Numerical study on the influence of initial ambient temperature on the aerodynamic heating in the tube train system

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Research

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Abstract

The evacuated tube transportation has great potential in the future because of its advantages of energy saving and environmental protection. The train runs in the closed tube at ultra-high speed. Because the heat quantity generated by aerodynamic heating is not easy to spread to external environment and will be accumulate in the tube, the phenomenon that the ambient temperature in the tube will gradually rise will be induced. In this paper, a three-dimensional geometric model and the Shear Stress Transport (SST) $\kappa$-$\omega$ turbulence model are used to study the influence of initial ambient temperature on the structure of the flow field in the tube. Simulation results show that when the train runs at transonic speed, the supersonic flow region with low temperature and low-pressure is produced in the wake. The structure of the flow field of the wake will change with the initial ambient temperature. And the higher the initial ambient temperature, the shorter the low temperature region in the wake. Considering that the larger temperature difference caused by the low temperature region may increase the temperature stress of the tube and affect the equipment inside the tube. Consequently, the temperature inside the tube can be maintained at a reasonable value to reduce the influence of the low temperature region in the wake on the system.

Introduction

With the development of economy and technology, modern society is demanding more and more from travel speed, which begins looking at a way of transportation that is superspeed on the ground, beyond aircraft speed. In the dense atmosphere, the maximum economic speed of high speed vehicle should not be higher than 400 km/h\cite{1-3}. The measured data from German TR and Japanese Shinkansen show aerodynamic drag will account for more than 80% of total drag when the train speed exceeds 400 km/h\cite{4}. Besides, the high-speed train will cause serious problems of aerodynamic noise. This aerodynamic noise increases rapidly with 6\textsuperscript{th} power to 8\textsuperscript{th} power of speed\cite{5}. In this background, the tube train transportation\cite{6-8} emerges as the times requirement. It aims to reduce the aerodynamic drag of the train under high speed by decreasing air pressure in the tube, so then promote the train to a higher speed. Due to its advantages of environmental protection and energy conservation, it becomes the most potential development of ultra-high-speed rail transit in the future\cite{9}. However, it also brings many new aerodynamic problems. For instance, when the high-speed train runs in a closed tube, owing to tube wall's restrictions, and improper choice of air pressure, it will result in the aerodynamic drag of the train rising sharply. Furthermore, with the increasing speed of the train, there will appear some aerodynamic heating problems gradually. Heat quantity generated in the tube when the train runs is not as easy to radiate through the surrounding airflow as it in the open air. Instead, it is much easier to aggregate which causes higher and higher temperature in the tube. As a result, the strength of trains and the tube may be affected, which will further endanger the system's safety\cite{10}. Therefore, the aerodynamic problems of the tube trains are worth studying, which can provide the basis for future tube trains' design.

In recent years, a growing number of scholars begin to research the characteristics related to aerodynamic aspects of the tube train, such as aerodynamic drag, aerodynamic noise, aerodynamic
heating, etc. Zhou et al.\cite{11} studied the influence of air pressure and running speed on the aerodynamic drag of trains. It is reported that the higher the speed of the train, the greater the reduction in aerodynamic drag will be with the decrease in air pressure. Subsequently, Zhou et al.\cite{12} studied the effect of blockage ratio on aerodynamic drag. It is found that the greater the blockage ratio is, the greater the aerodynamic drag of the train. However, when the blockage ratio is small, the influence of its change on the drag of the train is small, but when the blockage ratio is large, the drag of the train rises sharply. Mi et al.\cite{13} used the dynamic mesh to study the regularities of the influence of train running speed, air pressure and blockage ratio on the aerodynamic drag. The law suggests when the train is running in low air pressure, there is a good linear relationship between the aerodynamic drag and the blockage ratio. And when the air pressure is high, the linear relationship will be weakened. What’s more, the aerodynamic drag has an approximate linear relationship with the square of running speed. Chen et al.\cite{14} analyzed these aerodynamic drag characteristics of different shapes of the head car and the tail car under different air pressures and blockage ratios. The result reflects that the air pressure in the tube of 1000 Pa and blockage ratio of 0.25 can effectively reduce aerodynamic drag. And under this air pressure, different streamlined shapes of the head car have no significant difference in reducing aerodynamic drag, but the blunt tail can reduce the aerodynamic drag more effectively. Zhang\cite{15} calculated and compared the aerodynamic drag of trains with different blockage ratios and different air pressures in the tube, and found that for the same aerodynamic drag condition, the energy saving of vacuum pumping by reducing the cross section is greater than that by increasing the vacuum degree. Ma et al.\cite{16} based on the evacuated tube test device, analyzed that the air pressure, running speed and the blockage ratio are three very important factors leading to the energy loss of the evacuated tube. Liu et al.\cite{17} modeled the aerodynamic calculation model of high-speed train with the evacuated tube under low-pressure environment, studied the influence of air pressure, the blockage ratio and train’s running speed on the aerodynamic drag of the train, and gave the optimal relationship between air pressure, blockage ratio and train’s speed of the evacuated tube transportation system. Bao et al.\cite{18} found the shape of the train body and the structure of the tube can affect the aerodynamic drag, and the blockage ratio is the main factor. In addition, Kim et al.\cite{19} also found that when shock waves are generated during the tube train operation, the aerodynamic drag will increase dramatically. It is suggested to keep a low air pressure to alleviate the shock wave effect. Zhou et al.\cite{20,21} further studied the shock wave’s structure and its change law of the tube train, and found that the shock wave is mainly composed of expansion wave, reflected shock and normal shock. The intensity of the normal shock wave in front of the head car experiences four states: rapid increase, initial stability, sudden decrease and final stability. Influenced by the interaction between the expansion wave and the reflected shock wave, the wake velocity decreases obviously in the opposite direction of the train’s movement. Liu et al.\cite{22} and Zhang et al.\cite{23} conducted a study on the aerodynamic noise of the tube train. The results showed that the greater the running speed of the train, the greater the aerodynamic noise will be produced. And when the train runs at a constant speed, the intensity of the aerodynamic noise source of the high-speed train can be reduced by decreasing the air pressure and the blockage ratio.
At present, most research on the aerodynamic aspects of the tube train is focused on the aerodynamic drag, but the research on aerodynamic heating is less. Jia et al.\cite{24} found that when the running speed of the train and the air pressure in the tube are constant, the aerodynamic heating effect increases exponentially with the increase of the blockage ratio, and with the increase of Mach number, the maximum temperature in the flow field increases in a parabola trend. Duan\cite{25} found that the maximum temperature increases with the decrease of the air pressure in the tube. Dong\cite{26} found that the aerodynamic heating in the tube gradually decreases with the increase of the train running time, which is a monotonous increasing parabola. When the running time of the train is short, the aerodynamic heating increases sharply with the time. With the increase of the running time of the train, the increment of aerodynamic heating decreases gradually until it approaches a certain temperature infinitely. In the further study of aerodynamic heating, Niu et al.\cite{10} and Zhou et al.\cite{27} found that the aerodynamic heating effect will increase significantly when there is a shock wave in the tube. And with the increase of the blockage ratio, the choking limit formed in the flow field will intensify the aerodynamic phenomenon, which will further worsen the aerodynamic heating environment in the tube\cite{28}.

The above research shows that when the train runs at ultra-high speed in the tube, the aerodynamic heating effect will make the ambient temperature in the tube increase. If the heat quantity cannot release to the outside, the heat quantity generated when the next train passes will further increase the ambient temperature. However, the effect of the initial ambient temperature on the aerodynamic heating effect has not been studied so far. Excessive temperature in the tube may affect some equipment carried in the tube and outside the train, which may endanger the driving safety. In addition, in the study of aerodynamic heating of the tube train, most scholars adopt a two-dimensional geometric model, which makes it impossible to further observe the temperature distribution on the train surface and in the tube. In the future, most of the trains in the tube will be maglev trains\cite{1}, some types of the maglev trains’ external equipment cannot be in high temperature environment, such as the high temperature superconducting maglev of Southwest Jiaotong University\cite{18}, whose bottom contains several cryostats similar to the wheels of wheel-rail trains, which need to be far away from high temperature environment. Therefore, it is necessary to study the influence of the initial ambient temperature on the aerodynamic heating and the temperature distribution in the tube.

2. Numerical simulation

2.1 Geometric model

Currently, there is no a mature shape of the tube train, so a simplified three-dimensional geometric model of the train was used in this paper. The approximate dimensions of the tube and the train are shown in Fig. 1. The height of the train is $H/3.2$ m, which is defined as the flow characteristic length\cite{17}. The total length of the train body is $24.688H$, the width of the train is $1.060H$, and the nose tip length of the head and tail car is $1.875H$ (6 m). The total length of the tube is $125H$, which consists of a circular arc with a radius of $1.063H$ and a plane with a width of $1.407H$. The distance from the bottom of the train to the bottom of the tube is about $0.156H$, and the distance between the stagnation point of nose tip of the
head car and the inlet is $31.250H$. The blockage ratio ($\beta$) of this geometric model is about 0.28. The blockage ratio is defined as the ratio of the maximum cross-section area of the train to the cross-section area of the tube. The stagnation point of the nose tip of head car is set a the coordinate origin of the flow field.

### 2.2 Numerical model

When the train runs in a closed tube at a super-high speed, the flow field around the train is in a turbulent flow state. Since turbulence is the irregular motion of fluid micro-clusters, the transport of mass, momentum and energy generated by turbulent motion will be much larger than the macroscopic transport generated by molecular thermal motion, while turbulent fluctuation leads to additional energy dissipation resulting in an increase in aerodynamic heating. So, the turbulence calculation is very important for accurate prediction of aerodynamic heating. In the prediction of aerodynamic heating, the near-wall region is the region where aerodynamic heating produces heat flux exchange, and the viscosity is dominant in the boundary layer viscous sublayer\(^{[29]}\). Therefore, a precise prediction of the boundary layer is required. The shear stress transport (SST) $k$-$\omega$ turbulence model combines the advantages of $k$-$\varepsilon$ turbulence model with $k$-$\omega$ turbulence model. It has a good ability to predict the low Reynolds number flow within the boundary layer and the fully developed turbulence flow outside the boundary layer\(^{[30]}\). Consequently, the SST $k$-$\omega$ turbulence model is used to predict aerodynamic heating in this paper. The speed of the train studied in this paper is 1000 km/h, and the corresponding Mach number is obviously higher than 0.3, so the compressibility of air needs to be considered. On the other hand, the tube is sealed, and the influence of air compressibility also needs to be considered. The flow simulation is based on the finite volume method, and the solver is the coupled implicit steady state solver with the second-order upwind discretization scheme. The AUSM+ -up scheme can be employed for solving a wide range of flow problems including incompressible to compressible. Hence, the AUSM+ -up scheme was selected to process the inviscid flux to improve the prediction accuracy of aerodynamic heating.

### 2.3 Boundary conditions and initial conditions

As shown in Fig. 2, a diagrammatic sketch of the tube train system is used to describe the boundary conditions of the computational domain. The inlet of the computational domain is defined as the stagnation-inlet, and the outlet is defined as the pressure-outlet. The train is set at a fixed wall with no slip. The thermal boundary conditions of the train and the tube are set at adiabatic. In this paper, we mainly study the aerodynamic heating effect of the tube train at a speed of 1000 km/h. So, the initial velocity is set at 1000 km/h. And the reference pressure is 0.1 atm (1 atm = 101325 Pa) in Section 4. Since this paper studies the influence of initial ambient temperature on aerodynamic heating, the initial temperatures are set at 243 K, 293 K, 343 K and 393 K, respectively.

### 2.4 Mesh generation

The trim mesh and the prism mesh in STAR-CCM+ are used to divide the computational domain. The trim mesh is the main volume mesh in computational domain. For obtaining the flow field information of
near-wall area more accurately, the volume mesh of near-wall area of the train surface adopts the prism mesh. The thickness of near wall prism layer is determined by $y^+\approx 1$, about 0.01 mm. The number of prism layers is set at 20. The prism layer stretching ratio is set at 1.4. The prism layer total thickness is set at 20 mm. The flow field near the train is complex, especially in the wake of the train. In order to ensure the accuracy of the simulation, the mesh in front of the head car and the mesh in the wake of the tail car are refined with reference to the Muld’s\textsuperscript{[31]} mesh layout method. The diagrammatic sketch of the mesh refinement is shown in Fig. 3. The minimum size of the trim mesh is defined as $L_{\text{min}}$. The mesh size of the front of the head car is $L_{\text{min}}$. Due to the wake region of the train is longer, 3 mesh refinement blocks are arranged at the rear of the train, and the size is gradually increased from $L_{\text{min}}$ to $4L_{\text{min}}$. Fig. 4 shows the longitudinal section of the mesh near the train.

3 Verification

3.1 Influence of fixed wall on calculation

In the computational domain, the tube wall is very close to the train, so setting the tube wall to a fixed wall may affect the calculation results. It is necessary to make a simple discussion on whether the fixed wall has influence on the calculation results. In this part, the boundary condition of the tube wall is set at the moving wall with no slip and the fixed wall with no slip respectively and compared the two calculation results. The air pressure in the tube is 0.5 atm. The tangential velocity of the moving wall is equal to the airflow velocity. The initial ambient temperature in the tube is 293 K. The number of mesh is about 18.8 million, and the $L_{\text{min}}\approx 0.05$ m (approximately 0.0156 $H$).

In this section, the drag coefficient ($C_d$) and pressure coefficient ($C_P$) are defined as follows:

\[
C_d = \frac{2F_d}{\rho_0 v^2 S_{\text{train}}} \quad (1)
\]

\[
C_P = \frac{2P}{\rho_0 v^2} \quad (2)
\]

where $F_d$ and $P$ are the aerodynamic drag and the pressure measured in the flow field, respectively. And the pressure ($P$) in this paper represents the difference between absolute pressure and reference pressure. $\rho_0$ is the initial density of air in the flow field. When air pressure is 0.5 atm and the ambient temperature is
293 K, the air density is about 0.602 kg/m$^3$. $v$ is the train speed (1000 km/h), and $S_{\text{train}}$ is the maximum cross-section area of the train, which here is about 9.637 m$^2$.

Table 1 shows the aerodynamic drag coefficients calculated by using a moving wall and a fixed wall, respectively. The difference of aerodynamic drag coefficient ($C_d$) between the moving wall and the fixed wall is great.

Fig. 5 shows the distribution of temperature and $C_P$ on the intersection line between the train upper surface and the $xy$ plane, respectively. Here, the surface above the train stagnation point is defined as the upper surface, and the surface below the train stagnation point is the lower surface. It can be seen from Fig. 5 that when the boundary condition of the tube wall is the fixed wall, the distribution of temperature and $C_P$ is quite different from that of the moving wall. The reason for this difference should be that the distance from the tube wall to the train is very close, and the boundary conditions have great interference in solving the flow field around the train.

Therefore, when solving the flow field of the tube train, if the train is considered to a stationary wall, it is more reasonable to set the boundary condition of the tube to the moving wall, so that the train moves relative to the tube, which is more consistent with the actual situation. Based on this result, in the following calculations, the tube wall is all set at the moving wall.

### 3.2 Mesh independence verification

In order to ensure the rationality of the calculation, three different sizes of the mesh were generated to observe the influence of the number of mesh on the calculation results. Table 2 shows the details of the mesh, including the minimum size of the trim mesh $L_{\text{min}}$ and the total number of the mesh. The initial conditions in this section are the same as in Section 3.1.

Table 3 shows the $C_d$ calculated from the coarse, medium and fine mesh, respectively. The difference of the $C_d$ between coarse mesh and fine mesh is 0.33%; the $C_d$ of the medium mesh is closer to that of the fine mesh, and the difference is only 0.05%.

Fig. 6 shows the distribution of temperature and $C_P$ on the intersection line between the train upper surface and the $xy$ plane under the three types of the mesh. It can be found that both the temperature and $C_P$ of coarse and medium meshes are comparable to those of fine mesh, and the temperature and $C_P$ of medium mesh are closer to that of fine mesh. In addition, the temperature and $C_P$ curves of the coarse mesh fluctuate at the shoulder of the tail car, while those of the medium and the fine mesh are relatively gentler. Overall, the calculation results of medium and fine mesh are more reasonable. Considering that the fine mesh will spend more time and computing resource, it is a good choice to use medium mesh to achieve reasonable calculation results.

**Results And Discussions**
4.1 Temperature distribution

To observe the temperature distribution in the tube, the initial ambient temperature of 293 K and the air pressure of 0.1 atm was taken as an example. Fig. 7 shows the temperature distribution on the train surface. A, B line represent the intersection line between the upper and lower surface of the train and the \(xy\) plane, respectively. C line represents the intersection line between the left surface of the train and the \(xz\) plane. As it can be seen from Fig. 7, the temperature of the train surface is between 308 K and 340 K, which is higher than the initial ambient temperature. The highest temperature is located at the stagnation point of the nose tip of the head car, near 340 K, and the lowest temperature is located near the stagnation point of the nose tip of the tail car, about 315 K. In addition, the temperature distribution of the nose tip of the head and tail car shows a large gradient. The temperature distribution on the middle part of the car body is relatively flat, and the temperature gradient is small.

Fig. 8 shows the temperature distribution on the tube wall. Along the tube wall, temperature data on 6 lines were collected, and the arrangement of these 6 lines is shown in the figure. With the operation of the train, under the condition that the flow field is stable, it can be found that the temperature difference on the cross section of the same pipe wall in front of the wake is small. Because of the complex wake area, the temperature distribution on the tube wall which located behind the train fluctuates with different amplitude. And there is a low temperature region in the wake area, which makes the temperature of the tube wall also very low. Subsequently, some areas with higher temperature appeared on the tube wall. Finally, the temperature distribution on the tube wall tends to be consistent.

Fig. 9 shows the change of Mach number along the gap between the train and the tube. The air flows into the gap between the train and the tube is similar to the air flow into the Laval nozzle. The nose tip of the head car together with the tube wall forms a similar convergent section, and the nose tip of the tail car together with the tube wall forms a similar divergent section. As is shown in Fig. 9, the air flows into the gap from the nose tip of the head car at subsonic speed and accelerates continuously in the gap, then the velocity exceeds the local sound velocity at the shoulder of the tail car. Because the transonic fluid no longer follows the principle of “The smaller the cross section, the faster the airflow velocity; the larger the cross section, the slower the airflow velocity”. On the contrary, the larger the cross section, the faster the velocity. Therefore, the airflow continuously accelerates and expands and produces expansion waves behind the train. As a result, a supersonic flow and low-pressure region is formed in the wake, shown in Fig. 10. In addition, because the tube wall and the train surface are adiabatic, it can be regarded as isentropic flow in the whole flow. Eventually, the temperature in this supersonic flow and low-pressure region becomes very low, forming a low temperature region.

When the airflow velocity in the flow field reaches the local sound velocity, it is possible to generate shock waves. Fig. 10 shows the contours of pressure, temperature and Mach number. As analyzed earlier, the Mach number of the train tail exceeds 1 and the maximum Mach number reaches 2. Therefore, shock waves are generated at the rear of the train. Fig. 10(b) shows the horizontal cross-section of the contour of pressure, temperature and Mach number in the wake area, respectively. It can be seen from the figure
that the expansion wave has an obvious influence on the structure of the flow field in the wake area. Due to the limitation of the tube wall, the continuous reflection and interaction of the expansion wave significantly change the structure of the flow field in the tube and complicate the wake.

4.2 The influence of initial ambient temperature ($T_0$) on flow field

In the future, several high-speed trains will continuously run in the tube, so that the ambient temperature inside the tube will be constantly rising. For the trains running in the tube at different times, the initial ambient temperature ($T_0$) of the flow field is different. The earlier the train runs, the lower the ambient temperature, and the later the train runs, the higher the ambient temperature may be. Accordingly, this section mainly discusses the influence of the $T_0$ on the structure of flow field. The $T_0$ assumed in the calculation cases in this section are 243 K, 293 K, 343 K and 393 K, respectively. The assumptions for some of the $T_0$ may not be in line with the actual situation, which is only for exploratory discussion here.

Fig. 11 shows the pressure distribution on the intersection line between the train upper surface and the $xy$ plane. It can be seen from Fig. 11 that the regulation of pressure distribution at different $T_0$ is roughly approximate as a whole. But there are some obvious differences at nose tip of the tail car, as shown in Fig. 11(b). The pressure distribution at $T_0=243$ K is similar to $T_0=293$ K. However, when the $T_0$ is 343 K and 393 K, the pressure distribution at the nose tip tends to increase gradually. In addition, with the increase of $T_0$, the pressure on the train surface tends to decrease, as shown in Fig. 11(a). And the maximum pressure on the train surface gradually decreases, the minimum pressure gradually rises, as shown in Fig. 12. The pressure change on the train surface further affects the aerodynamic drag. Fig. 13 shows the aerodynamic drag at different $T_0$. The aerodynamic drag, that is the total drag in Fig. 13, decreases with the increase of $T_0$. When $T_0=393$ K, the aerodynamic drag is about 10 kN lower than that $T_0=243$ K. The total drag consists of pressure drag and shear force. The pressure drags accounts for 90% of the total drag, so the pressure drag plays a leading role and is the main reason for the decrease of the total drag.

Fig. 14 shows the temperature rise curve on the intersection line between the train upper surface and the $xy$ plane. The temperature rise here is defined as the difference between the temperature of the stable flow field and the $T_0$. As shown in Fig. 14, the regulation of temperature rise curve distribution at different $T_0$ is roughly approximate. But when the $T_0$ changes, its temperature rise also changes, the higher the $T_0$, the higher the temperature rise. Fig. 15 shows the temperature rise of the maximum temperature ($T_{max}$) on the train surface at different $T_0$. The temperature rise of $T_{max}$ has an approximate linear relation with $T_0$. This means that when the increment of the $T_0$ is constant, the increment of temperature rise is also approximately constant.

To explore the influence of the $T_0$ on the Mach number, the Mach number on the straight line near the top of the tube was collected, as shown in Fig. 16. The $x$ coordinates of the straight line range from -15 to 130 m, and the $x$ coordinate of the stagnation point at the nose tip of the tail car is about 80 m, so this is
also the position at the beginning of the wake area. It can be seen that the Mach number distribution in front of the wake area is basically consistent at different $T_0$. However, the distribution of Mach number in the wake area is quite different. Combined with the contour of the Mach number (as shown in Fig. 17) in the wake area, it can be found that the $T_0$ has a great influence on the supersonic flow region. When the $T_0$ is low, there is a longer supersonic flow region appearing in the wake area, and when the $T_0$ increases, the supersonic flow region becomes shorter. Moreover, when the $T_0$ rises from 243 K to 343 K, the change of supersonic flow region is more obvious, while when $T_0$ rises from 343 K to 393 K, the change of supersonic flow region is relatively small. Meanwhile, the maximum Mach number on this straight line also decreases with the increase of $T_0$, especially $T_0$ rises from 293 K to 393 K, the maximum Mach number changes greatly.

Subsequently, the pressure data was collected on the straight line which used in Fig. 16, and the pressure curves at different $T_0$ were plotted in Fig. 18. It can be found from Fig. 18 and Fig. 19 that the influence of $T_0$ on pressure is similar to that of $T_0$ on Mach number. The $T_0$ also has a great influence on the air pressure in the wake area. The reason for this phenomenon is probably due to the acceleration of the expansion of the airflow, resulting in the faster the airflow velocity and the lower the pressure, as analyzed in Section 4.1. Therefore, the air pressure will change with the change of the Mach number. Finally, according to the isentropic flow, the structure of the temperature field in the wake will also change with the Mach number and pressure.

As shown in Fig. 20, it can be seen from the contour of the temperature field in the wake area that the $T_0$ has a great influence on the structure of temperature field. When the $T_0$ rises from 243 K to 293 K, the length of the low temperature region in the wake area is shortened from about 51 m to about 20 m, but the contours of their low temperature region have a similar profile. When the $T_0$ continues to rise to 343 K and 393 K, the length of its low temperature region is not only shortened, but also the profile of its temperature contour is changed. Obviously, when compared with the $T_0$ of 243 K and 293 K, a high temperature region appears in the wake with $T_0$ of 343 K and 393 K.

**Conclusions**

This paper mainly studied the influence of initial ambient temperature ($T_0$) on the aerodynamic heating at transonic speed (1000 km/h) and studied the temperature distribution in the tube. Some conclusions are drawn as follows:

(1) Because of the influence of aerodynamic heating, the temperature of the head car is higher than that of the tail car, and the maximum temperature of the train surface is located at the stagnation point of the nose tip of the head car. Due to the complex wake area, the temperature distribution of the tube wall in the wake area fluctuates greatly.
(2) When the train is running at transonic speed, the velocity of the air flow at the shoulder of the tail car reaches sonic speed and continues to accelerate and expand, resulting in a supersonic flow area with low temperature and low-pressure in the wake area. At the same time, the structure of the wake flow field becomes complicated because of generation and disturbance of the shock wave.

(3) The increase of the $T_0$ has a great influence on the structure of the flow field in the wake, which makes the length of the low temperature region shorter and the structure of the temperature distribution changes.

(4) The aerodynamic drag of the train decreases with the increase of the $T_0$, and the temperature rise of the train surface increases with the increase of the $T_0$.

Considering the above, it is necessary to maintain the thermal equilibrium of the tube train system. If the heat dissipation of the tube is insufficient, it may lead to a higher and higher temperature rise and endanger the safety of the system. In addition, the low temperature region in the wake leads to a larger temperature difference, it may increase the temperature stress of the tube and affect the strength of the tube. And larger temperature change may also affect the normal operation of the equipment in the tube. Consequently, the temperature inside the tube can be maintained at a reasonable value to reduce the influence of the low temperature region in the wake on the system. At present, the reasons for the influence of initial ambient temperature on the structure of the flow field is not very clear. Therefore, we will continue to study this problem and explore the influence mechanism.

**Declarations**

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**Authors’ contributions**

SB was a major contributor in writing the manuscript, and carried out the numerical simulation. XH directed the numerical simulation and put forward suggestions for the manuscript. JW processed the calculated data. YR drew some diagrams. ZD reviewed and revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1 Drag coefficient

| Item | Moving wall | Fixed wall |
|------|-------------|------------|
| $C_d$ | 2.2776 | 0.4743 |

Table 2 Details of the three types of the mesh

| Items | Coarse mesh | Medium mesh | Fine mesh |
|-------|-------------|-------------|-----------|
| $L_{\text{min}}$ | $0.0188H$ | $0.0156H$ | $0.0125H$ |
| Total number of mesh (million) | 10.4 | 18.8 | 29.1 |

Table 3 Drag coefficients ($C_d$) for different meshes

| Items | Coarse mesh | Medium mesh | Fine mesh | Error (relative to fine mesh) |
|-------|-------------|-------------|-----------|------------------------------|
| $C_d$ | 2.2689 | 2.2776 | 2.2764 | 0.33% and 0.05% |

Figures
Figure 1

Diagrammatic sketch of a 3D full-scale model of train and tube: (a) the size of the train; (b), (c) the size of the tube train system.

Figure 2

Diagrammatic sketch of the computational domain
Figure 3

Diagrammatic sketch of the volume mesh refinement near the train

Figure 4

Longitudinal section of the volume mesh near the train

Figure 5

Temperature and pressure coefficient (CP) distribution on the intersection line between the train upper surface and the xy plane: (a) Temperature distribution; (b) CP distribution
Figure 6

Temperature (a) and CP (b) distribution on the intersection line between the train upper surface and the xy plane
Figure 7

Temperature distribution on train surface: A, B line is the intersection line between the upper and lower surface of the train and the xy plane, respectively; C line is the intersection line between the left surface of the train and the xz plane.

Figure 8

Temperature distribution along the tube wall: x coordinate range from -30 m to 160 m
Figure 9

Mach number along the top of tube wall: x coordinate range from -10 m to 110 m

$v = 1000 \text{ km/h}$

$P = 0.1 \text{ atm}$

$T_0 = 293 \text{ K}$
Figure 10

The contours of pressure coefficient, temperature and Mach number: (a) The longitudinal section of the flow field around the train; (b) The horizontal cross-section of the wake area.
Figure 11

Pressure distribution on the train surface at different T0: Partial enlarged detail at the nose tip of the head car (a) and the tail car (b)
Figure 12

Maximum and minimum pressure on the train surface at different T0
Figure 13

Aerodynamic drag at different T0
Figure 14

Temperature rise on the intersection line between the train upper surface and the xy plane at different $T_0$
Figure 15

Temperature rise of the maximum temperature on train surface
Figure 16

Mach number along the top of the tube wall at different T0: x coordinate range from -5 m to 130 m

Figure 17

The contours of Mach number in the wake area at different T0
Figure 18

Pressure along the top of the tube wall at different $T_0$: x coordinate range from -5 m to 130 m

Figure 19

The contours of pressure in the wake area at different $T_0$
Figure 20

The contours of temperature in the wake area at different $T_0$