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A comparative study on the flame-retardant performances of four thermal insulation materials

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Abstract. *The present work chooses blaze growth rate, specific extinction area, effective heat combustion, flammability index, and retardant characteristic factor (RCF) as the fire-hazard indices of insulation materials. The flame-retardant performances of common insulation materials are evaluated, and an analytic hierarchy process is utilized to obtain weights. The consistency ratio is shown to be less than 0.1, indicating that the eigenvector of the judgment matrix can be used as the weight of the five flame-retardant indices. Comprehensive risk indicators show that the extruded polystyrene plate has the largest combustion hazard, and the RCF of the materials is in the order of the modified phenolic composite < phenol formaldehyde resin < rubber-plastic laminate < extruded polystyrene plate.*

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I. Introduction

Flame retardancy is one of the most important properties for engineering materials [1,2]. The combustion characteristics can be analysed using ignitability and low-flammability tests [3−5], whose main indicators include flame spread, heat release, and smoke release characterisations, as reported in previous papers [6−8]. Based on these indicators, a correlation model between the combustion characteristics and fire risk must be established. Many raw materials are combustible polymers that can easily reach their ignition points [9], and the ignition process can be described as the transition from nonreactive air to a stable heat release. Once exposed to a fire source, the material burns rapidly as the flame spreads.

In the area of combustion, thermal insulation materials are heated via pyrolysis and gasification to produce gas-phase flames [10,11]. The heat release rate (HRR), which is a calorimetry parameter to describe fire risk, is typically used to indicate a material's release capacity [12]. A higher HRR results in faster pyrolysis and flame propagation [13]. The majority of smoke particulates produced by combustion are opaque to visible light, which reduces their ability to identify surrounding targets. Shading percentage, smoke generation rate, and total smoke production can be determined using a cone calorimeter and smoke density box [14,15]. The thermal and smoke effects of incendiary materials are distinctive features in terms of the fire hazards of building insulation. The flammability limit refers to the difficulty in achieving flaming combustion at elevated temperatures [16]. The higher the oxygen index (OI), the more difficult it is to ignite an insulation material.

This study recommends a coordinated approach for estimating the flame retardancy of four common insulation materials (modified phenolic composites, extruded polystyrene plates, phenol formaldehyde resins and rubber-plastic laminates). Blaze growth rate (BGR), specific extinction area (SEA), effective heat combustion (EHC), flammability index (FI), and retardant characteristic factor (RCF) are used as the fire-hazard indices of the insulation materials considered in this paper. We gain the weights via an analytic hierarchy process (AHP) to evaluate the flame-retardant performances of the four insulation materials, and further investigate the combustion performances using a cone calorimeter and automatic oxygen index tester.

II. Methodology

2.1 Burning index

In terms of thermal and smoke effects, the following fire-hazard indices of thermal insulation materials are proposed under given test conditions. Both the ignition time (IT, s) and apex heat release rate (AHRR, kW m^{-2}) are used as indicators to measure the combustion performance [17]. Hence, BGR (MJ s^{-1}) is defined as the ratio of HRR to IT. This reflects the sensitivity of materials to heat.

$$\mathrm{BGR} = \frac{\mathrm{AHRR}}{\mathrm{IT}} \tag{1}$$

The SEA (m^2 kg^{-1}) refers to the amount of smoke per unit mass at a given time during combustion. It reflects the smoke production capacity of the combustibles and represents a dynamic response over time for measuring the smoke hazards of insulation materials.

$$\mathrm{SEA} = \frac{b \times V_{\mathrm{f}}}{\mathrm{MLR}} \tag{2}$$

where b is the extinction coefficient (m^{-1}); V_{f} is the volume flow velocity (m^3 s^{-1}), and MLR is the mass-loss rate (kg s^{-1}).

The EHC (MJ kg^{-1}) is the ratio of HRR to MLR, which facilitates volatile gas combustion in a gas-phase flame.

$$\mathrm{EHC} = \frac{\mathrm{HRR}}{\mathrm{MLR}} \tag{3}$$

The limiting oxygen index (LOI, %) refers to the oxygen concentration of materials that can maintain continuous combustion in a nitrogen-oxygen mixture [18]. Accordingly, FI is the difficulty of ignition of the material and defined by the logarithm of the LOI.

$$\mathrm{FI} = -\log(\mathrm{LOI}) \tag{4}$$

The generalized index RCF is calculated using a nonlinear method.

$$\mathrm{RCF} = \sum_{k=1}^{n} \left(\frac{R_k}{S_k} \times W_k\right) \tag{5}$$

where S_{k} and R_{k} are the normal and measured values of the combustion behavior, respectively, and W_{k} is the weight.

2.2 AHP approach

Because a single index can express only one risk exposure of insulation materials, a thorough assessment of burning index is impossible. Hierarchy analysis is therefore applied to determine the weights with acceptable judgments. Table 1 indicates optimisation indices, and the AHP is employed to compare the five parameters (BGR, SEA, EHC, FI, and RCF).

Table 1. Judgment matrix of flame-retardant indices.

Matrix	a_1	a_2	a_3	a_4	a_5
a_1	1	3	4	5	6
a_2	1/3	1	2	3	4
a_3	1/4	1/2	1	2	3
a_4	1/5	1/3	1/2	1	2
a_5	1/6	1/4	1/3	1/2	1

a represents the order of judgment matrix.

The maximum root of judgment matrix ($\lambda_{\max}$) is surveyed.

$$\lambda_{\max} = \sum_{k=1}^{n} \frac{(WA)_k}{nW_k} \tag{6}$$

$$A = \begin{bmatrix} 1 & 3 & 4 & 5 & 6 \\ 1/3 & 1 & 2 & 3 & 4 \\ 1/4 & 1/2 & 1 & 2 & 3 \\ 1/5 & 1/3 & 1/2 & 1 & 2 \\ 1/6 & 1/4 & 1/3 & 1/2 & 1 \end{bmatrix}; W = \begin{bmatrix} 0.4867 \\ 0.2268 \\ 0.1409 \\ 0.0863 \\ 0.0547 \end{bmatrix}$$

The consistency ratio (C_{R}) is used to obviate deviation (n = 5).

$$C_{\mathrm{R}} = \frac{\lambda_{\max} - n}{1.12(n-1)} \tag{7}$$

The C_{R} value is calculated to be less than 0.1, indicating that the judgment matrix is practicable within the allowable range [19]. It can be inferred that the consistency of the judgment matrix is good, and its eigenvector is used as the weight of the five flame-retardant indices.

III. Results and discussion

To identify whether the selected indices could be used in an effective investigation of the fire protection of insulation materials [20], we verified the proposed risk assessment for common insulation materials. Energetic combustion experiments were conducted using the following standards: GB/T 16172-2007 "Test method of heat release rate of building materials" and ISO 5660-1:2015 "Reaction to fire tests–Heat release, smoke production, and mass loss rate–Part 1."

Based on the measured signals using the oxygen index tester and cone calorimeter, the relevant results of the BGR, SEA, EHC, FI, and RCF indices are listed in Table 2. Since SEA posed more threat to the human, therefore this was given priority. The combustion performance of solid composites played an important role in the selection of insulation materials.

Table 2. Flame-retardant data of thermal insulation materials.

Specifications	OI (%)	HRR (kW m^{-2})	AHRR (kW m^{-2})	IT (s)
Modified phenolic composite	58.99	17.37	30.82	90
Phenol formaldehyde resin	38.26	29.54	89.65	30
Rubber-plastic laminate	39.08	145.91	201.07	20
Extruded polystyrene plate	27.52	119.86	322.85	50

The individual flame conditions were first summarised in terms of calorimetry standards. The insulation materials were then cut to a size of 10 × 10 × 1.2 cm for combustibility investigation (Figure 1). Prior to each experiment, the materials were preserved at a temperature of 22 ± 1 °C and relative humidity of 50 ± 2% to stabilize their quality. Subsequently, their heat radiation intensities of combustibles in small- and medium-scale fires were then determined.

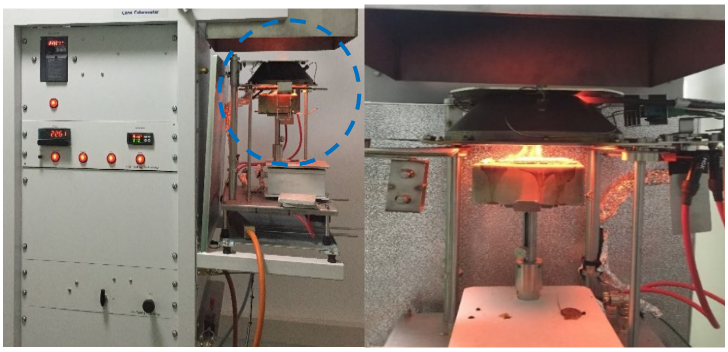

Figure 1. Schematic of combustibility investigation using a cone calorimeter.

The heat release capacity of the fire source was fed back to the material surface while accelerated pyrolysis and the formation of volatile combustibles were considered. From Figure 2, the HRR of the extruded polystyrene plate was the most unstable, and its AHRR was higher than those of the other three materials, thereby promoting flame propagation. This was attributed to the foam structure of the polystyrene plastics, which rendered real-time combustion optimisation possible in an open environment. The rubber-plastic laminate reached the allowable apex value earlier with a high rate, whereas the AHRR of the phenol formaldehyde resin and modified phenolic composite exhibited a relatively safe combustion process.

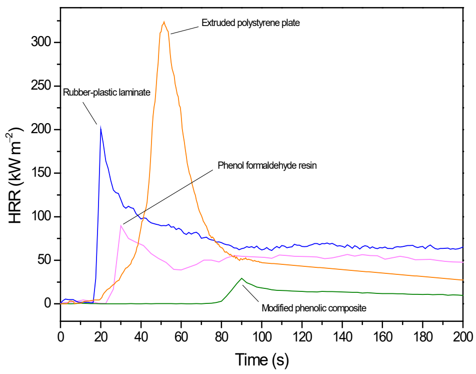

Figure 2. HRR curves of four insulation materials at 20 kW m^{-2} external heat radiation.

Table 3 displays the calculation results for characterising the combustion parameters. The BGR of the materials was in the order of the modified phenolic composite < phenol formaldehyde resin < extruded polystyrene plate < rubber-plastic laminate. The SEA of the rubber-plastic laminate and extruded polystyrene plate both exceeded 420 m^2 kg^{-1}. The EHC followed the order: rubber-plastic laminate < modified phenolic composite < phenol formaldehyde resin < extruded polystyrene plate. Finally, the FI was in the order of the modified phenolic composite < rubber-plastic laminate < phenol formaldehyde resin < extruded polystyrene plate. Notably, the FIs of the phenol formaldehyde resin and extruded polystyrene plate were 0.36 and 0.51, respectively. These fluctuations were statistically analysed to obtain the average signals derived from the residues of the active ingredients.

Thermal and smoke hazards were considered as the level indices of polymers, and we derived the generation rate and included it in the integrated indicator (Table 4). For the convenience of comparison, the value for the modified phenolic composite was adopted as a reference for calculating the comprehensive risk indicators. Modified phenolic composite consisted of low-flammability ingredients. Fire-risk analysis demonstrated that the extruded polystyrene plate possessed the largest combustion hazard (RCF > 84), whereas the RCF of the materials was in the order of the modified phenolic composite < phenol formaldehyde resin < rubber-plastic laminate < extruded polystyrene plate.

Table 3. Fire-hazard indices of combustion characteristics.

Specifications	BGR (MJ s^{-1})	SEA (m^2 kg^{-1})	EHC (MJ kg^{-1})	FI
Modified phenolic composite	0.34	1.82	8.64	0.19
Phenol formaldehyde resin	2.98	2.05	13.29	0.36
Rubber-plastic laminate	10.05	421.03	5.42	0.33
Extruded polystyrene plate	6.47	668.30	19.85	0.51

Table 4. Comprehensive risk indicators of thermal insulation materials.

Specifications	BGR (MJ s^{-1})	SEA (m^2 kg^{-1})	EHC (MJ kg^{-1})	FI	RCF
Modified phenolic composite	0.14	0.21	0.08	0.06	0.94
Phenol formaldehyde resin	1.25	0.24	0.13	0.11	2.61
Rubber-plastic laminate	10.87	48.62	0.92	0.09	63.35
Extruded polystyrene plate	3.95	77.30	0.18	0.15	84.32

IV. Conclusion

The insulation materials were cut to a size of 10 × 10 × 1.2 cm for combustibility investigation. A quantitative assay of BGR, SEA, EHC, FI, and RCF was used for the reasonable evaluation of the fire risks of four thermal insulation materials based on the measured signals using an oxygen index tester and cone calorimeter. The HRR of the extruded polystyrene plate was the most unstable, and its apex value was higher than those of the other three materials. It was determined that a single index could not truly reflect the fire risks of polymers. However, an AHP-based synthetic evaluation effectively addressed this issue. The SEA and MLR were proven to be noteworthy for insulation selection. The RCF of the materials increased in the order of the modified phenolic composite < phenol formaldehyde resin < rubber-plastic laminate < extruded polystyrene plate, where the modified phenolic composite gave the best performance in terms of flame retardancy.

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