditions

Under normal circumstances, when the fire reaches flashover, smoke and flame radiation temperature of objects are 75 kW/m^2. In experimental research of materials' fire behavior, the radiation intensities of 25, 35 and 50 kW/m^2 are usually taken to represent thermal radiation levels of small-scale and medium-scale fires[16-17]. Specific test conditions are shown in Table 2.

Fig. 1. Cone calorimeter.

Table 1. Material properties.

Materials	Density/ $(kg\cdot m^{-3})$	Thermal conductivity$\times 10^3$/ $(kW\cdot m^{-1}\cdot K^{-1})$	Heat capacity / $(kJ\cdot kg^{-1}\cdot K^{-1})$	Heat of combustion / $(MJ\cdot kg^{-1})$
Rock wool	110	0.036-0.041	—	—
Adhesive polystyrene granule	281.57	0.060	—	—
Phenolic resin	52.95	0.025	1.6-1.8	13.47
EPS	17.06	0.041	1.3	40.18
XPS	31.52	0.030	1.46	40.18
RPU	43.99	0.024	1.7-2.3	23.04

Table 2. Experiment conditions.

Number	Materials	Radiative heat flux /(kW/m^2)
1	Rock wool, Adhesive polystyrene granule, Phenolic resin, EPS, XPS, RPU	50
2	XPS, EPS	35, 50, 75
3	RPU of B_1, B_2	25, 35, 50, 75

3. Results and analyses

3.1. The analysis of apparent characteristics and combustion performance of different thermal insulation materials under the same heat flux intensity

In the radiation intensity of 50 kW/m^2, the curve of heat release rates of 6 kinds of thermal insulation materials are shown in Fig. 2. It can be seen that rock wool, powder polystyrene particles and phenolic materials have low heat release rates. When the heat release rate is below 50 kW/m^2, there is no violent burning, and only the surface of the material is pyrolytic, showing good fire resistance. The other 3 kinds of organic materials are ignited in a relatively short period of time. The heat release rate of RPU increased first, with the shortest ignition time. EPS and XPS had obvious contraction before combustion, which increased the distance between the material surface and the igniter, with a long ignition time. XPS's peak heat release rate was the largest. Its combustion is the most violent, and there is greater risk of fire. Fig. 3 shows the combustion of different insulation materials. During the experiment, the rock wool was not set, but there was mass loss. After thermal expansion appeared, there was a slight increase in thickness; the surface decomposed; the surface color deepened, and a flammable gas or volatile gas generated. Powder polystyrene particles insulation mortar belongs to an inorganic-organic composite material. There was no obvious combustion phenomenon, with the volume change rate of 0. Phenolic and RPU are both thermosetting materials. A decomposition and carbonization was conducted after heated. In the combustion process, the former only had burning and smoldering on the surface, with no flame and small volume of smoke; the latter was easy to be ignited, with violent burning, complete carbonization of materials, and a large amount of smoke. EPS and XPS are both thermoplastic materials. When heated they quickly deformed, leading to shrinkage and melting. The volume changes and the mass loss were large, and there was wild burning and large smoke.

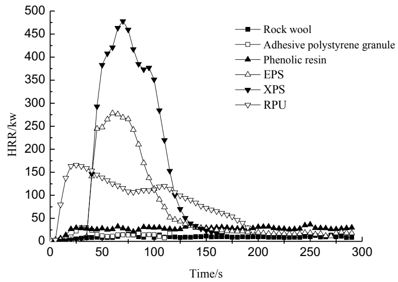


Fig. 2. Heat release rate varying with time in 50 kW/m^2.

(a) rock wool (b) adhesive polystyrene granule (c) phenolic resin (d) RPU (e) XPS (f) EPS

Fig. 3. Combustion state of different insulation materials in 50kW/m^2.

According to Table 3, combustion performance parameters of different insulation materials under the radiation intensity of 50 kW/m^2 were listed, from which we could derive fire growth index (FGI), heating index (THRI6min), smoking index (TSPI6min) and toxic gas generation rate index (ToxPI6min) of these kinds of insulation materials (see Table 4). As per Table 4, the former 3 materials have small fire growth indexes, heat release index and smoke emission index, which are large for the latter 3 kinds of materials. XPS has the maximum thermal risk while rock wool has the minimum one. Phenolic material is the largest on the rate of CO formation, followed by rock wool, EPS, XPS and RPU which are relatively close; powder polystyrene particles are the smallest. By calculating fire risk index (IFHI) of these 6 kinds of thermal insulation materials, we know that fire hazards of several insulation materials selected rank from big to small as: XPS>RPU>EPS> powder polystyrene particles > phenolic > rock wool, as shown in Table 5.

Table 3. Combustion performance index of different insulation materials in 50kW/m^2.

Materials	Ignition time/s	Heat release rate / (kW • m^{-2})		Effective heat of combustion / (MJ • kg^{-1})	Mass Loss Rate / (g • s^{-1})		Specific Extinction Area / (m^2 • kg^{-1})	CO productive rate / (kg • kg^{-1})
		Average	Peak		Average	Peak		
Rock wool	no	9.21	15.62	4.48	0.047	1.015	4.859	0.081
Adhesive polystyrene granule	17	15.91	29.56	7.99	0.017	0.041	13.746	0.0697
Phenolic resin	12	28.45	36.55	12.89	0.045	4.063	12.546	0.336
EPS	37	71.76	278.22	23.59	0.062	0.147	916.517	0.0756
XPS	33	231.06	478.15	28.71	0.071	0.169	1300.752	0.0647
RPU	4	101.92	165.82	15.95	0.056	0.138	914.780	0.0892

Table 4. Combustion characteristics index of different insulation materials.

Materials	Heat related hazards		Smoke hazards	
	FGI	THRI6min	TSPI6min	ToxPI6min
Rock wool	0.208	0.521	0.915	0.581
Adhesive polystyrene granule	0.8445	0.758	0.925	0.0737
Phenolic resin	0.146	1.011	1.308	1.18
EPS	4.637	1.412	3.311	0.671
XPS	6.831	1.92	3.522	0.662
RPU	6.633	1.565	3.266	0.70

Table 5. Fire danger indexes of different insulation materials.

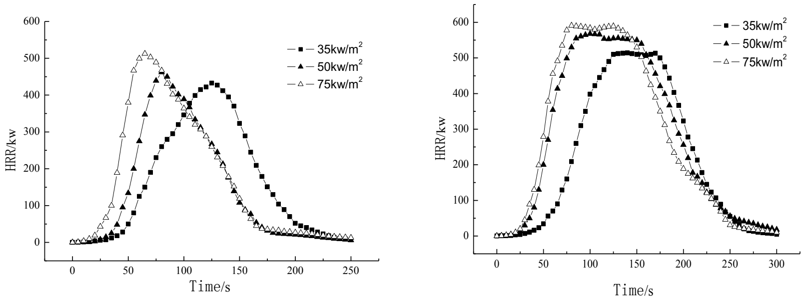
Materials	Rock wool	Adhesive polystyrene granule	Phenolic resin	EPS	XPS	RPU
IFHI	1	2.417	1.259	11.672	16.91	16.26

3.2. Comparison and analysis of the combustion performance of EPS and XPS in different heat flux intensities

Heat release rates of PS under different radiation intensities are shown in Fig. 4. As is shown, the heat release rate of EPS showed a single peak, while XPS showed a more stable combustion phase, which might be due to XPS's large density. The liquid layer formed after melting is thick and can maintain stable combustion for a long time. Table 6 shows the variations of heat release rate peak, peak time and the time ignition of EPS and XPS along with the radiation source strength. As thus, along with the increase in radiation source, the heat release peak rate increased and the ignition time and the peak time reduced. The heat release peak rate and the peak time points showed inverse proportion. Through the above analysis it can be concluded that XPS thermal hazard was greater.

3.3. Comparison and analysis of B_1 and B_2 RPU's combustion performance in different heat flux

Fig. 5 gives the heat release rate curves of 2 kinds of samples at different radiation intensities. As can be seen, for the same material, with increasing radiation intensity, the heat release rate increased linearly; the heat release peak rate's appearing time and ignition time were shortened. The heat release rate was low in the radiation intensity of 25 kW/m^2 and it decreased quickly, showing that the flame retardant RPU foam can effectively resist small fires. However, in large-scale fires the retardant effect will gradually lose. At the same radiation intensity, B_2 RPU's peak heat release rate was about 2 times of B_1. We also can find that the heat release curve of the same material under different heat flux shows similar characteristics. B_2 RPU's heat release curve shape is: generally there will be a double peak; after the fire there will soon be steep peaks due to rapid combustion; due to the isolation of the charring layer, with pyrolysis and charring of RPU, heat release rate decreases gradually; with the stable burning reaction, carbonized layer begins to decompose, and combustible matter increased, the heat release rate increased gradually, showing the second exothermic peak. B_1 RPU soon reaches a higher heat release rate of combustion. The barrier effect of charring layer and charring layer wrapped under the material itself is difficult to burn, so that the heat release rate decreases gradually. Until the end of the combustion reaction, the radiation condition is big; the carbonized layer decomposes resulting in the department of flammability; heat release shows a small peak rate.

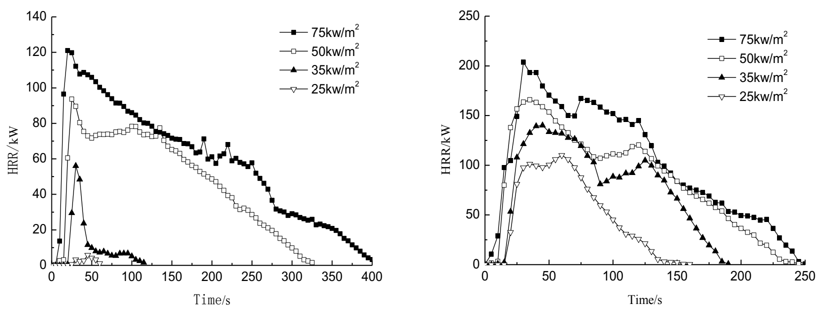


(a) EPS (b) XPS

Fig. 4. Heat release rate of PS under different radiation intensities.

Table 6. Peak heat release rate, peak time and ignition time of EPS and XPS.

Materials	Radiative heat flux /(kW • m^{-2})	pkHRR/(kW • m^{-2})	Peak time/s	Ignition time /s
	35	432.6	125	113
EPS	50	462.2	65	54
	65	512.5	55	38
	35	514.1	129	98
XPS	50	560.6	73	44
	65	591.3	62	31



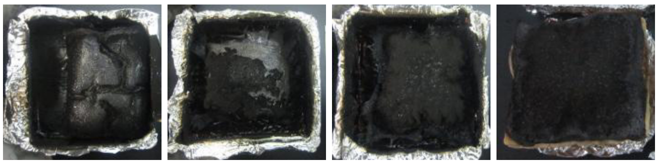
(a) RPU in class B_1 (b) RPU in class B_2

Fig.5. Heat release rate of RPU under different radiation intensities.

Fig. 6 and Fig. 7 show the combustion conditions of 2 kinds of materials in different radiation conditions. As can be seen, when the radiation intensity was above 50 kW/m^2, the combustion degrees of the 2 kinds of materials were very serious, in which B_2 RPU showed shrinkage, edge curling, large volume change, and fierce burning. When the radiation intensity was reduced to below 50 kW/m^2, B_1 RPU exhibited better flame retardance, with a lesser extent of pyrolysis and charring. Although the surface was ignited, it quenched soon after the fire. It did not appear large area burns. When the radiation intensity was 25 kW/m^2, B_1 RPU's pyrolysis thickness was 8.75 mm, B_2 RPU 23.33 mm, and B1 RPU flame retardant efficiency increased by 37.53 %.

(a) 75kW/m^2 (b) 50kW/m^2 (c) 35kW/m^2 (d) 25kW/m^2

Fig. 6. Combustion state of RPU in class B1 under different radiation intensities.



(a) 75kW/m^2 (b) 50kW/m^2 (c) 35kW/m^2 (d) 25kW/m^2

Fig. 7. Combustion state of RPU in class B_2 under different radiation intensities.

4. Conclusions

(1) By comparing the fire danger indexes, the fire risks of 6 kinds of typical thermal insulation materials were arranged in a descending order: XPS>RPU>EPS> adhesive polystyrene granule> phenolic resin> rock wool. The heat preservation material combustion characteristic database has been established, providing the basis for the selection of insulation materials.

(2) By comparing the combustion performance of EPS and XPS under different heat flux intensities, the experimental results show that the heat release rate of EPS showed a single peak, while XPS showed a more stable combustion phase, which might be due to XPS's large density. The liquid layer formed after melting is thick and can maintain stable combustion for a long time. Along with an increase in radiation source, the heat release peak rate increased and the ignition time and the peak time reduced. The heat release peak rate and the peak time points showed inverse proportion. XPS thermal hazard was greater compared to EPS.

(3) By comparing the combustion performance of RPU in B_1 and B_2 class under different heat flux intensities, the experimental results show that the heat release rate curve shape of the same material is similar; with the increase of the radiation intensity, the heat release rate reveals a linear decreasing trend and the total HRR reduces; the ignition time reveals exponentially attenuation decreasing trend; the time to the peak HRR value shortens and the extinction time extends; the peak HRR value of RPU in class B_2 is 2 times of the RPU in B1 class; the efficiency of fire retardant of B_1 RPU increases by 37.53 % compared to B2 RPU; When the heat flux intensity reaches more than 50 kW/m^2, these two materials both lose fire resistance.

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