Research on Combustion Characteristics of Vulcanized Rubber Based on Fire Propagation Apparatus

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Abstract: Vulcanized rubber is widely used as a vibration damping material for high-speed train floors. This paper aims to study the combustion characteristics of vulcanized rubber materials under fire propagation apparatus at 20-50 kW/m². The results show that the ignition time and the time to peak heat release rate of the vulcanized rubber decrease with the increase of the external heat flux, and the transformed ignition time \(\left(\frac{1}{t_{\text{ign}}}\right)^n\) increases linearly with the external heat flux. The fire risk of vulcanized rubber and the possibility of flashover increase with the increase of external heat flux. In addition, higher external heat flux will accelerate the generation of smoke in the fire scene, threatening the lives of people on the train. These data and results can be used to evaluate the interior materials of high-speed trains.

1. Introduction

Vulcanized rubber has many applications on the floor shock absorber of high-speed trains due to its excellent shock absorption performance, reducing vibration shock and absorbing noise from vibration sources. In recent years, high-speed train fires have occurred frequently. In 1998, 101 people died when an ICE high-speed train derailed, crashed and burst into flames in Germany. In 2011, 40 people were killed when a high-speed train crashed and caught fire in Wenzhou, China. It can be seen that the consequences of high-speed train fire accidents are extremely serious[1]. Although vulcanized rubber treated with flame retardant has relatively low flammability, it can still ignite under certain conditions and release a lot of heat and toxic smoke.

The current research on vulcanized rubber is mainly on its flame-retardant properties and mechanical properties. Li[2] added ultrafine fully vulcanized powdered rubber to the flame-retardant polypropylene. The mechanical properties of flame-retardant polypropylene are improved, but the mechanical properties will decrease when the amount is too large, and the addition of ultra-fine fully vulcanized powdered rubber will cause the flame-retardant properties to decline. In the study of the combustion performance of vulcanized rubber, Naumov[3] studied the effect of aluminum-magnesium flame retardants with different degrees of dispersion on rubber. The research shows that the increase in flame retardant particle size will cause changes in rubber structure and performance, and improve its flammability. Li[4] studied the flammability of melamine phosphate-filled room temperature vulcanized rubber composites. The results show that the composites with better properties can be obtained by adding some organic nano-montmorillonite instead of melamine phosphate. Liu[5] has developed a composite...
cable composed of a vulcanized silicone rubber composite refractory layer, which has excellent flame retardancy and fire resistance. Yan[6] prepared flame-retardant high-temperature vulcanized silicone rubber, and tested the performance of vulcanized silicone rubber under the conditions of Al(OH)₃, Mg(OH)₂, nitrogen-containing flame retardant and phosphorus-containing flame retardant as fillers. Magnesium hydroxide modified flame retardant vulcanized silicone rubber has good thermal aging stability. Kang[7] also studied the effects of different flame retardants including Al(OH)₃, Al(OH)₃/Sb₂O₃, Al(OH)₃/MoO₃ on the flame retardant performance of vulcanized silicone rubber. Although the flame-retardant properties of vulcanized silicone rubber are improved, its mechanical properties will decline. Most of the existing research is on the flame-retardant properties of vulcanized rubber, and there are few studies on the combustion characteristics of vulcanized rubber. Most of the existing research is on the flame-retardant properties of vulcanized rubber, and there are few studies on the combustion characteristics of vulcanized rubber. Therefore, it is necessary to study the combustion characteristics and fire risk of vulcanized rubber in fire environment.

In this paper, the fire propagation apparatus (FPA) was used for testing. In order to simulate different fire environments, four external heat fluxes of 20, 30, 40 and 50 kW/m² were selected and the samples were tested according to ASTM E 2058[8]. Through the test, the combustion characteristic parameters such as the ignition time and heat release rate (HRR) of the material under different external heat fluxes are obtained, and these combustion characteristic parameters were analysed to understand the combustion characteristics of the material.

2. Experiments

2.1. Materials

The material tested in the experiment is vulcanized rubber for floor shock absorbers. The basic properties of vulcanized rubber are shown in Table 1. The size of sample tested by FPA is 100 mm*100 mm. The bottom and sides of the sample were wrapped with aluminum foil, which was placed horizontally on the bracket. The ceramic fiber cotton was placed between the sample and the aluminum foil at the bottom to prevent heat loss and ensure the accuracy of the results.

2.2. Apparatus and experimental methods

The tests were carried out in FPA, which is composed of combustion chamber, exhaust device, weighing system and gas analysis device. The heat release is calculated by the principle of oxygen consumption, that is, the heat release of consuming per unit of oxygen by the complete combustion of material is basically the same (13.1 MJ/kg). The parameters of combustion such as ignition time, HRR, mass loss rate, and effective combustion heat can be measured by FPA, which can be used to evaluate the combustion characteristics of materials or products. The main feature of FPA is that it has a unique gas distribution chamber, which can provide test environment with a controllable oxygen concentration range, including oxygen-depleted, oxygen-enriched, and normal oxygen atmospheres. The heating part of FPA adopts the horizontal distribution method, which can simulate the actual fire scene environment more realistically by heating the surroundings of the material.

During the experiment, the ambient temperature was 29.8°C, atmospheric pressure was 100380 Pa, and relative humidity was 55%. At least two repeated tests are carried out in each condition to reduce the experimental error[9]-[10].

| Category                  | Value   |
|---------------------------|---------|
| Thermal conductivity (W/(m·K)) | 0.4791  |
| Specific heat capacity(J/(kg·K)) | 1112    |
| Density (kg/m³)            | 1640    |
3. Results and discussion

3.1. Visual observation
When exposed to the external heat flux, the vulcanized rubber released a lot of grey volatile gases. With the heat accumulated, the sample was ignited by the pilot with black smoke released. After ignition, the sample arches and peels gradually. With the combustion proceeded, the sample expanded a lot and burst into pieces with the sound of breaking, accompanied by a larger number of black smoke. The samples after combustion under different heat fluxes are shown in the Figure 1. It can be seen that the sample was break into pieces after combustion. Under the heat flux of 20 kW/m², the residue is presented as strips which is larger than the residue under other heat fluxes. The pieces of residue at 50 kW/m² are smaller indicating that the burning is more intense and complete.

3.2. Ignition time
Ignition time (tign) is one of the important parameters to characterize the fire hazard and thermal decomposition properties of materials[11]. Materials with a long ignition time have a low fire hazard and strong heat resistance. The ignition time measured in experiments is shown in Table 2. As can be seen, with the increase of heat flux, the ignition time gradually decreases, and the time to reach the peak heat flux also gradually decreases.

| Heat flux (kW/m²) | Ignition time (s) | Peak HRR (kW/m²) | Time to Peak HRR (s) |
|------------------|------------------|------------------|---------------------|
| 20               | 193              | 293.45           | 826                 |
| 30               | 77               | 172.41           | 439                 |

Table 2 Summary of combustion parameters

Figure 1. Samples after combustion: (a) 20 kW/m², (b) 30 kW/m², (c) 40 kW/m², (d) 50 kW/m².
In order to determine the relationship between ignition time and material properties, the method provided by Janssens was used to calculate the ignition time[12]-[13]. According to his research, ignition time can be converted to \( \left( \frac{1}{t_{\text{ign}}} \right)^n \) to be correlated with the external heat flux, where \( n \) is a coefficient, in this study \( n \) are 0.3, 0.5, 0.55, 1. The relationship between the transformed ignition time and heat flux \( (q''_{\text{ext}}) \) can be expressed by the following formulas:

\[
\left( \frac{1}{t_{\text{ign}}} \right)^{0.3} = 0.00533q''_{\text{ext}} + 0.10671 \quad (1)
\]

\[
\left( \frac{1}{t_{\text{ign}}} \right)^{0.5} = 0.00385q''_{\text{ext}} - 0.00242 \quad (2)
\]

\[
\left( \frac{1}{t_{\text{ign}}} \right)^{0.55} = 0.00345q''_{\text{ext}} - 0.01173 \quad (3)
\]

\[
\left( \frac{1}{t_{\text{ign}}} \right)^{1} = 0.00010q''_{\text{ext}} - 0.01556 \quad (4)
\]

The Figure 2 can be obtained by analysing the data, where \( R^2 \) represents the correlation between the experimental data points and the straight line of the formula, and the larger \( R^2 \) is, the better the correlation is[12]. It can be seen that there is a linear relationship between transformed ignition time and external heat flux, and when \( n=1, R^2=0.99408 \) reaches the maximum value, and the correlation between the experimental data and the fitting line is better. Therefore, according to the heat flux, Equation (4) can better predict the ignition time of the material, and the material can be treated as a thermally thin material.

3.3. Heat release rate
HRR refers to the heat released per unit time by material combustion, which is an important parameter to evaluate the fire risk of material[1]. According to the experimental results, the change of HRR with time under different external heat flux is shown in the Figure 3. It can be seen from Figure 3 that the time to reach the peak HRR decreases with the increase of the external heat flux. After vulcanized rubber is ignited, HRR increases slightly and stabilized for about 100s, then HRR increases sharply and reached the first peak. The HRR then declines slightly followed by a second stage of steady vigorous burning, and HRR finally decreases slowly. For 30, 40, and 50 kW/m², the higher the heat flux, the higher the HRR. While when the heat flux is 20 kW/m², the peak HRR is 293.45 kW/m², which means that the energy released by the vulcanized rubber is high even under low heat flux.

Figure 2. Correlations between transformed ignition time and heat flux.

Figure 3. HRR under different heat fluxes.
3.4 Fire hazard
In order to comprehensively analyze the fire risk of materials, many scholars integrated the measurement parameters and put forward some comprehensive evaluation indexes. Fire growth rate index (FIGRA) is the ratio of the heat release peak to the peak time of arrival of the material, which can be used as an evaluation index to predict the fire spread rate and fire size[14]-[15]. The higher the fire growth rate index is, the higher the fire risk will be, and it can be used to classify the fire risk of the material. The fire growth index (FGI) is the ratio between the peak heat release rate of materials and the ignition time, which can be used as an index to evaluate the possibility of flashover of material[16]. If the material has a short ignition time and a high peak heat release rate, FGI will be high and the probability of flashover of materials under fire conditions will be high.

Using the data in Table 2, the FGI and FIGRA can be calculated to evaluate the fire risk of vulcanized rubber. The FGI and FIGRA are shown in Figure 4. It can be seen from the figure that as the heat flux increases, both FIGRA and FGI increase. Thus, it can be concluded that the fire hazard and the probability of flashover of the vulcanized rubber will increase as the external heat flux increases.

3.5 Smoke generation
When fire breaks out on the train, the smoke produced by combustion will reduce visibility and affect evacuation on the one hand, and may produce toxic and harmful gases on the other hand, posing a threat to human life and safety. Therefore, this paper tested the smoke production rate (SPR) of vulcanized rubber materials and the production rate of CO and CO2. The SPR is defined as the ratio of the specific extinction area to the mass loss rate in m2/s. It can be seen from Figure 5 that SPR is closely related to the external heat flux. With the increase of the external heat flux, the time required to reach the peak SPR gradually decreases.

It can be seen from Figure 6 that during the entire combustion process, the CO production rate increases slightly after ignition, and keeps stable for a period of time after the first small peak, then increases rapidly reaching the maximum peak, and then decreases. The curve of the external heat fluxes of 40 and 50 kW/m2 has a stable period in the middle of the process of decline. After the CO production rate drops to a certain value, it begins to rise rapidly, reaching the third peak, and finally gradually decreases until the end of the combustion process. According to the experimental phenomenon, the third peak appeared after the flame was extinguished, because the radiation lamp of the device was turned off after the fire was extinguished for 60 s. In addition, the CO production rate is closely related to the external heat flux. As the external heat flux increases, the time required to reach the maximum peak of the CO production rate gradually decreases. And for 30, 40, 50 kW/m2, the CO production rate increases with the increase of the external heat flux.
It can be seen from Figure 7 that after the vulcanized rubber is ignited, the CO2 production rate first rises slightly and stabilizes for about 100 s, then increases dramatically and reaches the first peak. Subsequently, the CO2 production rate decreased slightly, and then the second stage of stable combustion appeared. Finally, the CO2 production rate decreased slowly. For the heat fluxes of 30, 40, and 50 kW/m², the higher the heat flux, the greater the CO2 production rate of the burning, indicating that the combustion is more sufficient. Comparing Figure 3 and Figure 7, it is not difficult to find that the heat release rate is basically consistent with the change trend of CO2 with the combustion process, because the material will fully burn and generate CO2 when the air is sufficient, so the two have the same trend with time.

4. Conclusion
In this paper, the combustion characteristics of vulcanized rubber in different heat fluxes were measured by FPA and its fire risk was evaluated. The following conclusions can be drawn:

● With the increase of heat flux, the ignition time of vulcanized rubber is shortened, and the ignition model of thermal thin material is more suitable to describe the heating process of vulcanized rubber. The ignition time can be better predicted by Equation (4):\
\[
(1/t_{ign})^1 = 0.00010 q''_{ext} - 0.01556
\]

● With the increase of heat flux, the time for vulcanized rubber to reach the peak of HRR is shortened. HRR increased slightly and stabilized for about 100 s, then HRR increased sharply and reached the first peak. The HRR then declined slightly followed by a second stage of steady vigorous burning, and HRR finally decreased slowly.

● The FIGRA and FGI of vulcanized rubber increase with the increase of heat flux, which means the fire risk and the probability of flashover of the material increase.

● The increase of the external heat flux will accelerate the combustion of vulcanized rubber to produce smoke, including the rate of toxic and harmful gases generated, which will reduce the visibility, threaten the lives of people, and increase the risk of fire.

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