Acta Technica *61*, No. 4B/2016, 219–230

Temperature analysis on electromechanical composite brake of automobile based on numerical simulation[1]

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Abstract. The structure and principle of a new type of electromechanical composite brake for automobile are introduced. The mathematical models of electromagnetic field and temperature field of the electromechanical composite brake are established. The boundary conditions of electromagnetic field and temperature field of electromechanical composite brake are analyzed. The coupling analysis method of temperature field of brake disc is put forward. The temperature distribution of brake disc is calculated when the brake strength is small and the electromagnetic brake works alone, and the temperature distribution of brake disc is also calculated when the brake strength is large and the electromagnetic brake and the friction brake work at the same time. The results show that the temperature rise will not affect the magnetic performance of electromagnetic brake, and the temperature rise is reduced by 15.7 % compared to the traditional friction brake, which effectively enhances the performance of resisting heat recession of automotive brake. This provides a theoretical basis for the design of electromechanical composite brake.

Key words. Automotive engineering, electromechanical composite brake, temperature coupling analysis, numerical simulation..

1. Introduction

The electromechanical composite brake is a new type of brake for automobile, in which an electromagnetic retarder is equipped based on the traditional disc brake

[1]This research is supported by the University Science Research Project of Jiangsu Province (13KJB580005), the Jiangsu Province Ordinary University Graduate Research and Innovation Project (CXXZ13_0659), and the Basic and Applied Basic Research Fund Project of Jiangsu University of Technology (KYY14009).

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[1]. The electromagnetic retarder may change the braking energy of automobile in to heat energy and send off, so as to reduce the burden of traditional friction brake [2].It can effectively prolong the service life of friction brake and resist the heat recession of automotive brake, the braking performance of automobile will be improved at the same time. Therefore, the electromechanical composite brake is one of the development trends of automotive brake [3]. When the electromagnetic brake and the friction brake work at the same time, the brake disc not only has an external heat source, but also has an inner heat source. The inner heat source is mainly due to the eddy current loss in the brake disc caused by the brake disc's motion of cutting magnetic lines in the magnetic field. With the work of friction brake, the temperature of brake disc increases, which will weaken the magnetic conductivity between the coils and iron core of electromagnetic brake and affect the braking performance of automobile. In addition, there is a weak coupling relationship between the temperature field and the magnetic field of brake disc. There is a big difference between the coupling factors are considered and the coupling factors are not considered [4], [5]. Therefore, there is great practical significance to study the distribution of temperature field and electromagnetic field to the design of electromechanical composite brake. In this paper, the electromechanical composite brake is taken as research object, the sequential coupling method is adopted, and the coupling of electromagnetic field and temperature field of electromechanical composite brake are simulated and analyzed when the electromagnetic brake and the friction brake work at the same time.

2. Structure and principle of composite brake

The electromechanical composite brake consists of friction brake and electromagnetic brake. The friction brake is mainly composed of a brake disc and a brake caliper body, and the electromagnetic brake is mainly composed of iron core and coils. Its structure is shown in Fig. 1.

The brake piston and the friction block are pushed to the brake disc by the high pressure oil in the brake cylinder of friction brake. The friction between the friction block and the brake disc transforms the kinetic energy of automobile into the heat energy of brake disc, which makes the automobile slow down or brake. When the electromagnetic brake works, the electric current passes through the coil, the brake disc turns for cutting the magnetic line in the magnetic field. At this time, the brake disc will produce eddy current and the eddy current will produce the braking torque on the brake disc which hinders the rotation of brake disc. In the process of braking, the control unit can dynamically distribute the braking torque to the friction brake and the electromagnetic brake according to the braking conditions of automobile.

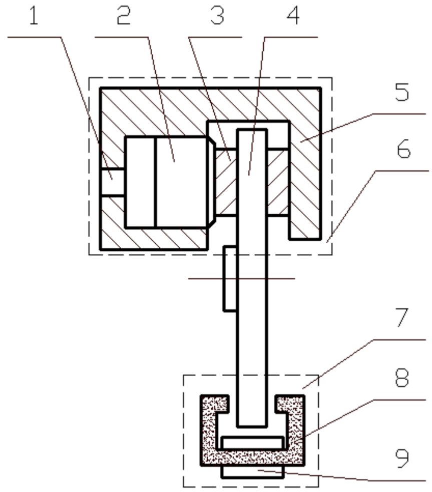

Fig. 1. Schematic diagram of electromechanical structure of composite brake: 1–oil hole, 2–brake piston, 3–friction block, 4–brake disc, 5–brake caliper body, 6–friction brake, 7–electromagnetic brake, 8–iron core, 9–coil

3. Establishment of mathematical models

3.1. Mathematical models of electromagnetic field

The formation mechanism of electromagnetic field of electromechanical composite brake is shown in Fig. 2. After the coil is electrified, the two terminals of iron core are changed into two magnetic poles. The brake disc turns relative to the iron core for cutting the magnetic line. The counter clockwise and clockwise vortices are generated separately in the front and rear sides of brake disc. According to the law of left hand, the ampere force generated by the vortices will generate braking torque on the brake disc, which will prevent the rotation of brake disc.

It can be seen from Fig. 2, the closer to the center of brake disc, the smaller the induction current generated in the magnetic field. Therefore, the whole brake disc is divided into a vortex area and a non-vortex area in the calculation. The magnetic field and electric field are required to be calculated in the vortex region, and only the magnetic field is calculated in the non-vortex region. According to the Maxwell equation group and the law of conservation of charge, the differential equations of the vortex region and the non-vortex area can be expressed as

$$\mathrm{curl}\ \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}\,, \quad \mathrm{curl}\ \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}\,, \quad \mathrm{div}\ \boldsymbol{D} = \rho\,, \quad \mathrm{div}\ \boldsymbol{B} = 0\,, \tag{1}$$

where $\boldsymbol{H}$ is the magnetic field strength vector, $\boldsymbol{J}$ is the eddy current density vector, $\boldsymbol{B}$ is the magnetic flux density vector, $\boldsymbol{E}$ is the electric field strength vector, $\boldsymbol{D}$ stands for the electric displacement vector and ρ is the electric charge volume density.

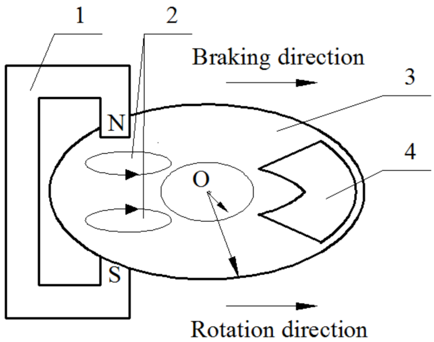

Fig. 2. Formation mechanism of electromagnetic field of composite brake 1–iron core, 2–eddy current, 3–brake disc, 4–friction block

This system must be supplemented with the constitutive equations in the form

$$\boldsymbol{D} = \varepsilon \boldsymbol{E}\,, \quad \boldsymbol{B} = \mu \boldsymbol{H}\,, \quad \boldsymbol{J} = \gamma \boldsymbol{E}\,, \tag{2}$$

where ε is the dielectric permittivity, μ is the magnetic permeability and σ is the conductivity.

The vectors used in the Maxwell equations represent the relationship of electromagnetic field are difficult to calculate. Therefore, in the analysis of electromagnetic field problems, certain potential functions are often introduced as the auxiliary quantity. In the vortex area, the scalar electric potential φ is used to describe the electric field and scalar magnetic potential ψ for magnetic field, while the magnetic vector potential $\boldsymbol{A}$ is used to express the magnetic field in the non-vortex area.

The potential function of the electric scalar potential in the vortex area in plane x, y is defined by

$$\boldsymbol{E} = -\mathrm{grad}\ \varphi = -\mathbf{i}\frac{\partial \varphi}{\partial x} - \mathbf{j}\frac{\partial \varphi}{\partial y}\,. \tag{3}$$

Similarly, the potential function of the magnetic scalar potential in the vortex area in plane x, y is defined by

$$\boldsymbol{H} = -\mathrm{grad}\ \psi = -\mathbf{i}\frac{\partial \psi}{\partial x} - \mathbf{j}\frac{\partial \psi}{\partial y}\,. \tag{4}$$

Finally, in plane arrangements the vector potential has only one component A_z in the z-direction and may be defined by the relation

$$\boldsymbol{B} = \mathrm{curl}\ \boldsymbol{A} = \mathbf{i}\frac{\partial A_z}{\partial y} - \mathbf{j}\frac{\partial A_z}{\partial x}\,. \tag{5}$$

Substitution of equations (3) and (5) into (1) provides two equations of electric and magnetic field distributions in the form

$$\nabla^2 \varphi = \frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = -\frac{\rho}{\varepsilon}\,,$$

$$\nabla^2 A_z = \frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} = -\mu J_z\,. \tag{6}$$

In non-vortex area without currents there holds

$$\nabla^2 A_z = \frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} = 0\,. \tag{7}$$

3.2. Mathematical models of temperature field

A small portion of the heat generated by the friction brake and electromagnetic brake is emitted into air, and the most of the heat is absorbed by the brake disc, which leads to the increase of the brake disc temperature. With the increase of the brake disc temperature, the heat conduction, heat convection and heat radiation will be generated in the interior and on the surface of brake disc. According to the principle of heat transfer, the 3D transient heat conduction equation of brake disc and friction block can be obtained [6].

$$k(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + q_{\mathrm{V}} = \rho c \frac{\partial T}{\partial t}\,, \tag{8}$$

where k is the thermal conductivity, T is the temperature, q_{V} represents the volumetric heat losses, ρ is the density of material, c is the specific heat of material at a constant pressure, and t is the time.

During the braking process in the brake disc, the eddy currents in it are the internal heat source, and its strength is [7]

$$q_{\mathrm{V}} = \gamma \omega^2 \left|A\right|^2\,, \tag{9}$$

where γ is the electric conductivity of material and ω is the current angular frequency.

The following boundary condition of the temperature field is applied [8]

$$k\frac{\partial T}{\partial n} = -h(T - T_a) - C\sigma(T^4 - T_a^4)\,, \tag{10}$$

where T_a is the environmental temperature, h is the coefficient of convective heat transfer, C is the radiation coefficient, σ is the Stefan–Boltzmann constant, and n denotes the direction of the outward normal.

Another boundary condition should be satisfied on the contact area between the brake disc and the friction block:

$$q = F_{\mathrm{w}} \cdot f \cdot P(t) \cdot \omega(t) \cdot r\,, \tag{11}$$

where F_w is the weight of friction heat flux density input to the brake disc, f is the friction coefficient between the brake disc and friction plate, $P(t)$ is the transient variation of brake pressure, $\omega(t)$ is the transient variation of the angular velocity.

The third kind of boundary condition should be satisfied in the non-contact area between the brake disc and friction block. This condition has the form

$$h = 0.664\,\mathrm{Pr}^{1/3}\mathrm{Re}^{1/2}\,, \tag{12}$$

where Pr is the Prandtl number and Re is the Reynolds number.

4. Coupling calculation and analysis

The sequential coupling method is adopted for coupling between the electromagnetic field and the temperature field of electromechanical composite brake. The ANSYS software is used for simulation and calculation. In this paper, the Jetta car with 1.6MT CTX engine is taken as the research object. The total weight of the car is 1650 kg, the tire model is 245/45R18 and its structure parameters are 85 mm and 115 mm. The number of turns of a single coil is 820, the air gap is 2 mm, the current of exciting coil is 25 A, and the ambient temperature is 293 K. The material of brake disc is copper, its thermal conductivity is 383 W/(m °C), specific heat is 390 J/(kg °C), and its density is 8889 kg/m^3. Next step, the temperature rise of brake disc is calculated respectively in the two working conditions of small strength and high strength based on the ANSYS software.

4.1. Continuous braking with small strength

The first hypothesis is that the speed of automobile is 30 km/h, the slope of road is 10 degrees, and the observation time is 30 seconds. Because the strength of braking is small at this time, only the electromagnetic brake works in the electromechanical composite brake. Therefore, it is only necessary to consider the influence of eddy current and electromagnetic coil on the temperature rise of brake disc.

According to the characteristic of left and right symmetry of the electromagnetic brake with respect to the brake disc, the two dimensional computational domain model of the electromagnetic brake and the brake disc is established. In this time, the electric current of electromagnetic brake is 15 A and the speed of brake disc is 980 rpm.

Through analysis, it can be seen that the maximum magnetic flux density of brake disc is 1.454 T, the maximum eddy current density is $8.32 \times 10^4\,\mathrm{A\,m^{-2}}$, the maximum eddy current loss density is $9.028 \times 10^7\,\mathrm{W\,m^{-3}}$. The direction of eddy current density and the direction of magnetic induction intensity are perpendicular to each other. The position of eddy current loss is on the outer layers of two sides of the brake disc, which corresponds with the actual analysis. Therefore, the heat rate of brake disc can be calculated through the analysis of electromagnetic field. The heat rate of brake disc is the eddy current loss per unit volume of brake disc under the role of electromagnetic brake, which is used as the boundary condition to analyze the temperature field of brake disc. Under the continuous braking with small brake strength, the temperature field of brake disc can be calculated, as shown in Fig. 5, and the temperature curves of different tori in the same radial direction is shown in Fig. 6.

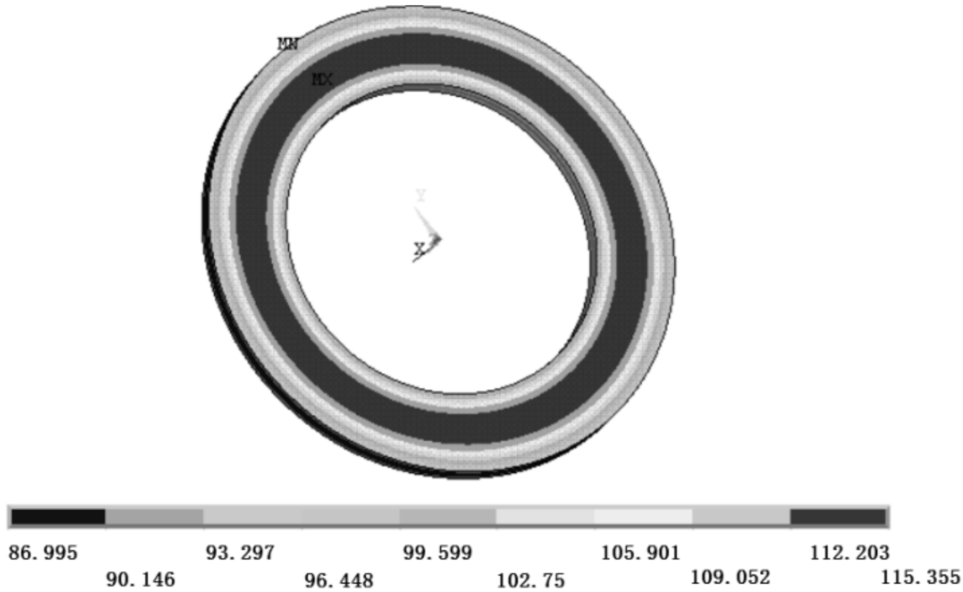

Fig. 3. Contour map of temperature field (MN denotes mimimum temperature, MX denotes maximum temperature)

The region with high temperature is mainly concentrated in the middle of brake disc, the temperatures of the inner and outer surfaces of the brake disc are lower than that of the middle torus. The maximum temperature is about 115 °C, the minimum temperature is about 87 °C and the temperature change trend of brake disc is same in the same radial direction. The main reason is that the vehicle speed is constant, and the inner heat source of brake disc is constant during the continuous braking, so that the heat generation rate caused by eddy current loss is constant. The internal heat source absorbed by the middle torus is greater than its heat dissipation, and the heat of the inside and outside tori which are far away from the action position of magnetic pole and brake disc is passed through the heat transfer. The distance from the middle torus is farther away, the lower the temperature.

4.2. Braking condition with high brake strength

Assuming that the automobile slows down from 120 km/h to 30 km/h, then runs at the speed of 30 km/h for 30 minutes. At this time, the electromagnetic brake and the friction brake play a role at the same time, and the braking torque of the two brakes is needed to be dynamically allocated. The total braking torque of

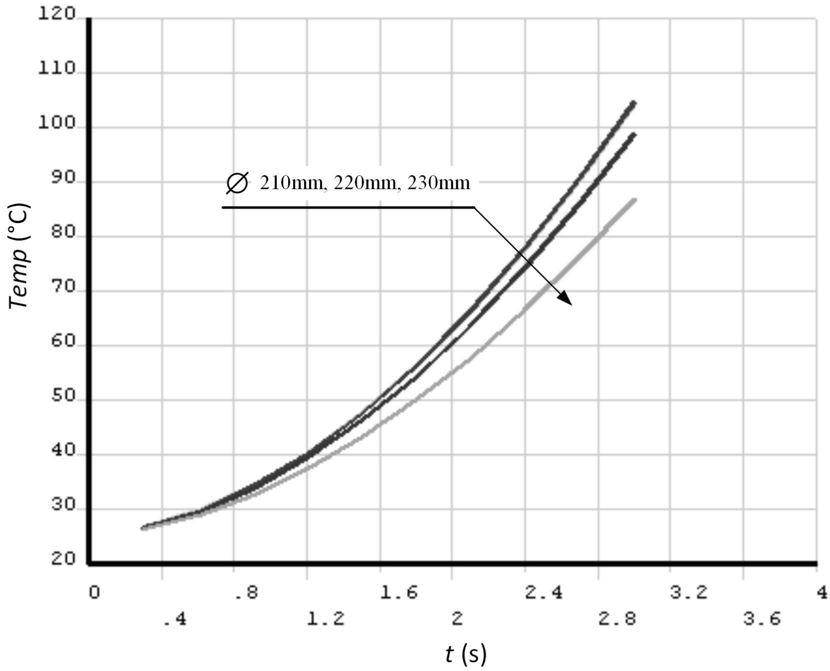

Fig. 4. Temperature curves of different tori

electromechanical composite brake is as follows.

$$T = T_{\mathrm{m}} + T_{\mathrm{h}} = \frac{1}{3} f \pi d^2 p \frac{\left(R_2^3 - R_1^3\right)}{\left(R_2^2 - R_1^2\right)} + \frac{16\sqrt{2}\pi\rho\Delta_{\mathrm{h}}\omega ab^2 L(\mu_0 NI)^2}{\left(16\pi\rho l_{\mathrm{g}} + \sqrt{2}ab\Delta_{\mathrm{h}}\mu 0 k_{\mathrm{e}}\omega\right)^2}, \tag{13}$$

where T_{m} is the brake torque of friction brake T_{h} is the brake torque of electromagnetic brake, d is the piston diameter, p is the brake fluid pressure, R_1 is the inner diameter of friction block, R_2 is the external diameter of friction block, ρ is the resistivity of brake disc, Δ_{h} is the skin depth of eddy current on the brake disc, ω is the angular velocity of the brake disc, L is the distance from the center of brake disc to the center of pole, I is the electric current of electromagnetic brake, μ_0 is the magnetic permeability of vacuum, l_{g} is the air gap between the brake disc and the magnetic pole, and k_{e} is the conversion coefficient.

In the above formula, there exist the relationship

$$\Delta_{\mathrm{h}} = \sqrt{\frac{2\rho}{\omega\mu_0\mu_r}}, \tag{14}$$

where μ_r denotes the relative permeability.

The integrated control strategy is adopted to dynamically allocate the braking torque between the friction brake and the electromagnetic brake. The allocation results are shown in the Fig. 7.

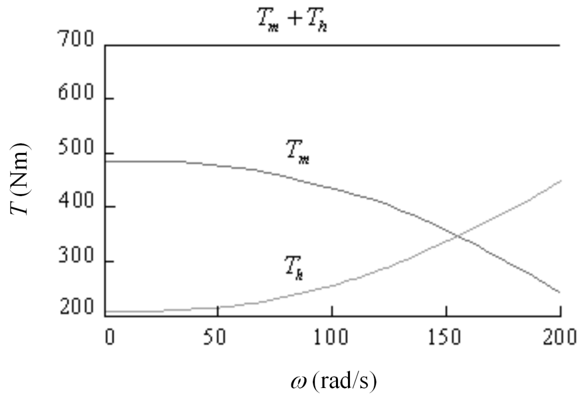

Fig. 5. Distribution curves of brake torque

The distribution results of brake torque in Fig. 7 are used to determining the above thermal boundary conditions of the electromagnetic brake and the friction brake. In the coupled analysis, the thermal boundary conditions comprise the heat generation rate of electromagnetic field, heat of electromagnetic coil, and heat flux density, thermal radiation, heat convection between the friction block and brake disc. Under the braking condition with high brake strength, the temperature field of brake disc can be calculated, as shown in Fig. 8, and the temperature curves of different tori in the same radial direction is shown in Fig. 9.

In the process of high-strength braking, the temperature of brake disc shows a gradient distribution from the middle of brake disc to the inner and outer sides. The high temperature zone is the contact area between the brake disc and friction block. The temperature of brake disc rises rapidly, and the temperature reaches the highest value which is about 365 °C at 1.8 s, and then begins to slow down. The reason is that the friction heat and current loss, which are just absorbed, do not have time to spread to the periphery. It results in a sharp increase of temperature on the inner surface of brake disc. With the extension of braking time, the speed of brake disc decreases continuously, and the heat flux density absorbed by it is also decreasing. However, the heat flux transmitted through heat conduction mode exhibits a little change in its interior. At this time, the heat absorbed by the inner surface of brake disc is lower than the heat loss, which causes the temperature of brake disc to drop, but the decline is slow.

Through the dynamic distribution of the brake torque and the temperature field analysis, the relationship between the temperature of brake disc and the brake torque can be simulated as shown in Fig. 10.

In the picture above, the curve of 1 is the temperature curve of friction braking torque, the curve of 2 is the temperature curve of integrated braking torque, and the curve of 3 is the temperature curve of electromagnetic braking torque. The trends of the three curves are basically the same. With the increase of the braking torque,

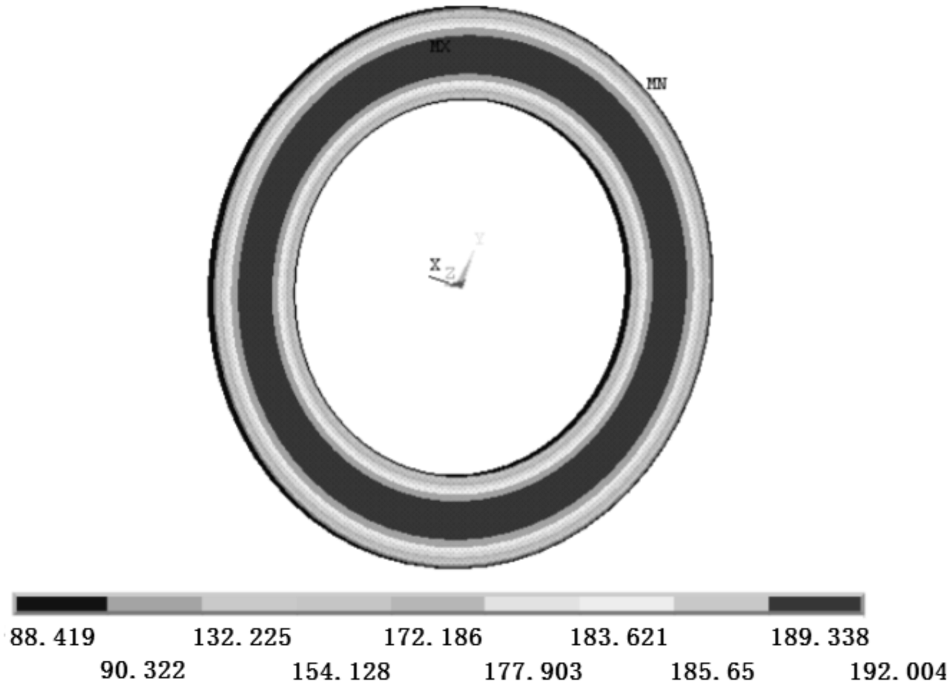

Fig. 6. Contour map of temperature field (MN denotes mimimum temperature, MX denotes maximum temperature)

the temperature of brake disc is increasing. Among them, the temperature rise of electromagnetic brake is slow, and the temperature rise of friction brake is the most obvious. When the braking torque reaches 700 N m, the temperature of friction brake is about 545 °C, and the temperature of integrated brake is about 440 °C, which represents a decrease by about 15.7 % compared with the traditional friction brake. And the maximum temperature of the integrated brake is much smaller than the Curie point of the iron material, so that it will not affect the magnetic conductivity of the integrated electromagnetic brake.

5. Conclusion

The thermal analysis of electromechanical composite brake is carried out, particularly, temperature fields under two kinds of typical braking conditions are obtained. The simulation results show that the temperature rise of electromechanical composite brake will not affect its electromagnetic force. The temperature rise of electromechanical composite brake has a clearer decline than that of the traditional friction brake. It can be seen that the models and calculation method presented in this paper are accurate and practical, which can meet the needs of engineering practice. This provides the theoretical basis for the design of electromechanical

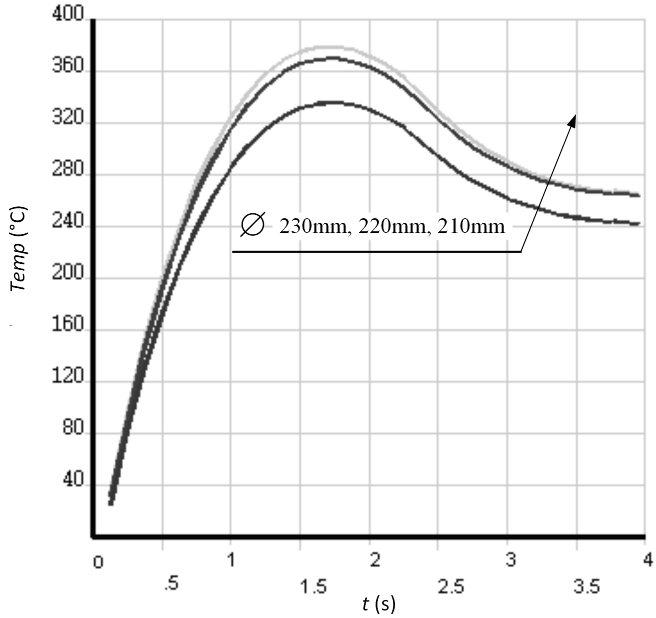

Fig. 7. Temperature curves of different tori

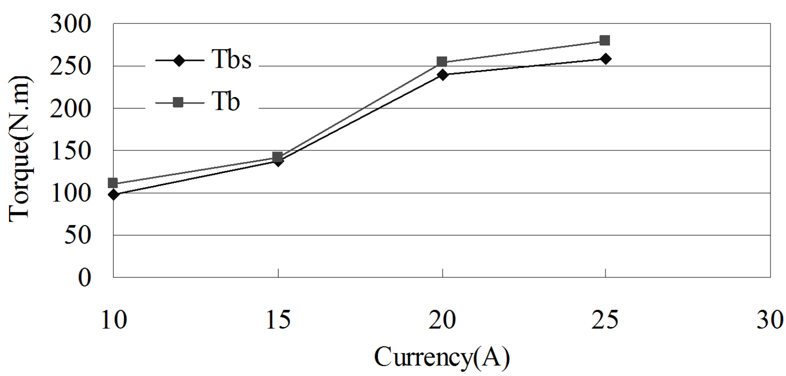

Fig. 8. Relation between temperature and brake torque

composite brake.

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Received November 16, 2016