Numerical Simulation of Air Flow Properties around High Speed Train in Very Long Tunnel

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***Abstract*—Numerical simulation of air flow disturbed around a train body with different angle of train nose and different velocity of high speed train in a very long tunnel have been made. Three-dimensional flow theory is capable of modeling the effects of interest in the tunnel environment. The scale of train is 2500mm× 320mm× 427mm length× width× heigh, and the scale of tunnel is 150m× 10.4m× 8.2m length× width× heigh. Train speed is 432km/h, 500km/h and 600km/h respectively. The distributions of pressure, velocities streamline and second flow around high speed train in a very long tunnel space can be obtained by simulating. Results show that the train nose angles and train speed affects the air flow around the train strongly. The pressure drag increases with rising of the nose angles and train speed, and it reaches to the highest value of 23073 Pa when the angle is 60^0 and 32466Pa as the velocity is 600km/h. The air velocity in the annular space is quite enormous and the maximize value is 178m/s with train nose 60^0 and 247m/s with train speed 600km/h. The simulation results can be taken to help us for study the high-speed train energy-consuming, maximum velocity, safety and stabilization when it running in a very long tunnel.**

***Index Terms*—-high-speed train; nose angle; velocity; pressure drag; velocities streamline; second flow**

I. Introduction

High-speed rail transportation is quickly becoming a popular form of mass transit throughout the world. With the speed-up of train, many engineering problems which have been neglected at low train speeds are being raised. Especially more and more deep buried long tunnel has appeared in the construction of high-speed railway engineering. When a train travels through a long tunnel, the compressed air will not flow timely and swimmingly along the train side and upside as in the opening because of the air viscosity and friction resistance distribution in the 'smooth' tunnel surface and 'rough' train surface. When the train velocity and angle of train nose changes, aerodynamic phenomena gain in complexity and importance. As the train speed or train nose angle increased, air pressure will be increased with it; wind which is induced by train will be amplified; aerodynamic drag will be also magnified several times and disturbing of aerodynamic noise will appear in long tunnel.

The first studies of train aerodynamics in tunnels were carried out in 1927 by von Tollmien [1], who searched for an analytical expression of train drag by using a quasi-static incompressible model. In the 1960s and 1970s, a very significant contribution to the subject was made by Japanese researchers [2, 3]. The present study concerns the analysis of aerodynamic phenomena in long tunnels. The approach described consists in a numerical analysis using a quasi one-dimensional finite volume model of air flow and train motion in the tunnel. W.A.Woods[4] investigated a generalized one-dimensional flow prediction method for calculating the flow generated by a train in a single-track tunnel. Raghu S. Raghunathana, H.-D. Kimb, and T. Setoguchi [5] indicated the aerodynamics of high-speed railway train, Pierre Riccoa,b, Arturo Baronb, Paolo Molteni [6] investigated the nature of pressure waves induced by a high-speed train traveling through a tunnel. Yanfeng Zhu and Yapping Wu [7-9] studied the temperature rise by high speed train traveling through a long tunnel with different speed and different blockage ratio, result show that the temperature field in long tunnel is indispensably. Arturo Baron, Michele Mossi and Stefano Sibilla [10] calculated the alleviation of the aerodynamic drag and wave effects of high-speed train in very long tunnels. However, the air flow properties around a train body influence the safety and stability of the train-tunnel system and traction capacity of high-speed train. Comprehensively considered the heating of auxiliary equipment, train equipment, train braking, pantograph electric arc etc and the energy loss of heat conduction induced by tunnel wall, this paper carried simulation to study the air flow properties around high speed train with different train nose angles and different train speed.

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Pressure distributing, velocity streamlines and second flow behind train tail have been obtained.

II. GOVERNING EQUATIONS AND NUMERICAL MODEL

A. Governing Equations

The unsteady three-dimensional flow of a viscous, compressible fluid is governed by the Navier-Stokes equations, namely by a set of partial differential equations which express the physical principles of conservation of mass, momentum and energy. The quality force can be assumed to be zero because of the density of air is very small. The governing equations shown as follows:

$$\frac{\partial r}{\partial t}+\nabla\cdot(r\boldsymbol{V})=0 \qquad (1)$$

$$\frac{\partial(ru)}{\partial t}+\nabla\cdot(ru\boldsymbol{V})=-\frac{\partial p}{\partial x}+\frac{\partial t_{xx}}{\partial x}+\frac{\partial t_{yx}}{\partial y}+\frac{\partial t_{zx}}{\partial z}$$

$$?\frac{\partial(rv)}{\partial t}+\nabla\cdot(rv\boldsymbol{V})=-\frac{\partial p}{\partial y}+\frac{\partial t_{xy}}{\partial x}+\frac{\partial t_{yy}}{\partial y}+\frac{\partial t_{zy}}{\partial z} \quad ?$$

$$\frac{\partial(rw)}{\partial t}+\nabla\cdot(rw\boldsymbol{V})=-\frac{\partial p}{\partial z}+\frac{\partial t_{xz}}{\partial x}+\frac{\partial t_{yz}}{\partial y}+\frac{\partial t_{zz}}{\partial z}$$

$$(2)$$

$$\frac{\partial}{\partial t}\left[r(e+\frac{\boldsymbol{V}^2}{2})\right]+\nabla\cdot\left[r(e+\frac{\boldsymbol{V}^2}{2})\boldsymbol{V}\right]$$
$$=\frac{\partial}{\partial x}(k\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(k\frac{\partial T}{\partial z}) \qquad (3)$$
$$-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}$$

Where $\boldsymbol{V}=u\boldsymbol{i}+v\boldsymbol{j}+w\boldsymbol{k}$ is the mean of air velocity vector coincident with its component u along the tunnel direction, represented by the unit vector i; component v and w along the other normal direction, represented by the unit vector j, k; ? is air density, p is pressure, t is time. t is air shear stress, e is the internal energy per unit mass, k is thermal conductivity of air, T is air temperature.

Borrowing in the state equation for ideal gases, the constitutive equations are finally used to define the thermodynamic state and balance the number of unknown quantities:

$$p=rRT \qquad (4)$$

$$e=C_VT \qquad (5)$$

R is ideal gas constant; C_V is the air specific heat at constant volume.

An unsteady, compressible, turbulent calculation was carried out using a RNG k- e turbulence model employing a second-order upwind discrimination scheme. The k- e equation is

$$\frac{\partial(rk)}{\partial t}+\frac{\partial(rV_jk)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(m+\frac{m_t}{s_k}\right)\frac{\partial k}{\partial x_j}\right]+S_k \qquad (6)$$

$$\frac{\partial(re)}{\partial t}+\frac{\partial(rV_je)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[(m+\frac{m_t}{s_e})\frac{\partial e}{\partial x_j}\right]+S_e \qquad (7)$$

Where

$$S_k=P_k-D_k\,,\quad P_k=t_{ij}^{(T)}\frac{\partial V_i}{\partial x_j}\quad ,\quad D_k=re$$

$$S_e=P_e-D_e\,,\quad P_e=C_{e1}\frac{e}{k}t_{ij}^{(T)}\frac{\partial V_i}{\partial x_j}\quad ,\quad D_e=C_{e2}r\frac{e^2}{k}$$

and $C_{e1}=1.44,\ C_{e2}=1.92,\ s_k=1.0,\ s_e=1.3$.

B. Numerical model

In this paper, the train models have conical noses with angles 30°, 45° and 60° between the axis and the directrix. The model is shown as in Fig.1. The simulation model of tunnel is L_T=150m long; cross-sectional area A_T=71.9m^2; perimeter of tunnel $?_T$=31.24m. Heat transfer coefficient of tunnel wall with air is 6 wm^{-2}k^{-1} and it with a friction coefficient C_{fT}=0.005, corresponding to a mean wall roughness of 0.5mm. We have studied the cases with blockage ratio ß=0.23, train speed u_t= 350km/h, 432km/h, 500km/h and 600km/h respectively.

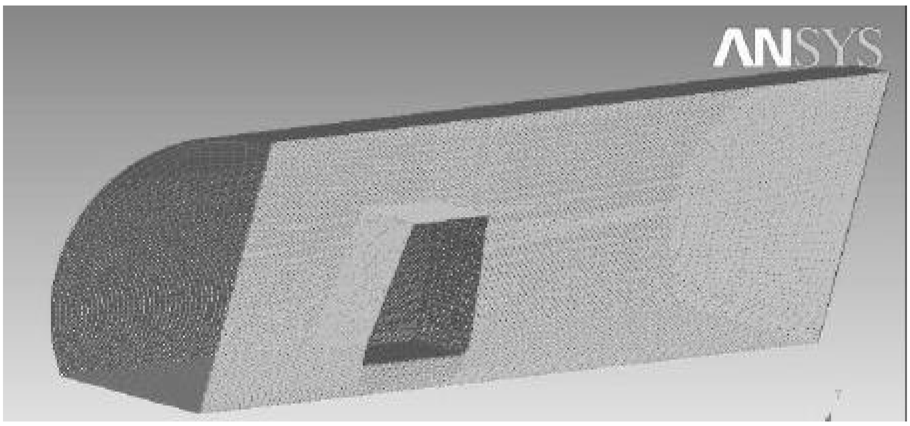


Figure1. Mesh of the tunnel and train

volumes for each main tunnel. Computations have been performed with Ansys-cfx.

III. COMPUTATIONALRESULTS

When the identical train passes through a long tunnel, a number of complications arise in comparison with the open air case. These include:

(a) Significant pressure is generated during high speed train running in long tunnel and total pressure magnitude along train body is varied enormous. it can signi?cantly increase the aerodynamic drag on a train traveling in a tunnel.

(b) Train velocity in annular space is quite tremendous. It would induce biggish skin friction drag.

(c) Coefficient of the flow resistance is quite large.

(d) The second flow behind the train tail.

There are discussed briefly in turn.

A. Pressure variation

When a high speed train runs in a long tunnel, a compression wave is formed ahead of the train which propagates along the tunnel at a nearly sonic speed. The air pushed ahead of the train causes a significant pressure increase in front of the train nose and creates a pressure decrease behind the tail. Fig.2 (a,b,c) presents the distributions of total pressure along the upstream and the downstream with different train nose angles at moving velocity 432km/h inside the tunnel with ß =0.23. We can see that all maximal total pressure appear in train nose, but minimum total pressure are in the difference of occurrence site. When a equal to 30°, on the distance behind train tail 5.5m, the minimum total pressure is 97859Pa and a equal to 45°, at 2.8m behind of the train tail, the minimum total pressure is 93698Pa. But when a equal to 60°, the minimum total pressure is 92981Pa appearing in the distance from train nose 2.8m. it is because that the separation occurring along the train top. at 1.5m behind of the train tail the total pressure drops greatly again and the minimum total pressure is 96696Pa.

Fig.2 (a,b,c) also shows that the trend of total pressure magnitude along train body is varied from downtrend to rising trend. This phenomenon is also because of separation occurring along the train top. In short, ?p increases with the rise of angle. These differences magnitude are about 13801Pa, 20726Pa and 23073Pa respectively in the long tunnel. Behind of the train tail 2m, total pressure is 108598 Pa, 105500 Pa , 100066Pa.

In the same tunnel configuration, despite the similarities, the behavior of air flow around the vehicle is governed by different phenomena. The higher train velocity leads instead to a more pronounced piston effect when train nose angle is 45^0 (Fig.3 (a,b,c)).

Fig.4, 5 shows the comparison of the total pressure with different train nose angles (432km/h) and different train speed (train nose angle 45^0). In the long tunnel, the air total pressure difference is observably increased with train nose angle as train has same speed; and it is increased with train speed as train has same train nose angle. When train nose angle is 45^0, the ?p between the train ends is reduced from about 38362Pa as train speed 600km/h case to 12923 Pa as train speed 350km/h.

B. Velocities streamline

Fig.6 (a,b,c) presents the streamlines in the symmetric plane at train speed of 432km/h with different train nose angle and at different train speed with the same nose angle 45° (Fig.7 (a,b,c)). Around the train, the air flow accelerates along the train nose and the annular space in a quite spectacular way and the maximize value is 178m/s when train nose angle is 30° and 247m/s when train speed 600km/h. The separation occurs along the entire rear body and there is reattachment on the body, and the patterns are very similar. Some differences exist for the position of the reattachments and the intensity of the bottom corner vortex. The vortexes in make the energy loss increases.

C. Coefficient of flow resistance

The coefficient of the flow resistance is defined as follows:

The coefficient of flow resistance:

$$C_D = \frac{F_X}{\frac{1}{2} r v_\infty^2 \cdot A} \tag{8}$$

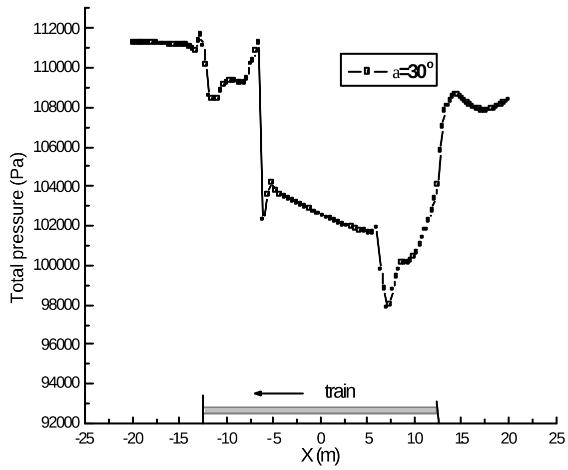
Where A is the maximum area of the train's cross section, F_X is total aerodynamic drag on the train, v_8 is the air speed in front of the train nose.

These differences in magnitude depicted as Fig.8 in the mode of coefficient of flow resistance vs. train nose angles. In general, the coefficient of flow resistance is not a constant. As expected, it increases with increasing of the nose angle. But we also find that train velocity effects are very little for the coefficient of flow resistance (Fig.9).

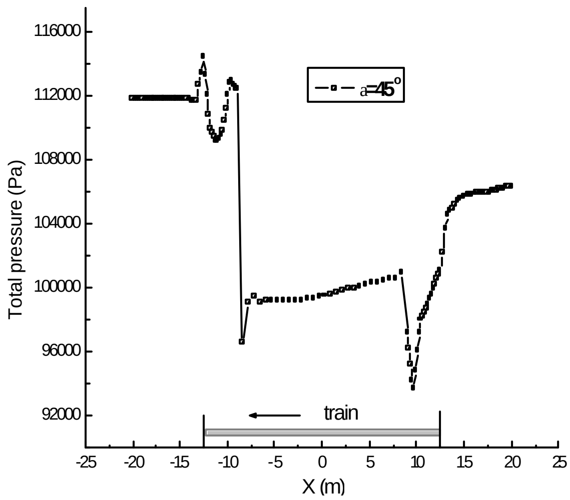
D. Second flow

In a full analysis of air flow properties around high speed train, besides the velocities streamline, however, it is also necessary to pay attention to the second flow behind the train tail. Because their realization forms are vortexes which lead to the energy loss. Figure 10, 11 presents the second flow at 2.5m and 5m behind of the train tail at moving velocity of 432km/h with different train nose angle. It can be seen that the vortexes are generated, and the intensity of vortexes is not only affected in train nose angle but also space positions.

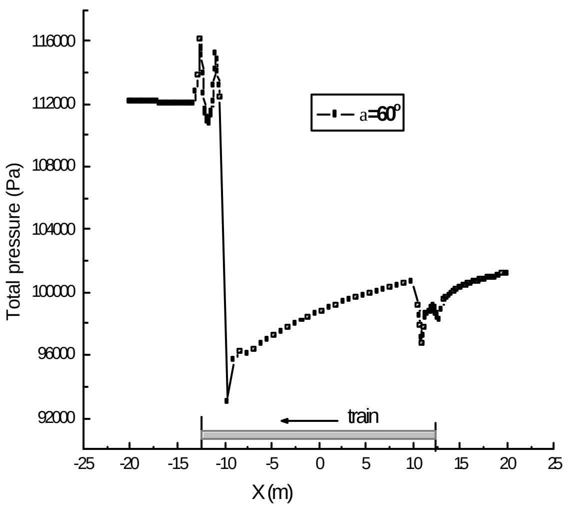
Figs. 12 and 13 present the second flow at different train speed which train nose is 45^0. It is found that train speed with less influence on the second flow than train nose angle. But as same as the former, distance effect is obviously.



(a) a=30°

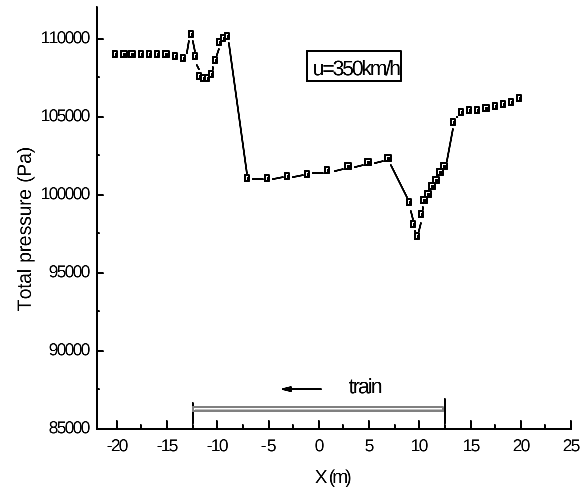


(b) a=45°

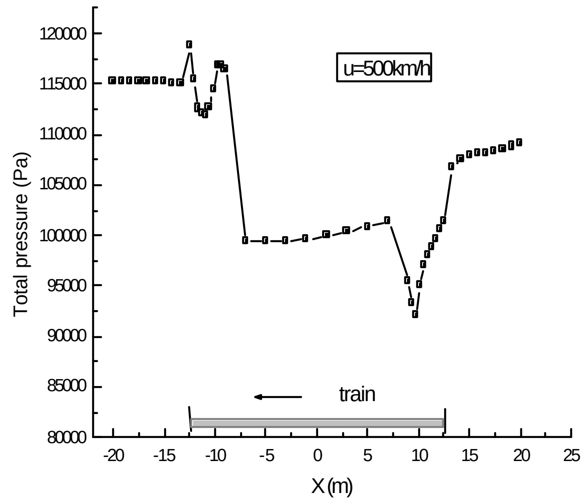


(c) a=60°

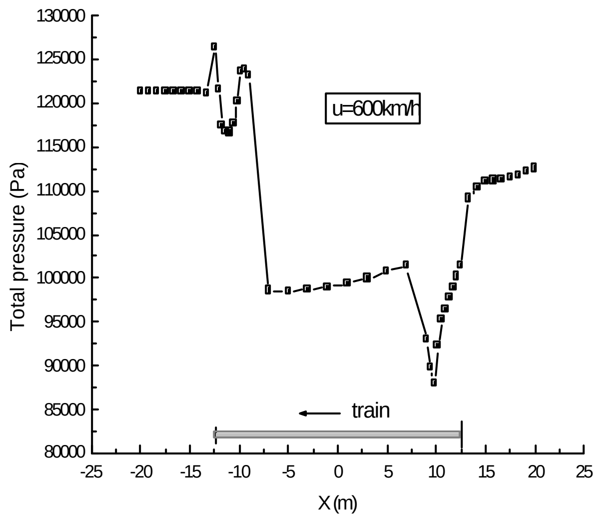
Figure2. Total pressure around the train with different train nose angles (ut=432km/h)



u=350km/h



u=500km/h



u=600km/h

Figure3. Total pressure around the train with different train speed (a=45°)

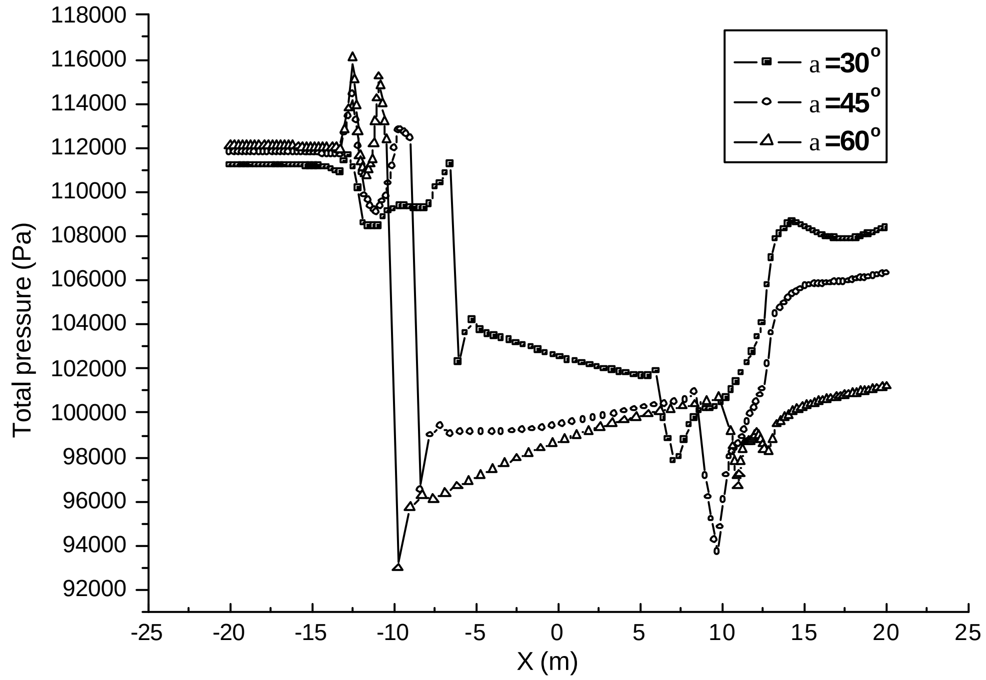


Figure4. Comparison of total pressure with different nose angles (432km/h)

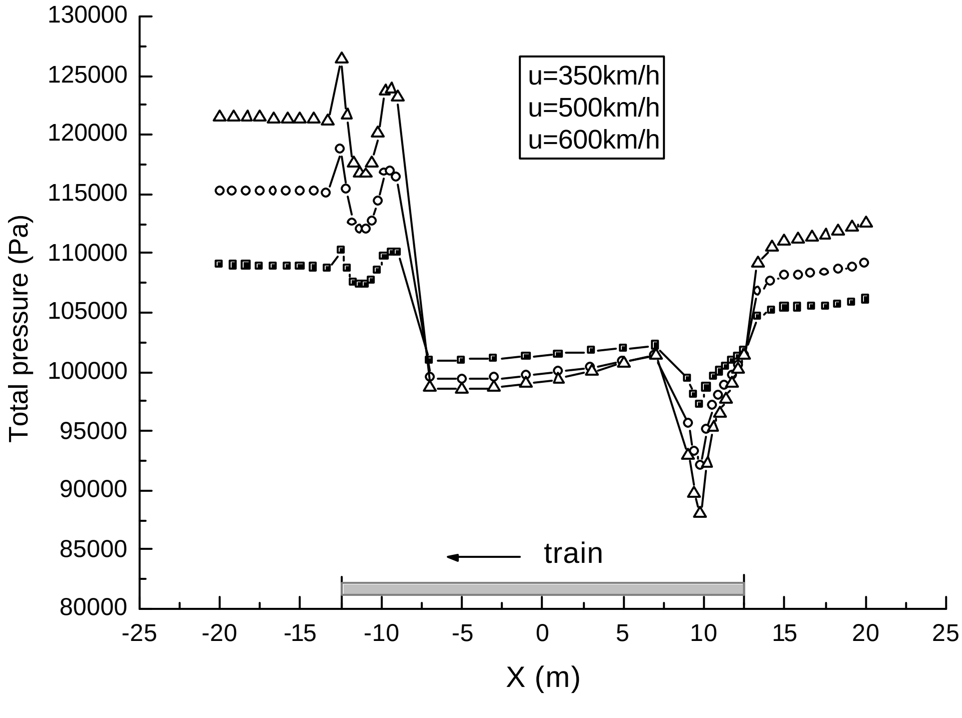
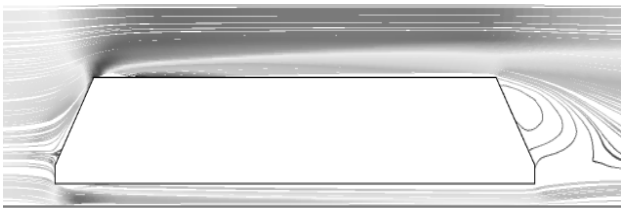


Figure5. Comparison of total pressure with different train speed (nose angles 45°)

(a) a=30°

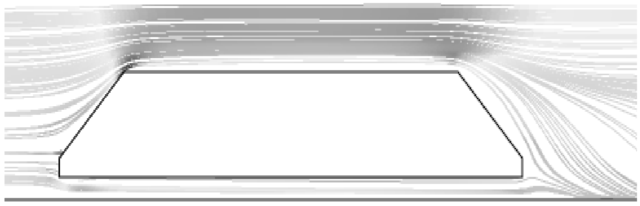
(b) a=45°



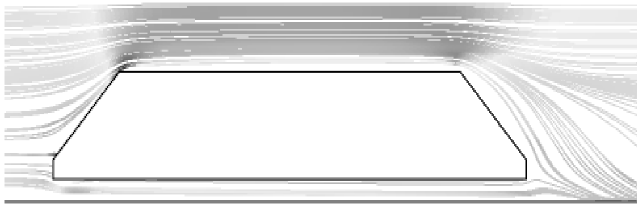
(c)a=60°

Figure6. Streamline around the high-speed train with different train nose angles (u_t =432km/h)

u=350km/h



u=500km/h



u=600km/h

Figure7. Streamline around the high-speed train with different train speed (a =45°)

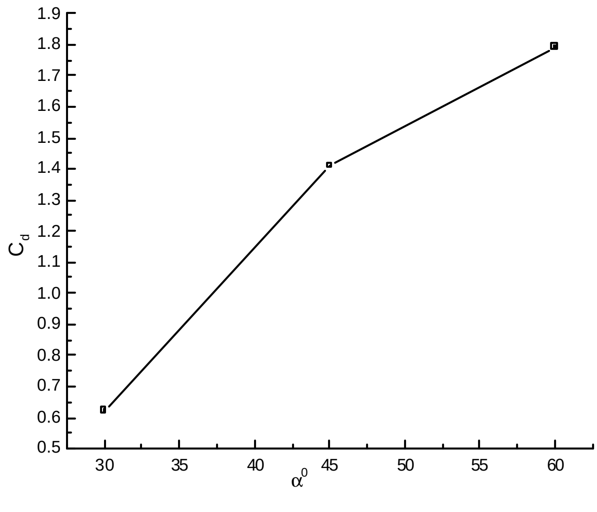


Figure8. Effect of the train nose angle on the coefficient of flow resistance (432km/h)

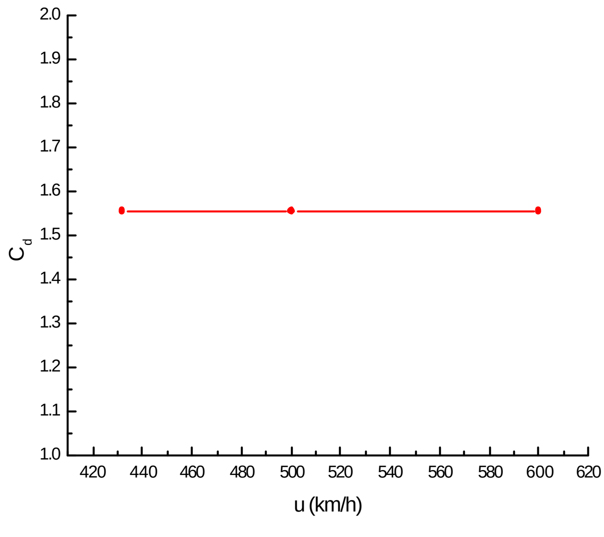
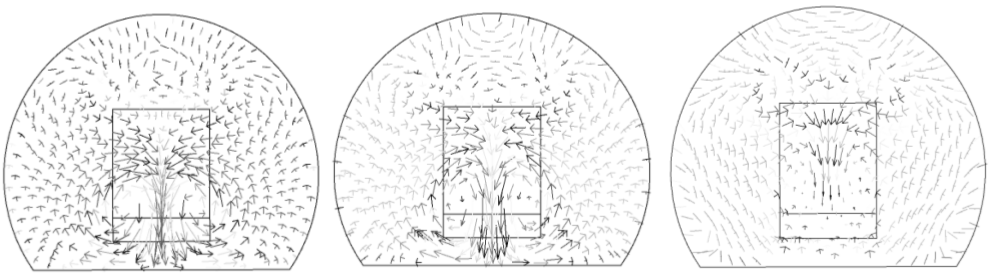
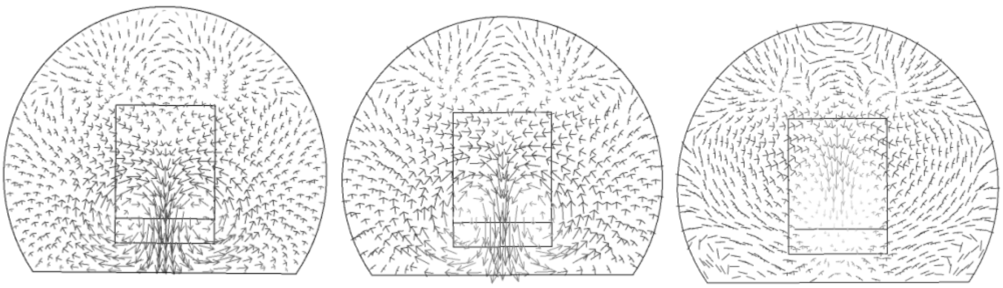


Figure9. Effect of the train speed on the coefficient of flow resistance (a =45°)



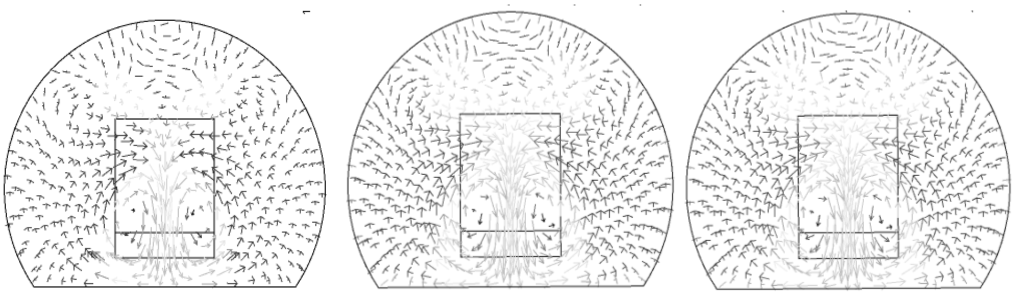
(a) a=30° (b)a=45° (c)a=60°

Figure10. Second flow at 2.5m behind the train with different nose angle (u_t=432km/h)



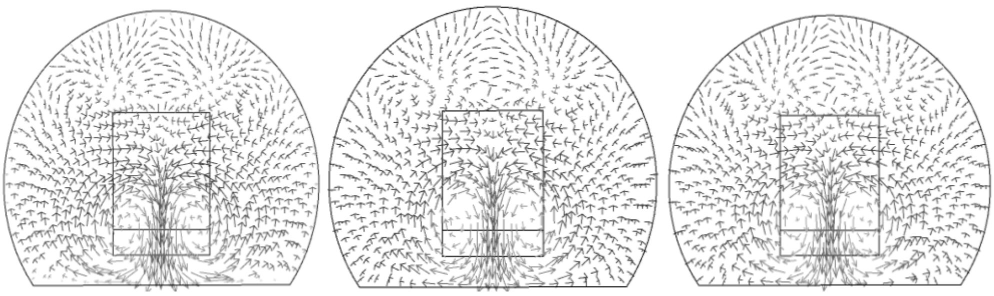
(a) a=30° (b)a=45° (c)a=60°

Figure11. Second flow at 5m behind the train with different nose angle (u_t=432km/h)



(a) u=350km/h (b) u=500km/h (c) u=600km/h

Figure12. Second flow at 2.5m behind the train with different train speed (a =45°)



(a) u=350km/h (b) u=500km/h (c) u=600km/h

Figure13. Second flow at 5m behind the train with different train speed (a =45°)

IV CONCLUSIONS

This study was focused on the character of air flow properties around a train body which generated by high-speed train running in long a tunnel. Simulations have been carried out with different train nose angle in same velocity and different train speed with train nose angle 45°. We have conducted numerical simulations with finite volume method. The velocity streamline, second flow at the wake flow, total pressure and the coefficient of flow resistance have been described in detail. According to the previous work, the train nose angle leads instead to a more pronounced effect in air flow properties around train body in despite of train speed and blockage ratio being known to be one of the most important parameters influencing the aerodynamics of train/tunnel system. We have confirmed:

1. For the train-tunnel system, with ß =0.23, around the train body, aerodynamics effects continuously increase with train nose angle. The larger the train nose angle, the larger the aerodynamic drag. ?p between the train ends is also significantly increased accompanying with nose angle and train speed. Air flow accelerates along the train nose and the annular space in a quite spectacular way, especially for train speed 600km/h.

2. The separation occurs along the entire rear body and the second flow generated vortexes at the wake flow. The effect of vortex kinetic energy will be enhanced with the increasing of train nose angle. In addition, the higher train speeds, the stronger vortexes. Distance also the other factor that influences the second flow.

3. The coefficient of flow resistance increases with the rise of the train nose angle. But it almost not changed with train velocity.

4. High speed long tunnel is different from short tunnel. With the train nose angle and train speed increasing, energy-consuming for trains released into the tunnel space is increased too. In order to reduce the effect of aerodynamics, decreasing energy consumption, a equal to 30° is better than 60°.

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