Research on the Improvement of Air Conditioning Filter Function Based on TRIZ Method

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Abstract. As the COVID-19 pandemic gradually comes under control, railway transportation in various regions is showing signs of recovery. However, new challenges have emerged, such as frequent cases of in-carriage transmission. At the same time, the filtration capacity of the air conditioning systems in China's high-speed rail carriages is insufficient to meet epidemic prevention requirements. Enhancing the filtration capacity of these systems and optimizing the layout of related facilities that affect both filtration efficiency and passenger experience have become critical priorities. This paper focuses on the air conditioning filtration systems of high-speed trains in operation in China, conducting an in-depth investigation into the phenomenon of in-carriage transmission during the COVID-19 pandemic. Based on the function-oriented search in TRIZ theory and the microclimate theory in human factors engineering, the study proposes a feasible design scheme for the mechanism and the layout of air supply and return vents. Using the fishbone diagram tool, the initial scheme is analyzed to identify optimization directions, ultimately resulting in a design and vent layout scheme that largely meets current environmental needs.

Keywords: COVID-19; air filter system; TRIZ; human factors; microclimate.

1. Introduction

This paper targets the HVAC (heating, ventilation, and air conditioning) systems of high-speed rail carriages for improvement. Based on the existing structure of the air conditioning filtration system, TRIZ theory is employed to study the problem and identify solutions, while human factors engineering serves as a reference standard for the design. After developing a solution suitable for the existing issues, systems engineering analysis methods are used to evaluate the effectiveness of the proposed solution. Based on the analysis results, further improvements are made, culminating in a feasible solution that effectively enhances the filtration capacity of train carriages.

2. Analysis of High-Speed Rail Air Conditioning Filtration Issues

2.1 Fishbone Diagram Analysis of In-Cabin Transmission in High-Speed Rail Trains

The primary mode of COVID-19 transmission is through droplets, which can remain in aerosol form in the air for up to 10 minutes. Taking in-cabin transmission as the final issue, the following causes were summarized through brainstorming: (1) virus transmission through the air; (2) cross-infection through contact with public facilities; (3) virus carried by contaminated items. The fishbone diagram method was used to study the problem, with in-cabin transmission as the target issue. The fishbone diagram is shown in Figure 1.

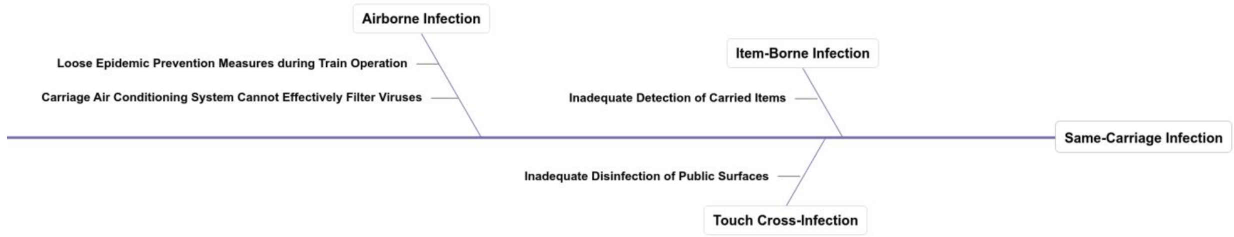

Fig. 1 Fishbone Diagram of COVID-19 Transmission

2.2 Analysis of High-Speed Train's Air Conditioning Filtration Issues Based on the Substance-Field Model

Based on TRIZ theory, after establishing the substance-field model of the problem system, applicable standard solutions were identified from the 76 standard solutions of the substance-field model, followed by in-depth analysis and design[2]. Within the technical system and super system, three relationships were identified as insufficient effects: (1) the air supply ducts in the passenger compartment have insufficient airflow capacity to the seating areas; (2) the top return air ducts have insufficient capacity to collect and exhaust waste air from the seating areas to the exhaust ducts, and the exhaust ducts have insufficient filtration capacity for the expelled waste air; (3) the filtration system has insufficient filtration capacity.

From the above analysis, it can be observed that the deficiencies in (1) and (3) are related to insufficient filtration capacity. This deficiency cannot be improved through the existing structure, meaning that the objects within the system cannot be altered as needed. This condition aligns with the second standard solution of the 76 Substance-Field Standard Solutions, which suggests adding a permanent internal additive to help the system achieve its intended function. Regarding the two deficiency flows in (2), the Substance-Field model issue lies in the overly centralized design of the return air vents, which can lead to insufficient or even harmful effects on the entire system. This characteristic aligns with the 17th standard solution of the 76 Substance-Field Standard Solutions: increasing the dispersion of substances to achieve the desired function. By combining this standard solution with the current system status, the general direction of the solution can be determined—adjusting the layout of the return air vents. Since the return air vents are closely related to the breathing environment of passengers in the cabin, involving the adaptation between humans and the environment, it is necessary to consider human factors engineering and microclimate-related research and standards when adjusting the layout. The relevant standard solutions, current status, and related notes are summarized in Table 1.

Table 1. Summary of Substance-Field Standard Solutions

Insufficient Airflow Description	Substance-Field Model	Solution Number	Standard Solution Description	Optimization Direction	Notes
Insufficient air supply from the cabin air duct to the seating area	Overly concentrated substance-field	17	Increase the dispersion of substances to complete the function	Adjust the layout of air supply outlets	Adjustments must meet microclimate requirements
Insufficient waste air collection capacity of the top return air duct for the seating area					
Insufficient filtration capacity of the exhaust air	Existing objects in the system cannot be	2	Add a permanent internal	Add filtration mechanisms	Need to find materials that meet the

duct	changed as needed		additive to help the system achieve its function		requirements
Insufficient filtration capacity of the filtration system					

3. Optimization Of High-Speed Train Air Conditioning Filtration Mechanism

3.1 Material Selection Based on TRIZ Function-Oriented Search

3.1.1 TRIZ-Based Function-Oriented Search

When selecting suitable photocatalytic materials, the function-oriented search method from TRIZ theory is employed. The current problem to be solved is: to identify a novel material and design a new structure and system that enhances the air conditioning filtration capability in high-speed train passenger carriages, meeting the demands of the current pandemic normalization. This material must meet the following criteria: (1) its filtration capability must surpass that of the fiber materials currently used in train air conditioning filtration systems; (2) it must be capable of self-cleaning during train operation to ensure the new filtration system is easy to maintain; (3) it must be able to disinfect organic pollutants using photocatalytic principles, a feature that can complement the second criterion.

3.1.2 Selection of New Filtration Materials

Based on the above description, a step-by-step investigation was conducted on relevant papers and patents in the field of photocatalysis, both domestically and internationally. Among the materials studied, titanium dioxide nanowires (TiO2 Nanowires, referred to as TiO2NWs) exhibit properties that align well with the target performance requirements[1]. TiO2NWs demonstrate excellent performance in the following aspects: (1) under ultraviolet light at a wavelength of 365nm, the exposed DNA on the surface of TiO2NWs was effectively degraded within 10mins of the experiment's commencement; (2) The fiber layer spacing formed by TiO2NWs is significantly smaller than the diameter of the COVID-19 (120nm) and Escherichia Coli (2μm), demonstrating excellent filtration performance.

3.2 Design of the Filtration Mechanism Based on TiO2NWs

3.2.1 Filtration Layer Design

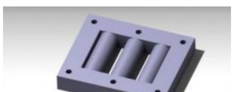

Fig. 2 Filter Layer

As shown in Figure 2, the filter layer in the filtration mechanism is depicted. The surrounding threaded holes serve as fixing devices, clamping the TiO2NWs filter mesh in the middle (since the shape of the TiO2NWs filter mesh is difficult to represent, it is substituted by three cylinders in the middle). Air flows into the filter from the upper side, passes through the filter, and is then transported through the outer air channel to other structures for further processing. Organic particulate pollutants in the air, such as COVID-19, cannot pass through the filter due to their diameter being much larger than the fiber spacing of TiO2NWs. These particles are retained on the outer side of the filter, thereby achieving the filtration effect.

3.2.2 Ultraviolet Light Source Design

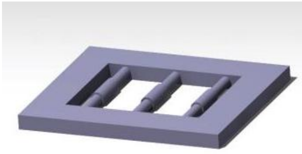

Fig. 3 Front View of the Light Source Layer

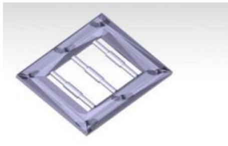

Fig. 4 Bottom View of the Light Source Layer

As shown in Figures 3 and 4, the ultraviolet light source is illustrated. Figure 3 shows the front view of the light source layer, while Figure 4 displays the bottom view. The bottom surface is equipped with threaded holes. The bottom surface is distributed with threaded holes. Similar to the filter layer structure, the surrounding fixtures secure the middle three sets of ultraviolet light sources while connecting to the entire mechanism. The ultraviolet light sources are responsible for emitting ultraviolet light when powered on, thereby disinfecting organic particulate pollutants fixed on the surface of TiO2NWs through photochemical catalytic reactions.

3.2.3 Working Principle of the TiO2NWs-Based Filtration Mechanism

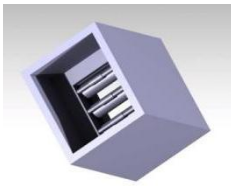

Fig. 5 Assembly Effect

As shown in Figure 5, the airflow enters from the top, carrying mixed organic particulate pollutants (such as COVID-19). These pollutants are filtered and retained on the surface of the filter layer (TiO2NWs surface), thereby achieving the filtration function. Subsequently, the first layer of ultraviolet light sources activates, releasing ultraviolet light. Under the catalytic effect of TiO2, the organic particulate pollutants on the surface of TiO2NWs are decomposed (including but not limited to DNA, cell walls, etc.), effectively producing a disinfection effect.

3.3 Design Improvement and Optimization of the Air Conditioning Filtration Mechanism

To achieve a certain degree of self-adjusting operation time functionality, the mechanism needs to understand the condition of "when it needs to be operated." This primarily requires that the surface pollutant concentration on TiO2NWs is high enough to necessitate the mechanism's operation. The improvement direction for the mechanism involves adding a sensor to enable the mechanism to detect the pollutant concentration on the filter layer. To this end, the design improvement shown in Figure 6 was implemented. A new pillar was added to the original three light sources, with a cylindrical protrusion at the center of the pillar serving as a reflective ultraviolet light sensor.

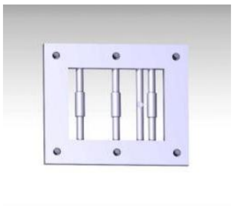

Fig. 6 Improved Light Source Layer

Figure 7 shows the control panel added to the exterior of the ultraviolet light source. The working principle is as follows: the control panel of the ultraviolet light source layer sets a specific light source activation frequency. At the moment the light source is activated, the sensor is triggered and receives the optical signal reflected from the surface of the filter layer. This signal is then transmitted back to the control panel for signal processing and analysis, resulting in three types of data: high pollutant concentration, low pollutant concentration, or insufficient signal data.

Fig. 7 Control Panel

After the control panel receives the signal from the sensor, performs calculations, and transmits control signals, the system operates in three different modes based on the type of signal received: (1) The ultraviolet light source is inactive; (2) The ultraviolet light source operates in a purification mode for a preset duration; (3) The sensor receives insufficient optical signals, making it unable to process the data accordingly. In this case, the system needs to repeat the process shown in the figure until it can obtain signals corresponding to the first two operating modes.

4. Design Improvement of the Air Conditioning Filtration Mechanism

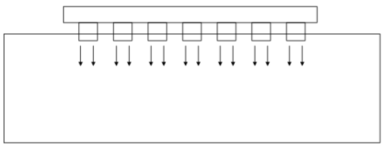

Fig. 8 Improved Top Air Supply Outlet

Regarding the optimization design of the air outlet, based on the pandemic environment, this paper proposes an optimized conceptual model as shown in Figure 8. Improvements are made to the centrally located air supply vents in the original carriage ceiling and the air diffusers for the entire vehicle, enabling the partition control of the microclimate of the internal air environment. The smallest and most ideal area is set to allow for independent control for each seat. After removing the original design, the microclimate partition design is implemented, followed by the addition of corresponding air outlets according to the partition design. Theoretically, this design can prevent the situation where the air conditioning system fails to effectively respond when the virus concentration increases in the central air environment of the carriage.

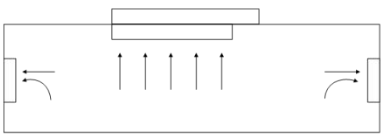

Fig. 9 Improved Return Air Vents

For the optimization design of the return air vents, the main issue arises from the singular placement of return air vents, leading to the inability to effectively collect air with higher concentrations of pollutants in some peripheral areas of the carriage. This situation can be resolved by adding return air vents in the peripheral areas, as illustrated in the conceptual model shown in Figure 9. Adding return air vents at both ends of the train car increases the coverage area of the return air system, enhances the volume of air sent to the air conditioning filtration system, and increases the working medium of the filtration system, thereby improving the performance of the high-speed train's air conditioning filtration system.

5. Conclusion

This paper utilizes TRIZ theory and knowledge from industrial engineering tools and theories to conduct an analysis of the high-speed train's air conditioning filtration system and the air supply and return systems that affect its performance. Tools such as the fishbone diagram were employed, leading to the conclusion that the current air conditioning filtration system in the train car does not meet the current epidemic prevention requirements. Based on the substance-field model, the paper identified the insufficient flow in the current air conditioning filtration system. By combining the standard solutions with the current system status, optimization directions were derived. A function-oriented search based on TRIZ was conducted to identify a suitable photocatalytic material—TiO2NWs—which was then used as a filtration layer in the design of a new filtration mechanism. Under the conditions of human factors engineering and microclimate requirements, the layout design of the air supply and return vents in the passenger compartment was optimized.

References

[1] E Horvath, Rossi L, Mercier C, et al. Photocatalytic Nanowires-Based Air Filter: Towards Reusable Protective Masks[J]. Advanced Functional Materials, 2020, 30(40):2004615.1-2004615.8.

[2] Zhang X., Liu J., Liu X., et al. Performance optimization of airliner cabin air filters[J]. Building and Environment, 2021, 187:107392.