Case Studies in Fire Safety 4 (2015) 39–48

Contents lists available at ScienceDirect

Case Studies in Fire Safety

journal homepage: www.elsevier.com/locate/csfs

Short communication

Combustion performance of flame-ignited high-speed train seats via full-scale tests[☆]

Jie Zhu [a,b,*], Xiao Ju Li [b], Cheng Feng Mie [b]

[a] Sichuan Provincial Key Laboratory of Public Fire Prevention Technology, Chengdu, Sichuan 610101, China
[b] Fire Engineering Research Institute, Sichuan Normal University, Chengdu, Sichuan 610101, China

ARTICLE INFO

Article history:
Received 29 December 2014
Received in revised form 20 May 2015
Accepted 29 May 2015
Available online 28 June 2015

Keywords:
High-speed train
Double seat
Heat release rate
Combustion characteristics
Full-scale test

ABSTRACT

Determining the combustion characteristics of combustibles in high-speed trains is the foundation of evaluating the fire hazard on high-speed trains scientifically, and establishing effective active and passive fire precautions. In this study, the double seats in the compartments of CRH1 high-speed trains were used as the main research object. Under different test conditions, including the power of ignition sources and ventilation rates, full-scale furniture calorimeter tests were conducted to study important fire combustion characteristics such as the ignition characteristics of seats, heat release rate, mass loss rate, total heat release, temperature variation, and smoke release rate. The relationships among these parameters were analyzed and summarized into combustion behavior and characteristics, thus providing fundamental data and reference for the development of fire precautions and safety design of high-speed trains. The results in this test are as follows: (i) The double seats of high-speed trains are relatively easy to ignite and susceptible to the fire ground environment. (ii) The combustion temperature in the test apparatus exceeded 600 °C in only 2 min for the larger ignition source. (iii) The heat release rate exceeded 800 kW. (iv) The total heat release resulted mainly from flame combustion. (v) The final mass loss rate was ~30%. (vi) The lowest light transmittance was <25%. (vii) The change process of temperature with time has the same trend as the change process of heat release rate. (viii) Suppressing flame combustion and controlling the smoke generated from the seat materials themselves played key roles in retarding the combustion of high-speed train seats.

1. Introduction

With the rapid development of social economy, science, and technology, the high-speed railway in China has undergone rapid development. Currently, the extent of high-speed railway operation in China ranks first in the world. According to the *Mid- and Long-term Development Plan of Integrated Transport Network in China* reference required, the operating mileage of the railway network in China will exceed 120,000 km by 2020, and that of the constructed passenger lines will exceed 16,000 km. However, fire safety of high-speed trains has not been investigated in detail in China [1,2].

[☆] Project supported by the National Natural Science Foundation of China (Grant No. 51446002).

[*] Corresponding author at: Sichuan Provincial Key Laboratory of Public Fire Prevention Technology, Chengdu, Sichuan 610101, China.
E-mail address: zhujie0805@163.com (J. Zhu).

http://dx.doi.org/10.1016/j.csfs.2015.05.002

A high-speed train has typically a narrow and confined space, where combustibles are relatively concentrated and there are a relatively small number effective fire safety and precaution systems are available. Thus, the fire has the potential to spread quickly and rescue becomes difficult in case of a fire. Thus, train fires can seriously threaten human life and traffic safety and easily lead to a crash tragedy and cause adverse social impacts. The fire precautions for high-speed trains have attracted attention in many countries. As representatives of developed countries, Japan, Germany, and the United States have set up professional fire research institutions that have conducted several fruitful studies [17–19,22]. Their research has mainly focused on selecting flame-retardant train body materials, establishing standards for fire precautions, and optimizing the structure of train. The results obtained in these studies have witnessed a certain success in their practical applications in high-speed trains [3–6].

Compared to other countries, domestic studies on high-speed train fire precautions are still scarce in China. The only reported studies are confined to qualitative descriptions and summarization of the reasons, fire characteristics, and fire and emergency management of high speed train fire safety, in addition to a small number of studies on FDS numerical simulation. These studies are nor directly relevant and unable to reflect the actual fire scenarios [7–9]. A complete system of high-speed train fire precautions has not been established yet in China, nor systematic studies on the characteristics of train combustion, smoke spread, personnel evacuation, fire precautions, and design for retarding fire growth. In particular, only a few studies have been conducted on the combustible characteristics of high-speed train compartments and materials, and full-scale tests have been rarely conducted.

The compartments of high-speed trains mainly consist of the train body, seats, baggage, curtains, and other materials. The train body is mostly noncombustible or difficult to burn; therefore, the combustion of high-speed trains is primarily the complex heat and mass transfer processes of combustibles that are composed of seats, passenger baggage, curtains, and other components under various environmental coupling effects. Once the potential for fire ignition and spread is known for high-speed trains, several types of effective and feasible, active and passive fire precautions can then be established. The first step is to determine the combustion behavior and characteristics of various combustibles, among which passenger seats play a relatively significant role in high-speed train compartments [1,2].

In this study, the double seats in the compartments of CRH1 high-speed trains were used as the main research object. Under different test conditions, including the power of ignition sources and ventilation rates, full-scale furniture calorimeter tests were conducted to study the important fire combustion characteristics such as the ignition characteristics of seats, heat release rate, mass loss rate, total heat release (THR), temperature variation, smoke release rate (SRR). The relationships among these parameters were analyzed quantitatively and summarized into combustion behavior and characteristics, thus providing fundamental data and reference for the development of appropriate fire precautions and safety design of high-speed trains.

2. Compartment model and materials

The CRH1 high-speed train has been widely used on Chengdu–Guan County high-speed railway, Suining–Chongqing railway, Beijing–Shanghai high-speed railway, Shanghai–Hangzhou high-speed railway, and Guangzhou–Shenzhen railway, usually with a speed up to 200 km/h. The compartments of CRH1 high-speed trains are divided into first-class, second-class, and dining compartments. Their setting situation and detailed parameters are shown in Table 1. The detailed profile and plan are shown Figs. 1–3 [1,2].

A first-class compartment of CRH1 high-speed train contains 77 seats that are distributed in the form of 2 + 2 with a seat width of 500 mm; a second-class compartment contains 101 seats that are distributed in the form of 2 + 3 with a seat width of 450 mm. The outer layer of seats is mainly composed of synthetic fiber, while the internal filling material is polyurethane foam [1,2].

3. Test equipment and method

The fire combustion characteristics in these tests were measured mainly based on the principle of oxygen consumption. The equipment and site of tests are shown in Figs. 4 and 5. The full-scale combustion structure was constructed in accordance with the GB/T27904-2011 standard [10], and the fume-collecting hood used had a cross section of 3 m × 3 m and a height of

Table 1
Setting situation and detailed parameters of first-class, second-class, and dining car compartments.

Number	Item	Type of compartment		
		First-class compartment	Second-class compartment	Dining compartment
1	Number of compartments	2	5	1
2	Seat distribution	2 + 2	2 + 3	2 + 3
3	Number of seats in every compartment	72	101	19((fixed seats)) + 24((dining car seats))
4	Width of seats	500 mm	450 mm	–
5	Front-back distance	970 mm	900 m	–
6	Width of passage	600 mm	580 m	–

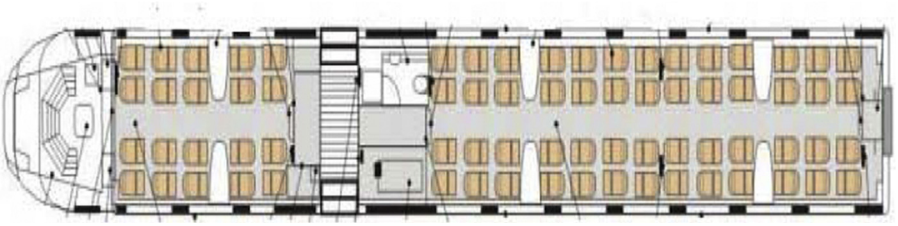

Fig. 1. Profile and plan of first-class compartment.

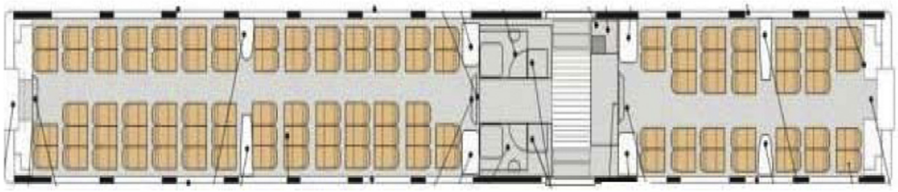

Fig. 2. Profile and plan of second-class compartment.

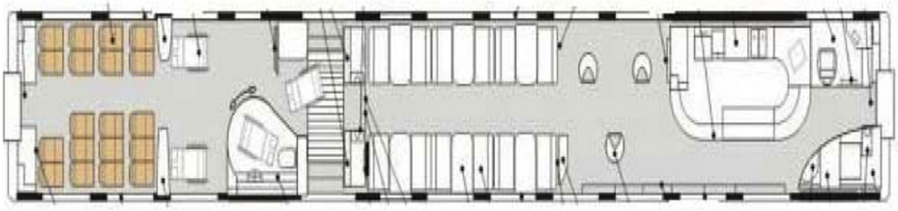

Fig. 3. Profile and plan of dining car compartment.

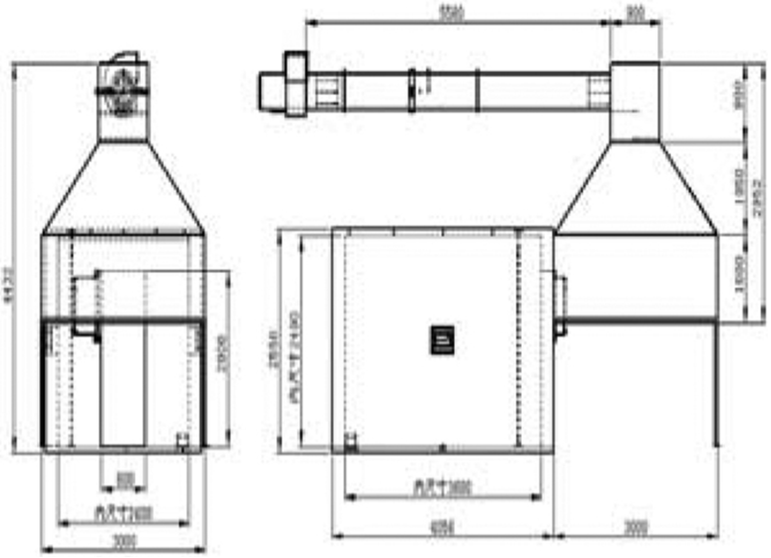

Fig. 4. Set-up diagram of large furniture calorimeter.

1.0 m. One side of the fume-collecting hood bottom was attached tightly to the test room, and the steel plates of the other three sides extended downward by 1.0 m. The effective height of the fume-collecting hood was 2.0 m. The hood was connected to a mixing chamber whose cross-section was 0.9 m × 0.9 m. The minimum height of mixing chamber was 0.9 m. For increasing the turbulence effect, two 0.5 m × 0.9 m division plates were placed in the mixing chamber. The design and manufacturing of the fume-collecting hood ensured no leakage of smoke. The exhaust pipe was also connected to the mixing chamber. The inner diameter of the exhaust pipe was 400 mm, and its straight part was $\geq$4.8 m.

Fig. 5. Picture of onsite test.

The gas current equalizers were placed on both ends of exhaust pipe to achieve a uniform smoke flow at the measuring points. The exhaust pipe and system were connected to each other. On the latter half of the exhaust pipe, one part was the measuring section, which was equipped with a gas sampling device and smoke density analyzer. The gas sampling device was connected to a gas analyzer to measure and analyze the O_2, CO_2, and CO concentrations in the smoke. An exhaust ventilator was installed on the end of the exhaust pipe. The capacity of the exhaust ventilator was $\geq$4 kg/s (under the standard atmospheric pressure, the capacity is $\sim$12,000 m^3/h) for collecting the entire generated smoke. The vacuum degree at the ventilator end was 2 kPa. During the test, the exhaust volume of the ventilator was continually adjusted between 0.5 and 4 kg/s. In the early stage of the test, the air flow was adjusted to a low value, assuming that it would affect the accuracy of the tests. The entire combustion chamber was set in an environment without mechanical ventilation, with a constant temperature and an adequate indoor space that ensured no impact on tests.

Because the basic layout of a high-speed train passenger compartment has double seats, a self-purchased double sofa of CRH1 was used as the test specimen. The ignition source was propane gas. The fire source was located 50 mm above the center of double sofa at an ambient temperature of 24.5 °C. The different test conditions were as follows: ignition powers of 20 and 100 kW and ventilation rates of 1.5 and 2.8 m^3/s; all the measuring devices were calibrated before each test, and each group of tests was repeated three times.

4. Test results and analysis

4.1. Characteristics of ignition process

Ignition time is an important parameter in evaluating the fire risk of materials [11]. A shorter ignition time indicates that the material is easier to ignite, thus creating the potential to spread the fire more easily to the surrounding substances and causing a higher fire risk. Table 2 shows the ignition time and flame duration of double seats under different test conditions. As shown in Table 2, when the double seats were ignited under different combustion conditions, different ignition times were observed. With an ignition power of 20 kW and a ventilation rate of 1.5 m^3/s, the ignition time of the double seats was 103 s; with an ignition power of 100 kW and a ventilation rate of 2.8 m^3/s, the ignition time was only 78 s. The time to ignition decreased when the power of the ignition source and ventilation rate increased. With an ignition power of 100 kW and a ventilation rate of 2.8 m^3/s, the flame duration of double seats was only 1092 s, much shorter than that under other test conditions. The result indicates that the fire ground environment significantly affects the burning characteristics of double

Table 2
Ignition time and flame duration of double seats under different test conditions.

Ventilation rate (m^3/s)	Power of ignition source 20 kW		Power of ignition source 100 kW	
	Ignition time (s)	Flame duration (s)	Ignition time (s)	Flame duration (s)
1.5	103	1673	86	1348
2.8	94	1497	78	1092

seats. A combination of higher ventilation rate that allowed more fresh air and oxygen and increased ignition power made it easier for the double seats to be ignited and completely combusted, with a shorter combustion duration.

The detailed combustion process in the tests undertaken is shown in Fig. 6. The ignition of double seats is a typical example of diffusion flame combustion. The outer layer of double seats was mainly composed of artificial synthetic fibers that were easy to ignite by radiant heat, followed by rapid melting and shrinking; the flames began to spread rapidly along the longitudinal direction from the front surface to the back of the double seats and simultaneously ignited the polyurethane filler in the cushion. The fire expanded further, while the mass of combustibles decreased with continuous combustion, thus gradually weakening the fire until it extinguished finally. Therefore, the vertical longitudinal spread of double seats was the main approach for the diffusion of combustion.

4.2. Heat release rate

The heat release rate is one of the most important indices in evaluating the combustion performance of materials, the size of fire, and the degree of damage. The peak value of heat release rate and the average heat release rate are two important indices in studying the heat release rate [12]. Fig. 7 shows the curves of heat release rate under different ignition powers and ventilation rates. Table 3 shows the peak values of heat release rate and the average heat release rate of double seats under different test conditions.

As shown in Fig. 7, the heat release rate curves under different test conditions show a consistent form, initially flat, then exothermic, and flat finally. In the time range 200–400 s, the heat release rate increased rapidly. The heat release rates reached the peak values with the full combustion of polyurethane filler in the time range 400–600 s; with the decrease in combustible mass, the heat release rate gradually decreased in the time range 600–1000 s. The heat release rate decreased to 30–60 kW at 1000 s, upon which the continuous test ended.

With the same ignition power, the peak values of heat release rate of seats and average heat release rate both increased with the increase in ventilation rate. The time to reach the peak value was significantly shortened. When the ignition power was 20 kW, the peak values of heat release rate were 946 and 1040 kW respectively, corresponding to the ventilation rates of 1.5 and 2.8 m^3/s, while the average peak heat release rates were 238 and 272 kW, respectively. A higher ventilation rate allowed more fresh air and provided adequate oxygen, thus helping the ignition and full combustion of double seat material and eventually leading to a higher heat release rate.

In a combustion environment with a higher ventilation rate, the peak value of heat release rate and average heat release rate both increased with increase in the ignition power. A higher ignition power reduced the energy loss by a convective process with the outer environment, thus accelerating the combustion rate, increasing the peak value of heat release rate, shortening the combustion duration, and increasing the average heat release rate. For example, under an ignition power of 100 kW and a ventilation rate of 2.8 m^3/s, the peak value of heat release rate and average heat release rate was 1144 and 454 kW, respectively, both higher than those (1040 and 272 kW) with an ignition power of 20 kW.

The test results show that in a combustion environment with a relatively low ventilation rate, the peak value of heat release rate was reduced and the time to reach the peak value of heat release rate occurred earlier when the ignition power was increased. For example, under a ventilation rate of 1.5 m^3/s and an ignition power of 100 kW, the peak value of heat release rate was 806 kW, which was lower than the 946 kW with an ignition power of 20 kW, while the average peak heat release rate was higher than the corresponding value with an ignition power of 20 kW. Based on these limited test results, the analysis suggests that a higher ignition power may ignite double seats sooner, and decreased the peak value of heat release rate; on the other hand, a higher ignition power reduced the duration of burning, while the average heat release rate increased with increase in the ignition power. Thus, the ventilation environment determined whether the double seats combusted completely and significantly contributed to the peak value of heat release rate.

4.3. Total released heat THR

THR is defined as the total released heat per unit area of material undergoing complete combustion. A higher THR represents a greater potential risk and overall fire size from the combustion of material [13]. The THR curves under different test conditions are shown in Fig. 8. With the ignition and self-sustaining combustion of double seats, the THR increased in the time range 200–400 s. After reaching the peak value of heat release rate, the THR increased slowly and became steady when the flame was extinguished.

The tests showed that the THR of double seats increased when the ignition power was increased, resulting in a higher heat release intensity to the outer environment, more complete combustion, and more thorough internal heat release. With an ignition power of 100 kW and a ventilation rate of 2.8 m^3/s, the THR was 383 MJ, which was higher than the THR (303 MJ) with an ignition power of 20 kW and a ventilation rate of 1.5 m^3/s. The curves also indicate that the THR was mainly provided by the flame combustion phase. Therefore, suppression of flaming combustion plays a key role in retarding the combustion of double seats.

4.4. Mass loss rate

Mass loss rate is an important parameter in reflecting the degree of pyrolysis, evaporation, and combustion, and evaluating the fire risk of substances. A higher mass loss rate indicates that the material can be ignited more easily and the

Fig. 6. Detailed combustion process in onsite tests.

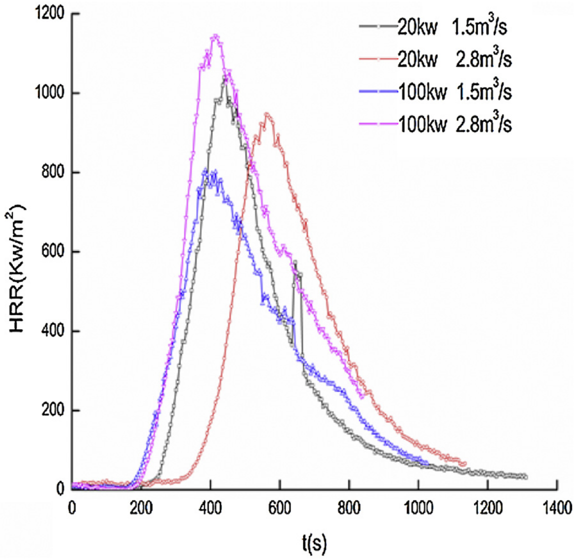

Fig. 7. Curves of double seat heat release rate versus time under different test conditions.

Table 3
Peak value of heat release rate and average heat release rate of double seats under different test conditions.

Ventilation rate (m^3/s)	Power of ignition source 20 kW			Power of ignition source 100 kW		
	Peak value of heat release rate (kW)	Time to peak value	Average heat release rate (kW)	Peak value of heat release rate (kW)	Time to peak value	Average heat release rate (kW)
1.5	946	560	238	806	385	294
2.8	1040	440	272	1144	415	454

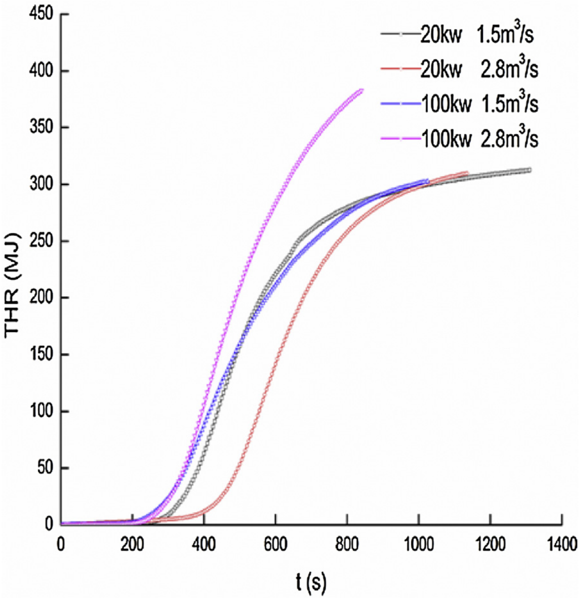

Fig. 8. Total heat release curves of double seats versus time under different test conditions.

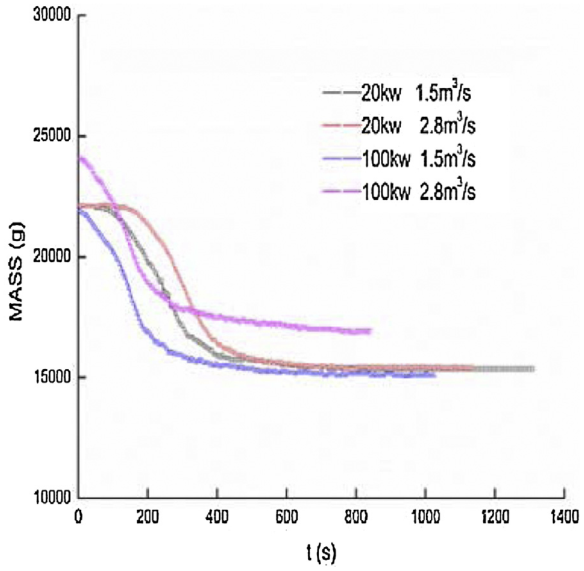

Fig. 9. Mass loss curves of double seats versus time under different test conditions.

combustion rate is higher. During the test, the initial masses of double seats were between 22 and 24 kg. The small difference between four initial masses resulted from the individual differences in seats used in tests. Fig. 9 shows the mass curves of double seats versus time under different test conditions.

During the initial stage of seat combustion, a certain difference in the mass loss rate was observed before the heat release rate reached its peak value. The mass loss rate difference increased with increase in the ignition power and the ventilation rate. However, with increasing duration of combustion, the combustible material of the seats burned completely. All the final mass losses under different test conditions were 31% of the total initial mass.

4.5. Temperature change

The combustion of high-speed train double seats generates a considerable volume of high-temperature smoke [14,15,12,16–19], which can spread under the combined effects of buoyancy, wind, etc. Fig. 10 shows the change of temperature within the exhaust pipe with time when the double seats were combusted under different test conditions. The curves are similar shape to the heat release rate curves. With the increase in heat release rate, with an ignition power of 100 kW and ventilation rates of 2.8 and 1.5 m^3/s, the rate of rise in temperature in the flue gas was relatively fast, reaching

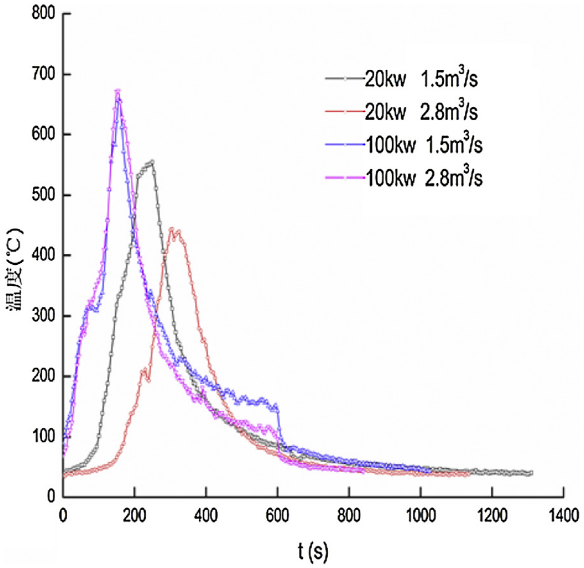

Fig. 10. Exhaust pipe temperature in combustion of double seats versus time under different test conditions.

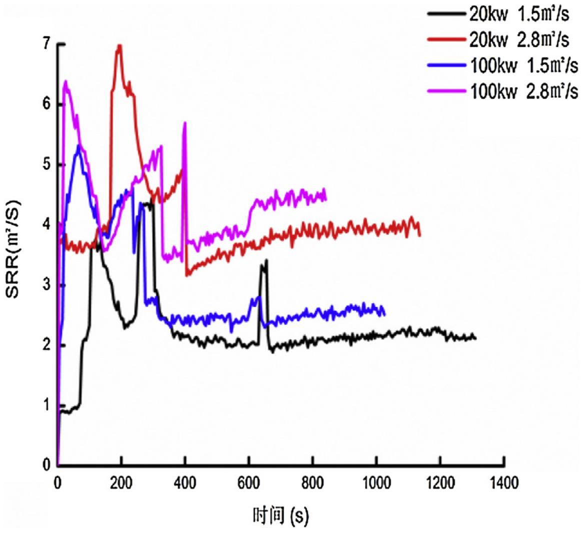

Fig. 11. Smoke release rate of double seats versus time under different test conditions.

the peak value (670 °C) in only 150 s. In a high speed train, such temperatures coved lead rapidly to a flashover stage, thus causing further expansion of fire and affecting the evacuation of personnel. With an ignition power of 20 kW and ventilation rates of 2.8 and 1.5 m^3/s, the temperature peaks were 550 and 440 °C, respectively.

4.6. Smoke release rate and light transmittance rate

The smoke release rate (SRR) of materials in combustion is an important index in evaluating the contribution of materials on fire [20,21]. Figs. 11 and 12 show the SRR and light transmittance curves versus time under different test conditions.

As shown in Fig. 11, under different test conditions, the SRR and light transmittance curves were somewhat consistent, and the SRR increased with the increase in ignition power and ventilation rate. With a higher ignition power and ventilation rate, the double seats were more easily ignited, and the time to release smoke increased. Fig. 12 shows that the initial transmittance at zero time was around 90% due to the environmental condition in the test laboratory and test apparatus; the light transmittance decreased with increase in the ignition power and ventilation rate, and that a higher ignition power and ventilation rate led to more thorough combustion, a large amount of smoke generation, and a lower light transmittance.

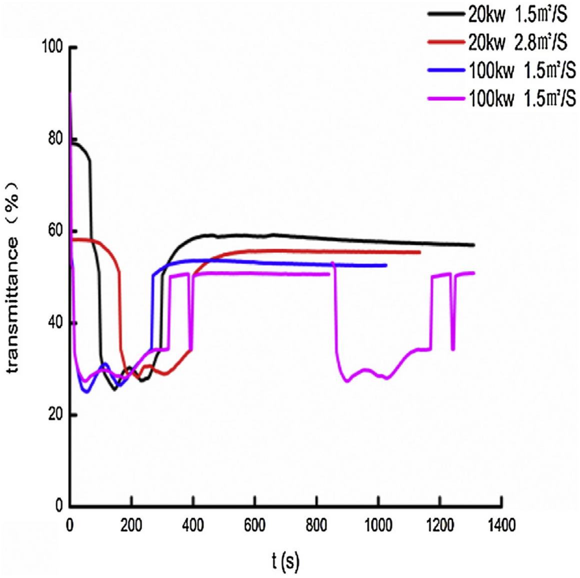

Fig. 12. Light transmittance versus time under different test conditions.

Therefore, measure to suppress the smoke generated from double seat materials themselves is one of the safety precautions necessary for enhancing the evacuation of personnel.

5. Conclusions

In this study, the double seats in the compartments of CRH1 high-speed trains were used as the main research object. A limited number full-scale furniture calorimeter tests were conducted to study the combustion behavior characteristics of these seats. Through discussion and analysis of these tests, the following indications of double seat performance in train carriages can be drawn:

(1) The combustion characteristics of high-speed train double seats depend on the ignition power, ventilation rate, and other factors of fire ground environment; the ignition time appears to be mainly determined by the double seat surface material and ignition power. The combustion duration of double seats is in the range 18–26 min based on these specific test conditions.
(2) The heat release rate of high-speed train double seats can exceed 800 kW, mainly dominated by the combustion of the polyurethane filler of cushion; the ventilation conditions significantly affected the peak value of heat release rate.
(3) The THR exceeded 300 MJ. Therefore, means to suppress the flaming combustion of seats is the key factor in retarding double seat fires; the final mass loss rate was $\sim$30%.
(4) The combustion of high-speed train double seats generates a large amount of high-temperature smoke. In these tests, the shortest time to achieve flaming combustion and a high temperature of 600 °C is 2 min.
(5) The SRR increased and the light transmittance decreased with the increase in ignition power and ventilation rate. The minimum value of light transmittance was $<$25%. Reducing the smoke generated by double seat materials is one potential measure to minimize casualties.

Understanding the fire behavior of seats on high speed train is one important factor, along with all ceiling and floor materials in designing trains in which the risks to train passengers and crews are minimized. This limited test program has identified some of the key factors in the interval train carriage environment which can affect train seat fire performance.

References

[1] National Railway Administration of the People's Republic of China, Railway passenger transportation procedures, Railw. Transp. 101 (1997).
[2] Z. Shu-guang, Harmony Electric CRH1 EMU, China Railway Publishing Hose, Beijing, 2008, pp. 5–20.
[3] M. Ahrens, Home Fires that Began With Upholstered Furniture, Fire Analysis and Research Division. National Fire Protection Association, 2008.
[4] M. Margret, D. Martin, B. Per, R. Andres, Combustion of chemical substances fire characteristics and smoke gas components in large-scale experiments. SP Report, Swedish National Testing and Research Institute, Sweden, 1994p. 28.
[5] ISO 9705, Fire Test-Full Scale Room Test for Surface Products, International Standards Organization (ISO), Geneva, 1993.
[6] K. Saito, J.G. Quintiere, F.A. Williams, Upward Turbulent Flame Spread. International Symposium on Fire Safety Science, Hemisphere Publishing Corporation, New York, Gaithersburg, 1985p. 75.
[7] X.-L. Yao, J.-M. Chen, Study on influence of passenger baggage on heat release rate of high-speed passenger train compartment, J. Saf. Sci. Technol. 10 (2) (2014) 51–56.
[8] J.-M. Chen, X.-L. Yao, G. Yan, C. Qian, Study on heat release rate of first class compartment, J. Saf. Sci. Technol. 10 (1) (2014) 51–56.
[9] S. Wu, The fireproof design for CRH3 multiple units, Railw. Veh. 50 (7) (2012) 16–18.
[10] GB/T25207-2010, Fire tests—Full-scale room test for surface products.
[11] Y. Zhang, Heat Release Rate Prediction Model of Upholstered Furniture, (a dissertation for the degree of M.Eng.), Harbin Engineering University, 2009.
[12] X.D. Cheng, Study on Melting and Flowing Combustion Behavior of Typical Thermoplastics in Compartment, (Ph.D. dissertation), University of Science and Technology of China, 2014.
[13] H. Zhang, W. Wan, Y. Yang, L. Xu, W. Zhu, Full-scale experimental study of sofa heat release rate in compartment, J. Eng. Thermophys. 26 (l) (2005) 277–279.
[14] Y. Yang, H. Zhang, W. Wan, L. Xu, Y. Wan, Study of heat release rate of typical lining materials in full-scale fire test, Fire Saf. Sci. 12 (4) (2003) 191–196.
[15] X. Peng, S. Liu, G. Lu, Experimental analysis on heat release rate of materials, J. Chongqing Univ. (Nat. Sci. Ed.) 28 (8) (2005) 122–125.
[16] L. Xu, The Study on Fire Performance of Typical Thermoplastic Lining, (Ph.D. dissertation), University of science and Technology of China, 2007.
[17] R. Peacock, P. Reneke, J. Averill, et al., Fire Safety of Passenger Trains, Phase II: Application of Fire Hazard Analysis Techniques, 2002.
[18] R.D. Peacock, D.V. Jason, D. Madrzykowski, et al., Fire Safety of Passenger Trains, Phase III: Evaluation of Fire Hazard Analysis Using Full-Scale Passenger Rail Car Tests, 2004.
[19] H. Ingason, A. Lonnermark, Heat release rates from heavy goods vehicle trailer fires in tunnels, Fire Saf. J. (40) (2005) 646–668.
[20] A. Lonnermark, H. Ingason, Gas temperatures in heavy goods vehicle fires in tunnels, Fire Saf. J. (40) (2005) 506–527.
[21] T. Teruo, Research on prevention of train fire, Rail Int. 8 (7–8) (1977) 395–406.
[22] M.P. Colino, E.B. Rosenstein, Tunnel emergency egress and the mid-train fire, in: Proceedings of the 4th International Symposium Aerodynamics and Ventilation of Vehicle Tunnels, York, UK, (1982), pp. 169–186.