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Development of Water-cooling Transmission Device for Magnetorheological Fluid

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Magnetorheological (MR) transmission that uses the rheological effect of MR fluid to transfer power is a new form of power transfer, which can achieve stepless control of torque and speed by adjusting the intensity of external magnetic field. In the study, a water-cooling heat dissipation scheme was proposed. The temperature simulation of MR transmission under natural heat dissipation and water-cooling heat dissipation was carried out by using the finite element method. Based on the design of the water-cooling MR transmission device (MRTD), the torque transmission and temperature rise characteristics of the MRTD were studied, and the influence of the heat dissipation mode on the transmission torque of the device was explored. Results show that the water-cooling method can control the temperature rise of the MRTD effectively.

Keywords : Water cooling, Transmission device, Magnetorheological fluid, Temperature

1. Introduction

Transmission device as a basic component of the mechanical system is the intermediate equipment that delivers the basic motion and power of the power plant to the actuator, which converts simple and single motion and power from the power plant to meet the needs of the actuator for complex and diverse movements [1]. The selection of transmission device plays an important role in the performance of the whole mechanical system. MRTD is a novel fluid transmission device, which uses MR fluid that is a kind of intelligent material as working medium and utilizes the reversible change of rheological property of MR fluid under the action of magnetic field to realize the transfer of torque and speed between the input and output shaft. Compared with the conventional transmission device, the MRTD has the characteristics of simple speed regulation, easy control, rapid response, good constant torque and so on [2-6] so that it has wide application prospects in the aspects of soft start, soft brake, stepless speed regulation and overload protection of mechanical and electrical equipment.

At present, the development of the MR transmission is mainly focused on small torque applications [7-10]. However, the application of MRTD has been restricted with the wide use of large and medium-sized machinery with high-power and high-slip. When the MRTD operates at high-power and high-slip situation, it will arise the continuous relative slip between the layers of the MR fluid in the working space and cause friction between particles because of a rotational speed difference between the input and output shaft of the device. In this case, the slip power of the transfer will be converted into heat that is absorbed by the device, which easily results in the rise of the overall device temperature and affects the work performance and control precision of the device ultimately.

Therefore, temperature effect of MR transmission has attracted the attention of many scholars. Kavlicoglu *et al.* [11] proposed a multi-plate MR limited slip differential clutch, and tested clutch heating under differential operating conditions. Park [12] modeled the dual disk MR brake and simulated the steady-state temperature field. Sarkar [13] studied the temperature rise of a single disk extruded MR brake. Patil [14] proposed a MR brake for electric bicycles, and tested the temperature rise and aging test of the brake. Furthermore, several relevant cooling methods have been proposed to solve heating status and heat dissipation problem of the high-power transmission. Dogruoz *et al.* [15, 16] processed several radiating fins in the shell to accelerate the heat dissipation from the MR fluid damper. Zheng J *et al.* [17] designed a new MRTD with pin-fin heat pipes to improve the heat-sinking capability. Chi-Kuan Kao *et al.* [18] put forward a liquid cooled MRC for automotive transmissions, which adopted

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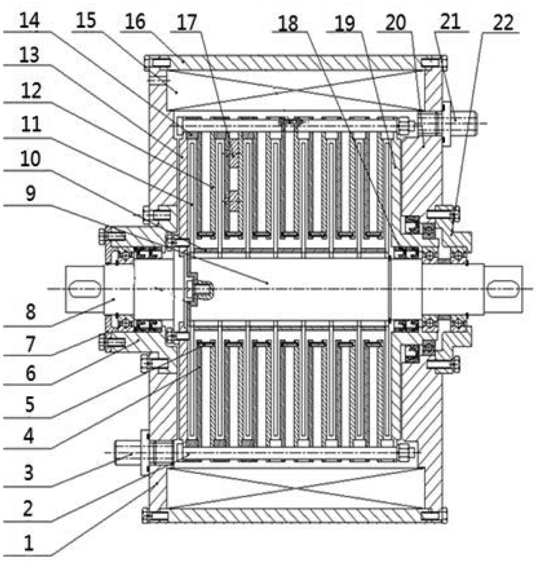
a single cylinder structure with unique flow channel design and high heat dissipation efficiency. D M Wang [19] proposed a multi-plate MR brake with a water cooling method for heat dissipation.

In this study, a multi-plate drive structure with a unique water-cooling channel was put forward and temperature field of the MRTD was analyzed by finite element method. Moreover, the experiment of the transmission performance and the temperature rise of the water-cooling MRTD under different slip power were carried out. Research results from this study may serve to provide a suitable cooling method for the development of high-power MR transmission technology.

2. Design of the Water-cooling MRTD

2.1. Structural model design

In order to make the MR transmission meet the requirement for high transmission torque and good heat dissipation, a heat dissipation scheme for water-cooling MRTD was proposed, as shown in Fig. 1. In this design, the MRTD comprises eight pairs of driving plates and driven plates. Eight pairs of driving plates are connected



1. left magnetic shell; 2. guide column; 3. inlet joint; 4. driving plate 2; 5. driving spacer ring; 6. left bearing block; 7. left end cover; 8. driving axis; 9. driven shaft; 10. driven spacer ring; 11. driven plate; 12. driving plate 1; 13. left-handed magnetic baffle; 14. driving magnetic separation ring; 15. excitation coil; 16. medium fixed magnetic shell; 17. magnetic column group; 18. seal ring; 19. right-handed magnetic baffle; 20. right magnetic shell; 21. outlet joint; 22. right bearing block

Fig. 1. Basic structure of water-cooling MRTD.

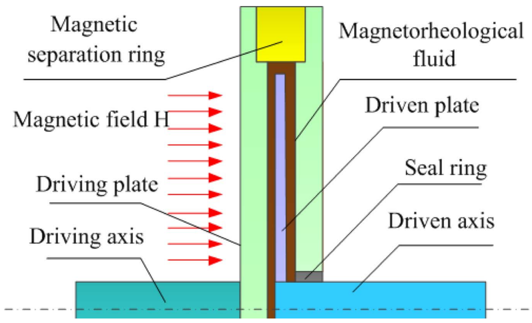


Fig. 2. (Color online) Structure diagram of transmission unit.

by a guide column to the left-handed magnetic baffle that is fastened to the driving shaft and the driven plates are connected by a spline to the driven axis. The adjacent driving plates are separated by the driving spacer rings and the driving magnetic separation ring, and the driven plates are separated by the driven spacer ring to form several working gaps of a certain width. The excitation coil provides an additional magnetic field for the MR effect of MR fluid in the working space.

The scheme is composed of a certain number of spacing transmission unit and the cooling unit, the former mainly realizes the power transfer and the latter is responsible for the heat dissipation. Figure 2 shows a schematic of the transmission unit. In the design, the transmission unit is mainly composed of the driving plate, the driven plate, the driving shaft, the driven shaft and the magnetic separation ring, the space between the driving plate and the driven plate is the working space of the MR fluid, which is sealed with a seal. The magnetic separation ring can limit the conduction of the magnetic force line along the radius of the plate, reduce the magnetic flux of the working space and enhance the effective magnetic field strength of the working space. When the external magnetic field is applied to the transmission unit, the MR fluid produces the MR effect under the action of the magnetic field, thus transmitting the power from the driving axis to the driven axis.

Figure 3 shows a schematic of the cooling unit, which is mainly composed of driving plate, magnetic column group and spacer ring. The space formed by the three parts is filled with cooling water, which can transmit heat generated by MR fluid out. There are four circles of the magnetic column between the two driving plates. The magnetic column is connected with the two driving plates to form a certain space. The cooling water can flow in the space, and it can fully contact with the two driving plate and the magnetic column group, which increases the heat dissipation area. Meanwhile, magnetic column group rotated with the driving axis stirs the cooling water, which

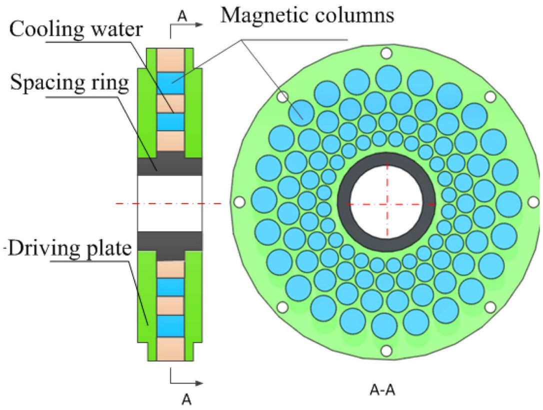


Fig. 3. (Color online) Structure diagram of cooling unit.

enhances the cooling effect of cooling water. The effect of cooling water on magnetic circuit reluctance can be reduced by using strong magnetic materials in the magnetic column group. The expansion port which is sealed on the spacer ring can resist volume expansion caused by the increase of temperature, and reduce the pressure in the working space so as to prevent the leakage of MR fluid.

2.2. Operating principle

In the design, the MRTD adopts the shear working mode and transfer torque by the rheological effect of MR fluid. When the coil is not in operation, the MR fluid is in a freely flowing state. Only a very small viscous torque is emerged by the off-field viscosity of the MR fluid at this time to make the driving and the driven part in a detached state. However, once energizing coil to produce an external magnetic field, there will be a controllable MR effect in the working gap. As a result, the MR particles gather to form many particle chains in the field direction. In the meanwhile, the mutual attraction between the adjacent particle chains leads to the formation of a columnar or reticular structure, which presents a controllable yield stress. At this moment, the driving and the driven part are in a synchronous state or slip state, which can be realized by adjusting the excitation current of the transmission device. In the slip state, the heated is mainly generated in the working gap by mutual friction between MR particles in each layer of the MR fluid. In the design, the cooling water flowed between two plates can bring the friction heat out produced by the MR fluid under the shear action to control the temperature rise of the transmission device. Main parameters of water-cooling MRTD are shown as Table 1.

3. Temperature Field Simulation

3.1. Simulation model

A temperature field simulation was conducted in order to evaluate the temperature rise condition and the heat dissipation capacity of the MRTD. For a better understanding of the internal configuration of the MRTD, a visualized MRTD model is established using the PRO/E software. As observed in Fig. 4, the coolant is injected into the MRTD from the inlet. Then, it flows over the coolant flow channel and out of the MRTD through the outlet. No.1 represents the shell, transmission disc, left and right connecting plates, whose area material is 20# steel. No.2 represents bearings, seals and air parts, which is uniformly treated as air. No.3 represents the excitation coil, whose area material is copper. No.4 represents cooling area, whose material is water. No.5 represents the driven spacer rings, which are made of brass. No.6 represents working gap, filled with MRF. No. 7 represents the magnetic column group. The material in this area is electrician pure iron. No.8 represents the drive shaft, the

Table 1. Main parameters of MRTD.

Design parameter	Value
Maximum output torque	50 N·m
Maximum output speed	1500 r/min
Maximum transmission power	7.5 kW
Workspace number	16
Inner diameter of the working gap	50 mm
outer diameter of the working gap	144 mm
Transmission unit number	8
Working gap of transmission unit	1.5 mm
Cooling unit number	7
working gap of cooling unit	5 mm
Coil turns of winding	2400
Excitation current	2.0A

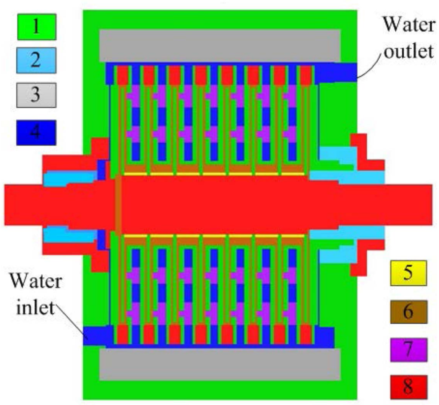


Fig. 4. (Color online) 3D simplified model of temperature field.

active magnetic ring and the bearing base. The material is stainless steel. Using the following initial values and boundary conditions: (1) the initial temperature of each part is set as 25 ºC; (2) The convection heat transfer coefficient between the outer surface of the MRTD and air is 10 W/(m^{2}K); and (3) apply heat generation rate on the heater, which is determined by the power of the heater.

3.2. Simulation results and discussion

In order to compare the heat dissipation under two conditions of natural cooling and water cooling, the distribution of temperature field at the power of 5.5 KW is obtained at the time of 60 second, as shown respectively in the Fig. 5 and 6.

From Fig. 5 we can see that the maximum temperature of the transmission device has reached 130 ºC at 60 s under natural cooling condition, beyond the critical temperature of the MR fluid, which reflects the heat dissipation capacity of natural cooling method is relatively poor due to the low heat exchange rate between the heating plates surface and ambient air.

In comprise, the maximum temperature inside the MRTD is only 55 ºC under the water cooling state, which is plotted in Fig. 6. This indicates that the heat exchange effect is better for water due to its higher thermal conductivity, thus water flow can effectively take the generated heat away from MRTD.

Figure 7 shows the temperature distribution of water-

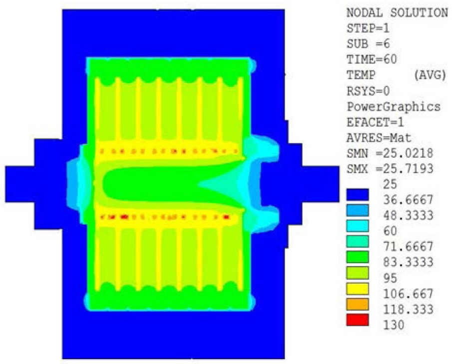


Fig. 5. (Color online) Temperature distribution of water-cooling MRTD with natural cooling.

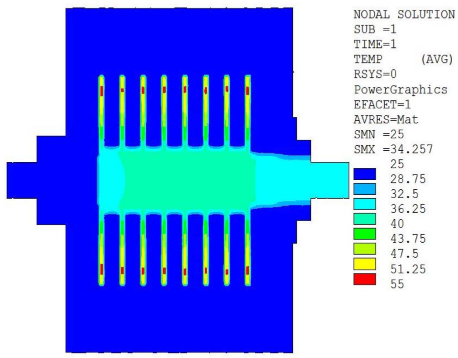


Fig. 6. (Color online) Temperature distribution of water-cooling MRTD with water cooling.

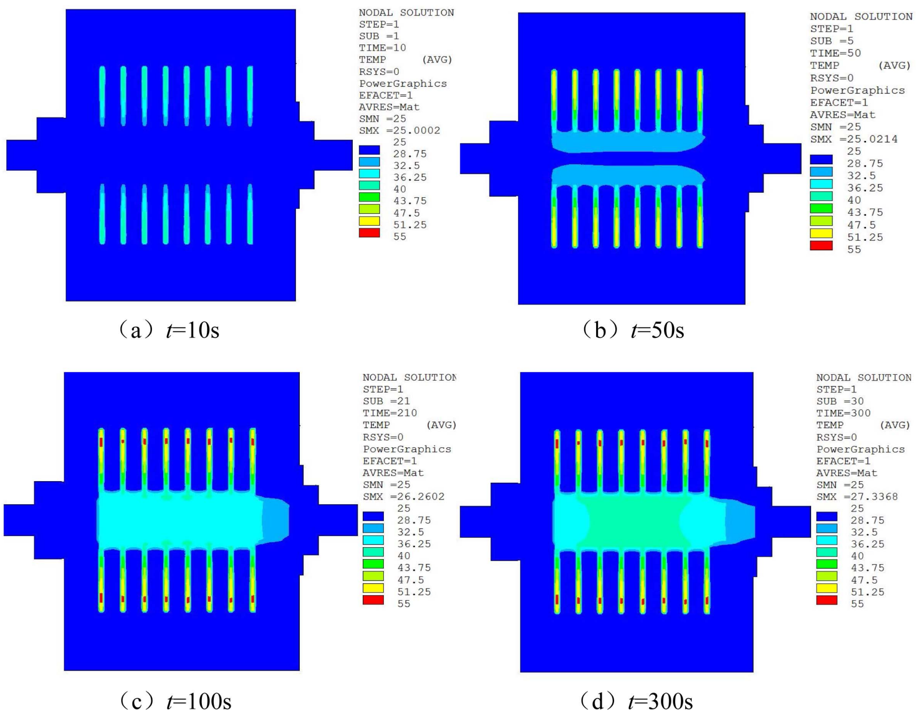


Fig. 7. (Color online) Temperature distribution of water-cooling MRTD with different times.

cooling MRTD with different times at the slip power of 5.5 KW. It can be seen that the maximum temperature of the MR fluid is about 36 ºC, 51 ºC and 55 ºC when the slip time is 10s, 50s and 100s, respectively. However, the temperature is finally steady at about 55 ºC after 100 seconds, which means the water cooling method greatly enhances the heat exchange between the heating plates surface and ambient air. Therefore, a greater allowance steady slip power could be available by improving the heat dissipation condition of MRTD.

4. Experimental Performance

4.1. Chosen MR fluid

The MRF-J25T was provided by the China Chongqing Materials Research Institute Co., Ltd. The operating temperature ranges from –40 to 130 ºC and its zero field viscosity is 0.8 Pa·s (γ = 10/s, 20 ºC). The tested relationship between the shear stress and magnetic induction intensity is presented as shown in Figure 8. It can be seen from the figure that the shear stress is more than 50 kPa when the magnetic induction intensity is 0.5 T. Moreover, the temperature has little effect on the shear stress of the MRF when the temperature vary between 20 ºC and 120 ºC.

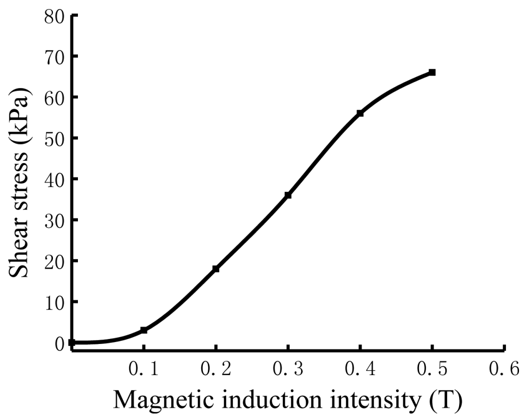


Fig. 8. Shear stress of the chosen MR fluid.

4.2. Experimental system

The prototype of a water-cooling MRTD was made a nd assembled as shown in Fig. 1. The main parameters of the device are shown in Table 1. The experimental system shown in Fig. 9 was conducted to evaluate the performance of the prototype, which is mainly composed of the mechanical transmission part, the data acquisition part, the heat dissipation part and the control part. The mechanical transmission part mainly includes the motor that provides the power for the system, the prototype of the water-cooling MRTD as the detection object, the magnetic powder brake for external load. The data acquisition part mainly includes the torque sensor for measuring the torque and speed of the test prototype, the turbine flowmeter for measuring the cooling water flow, the temperature sensor for measuring the temperature rise of the prototype, and the data recorder. The control part includes frequency converter that controls motor speed, 24 V voltage source supplied for torque sensor and excitation current source for controlling MRTD coil and magnetic powder brake.

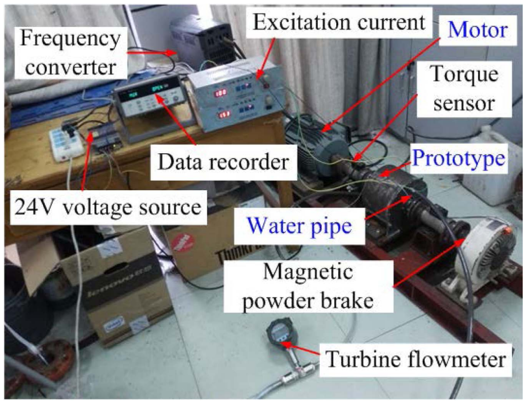


Fig. 9. (Color online) Photograph of test-bed system.

4.3. Experimental results and discussion

The experimental investigation into the torque transmission properties and the temperature rise properties of the water-cooling MRTD was conducted. The experimental results are shown as follows.

Figure 10 shows the transmission torque versus the input current with the slip speed of 750 r/min. In Fig. 9, the transmission torque presents an approximately linear

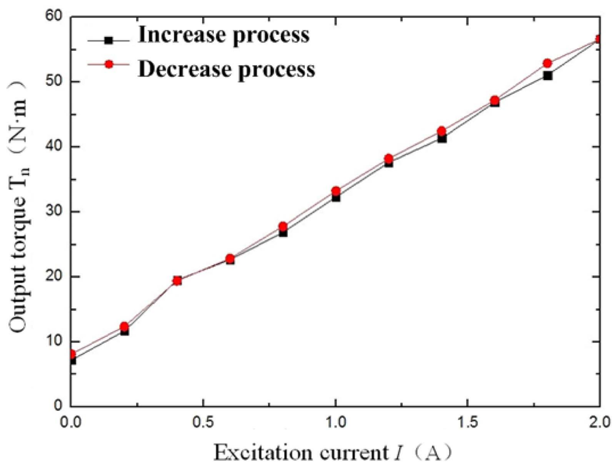


Fig. 10. (Color online) Relationship between output torque and excitation current.

increase with the current in the range of 0-2 A. This indicates the designed MRTD possess good torque control performance. The output torque can be controlled by changing the size of the input current. In theory, the torque transmitted by the MRTD consists of two parts, one is the torque (magnetic torque) produced by the magnetic tension of the magnetic chain, and the other is the viscous torque of the MR fluid flow in the working gap [20]. When the input current increases, the magnetic induction intensity of the coil increases, making the soft magnetic particles in the MR fluid arranged in chains in the magnetic field and adhere to the driving and driven disk to produce greater torque. Compared with the process of increasing the current, the torque of the transmission is greater slightly in the current reduction process, which may be caused by small amount of remanence due to the action of the magnetic circuit. Moreover, there exists a no-load torque at about 6 N·m when the coil is not energized. This phenomenon is induced by the friction moment produced by the rotation of the bearing and the seal ring, the fluid viscosity torque of the MR fluid and the inertia torque of the transmission part.

An applied transmission can maintain good constant torque characteristics. To verify this point, relationship between output torque and slip speed with different current was obtained as shown in Fig. 11. We can see that there exists similar change trend between the output torque and the slip speed under the action of different external current. As the slip speed increases from 150 to 1200 r/min and the current is 1.0 A, the output torque vary from 29.2 to 34.4 N·m, increasing by about 17.8 %; As the current is 1.5A, the output torque vary from 41.2 to 46.7 N·m, increasing by about 13.3 %; As the current is 2.0 A, the output torque vary from 52.5 to 57.5 N·m, increasing by about 9.5 %. As mentioned above, the total torque transmitted by the MRTD consists of two parts: magnetic torque and viscous torque. There is a positive correlation between magnetic torque and magnetic induction intensity or current intensity. With the rise of current, the magnetic torque and the proportion of the magnetic torque to the total torque will rise, indicating the transmission device will have better controllability. On the other hand, the viscous torque is linearly related to the slip speed. Therefore, with the rise of slip speed, the increase of viscous torque makes the total output torque increase slightly. Moreover, the variation of torque is kept within 18 % along with the change of speed, which reveals the designed MRTD has good performance of constant torque.

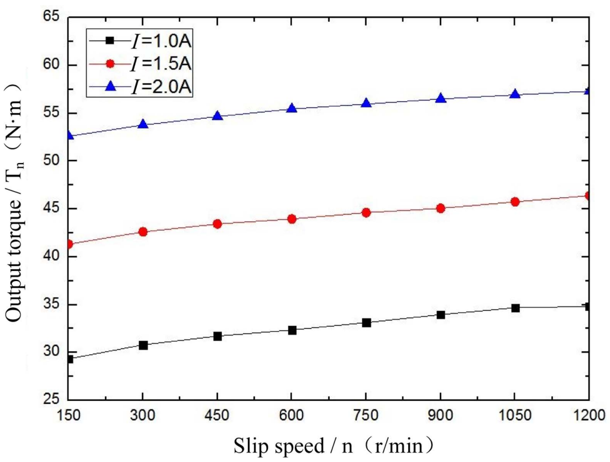


Fig. 11. (Color online) Relationship between output torque and slip speed.

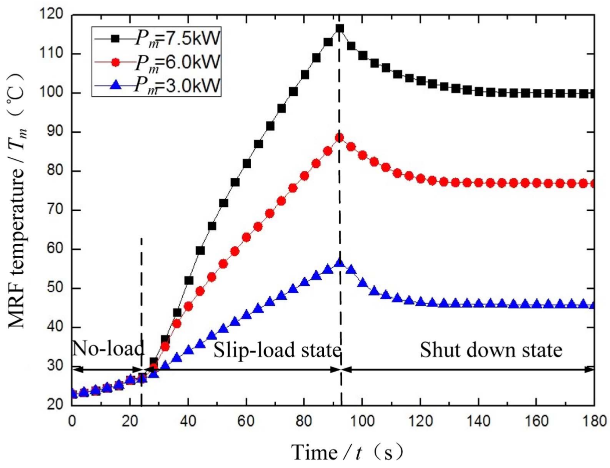


Fig. 12. (Color online) Temperature variation curves of MRF under different slip powers (Natural-cooling state).

Under the slip condition, mutual frictions among MR particles will lead to the temperature rise of MR fluid, which would cause adverse effect on the transmission performance of the MRTD. Figure 12 shows the temperature variation of MR fluid under different slip powers. At the no-load stage, the temperature increased slightly with the slip time due to the effect of no-load torque; when the device worked in the loaded state at 25 s, the temperature appeared to be an approximately linear increase with the slip time. It is mainly because that the heated generates and accumulates continuously in the working gap with the increase of the slip time, and there is not enough time for the heat to dissipate. Also, the temperature rises faster and faster with the increase of the slip power. After 92 s, the device worked in the shutdown stage. Because of the difference between the working gap and the outer shell, the heat would be conducted to the outer shell. As a result, the temperature of MR fluid

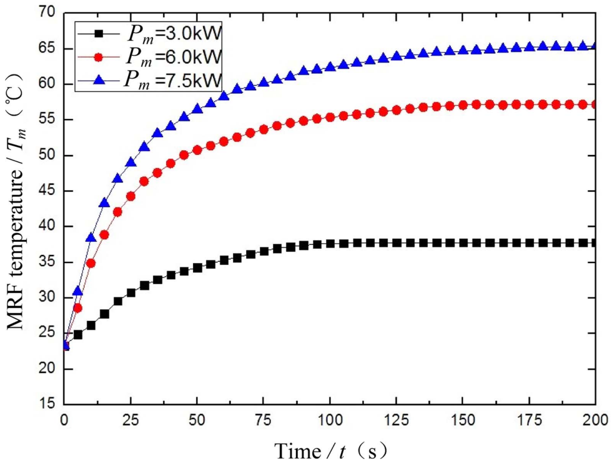


Fig. 13. (Color online) Temperature variation curves of MRF under different slip powers (Water-cooling state).

decline gradually in this period.

From the whole experiment process, we conducted that the heating condition of the device is extremely serious in the slip and load period. Therefore, a proper cooling method should be adopted to ensure the MRTD working within the operational temperature range of the chosen MR fluid. As a contrast, the temperature variation curves of MR fluid under water-cooling state was obtained, as shown in Fig. 13. It can be seen from the Fig. 13 that the temperature variation trends are similar under different slip power. That is, the temperature rises rapidly at the beginning. And then, the rate of increase in temperature gradually slows down until temperature reaches a steady value. Moreover, the larger the slip power is, the higher the steady-state temperature is. However, the temperature

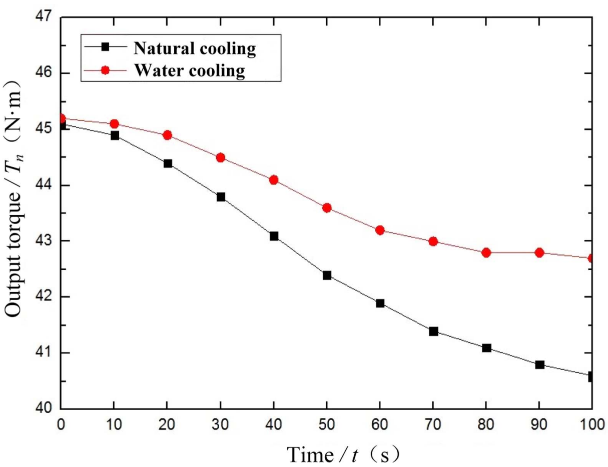


Fig. 14. (Color online) Variation curves of output torque under different cooling conditions.

will still stabilize at 65 °C, even in the case of the maximum slip power of 7.5 KW, which is far less than the upper limit temperature of MR fluid. It is mainly because there exists a balance between the heat dissipation by water cooling and the heat converted from slip power.

Under slip condition, temperature rise of MR fluid will affect the stability of the transmission torque. To verify the efficiency of the water cooling, the slip speed is 750 r/min, the excitation current is 1.5 A, and the output torque of the MRTD under natural-cooling state and water-cooling state was measured, as followed in Fig. 14. We can see that under natural cooling condition the output torque presents a great decline with the increase in time. At 100 s, the torque reduces from 45 to 40.5 N·m, the rate of decline being about 20 %. However, with the water cooling method, the torque shows a very slow decline in this period and the rate of decline is only 5.5 %. Therefore we can draw the conclusion that the water cooling method can effectively improve the stability of the MRTD output torque compared with the natural cooling method.

5. Conclusions

The proposed multi-plate MRTD possess good torque transmission performance: transmission torque presents an approximately linear increase with the current, the maximum torque value is nearly 56 Nm and torque almost remains invariable under different slip speed.

At load stage, a large amount of heat will be produced to influence the rheological properties of the MR fluid under natural cooling condition. Moreover, the higher the slip power, the higher the temperature is. Therefore, a forced cooling method should be used to control the temperature rise.

Water cooling method can not only effectively control the rate of increase in temperature, but also make the maximum temperature stable in the applicable range.

Compared with natural cooling, the water cooling method is more conducive to the stability of the transmission torque.

Acknowledgement

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References

[1] Datong Qin, J. Mech. Engin. **39**, 37 (2004).
[2] X. F. Wu, X. M. Xiao, Z. Z. Tian, and F. Chen, J. Magn. **21**, 229 (2016).
[3] Y. H. Huang, Y. H. Jiang, X. B. Yang, and R. Z. Xu, J. Magn. **20**, 317 (2015).
[4] Z. Z. Tian, F. Chen, and D. M. Wang, J. Intell. Mater. Syst. Struct. **26**, 414 (2015).
[5] Z. Z. Tian, C. Guo, F. Chen, and X. F. Wu, J. Magn. **22**, 281 (2017).
[6] M. Ashtiani, S. H. Hashemabadi, and A. Ghaffari, J. Magn. Magn. Mater. **374**, 716 (2015).
[7] C. Jedryczka, P. Sujka, and W. Szelag, Compel. **28**, 711 (2009).
[8] T. Kikuchi, K. Ikeda, and K. Otsuki, J. Phys. **149**, 012059 (2009).
[9] R. Rizzo, A. Musolino, and F. Bucchi, Smart Mater. Struct. **24**, 075012 (2015).
[10] D. Güth and J. Maas, J. Intell. Mater. Syst. Struct. 27, 2125 (2016).
[11] B. M. Kavlicoglu, F. Gordaninejad, and C. A. Evrensel, Smart Struct. Mater. 341 (2003).
[12] E. J. Park, D. Stoikov, L. F. Luz, and A. Suleman, Mechatronics **16**, 405 (2006).
[13] C. Sarkar and H. Hirani, Smart Mater. Struct. **22**, 115032 (2013).
[14] S. R. Patil, K. P. Powar, and S. M. Sawant, Appl. Therm. Eng. **98**, 238 (2016).
[15] M. B. Dogruoz, F. Gordaninejad, E. L. Wang, and A. J. Stipanovich, Smart Mater. Struct. **4331**, 343 (2001).
[16] M. B. Dogruoz, E. L. Wang, F. Gordaninejad, and A. J. Stipanovich, J. Intell. Mater. Syst. Struct. **14**, 79 (2003).
[17] J. Zheng, G. H. Zhang, and X. J. Cao, J. Mech. Eng. **45**, 305 (2009) (in Chinese).
[18] C. K. Kao, P. B. Usoro, A. L. Bartos, and A. L. Smith, US Patent 6,371,267, 2002.
[19] D. M. Wang, Y. F. Hou, and Z. Z. Tian, Smart Mater. Struct. **22**, 025019 (2013).
[20] D. M. Wang and Y. F. Hou, J. Intell. Mater. Syst. Struct. **24**, 640 (2012).