

Heat Simulation of High-speed Train's Brake Disc Considering the Wind Speed of Disc Surface Influence on Convection Coefficient

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Abstract. With the continuous improvement of train speed, disc braking are widely applied due to its high-power of braking, reliable working, etc. In this paper, relative wind speed of different locations on the brake disc surface during braking has been calculated, and the equivalent wind speed coefficient k is given, which is the ratio of relative wind speed and train speed. On this basis, the convection coefficient of the brake disc surface has been optimized. Its value has been reduced comparing to that before optimization. Combining the optimized convection coefficient and using finite element software ANSYS, it calculated the temperature field of brake disc based on the three-dimensional model in the emergency braking condition, the result and that before optimization were compared with experimental data.

Introduction

The cooling capacity of brake disc is restricted by material, structure and other factors, so in the interior of brake disc there will be accumulation of heat during the braking process. The heat of accumulation increases the temperature, and therefore thermal stress is generated in the interior of disc[1,2]. The highest temperature of the brake disc always appears in the friction surface during the braking process[3]. On the other hand, when the high-speed train is braking, air velocity is large and convective heat has great impact on the temperature of brake disc, so transient convection coefficient of brake disk becomes one of the key parameters of high-speed train brake disc heat capacity simulation. The air velocity of one point at the surface of the brake disc is synthesis of train speed and rotation linear velocity, and by vertical angle in the previous computational result[4,5]. In the real braking process of the high-speed train, the angles between the train speed and the rotation linear velocity of every point vary. In this paper, fitting and optimizing are based on the real situation, and the equivalent wind speed coefficient is given.

Determining Convection Coefficient Considering Wind Speed of Disc Surface

Describing conduction equation and setting the boundary conditions is the main content of this part. It focuses on calculating convection coefficient which takes relative wind speed of brake disk into account.

Convection coefficient has nothing to do with the material, but depends on the state of fluid flow, fluid physical properties, the wall temperature and the wall geometry. Brake disc surface convective heat transfer is simplified as plane heat transfer, according to the theory of heat transfer of plane[6]:

$$\alpha = 0.664 \left(\frac{v_{\infty} L}{\gamma} \right)^{1/2} \text{Pr}^{1/3} \frac{\lambda_a}{L} \quad (1)$$

In the formula, P_r is Prandtl constant; λ_a is air thermal conductivity, W/(m·K); L is wall length, m; v_∞ is air speed relative to the brake disc, m/s; γ is kinematic viscosity of air, m²/s.

According to the model of circular tubes with crossed air flow, the convection coefficient at the radiating rib is as follow:

$$\alpha = 0.248 \left(\frac{v_\infty d}{\gamma}\right)^{0.606} P_r^{0.38} \frac{\lambda_a}{d} \tag{2}$$

In the formula, d is the diameter of the cooling cylinder, m.

Ignoring the temperature of the brake disc for the surrounding temperature, γ , P_r and λ_a are constant, and α depends only on v_∞ and L . As the flow field around the rotating brake disc is complicated, the wind speed should be determined for different locations.

(1) Wind speed of the brake disc surface

The movement of the brake disc is the synthesis of wheel with flat dynamic of train and its own rotation, so the air velocity of a point at the surface of the brake disc is vector synthesis of train speed and rotation linear velocity, ω is brake disc angular velocity, shown in Figure 1:

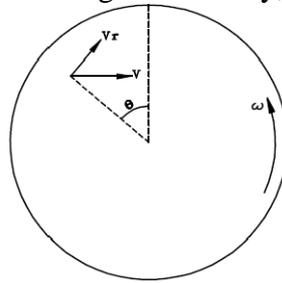


Fig. 1 The schematic of air relative speed

At certain point of time, the air speeds are all different at the same radius of brake disc, but they are about symmetrical on the vertical plane. Due to cyclical variation of the air speed at any point, the air speed at any point at the same radius is seen as variable only according to speed by integration and average equivalent in order to facilitate the numerical simulation. Equivalent wind speed of the same radius can be calculated through integration and average:

$$v_\infty = \int_0^\pi \sqrt{(v + \omega r \cos \theta)^2 + (\omega r \sin \theta)^2} d\theta / \pi \tag{3}$$

Here, v is train speed, m/s; ω is wheel angular velocity, rad/s; r is the radius of a point on the brake disc, m; θ is the angle as shown in Figure 1. As the wind speed of the entire disk is symmetrical on the vertical plane, the half of the computation is necessary.

For example, $v=350\text{km/h}$, $r=0.32\text{m}$, θ varies from 0 to 2π , the trend of real wind speed is shown as Figure 2; $r=0.175\text{m}$, shown as Figure 3.

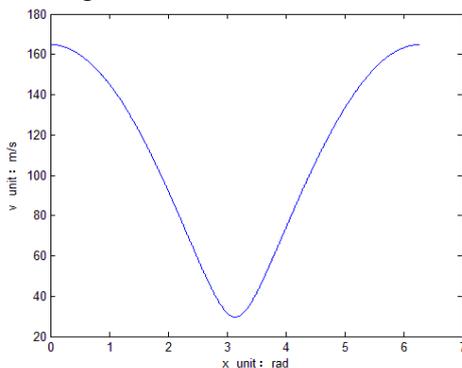


Fig. 2 The trend of real wind speed at the minimum radius

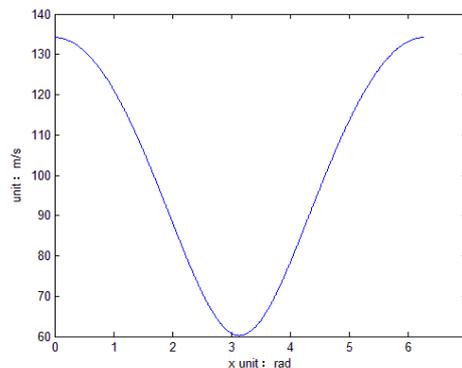


Fig. 3 The trend of real wind speed at the maximum radius

$\omega = v / R$, R is wheel radius, taking it into formula:

$$v_\infty = v \int_0^\pi \sqrt{1 + 2 \frac{r}{R} \cos \theta + \left(\frac{r}{R}\right)^2} d\theta / \pi \tag{4}$$

According to formula, equivalent wind speed of the same radius is only related with the train speed. Equivalent wind speed coefficient k is given:

$$k = \int_0^\pi \sqrt{1 + 2\frac{r}{R}\cos\theta + \left(\frac{r}{R}\right)^2} d\theta / \pi \quad (5)$$

$$v_\infty = kv \quad (6)$$

Numerical size and trend of k is gotten by numerical integration and average when r varies from 0.175m to 0.32m, shown as figure 4:

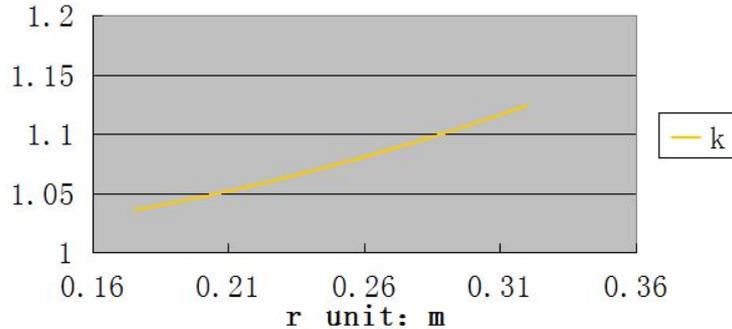


Fig. 4 Numerical size and trend of k

(2) Wind speed of the brake disc back

The geometric structure of the brake disc back is complicated due to the cooling cylinders, so it's difficult to describe the state of the real air flow. To simplify the calculation, formula (2) gives convection coefficient based on the model of circular tubes with crossed air flow, and relative wind speed v_∞ is replaced as train speed v .

Heat Capacity Simulation and Analysis of Typical Working Condition

The paper takes the example of a type of EMU shaft - disk, which is at speed of 300Km/h in emergency braking condition. The brake disc material is cast steel. According to Cast Steel Manual, the specific heat capacity is 489.9J/kg*C, density is 7.87~7.98g/cm³, Poisson's ratio is 0.28.

Physical model of the brake disc is shown as Figure 5. The hub and friction ring of the shaft - disc are flange connections fastened by 9 bolts. Considering the characteristics of the brake disc which has the structure of cyclic symmetry, the paper selects a basic cycle model of 1/9 disc as the computation model, which is meshed by element solid70. Finite element model is shown as Figure 6. This model is divided into 232,253 elements.



Fig. 5 Physical model of the brake disc Fig. 6 Finite element model of the brake disc

Under Emergency braking conditions, the initial braking speed is 300Km/h, and the entire process lasted 73 seconds. The temperature field of brake disc at any time are computed by ANSYS. Figure 7 to 8 show the temperature field contours at 30s and 70s during the braking process.

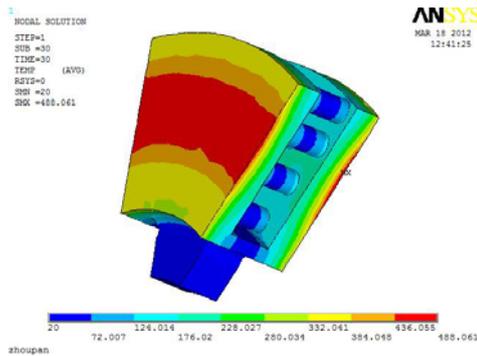


Fig. 7 The temperature field contours at 30s

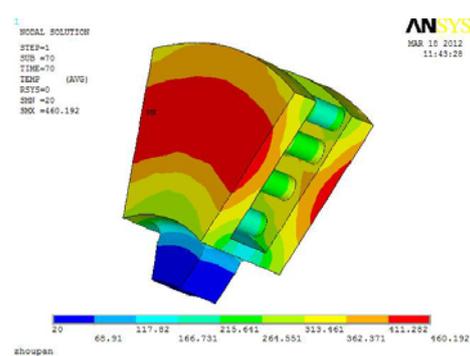


Fig. 8 The temperature field contours at 70s

It can be seen from Figure 7 to 8, when the train is implementing braking and brake pads are contacting brake disc, the temperature distribution of brake disc changes from the initial non-uniform lump hot spot to a clear broadband with the heat accumulation in the braking process. In the late braking process, due to the reduction of heat flow, the zonal distribution of the friction surface gradually disperses. Due to the strong thermal conductivity of the area at the disc hub connections, the temperature distribution does not show absolute circle, but shows the characteristics of cycle in the circumference direction. In the axial direction temperature distribution is gradually turning into the arc-shaped layer from the initial straight layer, and the temperature gradient becomes smaller, which shows that heat transfer has a significant time lag phenomenon and a consistent trend in the temperature of the entire disk is also presented. The maximum temperatures of brake disc are always in the middle of the friction surface during the whole braking process.

Figure 9 is comparison of the solved results, curve 1 is time history of the maximum temperature with the convection coefficient identified in this paper, and curve 2 is time history of the maximum temperature with the simplified convection coefficient. At the beginning of the braking process, the temperature of the brake disc rises sharply. The temperature of the brake disc is not high, so the impact of the change in convection coefficient on the temperature is not obvious and difference in temperature is small. Brake discs at the same time get the highest temperature in 48s. Subsequently, due to the reduction of the speed and the friction heat, the temperature of the brake disc is reduced. The temperature trend of the brake disc by the two computation methods is basically the same, but the maximum temperatures are significantly different.

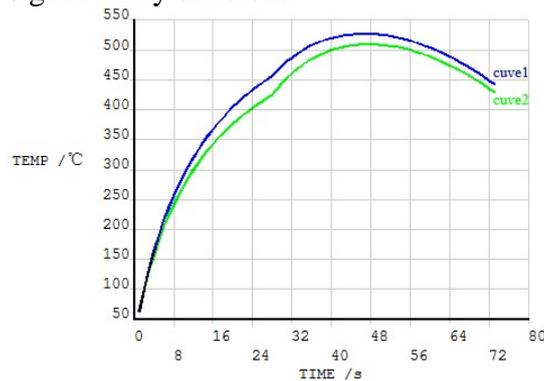


Fig. 9 The comparison of maximum temperature - time history curve

Figure 10 shows the temperature field contours at the time of the maximum temperature with the convection coefficient identified in this paper. Figure 11 shows the temperature field contours at the time of the maximum temperature with the simplified convection coefficient. The maximum temperature is 529.058°C in figure 12 and 508.293°C in figure 13. The two results differ by 21.235°C. Since the convection coefficient identified in this paper is smaller than the simplified convection coefficient, this solution result is bigger than that simplified. The result of simulation and the trend of theoretical analysis are the same. In the braking condition mentioned above a maximum temperature of 524 ° C was experimentally measured based on real vehicle[7]. The former is a difference of 5.058 ° C, and the latter a difference of 15.707 ° C. The computation is more accurate when wind

speed of disc surface on convection coefficient is considered accurately. The error is within reasonable limits. The result verifies the correctness and feasibility of the numerical simulation.

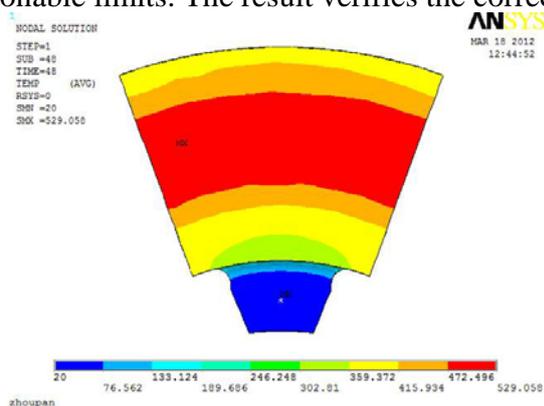


Fig. 10 Temperature field contours

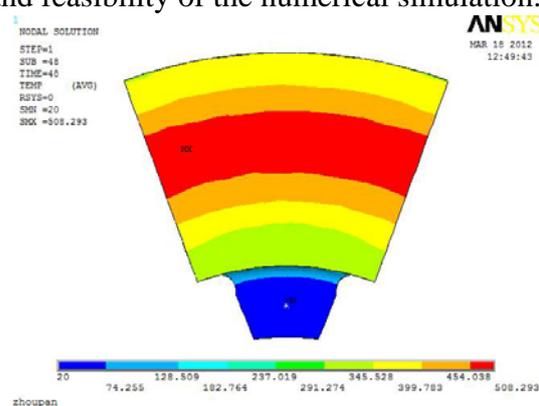


Fig. 11 Temperature field contours

Conclusion

Based on the three-dimensional model of cyclic symmetry, the relative wind speed of disc surface was calculated. The convection coefficient at the different points of the disk surface has been calculated with the given equivalent wind speed coefficient and other relative conditions. This value is smaller than simplified convection coefficient. Through the computation of ANSYS, it's easy to find that the result considering wind speed of disc surface on convection coefficient is closer to the experimental result, and it's consistent with the theoretical analysis. Convection coefficient of high-speed train is relatively large during braking, so it's significant for transient temperature field of brake disc that convection coefficient is calculated accurately. The paper has made some exploration accordingly.

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