Study on the Thermal Environment Inside a Fully-Enclosed Subway Noise Barrier

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Abstract. The thermal environment inside a fully-enclosed subway noise barrier shall be designed according to underground section tunnel standards. This article constructs a model using practical examples, simulates calculations on fully-enclosed noise barrier installations both with and without air vents via a three-dimensional numerical simulation method, and then conducts a comparative analysis of the effects noise barrier lengths and air vent widths have on an internal thermal environment. The calculation results show that when the length of the fully-enclosed noise barrier without air vents was 100m, the internal thermal environment exceeded the limit; as the width of the air vents increased, the temperature in the internal environment gradually decreased, but the reduction was less once the air vent width exceeded 2 m; When the top air vent width was 2 m, and the noise barrier length was 100m, the thermal environment was found to meet requirements. As the noise barrier length increased, the internal air temperature exceeded the standards by varying degrees.

1 Background

A fully-enclosed noise barrier is the best measure for controlling noise pollution in elevated sections in the subway, where noise can be reduced by more than 20 dB [1-5]. Once the fully-enclosed noise barrier is applied, the elevated section can form a closed space with only two ends of it directly connected with the atmosphere, which is similar to an underground section tunnel. Therefore, internal thermal environmental controls shall be considered. However, research on noise barriers both at home and abroad focus on aspects of predictive noise reduction theory, structural dynamics, acoustic materials, and landscape design. No in-depth studies have been conducted on thermal environments fully enclosed inside noise barriers.

The thermal environment problem in a fully-enclosed noise barrier is a complex physical problem that is coupled with multiple physical phenomena, such as heat radiation, heat transfer, and flow. It is also an engineering problem with a complex structural form, making it difficult to conduct calculations directly using theoretical methods. Therefore, according to this problem's characteristics, this research introduced a three-dimensional numerical simulation calculation method based on computational fluid dynamics (CFD) [6,7], utilizing practical projects as examples, and researched the thermal environment in a fully-enclosed subway noise barrier.

2 Subway Thermal Environment Requirements

Taking an elevated section of a subway project in East China as an example, this line is equipped with a fully-enclosed noise barrier over 8 km, the maximum continuous length is 1310 m, and the local ambient temperature is 34.5 ℃ in the summer.

The objective for designing this thermal environment inside fully-enclosed noise barriers is for the highest average temperature during the hottest month and day in the underground section of the tunnel to not exceed 40 ℃, and the most unfavorable point on the top of the train to be lower than 45 ℃, ensuring that the train air-conditioning condenser can operate without malfunctioning [8,9].

The elevated sections of the subway shall adopt natural ventilation to ensure a thermal environment. In cases of a fully-enclosed noise barrier, the best solution for natural ventilation is to establish inlet and exhaust vents both on the train's top and bottom. The air flow for ventilation could be created by the difference in densities of internal and external air generated by internal heat gain. However, from the perspective of noise control, the number of openings along the noise barrier should be reduced as much as possible. At the same time, in combination with the requirements for firefighting and smoke extraction, the openings for ventilation and smoke extraction shall be provided at the top of the fully-enclosed noise barrier.

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Different from underground section tunnels, the primary heat gain source in an elevated fully-enclosed noise barrier is heat transfer of the enveloping structure, which is determined by two factors - solar radiation and temperature difference inside and outside of the noise barrier. The primary main factor is solar radiation heat gain.

3 Calculation Model

3.1 Physical and discrete models

The models were formed separately according to a case lacking air vents in a fully-enclosed noise barrier and a case with air vents at the top of a fully-enclosed noise barrier. Considering that the temperature and flow fields were barely affected by cables, brackets, tracks, and other factors thinw the noise barrier, the model can be simplified to the structure shown in Fig.1.
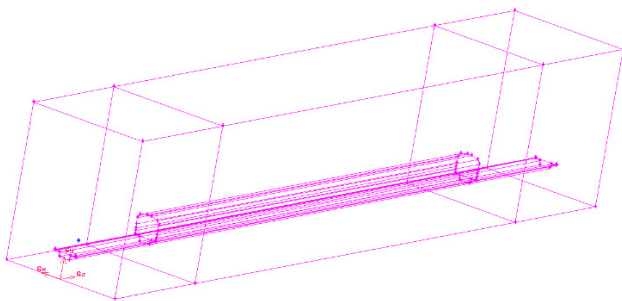

Fig.1. Overall Model Structure

The calculation domain in the model is divided into internal and external noise barrier sections. The width of the external calculation domain is 5 times that of the noise barrier, and its height is 7 times that of the noise barrier, with about 50m of space on both sides of the entrance and exit to the noise barrier. Presently, the influence the external space exerts on the internal heat and flow field tends to be stable.

Geometric discretization was conducted for the structural model. In order to improve accuracy and efficiency, hexahedral elements were used for discretization. The boundary layer was encrypted near the noise barrier wall. The element size at the encryption point was about 10cm. In other positions along the model, the discretized size was appropriately enlarged. The number of meshes along the entire model varied with the noise barrier length is over 2 million.

3.2 Calculation model

Throughout researching, solar radiation intensity would be described with the solar radiation model in the CFD three-dimensional numerical simulation program. Latitude and longitude were set according to the project's location, and the selection time was 2:00 pm in mid-July due to the strong solar radiation at this time, and solar radiation during clear weather was set at the same time. The model was set to the east-west direction, and the direct solar radiation intensity reaching the ground was 858.6 W/m^2,

scattered radiation intensity on the vertical plane was 96.3 W/m^2, scattered radiation intensity on the horizontal plane was 116.4 W/m^2, and the ground reflection and scattering intensity was 87.3W/m^2.

When considering solar radiation, radiation heat transfer should also be considered. The noise barrier for this project was made of soundproof materials, such as acrylic plates with excellent light transmission properties. Therefore, the DO radiation model is used in the calculation. The DO model used a gray belt model to calculate. It could calculate both gray body radiation and non-gray body radiation, while also considering the transparency characteristics of materials, such as glass.

In addition, the calculation model shall include the effects from gravity and lifting effects that result from temperature differences.

The air medium uses incompressible gas, and the buoyancy term caused by the temperature difference was considered via the Boussinesq hypothesis. The SIMPLE algorithm was used to solve the equations. While calculating, the residual error was 10^{-3}, and the physical quantity was stable in terms of convergence criterion.

3.3 Heat gain source and simplification

The primary heat gain factors inside the fully-enclosed noise barrier included:

1) Heat transfer from the enveloping structure caused by solar radiation and temperature difference;
2) Heat release from train personnel and equipment through the train air-conditioning condenser;
3) Heat converted from energy loss in the train traction system;
4) Heat transfer from inside and outside air convection caused by train piston wind.

Taking the fully-enclosed noise barrier with a length of 200m as an example, according to the literature[10], heat release from the train air-conditioning condenser was 325.6 kW. Taking the train speed as 72 km/h (20 m/s), and 20 pairs of trains scheduled per hour, thus, heat release from the train air-conditioning condenser in this noise barrier section was 36.2kW, which was two magnitudes lower than that of the solar radiation heat gain, which could be ignored. When the train was running normally, the energy loss from the traction system was one to two magnitudes lower than that of the air-conditioning condenser[11,12], which could also be ignored. The internal air temperature of the noise barrier was higher than the external environment, and the piston wind from the subway could promote heat dissipation. Conservatively, they could be considered unfavorable conditions, namely that the convection heat transfer caused by the piston wind could be ignored, and the effect of that piston wind should be ignored when researching.

Therefore, based on the above simplifications, the research assumed that the thermal environment in the fully-enclosed noise barrier could only gain heat from solar radiation.

4 Simulation Results without Air Vents

A thermal environment in a 100m-long fully-enclosed noise barrier without air vents should be examined. The simulation results are shown in Fig.2-5.
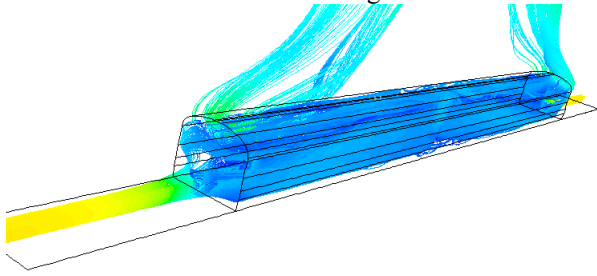

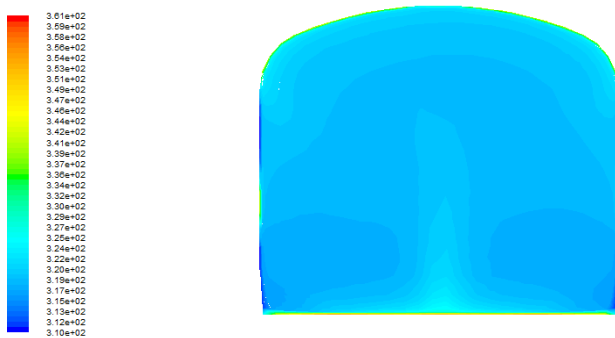**Fig.2.** Streamline Diagram I inside the noise barrier

Fig.3. Central Cross-Section Temperature Cloud Diagram I inside the noise barrier   Unit: K
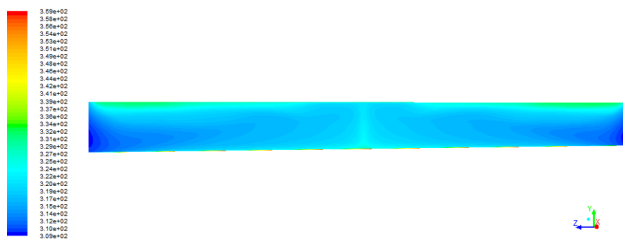

Fig.4. Central Longitudinal Section Temperature Cloud Diagram I inside the noise barrier   Unit: K
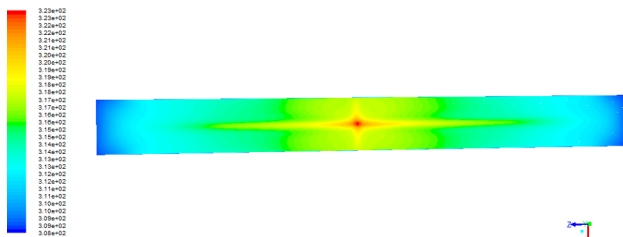

Fig.5.   Plane Temperature Cloud Diagram I at the Same Height of the Train Air-conditioning Air Inlet   Unit: K

The average temperature at the central position in the noise barrier was 47.1 ℃, the average temperature at a position 25 m away from the central position was 44.1 ℃, and the average temperature at a position 45 m away from the central position (i.e. near the terminal) was 42.5 ℃, all of which exceeded the section cross temperature limit of 40 ℃. The most unfavorable point was the position at the same height of the air-conditioning air inlet on the top of

the train. It could be observed an area in the middle exceeded the limit of 45℃.

Without air vents, non-compliance in terms of temperature in the noise barrier was obvious. When the length of the noise barrier was increased, the non-compliance phenomenon would inevitably become more prominent. It could be observed that it was necessary to provide a fully-enclosed noise barrier with air vents.

5 Simulation Results in the Case with Air Vents on Top of the noise barrier

5.1 Air Vents 2m Wide on Top of the noise barrier

When the length of the fully-enclosed noise barrier was 200m with air vents 2m wide on the top, the simulation results were shown in Fig. 6-9.
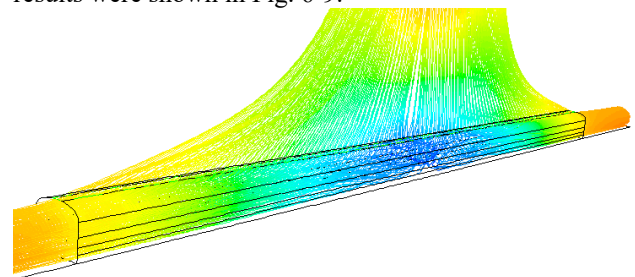

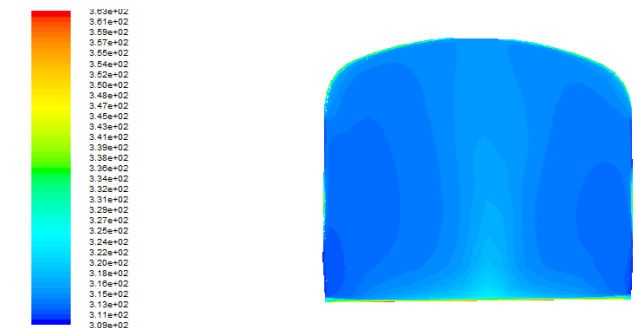**Fig.6.** Streamline Diagram II inside the noise barrier

Fig.7.   Cross-Section Temperature Cloud Diagram II inside the noise barrier   Unit: K

Fig.8. Central Longitudinal Section Temperature Cloud Diagram II inside the noise barrier   Unit: K
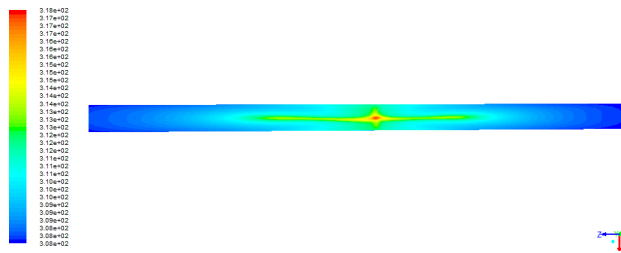
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Fig.9. Plane Temperature Cloud Diagram II at the Same Height of the Train Air-Conditioning Air Inlet   Unit: K

Results showed that the ambient air entered from both ends of the noise barrier and rose upward through the top opening. The temperature at both ends of the noise barrier was lower, and the air velocity was higher, but the direction was fundamentally horizontal. There was less moving air, and the temperature in the middle was higher. The air velocity was little, the movement direction was upward, and there was more stagnant air. After the air temperature in the noise barrier rose, the density would decrease and rise upward. The ambient cold air was replenished from both ends to the inside of the noise barrier. The replenished amount of cold air was greater at both ends, in the center less so, which caused the temperature at the end to be low and the middle high.

The highest temperature was near the center of the noise barrier, as shown in Fig.7, due to solar radiation absorption, the temperature of the orbital plane and the wall surfaces of the transparent material rose significantly, which caused the air temperature air in the noise barrier to rise. Among them, the effect of the orbital plane was relatively great, and the temperature decreased as height increased, except for in the vicinity of the two side wall surfaces. The average temperature of the section was 41.3 ℃, which exceeded the limit for the average temperature of 40 ℃. However, it could be seen from Fig.8 that the temperature only in the short length range near the center of the noise barrier was higher, and the temperature on both sides decreased rapidly. The length where the temperature exceeding the limit was 13 m. The temperature at the most unfavorable point was shown in Fig.9. The temperature in the noise barrier gradually rose from both ends to the center. The highest temperature in the section at the center point was 44.5 ℃, which was lower than the limit of 45 ℃.

3.2 Influence analysis of air vent width

Simulation calculations shall be conducted separately for the noise barrier thermal environment scheme with air vents 1 m, 2 m, 3 m and 4 m wide, and the length of the noise barrier shall be 100 m and 200 m. The results are shown in Table 1 and Table 2.

Table 1. Average cross-section temperatures for different air vent width schemes   Unit: ℃

Opening width	100m noise barrier	Width exceeding the limit	200m noise barrier	Width exceeding the limit
1m	40.8	About 3m	42.4	About 28m
2m	39.4	-	41.2	About 13m
3m	39.2	-	41.0	About 8m
4m	38.6	-	40.8	About 3m

From Table 2, it can be seen that the 1 m opening scheme in the 200 m noise barrier had a 28m-long area exceeding the limit; while in the 2m opening scheme, the length of area exceeding the limit was only 13 m, which was only about half a carriage's length. The length of area exceeding the limit was shorter in the other schemes. Table 2 showed the highest temperature at the most an unfavorable point in different schemes. The results showed that the temperature at the most unfavorable points in most schemes did not exceed the 45 ℃ limit, and only the 1m opening design with a 200 m noise barrier exceeded the limit by 0.6 ℃. The area exceeding the limit was small and would not affect the train's operation; As the width of the opening increased, the highest temperature at the most unfavorable point gradually decreased, and the reduction was also larger between 1 m and 2 m, and the decreasing range became smaller once the opening was more than 2 m.

Table .2. The Highest Temperature for Different Opening Width Schemes   Unit: ℃

Opening width	100m noise barrier	200m noise barrier
1m	44.7	45.6
2m	43.4	44.5
3m	42.9	44.5
4m	42.6	44.4

3.3 Influence analysis of noise barrier length

When the width of the air vent was set as 2 m, changed the length of noise barrier used for calculation from 100 m to 400 m, the results are shown in Table 3.

Table. 3. Temperature Results at Different noise barrier Lengths   Unit: ℃

Length	The highest average temperature in the cross section	Width exceeding the limit	The highest temperature at the condenser inlet
100m	39.4	-	43.4
200m	41.2	About 13m	44.5
300m	43.6	About 42m	46.4
400m	41.8	About 10m (two positions)	44.2

The results showed that as the length of the noise barrier increased, the highest average temperature of the cross section increased. When the length was 300 m, the average temperature was the highest, exceeding the limit of 3.6 ℃, and the length of the area exceeding the limit was longer, about two carriages' length. However, when the length of the noise barrier increased to 400 m, the cross-section temperature peak values were separated,

the peak value decreased, and the length of area exceeding the limit correspondingly reduced, with each about 10 m, similar to two 200 m noise barriers connected together. The highest temperature at a height of 1.8 m also increased with the increase of the length. Only when the length was 300 m, the temperature exceeded the limit by 1.4 ℃, and when the length was changed to 400 m, the highest temperature decreased to the level of the 200 m length scheme. See Fig.10 and Fig.11 for the calculation results of the 400 m long noise barrier.
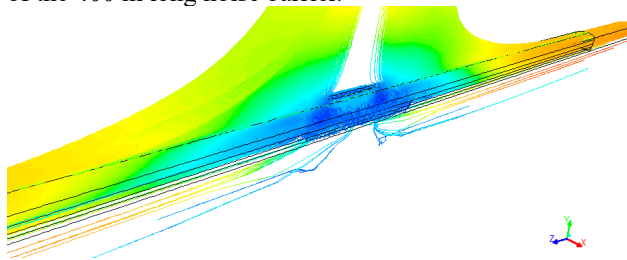

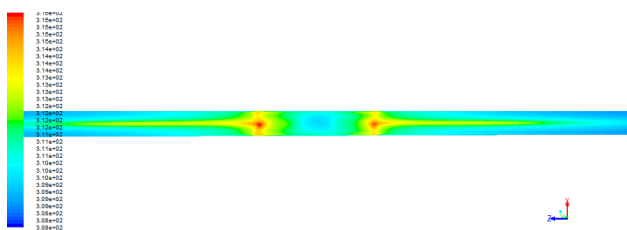**Fig.10.** Streamline Diagram III inside the noise barrier

Fig.11. Plane Temperature Cloud Diagram III at the Same Height of the Train Air-conditioning Air Inlet Unit: K

6 Analysis and Conclusion

Taking a practical project as an example, research on the thermal environment inside the fully-enclosed noise barrier was conducted based on the CFD three-dimensional numerical simulation method and the following conclusions were obtained:

The phenomenon of limit-exceeding temperatures are noticeable when the length of the fully-enclosed noise barrier without air vents is 100 m.

The temperature near the center of the fully-enclosed noise barrier with air vents on the top is higher, while the temperature on both sides is lower. As the width of the opening increases, the temperature inside the noise barrier decreases. As the length of the noise barrier increases, the temperature inside the noise barrier rises. The temperature peak value of the cross section divided into two, and the highest temperature would decrease once the length exceeded 300 m.

The cross section average temperature in the scheme with a 1m-wide air vent has more difficulties in conformity. After the length increases, areas over the limit appear with even more severe nonconformity once the length reaches 300 m. Although areas over the limit exist when the length is 200 m or 400 m, its length is less than that of a carriage. The temperature at the most unfavorable point of the scheme with 2m-wide opening and 300 m noise barrier exceeds the limit, while other length schemes do not exceed the limit.

As far as the practical design is concerned, the noise barrier noise control requirements shall be considered. It is a necessity to comprehensively consider the air vent layout of the fully-enclosed noise barrier in terms of firefighting and smoke extraction requirements. Protecting the overall environment around the subway as well as the internal small environment are both crucial to operations.

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