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Research Article

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Study on the Combustion Characteristics of Conveyer Belt under Different Thermal Radiation Intensities

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Abstract To study the combustion characteristics of conveyer belt under different thermal radiation intensities. In this paper, the pyrolysis characteristics of the conveyer belt and the combustion characteristics of five different thermal radiation intensities (20, 25, 30, 35, and 40 kW/m^2) were investigated by the synchronous thermal analyzer and FTT cone calorimeter. The parameters of the conveyer belt such as characteristic temperature, ignition time, continuous combustion time, heat release rate, mass loss rate, and flue gas composition change were analyzed. The variation of the time required to reach the peak with the intensity of thermal radiation was studied. The results show that with the increase of thermal radiation intensity, the ignition time and continuous combustion time are reduced, the peak heat release rate of the conveyer belt is increased, and the time required to reach the peak heat release rate is reduced. The heat release rate, mass loss rate, and CO_2 content tend to be similar – rising rapidly to the peak after ignition, then descending to a gentle phase, and slowly descending to the end of combustion after a while. The time required to reach the peak heat release rate and the time required to peak the mass loss rate vary significantly with the change in thermal radiation intensity, and the corresponding relationship is obtained by fitting them separately. The research result is important to the theoretical guiding in different conveyer belt fire scales.

Keywords Cone calorimeter, Thermal radiation intensity, Combustion characteristics, Heat release rate

Introduction

With the increasing demand for coal in society, the production of raw coal continues to rise, and the use of corresponding coal mine underground conveyers and conveyer belt has also increased significantly. Although conveyer belt are required to use flame retardant conveyer belt, combustion, meltdown and other fire accidents with conveyer belt still occur from time to time [1]. In January 2015, a conveyer belt fire occurred in the Xinghua Coal Mine of Longmei Group, and toxic and harmful gases entered the coal mining face along the wind flow, causing 22 people to die of poisoning and suffocation. In September 2020, a conveyer belt fire broke out in Chongqing Songzao Coal Mine, and the toxic and harmful gases produced quickly spread to the entire working face, killing 16 people and injuring 42 people [2].

In order to prevent the occurrence of conveyer belt fires and grasp the development degree and spread law of conveyer belt fires, scholars at home and abroad have carried out a series of relevant experiments and research.

The combustion properties of materials have an important influence on the development of fire, cone calorimeter can mimic real fire scenes well, and it has a good correlation with the combustion results of large fires, so many scholars use cone calorimeter to study the combustion properties of materials. To compare the different heat release rates of blank conveyer belt and used conveyer belt, Xiao Guoqiang [3] used a cone calorimeter to analyze the heat release rate of blank conveyer belt and used conveyer belt under a certain radiation intensity. Based on the random forest model, a prediction method for the heat release rate of conveyer belt fire was established. Wang Yuhuai. [4] used a cone calorimeter to study the combustion characteristics of combustible materials in coal mines under a certain radiation intensity and analyzed the differences in the fire resistance of several materials such as coal, wood, nylon conveyer belt, and rubber whole core flame retardant belt. Zhang Zheng [5] used a cone calorimeter to carry out combustion tests on aviation cables and analyzed the combustion characteristics and flue gas hazards of aviation cables under various radiation intensities. Wang Wei [6] studied the combustion characteristics of different types of PVC cables by cone calorimeter and analyzed the influence of combustion characteristics of different types of PVC cables. Hao Zhang [7] used a cone calorimeter to study the combustion characteristics of cross-linked polyethylene at multiple radiant intensities and established a cable ignition model to simulate the ignition time of cables under different radiant intensities. Liu Changchun [8] used a cone calorimeter to study the combustion characteristics of optical cables in different positions and analyzed the differences between parameters such as heat release rate, smoke production rate, ignition characteristics, and fire performance index of various optical cables under different thermal radiation intensities. Ji Jingwei [9] used a cone calorimeter to conduct an experimental study on the ignition performance of 800S PVC whole-core flame retardant conveyor belt and concluded that its average ignition temperature was 384°C.

In summary, cone calorimeters have been recognized as an important tool for measuring the combustion characteristics of various materials. In this paper, the effect of thermal radiation intensity on the combustion characteristics of conveyer belt was studied by changing the experimental conditions, which has important theoretical guiding significance for the development and prevention of conveyer belt fires of different scales.

Experimental Part

The equipment used in this experiment is the STA-449C synchronous thermal analyzer and the FTT standard cone calorimeter. The thermal analyzer analyzed the mass change of the conveyer belt samples during the heating process and obtained data such as characteristic temperature, endothermic and exothermic data. And then the cone calorimeter analyzed the heat release rate, mass change, and flue gas content change of the samples during combustion.

We prepared conveyer belt samples, weighed 15mg, and raised them from 10 °C/min to 30 °C/min in an atmosphere of air Thermogravimetric determination at 800°C. Prepared 100 mm× 100 mm × 10mm tape cubes for combustion experiments at different radiation intensities. In this paper, 20, 25, 30, 35, and 40 kW/m^2 radiation intensities were mainly used in the experiments. Performed three experiments and took the average.

Figure 1: STA-449C synchronous thermal analyzer

Figure 2: Cone calorimeter table

Results & Analysis

Pyrolysis characteristics

The T-G/DTG curve of the sample obtained by a synchronous thermal analyzer is shown in Figure 3.

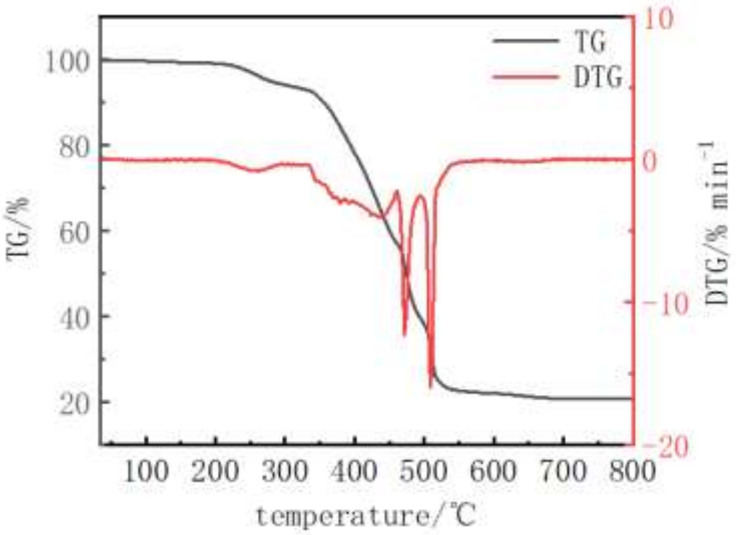

Figure 3: TG/DTG curve

We obtained that from the figure two weight loss peaks appeared during the whole pyrolysis process, which were at 471 °C and 509 °C. The residual amount by 650 ° C is about 21%, the mass is reduced by 79%, the reduction in the air atmosphere should be the content of the combustible material of the conveyer belt, and the final residual amount is the non-combustible content. The conveyer belt begins to thermally decompose at a furnace temperature of about 200 °C, and the mass begins to decrease significantly at about 350 °C, indicating that the conveyer belt begins to accelerate decomposition. 471 °C reaches the peak of weight loss, indicating that the tape has the first combustion peak here. Therefore, the ignition point of the sample should be between 350-471 °C, and the lowest radiation intensity of the cone calorimeter experiment should be 20 kW/m^2 and increase by 5 units in turn.

Ignition time and continuous burning time

The ignition time of the samples is the time from the opening of the cone heater furnace door until it is ignited by an electric spark. Continuous burning time refers to the time it burns from burning to extinguishing. The length of ignition time can evaluate the difficulty of burning, and the longer the ignition time, the better the heat resistance of the material. The continuous burning time can evaluate the fire resistance of the material to a certain extent, and the shorter the continuous burning time, the worse the fire resistance of the material [10]. The ignition time and continuous burning time results of the conveyer belt in this article are shown in Figure 4.

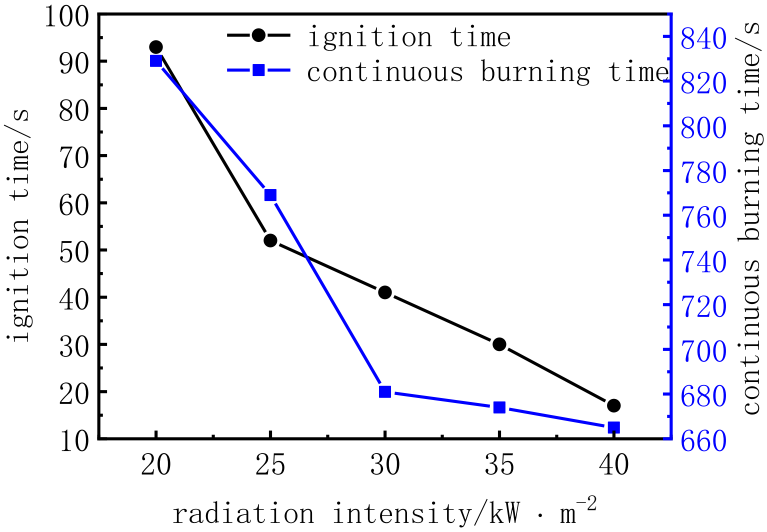

Figure 4: Ignition time and continuous burning time

This can be obtained from Figure 4, with the increase in thermal radiation intensity, the ignition time and continuous burning time of the conveyer belt are shortened to varying degrees. When the external thermal radiation intensity is 20 kW/m ^{2}, the average ignition time is 93s, and when the external thermal radiation intensity is 40kW/m^2, the ignition time is greatly shortened, and the average ignition time is greatly reduced to 17s, the ignition time is shortened by about 82%. The continuous burning time has also been shortened from 829s at 20kW/m^2 to 650s with a radiant intensity of 40kW/m^2, shortening the continuous burning time by about 22%. This shows that the external thermal radiation intensity has a great influence on the ignition characteristics of the conveyer belt, and under higher thermal radiation intensity, the thermal decomposition of the conveyer belt is accelerated, the concentration of combustible gas increases, and the ignition time becomes shorter.

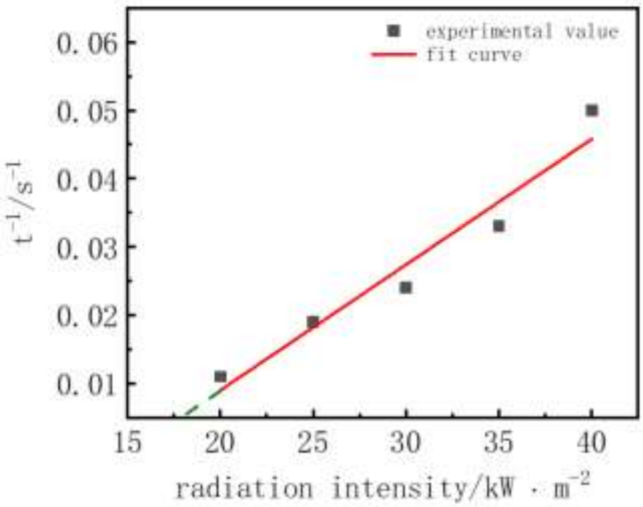

Figure 5: The relationship between the reciprocal of the ignition time and the radiation intensity

According to the ignition time t at each radiant intensity, the relationship between 1/t and the radiant intensity is plotted, as shown in Figure 5. It can be seen that the reciprocal of the ignition time has a linear relationship with the radiation intensity, and the intersection point with the horizontal axis can be obtained by fitting the extended fitting line, which is 18.2 kW/m^2, that is, the critical radiation intensity. The smaller the critical radiation intensity, the lower the heat required for ignition of the material, the easier it is to be ignited, and the greater the fire risk of the material.

2.3. Heat release rate

The heat release rate is one of the most important performance parameters for evaluating fire intensity, and it is also an important index for evaluating the combustion performance of materials, measured in kW/m^2, indicating the amount of heat released per unit area. During the experimental test, the instrument records the change in oxygen content during combustion, and the heat release rate of the sample can be calculated by the formula [11], the results are shown in Figure 6.

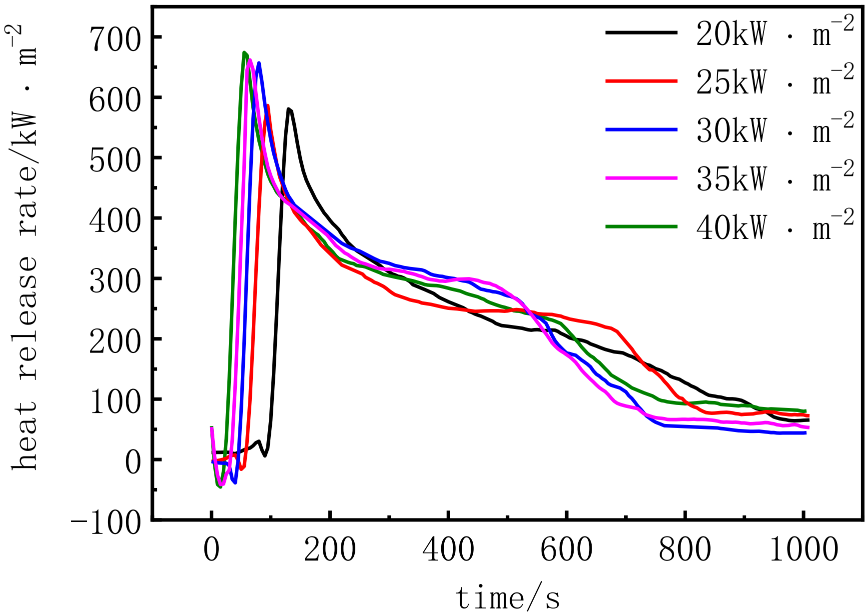

Figure 6: Heat release rate at different radiation intensities

As can be seen from Figure 6, there is a small fallback interval before the heat release rate rises sharply. The reason is that before the conveyer belt ignites, a series of chemical reactions occur, some of which are exothermic and some of which are endothermic. Before the conveyer belt is burned, a sufficient concentration of combustible gas is required, at which time the pyrolysis rate is accelerated, and at the same time a large amount of heat is absorbed to the outside world, resulting in less heat release than heat absorption during this time.

Under different heat radiation intensities, the trend of the heat release rate of conveyer belt is basically the same. After the conveyer belt is ignited, the heat release rate rises rapidly, because the combustible gas decomposed at high temperature collects on the surface of the conveyer belt and burns rapidly when ignited. After the accumulated combustible gas burns up in a short time, the heat release rate begins to decrease. With the gradual increase of heat radiation intensity, the peak heat release rate gradually increases, and the time to reach the peak gradually decreases. The higher the peak heat release rate, the more intense the burning of the material, the greater the danger.

The time of peak and the corresponding peak data are shown in Table 1. After adding the thermal radiation intensity from 20 kW/m ^{2} to 40 kW/m^2, the peak value increased by 16%, and the time to reach the peak was shortened by 58%。 Because the heat radiation intensity increases, the volatilization rate of combustible substances in the conveyer belt is accelerated, the peak of the maximum heat release rate is increased, and the time to reach the peak of the heat release rate is reduced.

Table 1: Related parameters of heat release rate

Thermal radiation intensity (kW/m^2)	**Peak of the heat release rate (pkhrr) (kW/m^2)**	**Peak time (t_{pkhrr}) (s)**
20	580.58	140
25	586.13	95
30	656.84	80
35	661.95	65
40	674.19	55

In order to further investigate the effect of thermal radiation intensity on peak and peak time, the function is used to determine its correlation relationship and fit it to a mathematical formula, as shown in Figure 7.

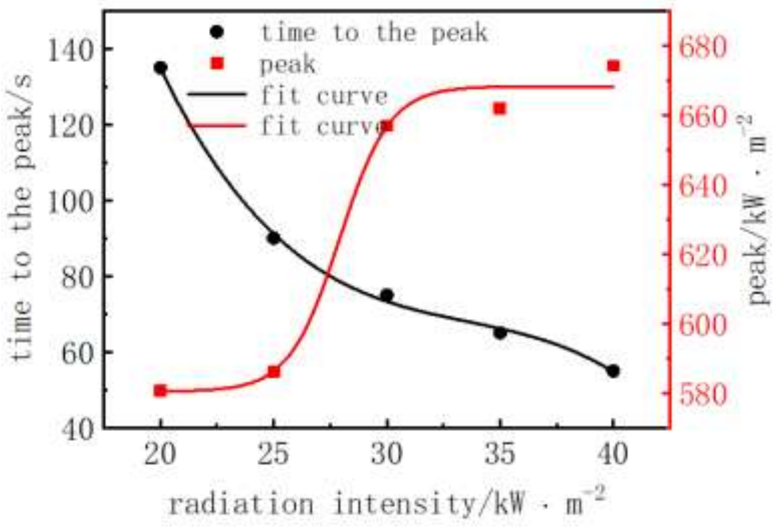

Figure 7: pkhrr and t_{pkhrr}

It can be obtained that the time required to reach the peak changes with the intensity of thermal radiation, the peak changes with the intensity of thermal radiation, and the relationship is shown in Equation (1) (2).

$$y = 866.14 - 68.86x + 2.01x^2 - 0.002x^3 \quad (1)$$

$$y = \frac{-87.85}{1+e^{\frac{(x-27.91)}{1.11}}} + 668.22 \quad (2)$$

It can be seen from Figure 7 that the time required to reach the peak is highly fitted to the thermal radiation intensity, which indicates that the increase in conveyer belt fire and the thermal radiation intensity are highly correlated. This correlation is mainly because the volatilization rate of combustible substances in the conveyer belt is greatly affected by temperature, and the strengthening of thermal radiation will accelerate the volatilization and accumulation of combustible substances, thereby reducing the time when the peak of the heat release rate appears. At the same time, the fitting degree of the peak to the thermal radiation intensity is also very high, and at 27.87 kW/m^2, the slope reaches the maximum, indicating that under the thermal radiation intensity, the heat release rate of the conveyer belt reaches a critical value, at which time the heat release rate rises rapidly and the peak value becomes larger. After that, the peak gradually tends to a fixed value. With the acceleration of the heat release rate, the concentration of combustible gas produced by pyrolysis before conveyer belt combustion increases to the maximum, the burning time is limited, and the corresponding peak value will also be affected and will not increase again.

Mass loss rate

During the burning process of the conveyer belt, a violent chemical reaction will occur, accompanied by a decrease in mass. The mass loss can react to a certain extent to the intensity of the burning of the conveyer belt and the burning resistance. The mass loss rate refers to the speed of mass loss of the material during the combustion process, which can reflect the pyrolysis speed of the material to a certain extent, and the larger the mass loss rate, the more intense the combustion of the material. The MLR value is derived from the differential equation [11] and the mass loss rate is shown in figure 8. As can be seen from Figure 8, the rate of mass loss rapidly rises to a maximum over time, then falls to a flat stage, and then slowly decreases over time until the end of combustion. As the intensity of heat radiation increases, the maximum mass loss rate of the conveyer belt also increases, and the time to peak decreases, and the overall trend is similar to the heat release rate. The detailed data is shown in Table 2.

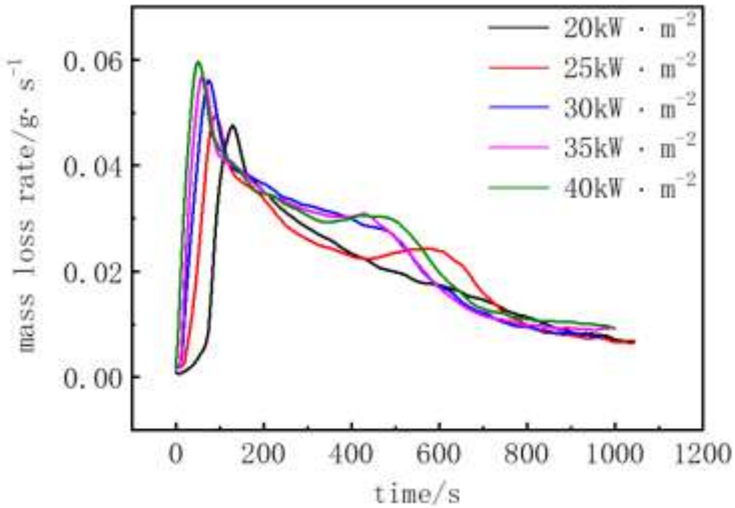

Figure 8: Mass loss rate at different radiation intensities

Table 2: Related parameters of quality loss rate

Radiation intensity (kW/m^2)	The peak of mass loss rate ($g{\cdot}s^{-1}$)	The time to reach the peak (s)
20	0.04759	130
25	0.04934	90
30	0.05615	75
35	0.05698	60
40	0.0596	50

From 20 kW/m^2 to 40 kW/m^2, the peak of mass loss rate is from 0.048 g/s to 0.06g/s, an increase of 25%. The time to the peak of the mass loss rate is reduced from 135s to 55s, the time is reduced by about 59%. It can be seen that the increase in radiation intensity has a large effect on the time to reach the peak of the mass loss rate, and the effect on the peak size is relatively small. To further investigate the effect of increasing radiation intensity on the peak of mass loss rate and the time to peak, the curves were fitted separately, as shown in Figure 9.

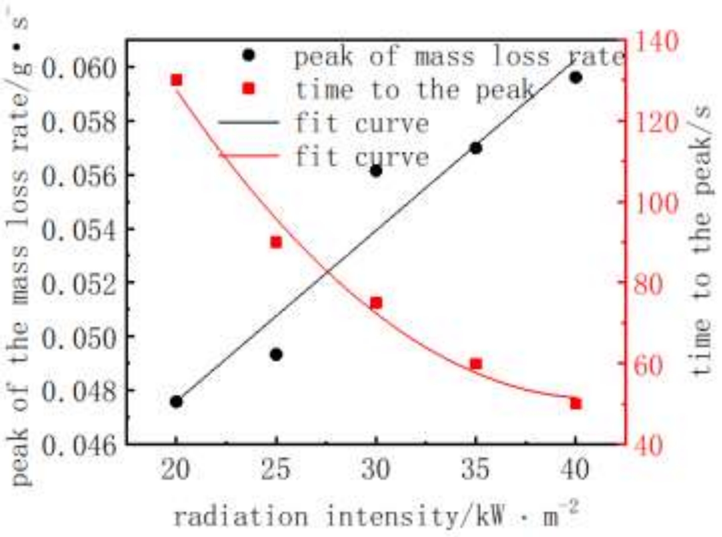

Figure 9: pkMLR and t_{pkMLR}

From the fitting results, the relationship between the thermal radiation intensity and the time to the peak of mass loss rate is shown in Equation (3)(4):

$$y = 0.035 + 6.34 \times 10^{-4}x \quad (3)$$

$$y = 340.71 - 14.09x + 0.17x^2 \quad (4)$$

This can be obtained from Figure 9 that the thermal radiation intensity and the peak of the mass loss rate can be fitted into a linear relationship, with the heat radiation intensity increasing, the faster the conveyer belt volatilizes the flammable gas, the faster mass loss rate, the more intense the combustion, the greater the peak value. The time required to reach the maximum value of the mass loss rate changes as a quadratic function of the thermal radiation intensity, and the equation shows that the axis of symmetry of the equation is 41.4, so it can be concluded that the time to the peak is the minimum when the thermal radiation intensity is 41.4 kW/m^2. According to Figure 7, the peak of the heat release rate will be limited and the principle of conveyer belt pyrolysis can be deduced: when the thermal radiation intensity is higher than 41.4 kW/m^2, the time to the peak will not be significantly shortened as the thermal radiation intensity increases.

Flue gas composition analysis

During the burning process of the conveyer belt, a large amount of O_2 is consumed, and toxic and harmful gases such as CO and CO_2 are produced, which are very harmful to the people trapped in the fire, so it is necessary to study the smoke generated by the burning of the conveyer belt. Figures 10 and 12 are the changes in CO2 and CO content during the combustion of conveyer belt samples under different thermal radiation intensities.

Changes in CO_2 content

As shown in Figure 10, as the experiment progressed, the content of CO_2 increased sharply first, then slowly decreased, and after the fire decayed, the content decreased rapidly for a while, and finally fell to extinguishing.

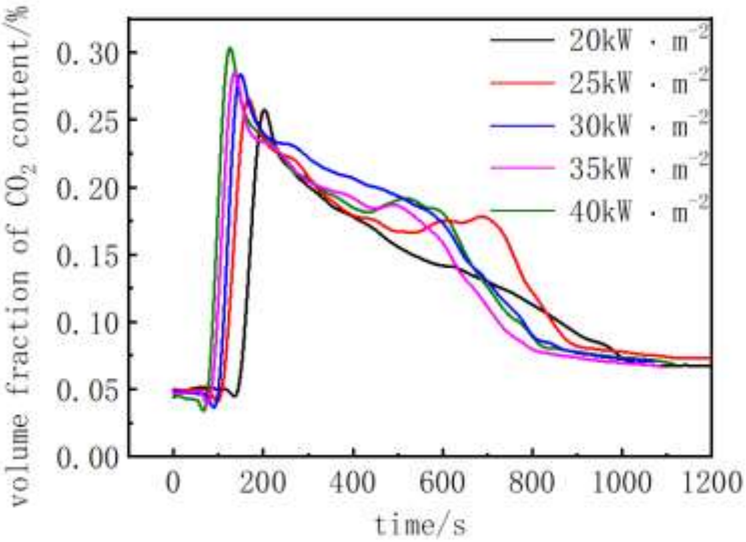

Figure 10: The volume fraction of CO_2 content

At the same time, with the increase of thermal radiation intensity, the peak of the CO_2 content increased, from 0.265% of the radiant intensity of 20 kW/m^2 to the radiant intensity of 400 kW/m^2 of 0.309%, an increase of about 0.044%. The time to the peak of CO_2 content was reduced, from 190s to 113s, and the time is shortened by about 40.5%. It can be seen that the increase in radiation intensity has a large effect on the time to the peak of CO_2 content, and the effect on the peak size is relatively small, which is the same as the effect on the heat release rate. Compared with the mass loss rate and heat release rate, the trend of change is roughly the same, but the time to the corresponding peak is slightly different, pkMLR is earlier than pkHRR and pkCO_2.

From the beginning of the thermal radiation of the conveyer belt, the surface begins to decompose flammable gases due to heat, resulting in a decrease in mass, and it begins to burn after accumulating to a sufficient concentration of combustible gas. With the fire increasing to the peak of heat release rate, a large amount of CO_2 is generated and reached the peak of CO_2 content.

Changes in CO content

CO is one of the most common toxic and harmful gases in fire smoke. Figure 12 shows the change in CO content during the combustion of conveyer belt samples, and there are two peaks in CO content during the whole combustion process. With the increase in radiation intensity, the first peak of CO content increases and the time to reach the peak decreases, and the change of the second peak is relatively insignificant.

As the combustion experiment progresses, it increases rapidly to the first peak, then falls. Then the CO content begins to increase to the second peak in the combustion to the decline stage, and gradually decreases as the combustion ends.

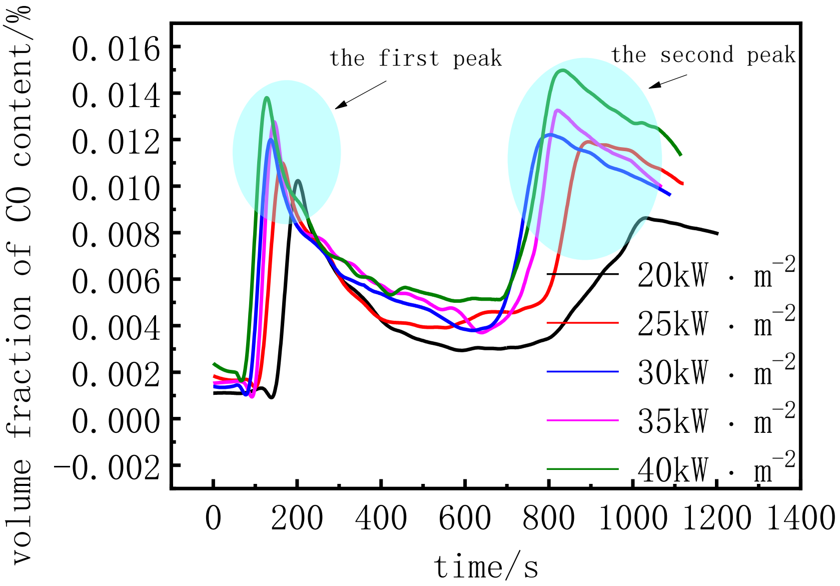

Figure 11: The volume fraction of CO contents

The reasons for the two peaks are: When the conveyer belt sample burns to the maximum fire, a variety of complex combustion reactions occur, producing a large number of toxic and harmful gases, at which time CO reaches the first peak, after which the combustion begins to flatten and CO production begins to decrease. Until the combustion begins to decline, due to its thickness of itself, the inside and bottom of the conveyer belt are not fully burned, the CO production increases again, reaching the second peak, and then the CO content decreases again with the decrease of combustibles.

Fire hazard analysis

The fire performance index (*FPI*) refers to the fire hazard during the combustion of the material, which is the ratio of the peak of the heat release rate (*pkHRR*) to the ignition time (T_i). , the formula is:

$$FPI = \frac{pkHRR}{T_i} \quad (5)$$

pkHRR is the peak of the heat release rate, kW/m^2 ; T_i is the ignition time, s; FPI is the fire performance index, kW/(m^2•s). The larger the peak of the heat release rate, the shorter the ignition time, the larger the FPI, the easier the material to be ignited, the more likely it is to occur during combustion, and the greater the fire risk; Conversely, the less likely it is to ignite, the less likely it is to fire.

The fire growth index (FGI) refers to the growth rate of the fire during the combustion of the material, which is the ratio of the peak of the heat release rate (pkHRR) and the time required to reach the peak (T_a), the formula is

$$FGI = \frac{pkHRR}{T_a} \quad (6)$$

T_a is the time required to reach the peak, s; FGI is the speed of fire growth, kW/ (m^2•s) . The shorter time to reach the peak of the heat release rate, the larger peak of the heat release rate, and the larger FGI, the faster the fire growth rate, and vice versa, the slower the fire growth rate.

The fire performance index and fire growth index of the conveyer belt are shown in the following table:

Table 3: FPI and FGI at different radiation intensities

Radiation Intensity (kW/m^2)	FPI (kW(m^2•s)$^{-1}$	FGI (kW(m^2•s)$^{-1}$
20	6.24	4.15
25	11.27	6.17
30	16.02	8.21
35	22.06	10.18
40	39.65	12.26

As can be seen from Table 3, the values of FPI and FGI increase as the intensity of thermal radiation increases, and the FPI and FGI at 40kW/m^2 are 6.35 and 2.95 times higher than those at 20kW/m^2. It shows that with the increase in radiation intensity, the fire risk of the conveyer belt becomes greater, and the fire growth rate becomes faster when burning.

Conclusion

In this experiment, the combustion characteristics of conveyer belt under different radiation intensities were studied by cone calorimeter, and the effects of increasing radiation intensity on conveyer belt ignition time, heat release rate, mass loss rate, flue gas composition, and fire hazard were analyzed. The conclusion is as follows:

(1) The increase in thermal radiation intensity will shorten the ignition time and continuous combustion time of the conveyer belt to a certain extent, and the reciprocal ignition time is linearly related to the radiation intensity, and the critical radiation intensity of the tape is 18.2 kW/m^2 obtained from the fitting curve.

(2) During the whole combustion process, the heat release rate, mass loss rate, and CO_2 content change trend are similar, with the combustion time, first rapidly increasing to the peak, then falling back to the flat stage, and finally slowly decreasing. With the increase in heat release rate, the time to reach the peak of all three was shortened to varying degrees, and pkMLR was earlier than pkHRR and pkCO_2.

(3) There are two peaks in CO content throughout the combustion process, and as the intensity of thermal radiation increases, the first peak increases, and the time to reach the first peak is also shortened. The second peak occurs because when the combustion begins to decay, the CO is produced by insufficient combustion of the conveyer belt, and the heat release rate and CO_2 can also be seen in Figure 6 and Figure 10 production has decreased significantly.

(4) With the increase in radiation intensity, both the fire performance index and the fire growth index of the conveyer belt have multiplied. The FPI and FGI at 40 kW/m^2 are 6.35 and 2.95 times higher than at 20 kW/m^2, respectively.

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