Research and development of fire extinguishing equipment for passenger compartment

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Abstract. In view of the problems of the passenger vehicle, such as single fire-fighting method, low degree of automation, long response time, poor fire extinguishing effect. In this paper, the high-pressure water mist fire extinguishing equipment for passenger compartment was researched and developed. The defects and characteristics of fire prevention and control of passenger vehicle were analyzed firstly, and on this basis, the functional requirements and selection schemes of fire prevention and control equipment were proposed. Then, the selection scheme was used for trial production of equipment, and the fire extinguishing performance test was carried out to verify the effectiveness of the equipment. The test results showed that the equipment had good fire extinguishing effect. After the equipment was activated, the fire in the passenger compartment was significantly suppressed. After 3 s of start-up, the open fire was almost extinguished. After 10 s of start-up, the toxic black smoke almost disappeared and the average temperature in the passenger compartment dropped to 60℃.

1. Introduction

Road passenger transport service has always been the focus and difficulty of industry safety supervision, because of its many stations, long lines, wide range and large number. Passenger vehicle has the characteristics of dense personnel, strong mobility, many combustible materials, closed spaces, and difficulty in escape. Once a fire occurs, it is easy to cause major property losses. Since 2008, violent terrorist incidents such as man-made arson and explosions have occurred in Urumqi, Xiamen, Yinchuan and other places in China, resulting in many casualties, seriously threatening the lives of the people, affecting the harmonious and stable development of society.

Judging from the passenger vehicle fire accidents in the past, the portable fire extinguisher equipped with passenger vehicle is difficult to effectively extinguish the fire in case of emergency. The water mist fire extinguishing system has the advantages of automatic control, high fire extinguishing efficiency, environmental protection and no pollution, and reduction of toxic smoke concentration, and it has great reference value in the fire prevention and control of passenger vehicle.

At present, the research of scholars mainly focuses on the analysis of passenger vehicle fire characteristics and numerical simulation, while the research and development of fire prevention and control equipment is less. Lei Bing[1] and others of Southwest Jiaotong University studied the influence of different working conditions on vehicle fire characteristic variables. Bi Kun[2] and others of University of science and technology of China used FDS software to conduct a fire simulation and obtained the heat release rate of the passenger vehicle fire. Butcher EG[3], Bennetts ID[4], Mangs J[5] and Keski Rahkonen O[6] conducted passenger vehicle combustion experiments to study combustion characteristics, combustion phenomena and combustion heat release rates.
The defects and characteristics of fire prevention and control of passenger vehicle were analyzed firstly. Then the functional requirements and selection schemes of fire prevention and control equipment were proposed. Finally, the selection scheme was used for trial production of equipment, and the fire extinguishing performance test was carried out to verify the effectiveness of the equipment. The technical scheme is shown in figure 1.

![Figure 1. The technical scheme.](image)

2. Analysis of fire prevention defects and fire accident characteristics of passenger vehicle

2.1. Analysis of the fire prevention defects of passenger vehicle

2.1.1 Increasingly complex structure. In recent years, automobile manufacturers have been guided by market demand to promote the development of passenger vehicle design towards high-end and humanization. On the one hand, in-vehicle entertainment facilities and terminals are widely used, and the grade of vehicle interiors has gradually improved. On the other hand, the structure of passenger vehicle is increasingly complex. The gradual promotion of new structures, new processes and new driving methods, and the increasing degree of circuit integration and complexity have increased the risk of fire in passenger vehicle.

2.1.2 Flammable and toxic materials. The use of combustible or flammable interior materials will also greatly increase the risk of passenger vehicle fire. On the one hand, in order to beauty and comfort, automobile manufacturers use a large number of combustible or flammable interior materials in the cabin. Most of the seats and side walls of the bus are made of polyurethane, plywood, PVC board, polymer materials and other combustible materials, which reduces the fire performance of the interior of the vehicle. On the other hand, under the trend of lightweight, more plastics and other composite...
materials are applied to various components of the passenger vehicle. These materials can release a series of toxic fumes when burned, which will seriously threaten the safety of the occupants.

2.1.3 Low efficiency of fire extinguishing equipment. At present, the fire extinguishing efficiency of on-board fire extinguishing equipments is low. The mandatory national standard of the People's Republic of China named Requirements for the Configuration of Fire Extinguishing Equipment for Passenger Cars specifies the fire extinguishing equipments that should be equipped in the passenger compartment of passenger vehicles, including the specifications, number and location of fire extinguishers. However, the portable dry powder fire extinguisher has a low degree of automation and a long reaction time. The occurrence of a fire will make the driver and passengers in a panic, resulting in the portable powder fire extinguisher can hardly be used effectively.

2.2. Analysis of fire characteristics of passenger vehicle

2.2.1 Not easy to detect at the beginning of the fire. The space structure of the passenger vehicle is complex, and the fire caused by the outside of the passenger compartment is difficult to be observed by the drivers and passengers. For this kind of fire, drivers and passengers often first feel the smell of carbonization before the fire, and then see the flame and smoke. Once there are obvious signs of a fire, the best time to extinguish the fire has been lost.

2.2.2 Burning violently and spreading rapidly. The materials of exterior decoration parts, interior decoration parts, seats and instrument panels of modern passenger vehicles are mostly made of plywood, foam plastic and fiber, and the large amount of combustible luggage carried by passengers greatly increases the fire load. Once a fire occurs, it will generate huge heat and cause the fire spread rapidly. In addition, leaked fuel and gas, damaged gas pipelines, and environmental winds will also contributes to the spread of fire.

2.2.3 Toxic fumes cause suffocation and evacuation difficulties. The windows of passenger vehicle are mostly fully enclosed and sealed well. In the event of a fire, a large amount of polyurethane foam, plastic and rubber used will rapidly burn and produce a large amount of toxic fumes that will fill the passenger compartment. On the one hand, the drivers and passengers will gradually lose consciousness or suffocate to death after inhaling a certain amount of toxic fumes. On the other hand, the smoke from the combustion will cause a significant reduction in visibility, so that the occupants are psychologically frightened and the ability to evacuate safely has been seriously hampered.

2.2.4 It is difficult to extinguish the fire. The passenger vehicle fire is highly unpredictable, and the time and place of the fire are random. In the event of a fire during a long-distance transportation service, problems such as untimely alarm and lack of fire-fighting resources are prone to occur. No doubt, untimely rescue and ineffective fire-fighting equipment will increase the difficulty of fire-fighting.

3 The functional requirements and selection schemes

Based on the above analysis results, the functional requirements and selection scheme of fire extinguishing equipment for passenger vehicles are proposed.

3.1 The functional requirements

3.1.1 Quick start and easy trigger. First, the start-up speed of the equipment shall be fast, that is, the time between the start-up of the equipment and the operation of the fire extinguishing equipment shall be shortened as much as possible. The low delay of the equipment plays an important role in effectively extinguishing initial fires. Second, equipment should adopt an easy-to-operate and reliable
trigger mode, so that it can only ensure to be effectively triggered in emergency, but also have the function of preventing accidental contact.

3.1.2 Efficient, fast and lasting. The ability to extinguish fire quickly and efficiently is the most important function of the equipment. The research shows that, the best escape time for occupants in a passenger vehicle is 11 seconds. Otherwise, the escape probability of the drivers and passengers will be greatly reduced.

The fire extinguishing equipment shall meet the following four requirements at least. First, it can effectively extinguish the floor fire. According to the investigation and statistical analysis of passenger vehicle fire accidents, about 80% of the passenger compartment fires start from the floor. Suppressing the floor fire in the first time can achieve the purpose of quickly extinguishing the initial fire, thereby greatly improving the success rate of fire extinguishing. Second, the fire extinguishing coverage of the equipment should be wide. Due to the unpredictable location of the fire and the rapid spread of the flames, the fire extinguishing coverage of the equipment should cover the entire compartment as much as possible. Third, the escape route of the vehicle should be available, that is, the fire extinguishing ability at the door should be improved. Fourth, the equipment should have a certain ability to continue to extinguish fire. The escape speed of the driver and passenger in the panic and crowded state is very slow. The continuous fire extinguishing and cooling of the equipment can be of great benefit to extending the available escape time.

3.1.3 Reducing the concentration of harmful smoke and dust. Reducing the concentration of harmful smoke and dust is not only an important function of this equipment, but also a feature of the water mist fire extinguishing technology. The high temperature and toxic fumes produced by fire is the most important fatal factor for the drivers and passengers. To a large extent, the degree of the impact of harmful smoke and dust determines the escape probability.

3.1.4 No secondary damage. The original intention of the equipment is to ensure the life safety of drivers and passengers to the greatest extent. Therefore, the equipment itself should be safe and reliable, that is, the equipment cannot be a source of danger. In addition, in addition, the substances produced by the vaporization or chemical reaction of the fire extinguishing agent should be environmentally friendly and non-toxic, and it will not cause secondary damage to the occupants.

3.1.5 Other. In addition to the above main functions, from the perspective of product promotion and use, the equipment should also meet the following requirements as far as possible.

First, the equipment should have good climatic and environmental adaptability and mechanical vibration reliability. Second, the volume and quality of the equipment should be reduced as much as possible to reduce the operating costs of road transport enterprise. Third, the equipment should be easy to maintain. Fourth, the equipment should be easy to install or modify.

3.2 The selection schemes
The water mist fire extinguishing equipment is composed of nozzles, drive equipment, extinguishing agent, control equipment, pipeline and various valve parts. Based on the above analysis of the functional requirements, the selection scheme of the equipment is proposed.

3.2.1 Structure of nozzle. According to the different forming principle of the water mist, the nozzle can be divided into single-phase flow system and two-phase flow system. The structure of the single-phase flow system nozzle is simple, but with the increase of the spray distance, the spray momentum of the water mist decreases obviously. For two-phase flow system, the spray momentum of the equipment is greater and the spray distance is longer due to the driving effect of the gas phase flow, so that more fire extinguishing agents can be sprayed into the root of the flame. In comparison, the two-phase flow system has a higher fire extinguishing efficiency, and it is more helpful to put out the floor fire. In
3.2.2 Flow coefficient of nozzle. Flow coefficient is one of the most important parameters of water mist nozzle, because it affects the spray cone angle and the intensity of the fog field and directly determines the effect of fire extinguishing. In different fire scenarios, the flow coefficient of the nozzle should be chosen according to the type of protection object and the risk of fire to avoid unnecessary waste and negative impact.

The flow coefficient of nozzle is related to the flow rate and working pressure. The setting distance of the water mist nozzle is generally 3 m. The heat release rate of passenger vehicle fire can reach 15-30 MW [7], so the nozzles are set at intervals of 1 m along the roof of the vehicle. Taking a 10 meters long vehicle as an example, 9 nozzles are required. In addition, an additional nozzle needs to be installed at the door. Therefore, the total number of nozzles is 10. Considering that the total weight of the equipment should not be too large, the total volume of the fire extinguishing agent is finally determined to be 80 L through discussion with industry experts. As a result, the volume of fire extinguishing agent sprayed by each nozzle is 8 L. Zhang Shuo[8] and others conducted a simulation study on the passenger evacuation characteristics of passenger vehicle, and the results show that the evacuation time for occupants does not exceed 40 s. The sustainable injection of the equipment is set to 30 s, so that the flow rate of the nozzle can be calculated as 16 L/min.

According to the public safety industry standard of the people's Republic of China named Fixed fire extinguishing systems for compartment of bus, the working pressure of the farthest end of the nozzle should be greater than or equal to 0.20 MPa and less than 1.20 MPa. And then the flow coefficient of the nozzle can be calculated to be 4.6 to 11.3.

3.2.3 Drive equipment. According to the different ways of water supply, the water mist system can be divided into pump group system and cylinder group system.

The pump group system generates pressure through the pump, so it has the disadvantage of having a long reaction time. In addition, the problem of power source of pump is not easy to solve. For example, If the battery is used for power supply, the pump pressure of the pump group will be significantly affected in winter because the operating performance of the battery is greatly affected by the ambient temperature, and then the effect of fire extinguishing will be affected. In contrast, the cylinder group system solves the above problems well. In addition, the characteristic of the pressure value of the gas cylinder release is that the pressure is maximum at the beginning and then gradually decreases. This characteristic is very consistent with the idea of fire extinguishing and the functional requirements of the equipment. Therefore, the cylinder group system is a better solution.

3.2.4 Extinguishing agent. Fire extinguishing additives can effectively improve the working performance and fire extinguishing performance of water mist equipment.

According to the action mode of the additive in the process of extinguishing fire, the extinguishing additive can be divided into physical mechanism additive and chemical mechanism additive. However, the application of chemical mechanism additives to water mist fire extinguishing equipments has two defects. On the one hand, chemical mechanism additives may change the physical properties of the aqueous solutions and then affect the formation of water mist and evaporation of droplets[9]. On the other hand, the chemical mechanism additive will be heated and volatilized in the fire extinguishing process. Less fire extinguishing agent to reach the root of the flame will lead to poor fire extinguishing effect. Therefore, the physical mechanism additive was selected.

3.2.5 Control mode. The control mode of fire extinguishing system can be divided into automatic control and manual control. The manual control mode is selected in this paper for the following three reasons. First, the reaction time of automatic control is longer. Second, The second is that automatic
control is more prone to failure and false start. Third, the passenger vehicle does not belong to the unmanned monitoring area.

3.2.6 Summary. The selection scheme of the equipment is shown in Table 1.

| No. | Equipment components | Selection scheme                  |
|-----|----------------------|-----------------------------------|
| 1   | Nozzle               | Structure                         |
| 2   | Flow coefficient     | Two-phase flow system             |
| 3   | Sustainable injection| 4.6~11.3                          |
| 4   | Number               | Not less than 30 s                |
| 5   | Setting position     | At the top of the compartment and the door|
| 6   | Drive equipment      | Cylinder group system             |
| 7   | Extinguishing agent  | Physical mechanism additive       |
| 8   | Control equipment    | Manual control mode               |

4. Fire extinguishing performance test
The fire extinguishing equipment was trial-manufactured based on the selection scheme. In order to verify the effectiveness of the fire extinguishing equipment, a full-size fire extinguishing test was carried out.

4.1 Test overview
The shape and size of the oil plate, the position of the oil plate, the fuel used for the test, the setting of temperature sensor and vent, the test steps, etc. are all referred to the public safety industry standard of the people's Republic of China named Fixed fire extinguishing systems for compartment of bus.

MT-X multi-channel temperature recorder was used to collect the temperature in the compartment, and the number of temperature sensor probes is 12.

4.2 Test results
The test record is shown in Table 2.

| No. | Relative time (s) | Test record                                                                 |
|-----|-------------------|-----------------------------------------------------------------------------|
| 1   | 0                 | Ignition and the first oil plate was ignited.                               |
| 2   | 5                 | All six oil plate were ignited and black smoke was generated in the compartment. |
| 3   | 15                | The fire extinguishing equipment was activated.                             |
| 4   | 15.5              | The fire extinguishing agent was sprayed from the nozzle.                  |
| 5   | 18                | The open fire was basically extinguished, a large amount of white water mist was generated in the compartment, and the black smoke was significantly reduced. |
| 6   | 23                | A large amount of white water mist is continuously generated and black smoke almost disappeared. |
| 7   | 37                | The concentration of white water mist reached the peak, indicating that all the nitrogen has been sprayed at this time. |
| 8   | 38-69             | The concentration of white water mist decreases gradually.                 |
| 9   | 70                | End of test.                                                                |

The external picture of the passenger compartment is shown in Figure 2, and the interior picture of the passenger compartment is shown in Figure 3. After the test, An oil plate was selected for the after-
combustion test. As shown in Figure 4, the re-ignition of the oil plate indicates that the reason for the flame extinguishing is not the burnout of the fuel.

![Figure 2. The external picture of the test.](image1)

![Figure 3. The interior picture of the test.](image2)

![Figure 4. After-combustion test.](image3)

4 temperature sensors are separately set up at 0.3 m, 1.0 m and 1.6 m heights in the compartment to record the change of the temperature during the test. The temperature data are shown in figure 5, figure 6 and figure 7 respectively. The horizontal coordinate represent time, the ordinate represent temperature, and the ignition time was the 60th s. Temperature data from 60 s before ignition to 120 s after ignition was recorded.

![Figure 5. Temperature data at 0.3 m height.](image4)

![Figure 6. Temperature data at 1.0 m height.](image5)
The first oil plate was ignited at the 60th s. At the 65th s, all the remaining oil plate were ignited, and the temperature in the passenger compartment rose rapidly and reached the peak value at the 75th s. The fire extinguishing equipment was activated at the 75th s, and the temperature began to drop indicating that the fire was significantly suppressed. The red dotted line in Figure 8 represents the average temperature in the compartment. At about the 84th s, that is, 10 seconds after the equipment was activated, the average temperature in the compartment dropped to 60 ℃. At about the 90th s, the temperature in the compartment continued to drop and finally reduced to the ambient temperature.

5 Conclusion
In this paper, the defects and characteristics of fire prevention and control of passenger vehicle were analyzed firstly, and the functional requirements and selection schemes of fire prevention and control equipment were proposed. Then, the selection scheme was used for trial production of equipment, and the fire extinguishing performance test was carried out to verify the effectiveness of the equipment. The test results showed that the equipment had good fire extinguishing effect. After the equipment was activated, the fire in the passenger compartment was significantly suppressed. After 3 seconds of start-up, the open fire was almost extinguished. After 10 seconds of start-up, the toxic black smoke almost disappeared and the average temperature in the passenger compartment dropped to 60 ℃.

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