Study on the influence of ventilation condition on the heat release rate of the CRH passenger rail car

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Abstract

The ventilation condition is one of the main factors that determine the Heat Release Rate (HRR). In order to reveal the influence of ventilation condition on the HRR of China Railways High-speed (CRH) passenger rail car and help the fire protection engineers to choose the right HRR during the fire risk assessment of high-speed rail system in China, the HRR and other thermal parameters of the individual materials and component assemblies of CRH passenger rail car, are measured with the Cone Calorimeter and other test instruments, as the input parameters of Fire Dynamics Simulator (FDS), and 2 fire scenarios have been designed to obtain the HRR vs. time curves of CRH passenger rail car on the different ventilation conditions, such as the location and number of the open windows. The research results show that the ventilation condition exerts a significant influence on the HRR of CRH passenger rail car, which is in the range of 18.4–37.9 MW according to the different ventilation conditions; if only one window is open, the closer the open window gets to the ignition source, the higher the HRR is; if several windows are open at the time, the HRR is the highest as 2 windows are open, which is 37.9 MW. The HRR of CRH passenger rail car dramatically fluctuates with the different ventilation conditions, so the HRR of CRH passenger rail car should be chosen and applied carefully.

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1. Introduction

7.23 Wenzhou high-speed rail collision accident sparked the public doubt on the safety of high-speed rail system in China. Although fire is the most frequent and serious disaster in our daily lives, fire hazard of the high-speed rail system is easily ignored because the CRH passenger rail car is now made of all kinds of flame retardant materials. In order to meet the requirements of continuously raising speed of the modern railway system and satisfy the passengers’ need for comfortable traveling environment, the lightweight design of CRH passenger rail car has become an inevitable trend. The lightweight design of CRH passenger rail car causes that all kinds of high polymer materials will be widely used as interior decoration materials, car body structure, etc., which will significantly increase the fire load of CRH passenger rail car. Once a fire occurs in the CRH passenger rail car, a lot of poisonous and high-temperature smoke will be produced to cause many casualties, huge economic losses and severely negative social and political impact, because of its high occupant density, small inner space, and high speed. With the rapid development of high-speed rail technology, it is urgent to carry out studies...
on the fire protection and control technology, which is generally regarded as one of the core technologies of high-speed rail system.

To some extent, the fire development speed and scale mainly depend on the HRR of passenger rail car, which is an important parameter for the fire protection and control technology, especially for the fire risk assessment and fire numerical simulation. So how to choose the reasonable HRR of passenger rail car is one of the inevitable problems to access the fire safety of high-speed rail system. As we all know, the fire load and ventilation condition are the two main factors that influence the HRR. After a fire occurs in a passenger rail car, the ventilation condition, such as the location and number of open windows, directly determines the air supply and also the HRR of passenger rail car, because the inner space of passenger rail car is very small, and the fire load is often relatively fixed.

In the following, the experiment and numerical simulation methods are combined to research the influence of ventilation condition on the HRR of high-speed rail system.

2. Research method of the HRR of passenger rail car

Now the main research methods in the fire science and technology field include the full scale experiment, model scale experiment, fire numerical simulation, etc. The result reliability of full scale experiment is the highest one among all the three main research methods mentioned above, but because the full scale fire experiment is a kind of destructive test, it will consume tremendous human and material resources, and what is more, at present the calorimeter is also not large enough to directly test the HRR of passenger rail car due to its large size. Therefore the model scale fire experiments are widely carried out instead of the full scale experiments, and the results can easily be translated from a model scale fire experiment into a full scale system, based on the theory of dimensionless groups, but the result reliability of model scale fire experiment still need the further validation.

With the rapid development of computer capacity and numerical simulation technology, the fire numerical simulation has become one of the main research methods in the fire science and technology field.

A 1993 study by the National Institute of Standards and Technology (NIST), sponsored by the Federal Railroad Administration (FRA), concluded that an alternative approach could provide a more credible and cost-effective means to predict the fire performance of passenger train materials [1]. This alternative approach employed fire hazard assessment techniques, using fire modeling based on test methods using the HRR data. In 1999, The John A. Volpe National Transportation Systems Center (Volpe Center) developed a comprehensive three-phase fire safety research program to prove the feasibility of applying HRR test methods and fire modeling and hazard analysis techniques to U.S. passenger trains. After that, an extensive effort was also underway to relate small-scale and real-scale fire performance using HRR and fire modeling by many other researchers [2-3]. Hansen and Ingason [4-6] proposed a potential engineering tool to calculate the HRR of multiple objects, which basically summed up the individual HRR curves from each object when ignition between objects occurs. The HRR for each object was represented by an exponential function of time. Migoya [7] showed a method to determinate the HRR using sensors that can be installed inside an operational road tunnels by comparison with CFD calculation.

To sum up, a lot of research results have proved the feasibility of the research method, that the HRR and other thermal parameters of the individual materials and component assemblies of big object, such as the passenger rail car, are measured with the Cone Calorimeter and other test instruments, as the input parameters of fire numerical simulation software, such as FDS, and then a lot of fire scenarios are designed to simulate and obtain the HRR vs. time curves, at last the HRR of the big object can be reasonably estimated.

In order to reveal the influence of ventilation condition on the HRR of CRH passenger rail car, the research methods used in this paper are shown as Fig. 1.

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Fig. 1. The technological roadmap of study on the influence of ventilation condition on the HRR of CRH passenger rail car.
3. Model and materials of CRH passenger rail car

3.1. Model of CRH passenger rail car

The model of the passenger rail car is built according to the second class car of the CRH1 train.

- **Car**: The car model is 26.95 m long, 4.04 m high and 3.328 m wide. The inner space of car model is 25.8 m long, 2.25 m high and 3.2 m wide. The floor of car model is 1.25 m above the railway track.
- **Windows**: There are 20 windows in a passenger rail car, which are 1.9 m long and 0.6 m high. The free distance between two windows is 1.9 m. The underside of the window is 0.6 m above the floor. In consideration of passengers' escaping in an emergency, there are five emergency escaping windows in a passenger rail car, the locations of the emergency escaping windows are all shown as Fig. 2 and Fig. 3. The outer layer of the window is 5 mm thick tempered glass, the inner layer is two layers of glass pane, and the space between the inner and outer layer is filled with inert gases.
- **Seats**: there are 101 seats in a passenger rail car, which are arranged in 2+3 pattern. The seat is 0.45 m wide, and the aisle is 0.58 m wide. The free distance between two rows of seats is 0.45 m. Seats consist of fabric-covered polyurethane foam cushions installed on steel seat frames with seat shrouds, back shells, and food trays made of fire-retardant wood.
- **Baggage racks**: The baggage racks, which are made of aluminium alloy, are arranged above the windows.
- **The interior materials**: Cars typically have floors, ceilings, and interior walls and doors partially covered with carpeting. The floor consists of three-layer batten board, the first layer is 0.5 mm thick aluminium plate, the second layer is 18 mm thick birch plywood and the third layer is 1 mm thick stainless steel plate. The ceiling mainly consists of aluminium plate. The interior wall consists of veneers. The interior door is 2.0 m high, 1.0 m wide, made of aluminium frame and fire proof glass.

3.2. Combustion performance of individual materials and component assemblies

According to the investigation results [8], the combustible objects include the windows, seats, baggage racks, interior materials and so on in a passenger rail car, and the main materials include the Polyvinyl Chloride (PVC), polycarbonate, aluminium alloy, polyurethane foam and fabric. The combustion performance parameters of all the materials are listed in the Table 1.
Table 1. The combustion performance parameters of all the materials

| Material              | Density (kg/m³) | Specific heat (J/kg K) | Coefficient of thermal conductivity (W/m K) | Peak HRR (kW/m²) | Ignition temperature (°C) |
|-----------------------|-----------------|------------------------|---------------------------------------------|------------------|---------------------------|
| PVC                   | 1380            | 1.20                   | 0.18                                        | 90               | 520                       |
| Polycarbonate         | 1280            | 1.40                   | 0.23                                        | 200              | 580                       |
| Aluminium alloy       | 2750            | 0.88                   | 200.00                                      | -                | -                         |
| Seat assemblies       |                 |                        |                                             |                  |                           |
| polyurethane foam     | 50              | 1.00                   | 0.05                                        | 280              | 370                       |
| fabric                | 120             | 1.00                   | 0.15                                        |                  |                           |

The Heat Release Rate per Unit Area (HRRPUA) vs. time curves of the seat, polycarbonate, and PVC, are shown as Fig. 4(a), (b), (c).

3.3. Fire scenarios

The location of the ignition source is in the middle of the passenger rail car, just shown as Fig. 2. The ignition source is set as the medium T-squared fire, the peak HRR is 1 MW, and the time to reach the peak HHR is 300 s after ignition. In order to reveal the influence of ventilation condition on the HRR of CRH passenger rail car, two kinds of fire scenarios are presented as follows.

- Fire scenario I: in order to reveal the influence of the location of the open window on the HRR, the ventilation conditions simulated, include 4 cases as follows: (1) all the windows are close, and the HRR in the case is designated as \( Q_{\text{all closed}} \); (2) the 1# emergency escaping window is open, and the HRR in the case is designated as \( Q_1 \); (3) the 2# emergency escaping window is open, and the HRR in the case is designated as \( Q_2 \); (4) the 3# emergency escaping window is open, and the HRR in the case is designated as \( Q_3 \). Because of the symmetry between the locations of the 4#, 5# emergency escaping window and the 1#, 2# emergency escaping window, it is not simulated repeatedly, when the 4# or 5# emergency escaping window is open.

- Fire scenario II: in order to reveal the influence of the number of open windows on the HRR, the ventilation conditions simulated, include 6 cases as follows: (1) all the windows are closed, and the HRR in the case is designated as \( Q_{\text{all closed}} \); (2) the 2# emergency escaping window is open, and the HRR in the case is designated as \( Q_1 \); (3) the 2# and 5# emergency escaping window is open, and the HRR in the case is designated as \( Q_2 \); (4) the 1#, 2# and 5# emergency escaping window is open, and the HRR in the case is designated as \( Q_3 \); (5) the 1#, 2#, 4# and 5# emergency escaping window is open, and the HRR in the case is designated as \( Q_4 \); (6) all the windows are open, and the HRR in the case is designated as \( Q_{\text{all open}} \).
window is open, and the HRR in the case is designated as $Q_4$; (6) the 1#, 2#, 3#, 4# and 5# emergency escaping window is open, and the HRR in the case is designated as $Q_5$.

4. Influence analysis of ventilation condition on the HRR of CRH passenger rail car

4.1. Influence analysis of the location of the open window on the HRR

According to Fig. 5, the 4 cases of fire scenario I all belong to ventilation control fire. Due to the small space of passenger rail car, after the fire is ignited in the middle of the car, the fire will spread, from the near to the distant, sequentially to the seats, interior materials, windows, and baggage racks. As the burned area increases continuously, the fire then rapidly grows toward flashover, but because of the limited ventilation area, the oxygen supply cannot meet the demand of the fire development, the HRR begins to decline dramatically after reaching the peak value.

Fig. 5. The influence comparison of the location of the open window on the HRR.

If all the windows are close, after ignition, the fire in the passenger rail car will reach flashover in 205 s; the HRR will reach the peak value, 18.4 MW, in 215 s; the HRR will reach the second peak value, 4.6 MW, in 227 s; the HRR will decline to zero after 250 s. If the 1# emergency escaping window is open, the HRR will reach the peak value, 24.2 MW, in 216 s; the HRR will reach the second peak value, 6.7 MW, in 245 s; the HRR will decline to 3.1 MW after 250 s. If the 2# emergency escaping window is open, the HRR will reach the peak value, 32.7 MW, in 217 s; the HRR will reach the second peak value, 6.5 MW, in 240 s; the HRR will decline to 3.5 MW after 250 s. If the 3# emergency escaping window is open, the HRR will reach the peak value, 23.3 MW, in 213 s; the HRR will reach the second peak value, 10.0 MW, in 223 s; the HRR will decline to 2.3 MW after 250 s.

According to the comparison results of the 4 cases mentioned above, the conclusion is $Q_{2#} > Q_{1#} > Q_{3#} > Q_{all\ closed}$, if the suffix means the serial number of the open emergency escaping window. If all the windows are close, the peak HRR, 18.4 MW, is the minimum among all the 4 cases because of the inadequate oxygen supply. Because the 2# emergency escaping window is the nearest to the ignition source, and the fresh air is very convenient to supply the combustion reaction, if the 2# emergency escaping window is open, the peak HRR, 32.7 MW, is the maximum among all the 4 cases. So on conditions that only one emergency escaping window is open, the nearer the window gets to the ignition source, the higher the peak HRR is.

4.2. Influence analysis of the number of open windows on the HRR

According to the Fig. 6, with the increase of the number of open windows, the peak HRR of passenger rail car increases to the maximum, and then begin to decline to a fixed value. If the number of open windows is less than 2, the fire in the passenger rail car belongs to the ventilation control fire; if the number of open windows is 2, the air supply and heat lost will reach balance, the peak HRR is the maximum; if the number of open windows is more than 2, the air supply is overload, and with the increase of the number of open windows, more heat are lost through the open windows, the peak HRR will keep declining.
If the 2# and 5# emergency escaping window is open, after ignition, the HRR will reach the peak value, 37.9 MW, in 216 s; the HRR will reach the second peak value, 10.9 MW, in 239 s; the HRR will decline to 4.8 MW after 250 s. If the 1#, 2# and 5# emergency escaping window is open, after ignition, the HRR will reach the peak value, 33.3 MW, in 216 s; the HRR will reach the second peak value, 14.5 MW, in 231 s; the HRR will decline to 7.1 MW after 250 s. If the 1#, 2#, 4# and 5# emergency escaping window is open, after ignition, the HRR will reach the peak value, 33.1 MW, in 214 s; the HRR will reach the second peak value, 18.7 MW, in 232 s; the HRR will decline to 9.4 MW after 250 s. If the 1#, 2#, 3#, 4# and 5# emergency escaping window is open, after ignition, the HRR will reach the peak value, 27.1 MW, in 209 s; the HRR will reach the second peak value, 18.9 MW, in 223 s; the HRR will decline to 11.8 MW after 250 s.

According to the comparative results of all the 6 cases mentioned above, the conclusion is $Q_2 > Q_3 > Q_4 > Q_5$, $Q_2 > Q_1 > Q_{all\ close}$, if the suffix means the number of open emergency escaping windows at the same time. If the number of open windows is less than 2, the fire in the passenger rail car belongs to the ventilation control fire, with the increase of the number of open windows, the peak HRR keeps increasing, due to the more and more air supply. If the number of the open windows is 2, the air supply and heat lost reach their balance, and then the peak HRR reaches to 37.9 MW. If the number of open windows is more than 2, with the increase of the number of open windows, heat lost through the open windows due to air convection, and then the peak HRR begin to decline.

![Fig. 6. The influence comparison of the number of open windows on the HRR.](image)

5. Conclusions and suggestions

If all the windows are close, the air in the car will be used up soon after ignition, and the fire of course belongs to the ventilation control fire, the peak HRR only reaches 18.4 MW. If only one window is open, the nearer the window gets to the ignition source, the higher the peak HRR is, and the peak HRR will reach 32.7 MW. If several windows are open at the same time, the peak HRR with 2 windows open is the highest among all the 6 cases of fire scenario II, which is 37.9 MW. If the number of open windows is more than 2, with the increase of the number of open windows, the peak HRR begins to decline.

In conclusion, the ventilation condition exerts a significant influence on the HRR of passenger rail car, which is in the range of 18.4–37.9 MW. Because the HRR of CRH passenger rail car dramatically fluctuates with different ventilation conditions, the HRR should be chosen carefully according to the ventilation condition and applied into the fire risk assessment, fire protection and emergency evacuation plan of high-speed rail system.

There are many other influence factors of the HRR except the ventilation condition, such as the baggage, so much more researches about the HRR of passenger rail car are suggested to be continuously carried out.
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