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Investigation in the Effects of Configuration Parameters on the Thermal Behavior of Novel Conical Friction Plate in Continuously Sliding Condition

Yanzhong Wang[1] and Xiangyu Wu[1, *]

Abstract: To investigate the effects of configuration parameters and operation condition on the thermal behavior of novel conical friction plate, a three-dimensional finite element model of conical friction plate is established for numerical simulation. The conical surface configuration and friction heat generation of novel conical friction surfaces are discussed. The results indicate that the thermal behavior of the conical friction plate during continuously sliding period is influenced by the conical surface configuration. Maximum temperature occurs in the conical friction plate with cone angle of 24°. The maximum temperature value of friction plate is increased 7.4°C, when cone depth increases from 3 mm to 4 mm. Thermal behavior investigation should be carried out when optimize conical surface configuration.

Keywords: Transmission, wet clutch, conical configuration, surface configuration, thermal behavior.

1 Introduction

Wet friction clutch is an important component of a transmission. The frictional clutch is designed to provide enough torque. The traditional wet clutch is composed of series of plain separator plates and friction plates. The novel friction plate consists of a series of conical surfaces. As shown in Fig. 1, the single cone friction pair is designed with two conical friction surfaces. The friction torque is generated by the conical interfaces and directly depends on the friction coefficient and the conical structure.

Torque capacity is critical for the overall behavior of the transmission. Thermal effects have significant influence on the torque transfer process. The overheating failure of wet multi-plate friction clutches is concerned widely in the engineering practice. During the continuously sliding period, a large amount of heat is generated due to the rough surface contact between the friction plate and the separate plate. The high surface temperature can lead to friction hot spots on separator plate, thermal deformation, oil breakdown of its properties and other thermal failure of the clutch. The temperature should be taken into account when we determine the transferred torque.

[1] School of Mechanical Engineering, Beihang University, 37 Xueyuan Road, Haidian District, Beijing, 100191, China.
* Corresponding Author: Xiangyu Wu. Email: 630092679@qq.com.

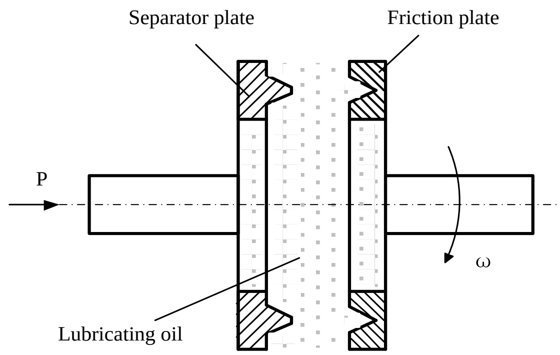


Figure 1: Two-dimensional model of single cone friction pair

In order to design and analysis clutch performance, the effect of interface temperature has been investigated by many researchers. Marklund et al. [Marklund, Mäki, Larsson et al. (2007)] used a temperature dependent model to evaluate the torque transfer for wet clutches. Marklund et al. [Marklund and Larsson (2008)] developed a test method to simulate the clutch plate friction behavior. The effect of interface temperature on the friction coefficient was investigated in a pin on disc test.

With the development of numerical method, numerical computations have become one of major ways to analysis the friction behavior of wet clutch. Jen et al. [Jen and Nemecek (2008)] conducted a theoretical model to simulate the temperature rise of the clutch and the temperature rise was measured with thermocouples. Jang et al. [Jang and Khonsari (1999); Jang, Khonsari and Maki (2011)] developed a three-dimensional model to investigate the effect of grooves on the performance of a wet clutch. Tatara et al. [Tatara and Parviz (2002)] constructed a two dimensional thermal model to simulate the heat transfer in a grooved wet clutch. The model is valid for continuously sliding process with experimental data. The surface groove geometry also influences the temperature distribution. Li et al. [Li, Khonsari, Mccarthy et al. (2014)] presented a three-dimensional thermo-hydrodynamic model to study the groove geometry parameters. The study shows that the triangular profile shows the smallest engagement time. Xie et al. [Xie, Tong, Wu et al. (2016)] simulated the oil groove forms on thermal behavior of friction pair. The result shows that the circumferential oil groove got the highest temperature.

In conclusion, the previous studies are concentrated on oil groove，friction material property and torque characteristic. It is difficult to measure the conical surface temperature and the thermal gradient when the frictional clutch is working. As the conical friction plate is a novel component, to obtain the optimal conical configuration, thermal behavior investigation should be carried out. In this paper, the three dimension finite element model is used to evaluate the effect of surface configuration parameters on thermal behavior. Based on the friction heat principle and conical surface configuration, the pressure, heat flux, heat distribution coefficient on the friction surface and the convection were calculated. The thermal gradients and conical surface temperature during continuously sliding period were given.

2 The friction heat generation

The frictional heat generated by the relative sliding process between the friction pair. The energy is regarded as a total heating of the friction pair. The heat flux generated by friction is determined by following simplified formula (1).

$$q_t = \mu p r \omega \tag{1}$$

Where q_t is heat flux due to the friction $(\mathrm{W/m^2})$, μ is the friction coefficient, p is the contact pressure (Pa), ω is the relative angular speed $(\mathrm{rad/s})$ and r is the radius of the friction plate (m).

As shown in Fig. 2, $\mathrm{r_i}$, $\mathrm{r_o}$ is the inner and the outer radii, respectively, r_1, r_2, r_3, r_4 is the vertex of the conical surface. The normal force is applied on the back of the friction plate.

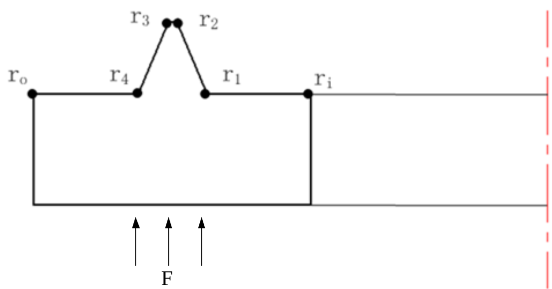


Figure 2: Simplified model of the equivalent pressure

The equivalent pressure of the conical friction plate was calculated as follows.

$$p = \frac{F}{\pi({r_2}^2 - {r_1}^2) + \pi({r_4}^2 - {r_3}^2)} \tag{2}$$

Where F is the normal force (N).

The distribution of heat flux between the friction plate and separate plate was decided by the physical properties of the material. Thermal distribution coefficient K of the contact pair can be calculated from the following formula (3).

$$\mathrm{K} = \frac{\mathrm{q_f}}{\mathrm{q_s}} = \frac{\sqrt{\rho_f c_f \lambda_f}}{\sqrt{\rho_s c_s \lambda_s}} \tag{3}$$

Where q_f represent the heat flux of friction plate, q_s represent the heat flux of separate plate, λ_f, ρ_f, c_f represent thermal conductivity, density, specific heat of friction material, and λ_s, ρ_s, c_s represent thermal conductivity, density, specific heat of separator plate.

3 Finite element model of the conical friction plate

The heat transfer process of friction plates includes the heat conduction, convection and radiation. We make some assumptions before the analysis of heat transfer process.

- The lost mechanical energy is transformed into frictional heat.
- The heat radiation is generally ignored in analysis.

- The pressures on the cone surface of the friction plate are distributed uniformly.
- The physical properties of the material are constant and the material of friction plate is isotropic.

In the Cartesian coordinate system, the transient heat conduction equation of friction plate is given as follows:

$$\rho c\frac{\partial T}{\partial t}=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{4}$$

Where T represent the temperature, ρ, c, λ represent density, specific heat and the thermal conductivity of the material, respectively.

Transient thermal analysis process is shown in Fig. 3. The geometry model, establishment of finite element model, boundary condition and post processing are required in the transient thermal analysis of the conical friction plate.

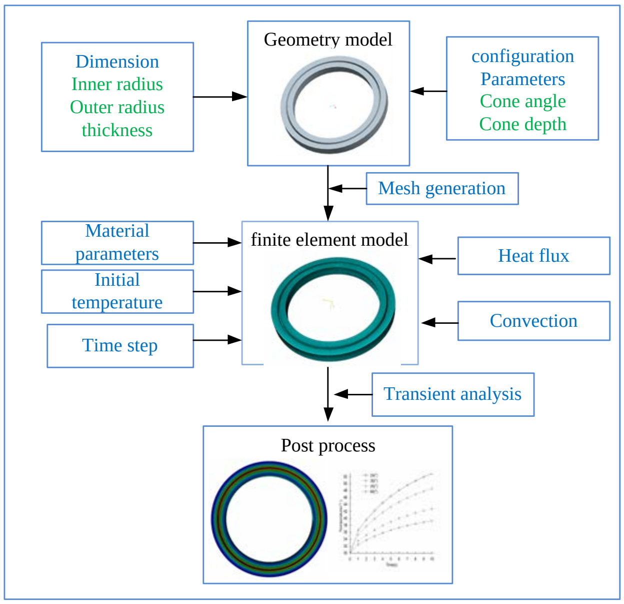


Figure 3: Flow diagram of transient thermal analysis

3.1 Geometrical model of the conical friction plate

Geometrical model of conical friction plate is shown in Fig. 4. Fig. 5 is a diagram of cross-sectional shape of the surface configuration. The cross-sectional shape of the conical friction surface is triangular. The inner radius, outer radius and thickness of friction plate are r_i, r_o, b, respectively. The surface configuration depends on the cone angle α and the cone depth h.

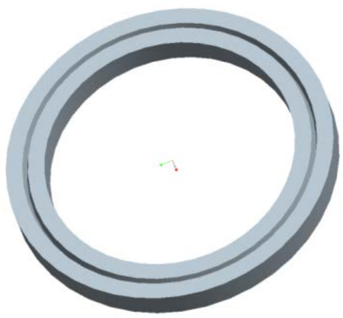


Figure 4: Conical friction plate

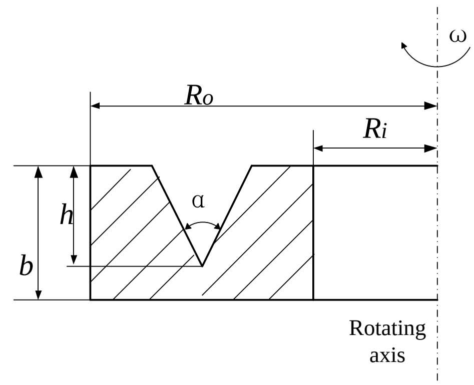


Figure 5: Surface configuration

As shown in Tab. 1, the inner radius, outer radius and thickness of a plate are 0.0325 m, 0.0425 m and 0.01 m, respectively.

Table 1: Dimensions

Parameters	Values
Inner radius r_i (m)	0.0325
Outer radius r_o (m)	0.0425
Thickness b (m)	0.01

3.2 Finite element model of conical friction plate

The temperature in the conical surface depends on the surface configuration parameters, boundary condition and operation parameters. The finite element formulation of transient heat can be written in the following matrix form as

$$[\mathrm{C_T}]\dot{\mathrm{T}} + [\mathrm{K}]\mathrm{T} = \mathrm{R} \tag{5}$$

Where $[C_T]$ respects the capacity matrix, [K] respects the conductivity matrix, and T and R respect the nodal temperature and heat source vector, respectively.

The finite element model of friction plate is shown in Fig. 6. Hexahedral elements are used to mesh the friction plate. After partition operation, the grids are more regular.

Figure 6: Finite element model of friction plate

In this paper, 10 s continuous sliding friction conditions are designed to evaluate the thermal gradient and the effects of the conical configuration on the temperature.

Operation parameters were listed in Tab. 2. Normal force F, rotating speed v, cone depth h and cone angle α are the variable. Coefficient of friction is set to 0.04. The time step is 1 s. When the normal force and rotating speed is given, the pressure is calculated by formula (2).

Table 2: Operation conditions

Item	Value
Normal force F (N)	500, 600, 700
Rotating speed v (r/min)	400, 500, 600, 1000
Cone depth h (m)	0.03, 0.04
Cone angle α (°)	24, 30, 45, 60
Coefficient of friction, μ (-)	0.04
Time step (s)	1

3.3 Boundary conditions of finite element model

In constant sliding period, the frictional heat is generated by the conical surfaces. The heat generated will exchange with the lubricating oil by convection and the conduct heat inside the plate. As shown in Fig. 7, the conical friction plate consists of four conical surfaces BC, CD, DE, EF, two circumferential grooves AB and FG and the inner ring surface AI , the outer ring surface GH and the back of the friction plate HI.

The boundary conditions of conical friction plate are listed in Tab. 3. Heat flux q_1 , q_2 , q_3 , q_4 is applied on the surface BC, CD, DE, EF of the friction plate. The heat flux is increased with the increasing radius from r_1 to r_2, that is $q_1 < q_2 < q_3 < q_4$. The convective heat transfer include two parts, convection on the annular oil groove AB and FG, and convection on ring surface AI and GH. The inner and outer surfaces of the friction plate are applied with heat convection h_1, h_2. The annular oil groove surfaces of the friction plate are applied with heat convection h_{avg}. The initial temperature is $T_0 = 30$℃ in this study. Temperature of the back surface is T_0.

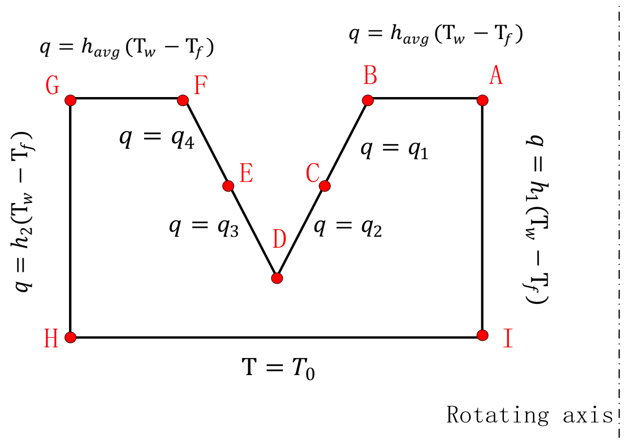


Figure 7: Boundary conditions for the transient thermal analysis

Table 3: Boundary conditions

Item	Boundary conditions	Location
Initial oil temperature (°C)	T_0 =30°C，t=0.	
Conical interface surface	$q = q_1$	BC
	$q = q_2$	CD
	$q = q_3$	DE
	$q = q_4$	EF
Outer ring surface	$q = h_2(T_w - T_f)$	GH
Inter ring surface	$q = h_1(T_w - T_f)$	AI
Annular oil groove surface	$q = h_{avg}(T_w - T_f)$	AB, FG
Back of the friction plate	$T = T_0$	HI

The friction material of Friction plate is copper alloy and the separator plates is generally made of steel 30 Cr. The values of physical properties of materials are presented in Tab. 4. Then the heat flux could be obtained by formulas (1) and (3).

Table 4: Material properties

Parameters	Friction plate	Separate plate
Thermal conductivity $\mathrm{W/(m \cdot k)}$	106	45.5
Density ρ $(\mathrm{Kg/m^3})$	8500	7750
Specific heat c $(\mathrm{J/(Kg \cdot k)})$	377	420

The properties of lubricating oil are listed in Tab. 5. The convective heat transfer coefficient of friction pairs is related to the oil supply mode and the configuration of the friction plate.

Table 5: Oil properties

Item	Value
Thermal conductivity λ_o $(\mathrm{W/m \cdot k})$	0.138
Density ρ_o $(\mathrm{Kg/m^3})$	852
kinetic viscosity υ_o $(\mathrm{Pa \cdot s})$	377
Specific heat c_o $(\mathrm{J/(Kg \cdot k)})$	2131

In order to investigate the temperature distribution on the plate surface, 14 nodes are chosen to form the surface temperature distribution. As shown in Fig. 8, the nodes are distributed along the radial direction. Node 4 to node 11 is the conical surface region. Node 1-3 and node 12-14 is annular oil groove region.

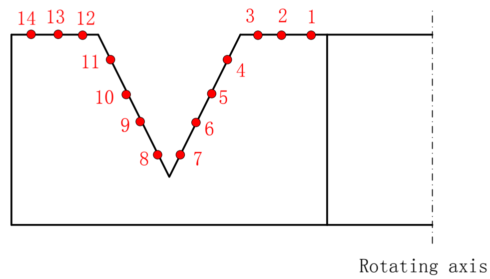


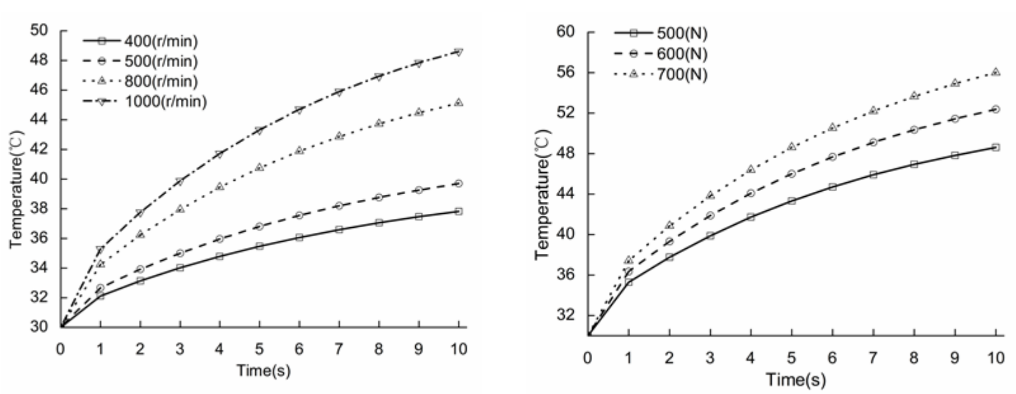
Figure 8: Diagram of node position

4 Results and discussion

4.1 Temperature variation and distribution under different normal force and speed

Fig. 9(a) is the variation of maximum temperatures under different rotating speed. The cone angle α is 30° and the cone depth h is 0.003 m. The normal force is 500 N. The temperature increases with time and the growth rate slows down obviously. The heat flux in 1000 r/min conditions is twice times larger than that in 500 r/min conditions and the rise in temperature is 1.22 times larger than that in 500 r/min conditions. When the rotating speed is 1000 r/min， the peak temperature is up to 48.61°C .

Fig. 9(b) shows the variation of maximum temperatures under different normal force. The rotating speed is 1000 r/min. The heat flux for 700 N is 1.4 times larger than that of 500 N, and the rise in temperature is 1.13 times larger than that for 500 N. The maximum value increases with the increase of the load.

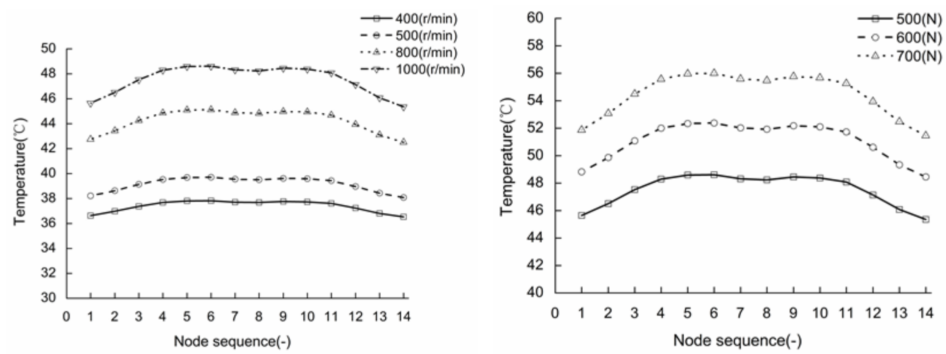


(a) (b)

Figure 9: Variation of maximum temperature with time

Notes: (a) Variation of maximum temperatures under different rotating speed; (b) Variation of maximum temperature under different normal force.

Fig. 10(a) shows the temperature distribution of conical friction plate. The cone angle α is 30° and the cone depth h is 0.003 m. The normal force is 500 N. The temperature gradient increases with the increase of the rotating speed variation in conical surface region. Fig. 10(b) shows the temperature distribution of conical friction under different normal force. The rotating speed is 1000 r/min. The temperature gradient increases with the increase of the load variation in conical surface region.



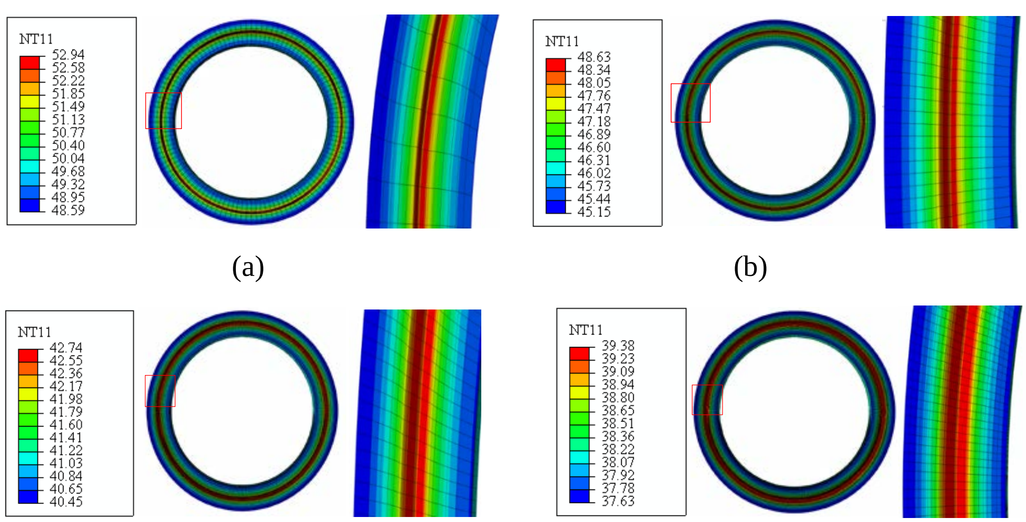
(a) (b)

Figure 10: Temperature distribution of conical friction plate

Notes: (a) Temperature distribution under different rotating speed; (b) Temperature distribution under different normal force.

4.2 Effect of cone angle on temperature field of conical friction plate

The temperature contours of the conical friction plate with different cone angle are shown in Fig. 11, the axial force is set to 500 N and the rotating speed is 1000 r/min. The temperature on the conical surface is higher than the annular oil groove surface. The highest temperature of conical friction plate with 24° cone angle is 52.94°C, and the highest temperature value of conical friction plate with 30°, 45°, 60° cone angle is 48.65°C, 42.74°C, 39.38°C, respectively.



(a) (b)

(c) (d)

Figure 11: Temperature field of friction plate with different cone angle

Note: (a) $\alpha = 24°$; (b) $\alpha = 30°$; (c) $\alpha = 45°$; (d) $\alpha = 60°$

The temperature distributions of the friction plate are shown in Fig. 12. The cone depth is 0.003 m, rotating speed is 1000 r/min and normal force is 500 N. The friction plate with 24° cone angle has the highest average temperature in conical friction surface and the temperature difference of friction plate with 24° cone angle is largest (about 3.93°C). Temperature difference decreases with the increase of cone angle. The temperature difference friction plate with 45° and 60° cone angle is very small.

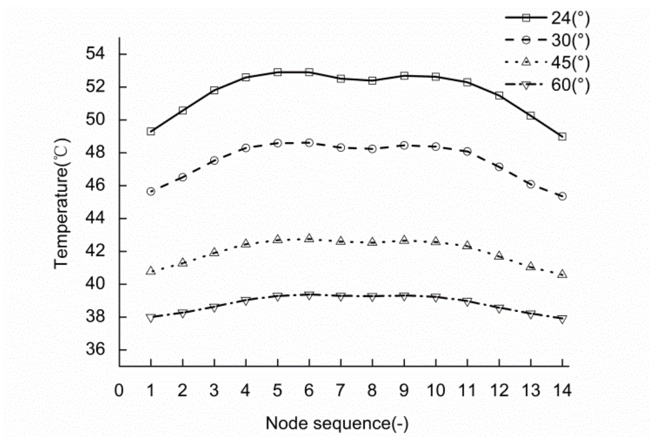


Figure 12: Temperature distribution of conical friction plate with different cone angle

4.3 Effect of cone depth on temperature field of conical friction plate

The variation of maximum temperature for different cone depth is shown in Fig. 13. The temperature increases with time. The maximum temperature value of friction plate with 4 mm cone depth is larger than that of 3 mm cone depth. The maximum temperature of conical friction plate with 4 mm cone depth is 56.01°C. Fig. 14 shows the temperature distribution of conical friction plate with different cone depth. The maximum temperature difference of conical friction plate with 4 mm cone angle is larger than that of 3 mm cone angle. The maximum temperature difference with 4 mm cone angle is 4.18°C.

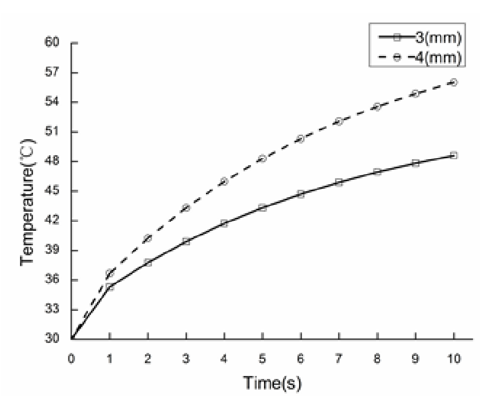


Figure 13: Temperature distribution of conical friction plate with different cone depth

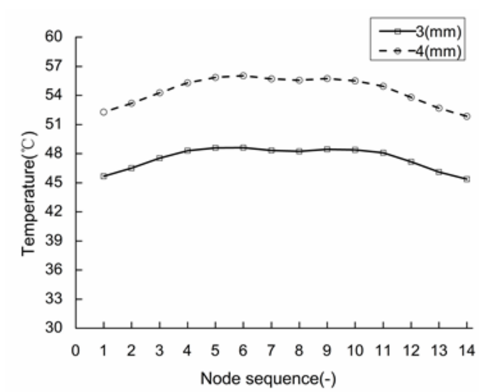


Figure 14: Variation of maximum temperature for different cone depth

5 Conclusions

The summary of the effects of conical configuration and operation condition on thermal behavior is as follows.

1. Rotating speed and load have great impact on the temperature rise in friction plate. The maximum temperature value increases with the increase of the rotating speed and load. High load and rotating speed could change the contact condition and create more heat.

2. The operation condition determines the energy level. High load rotating speed can increase the temperature gradient in friction plate. The temperature gradient is insensitive to the rotating speed and high load in conical surface region.

3. The effects of different cone angle on temperature field were investigated. The conical friction plate with 24° cone angle has the highest temperature. When the cone angle is 45° or 60°, the temperature rise is not obvious.

4. The cone depth could affect the maximum temperature and increase the temperature difference. As the cone depth increases from 3 mm to 4 mm, the maximum temperature value of friction plate is increased 7.4°C, and the maximum temperature difference is increased.

5. The smaller cone angle and greater cone depth may improve the torque transfer capability, but the temperature behavior is also required design. With proper surface configuration design, the thermal behavior can be improved.

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