ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 23(4), 529-535 (2018) https://doi.org/10.4283/JMAG.2018.23.4.529

Influence of Temperature on Torque Transmission Stability of Magnetorheological Fluid

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(Received 5 July 2018, Received in final form 18 December 2018, Accepted 19 December 2018)

Aiming to obtain the influence mechanism of temperature on the torque transmission stability of magnetorheological fluid, firstly, a magnetorheological transmission device and its test-bed are established, and then, the thermal expansion, temperature pressure effect, heat volatilization, viscosity temperature characteristic, magnetic temperature characteristic and other related temperature characteristics were experimented systematically. The results indicate that the thermal expansion rate of 30 wt% magnetorheological fluid is 6 % and 18 % respectively at 120°C and 220°C, and the working space pressure is 13 kPa when the temperature rises from 32°C to 63°C. The thermal volatilization rate is still lower than 1 % at 200°C for 8 hours. The viscosity of the silicone oil based magnetorheological fluid decreases by 78 % when the temperature increases from 20°C to 240°C, and the saturation magnetization decreased by 6.2 %, 13 % and 23 % respectively at 150°C, 250°C and 350°C. Furthermore, the temperature field distribution experiment shows that the highest temperature region is at the outer diameter of the disk and expands slowly along the radial direction. Moreover, compared with rotational speed, temperature is the main factor affecting the torque fluctuation of magnetorheological fluid.

Keywords : temperature, torque transmission, magnetorheological fluid, stability

1. Introduction

Magnetorheological (MR) fluid, which is composed of soft magnetic particles, carrier fluids and stabilizers, is a kind of intelligent materials. When there is no applied magnetic field, it behaves as a Newtonian fluid. As an external magnetic field is applied, it shows a visco-plastic solid behavior [1-5]. Due to the excellent characteristics, MR fluid has been a focused research on clutch, brake, damper control, polishing, etc [6-10]. Torque stability transfer is one of the important applications of MR fluids, while the torque fluctuations will appear due to working temperature rise of MR fluids. In general, when the slip power of torque transmission device is small, the temperature changes slowly and the torque fluctuation can be ignored, however, when the slip power is higher, the temperature changes severely causing the higher torque fluctuation and poor control performance of transmission device.

The temperature application range is an important performance parameter of MR fluid, which affects the torque transmission stability of MR fluid through three aspects mainly, including particles, base fluids and additives [11]. Firstly, temperature affects the magnetic torque of the particles. When the temperature rises, the magnetic permeability of the particles is reduced, especially when the temperature reaches Curie point, the ferromagnetism of some materials will even disappear. Secondly, the temperature affects the viscous torque of the carrier fluid. With the increase of temperature, the viscosity will decrease, which will weaken the viscous torque of MR fluid. Thirdly, the temperature affects the additive efficiency. Some additives have larger viscosity at the higher temperature, which affects the apparent viscosity of MR fluid. Besides, the MR fluid has obvious thermal expansion effect, which is easy to cause the increase of the working gap pressure.

Some researchers have analyzed the temperature properties of MR fluid, Kormann measured the temperature stability of a nano-sized MR fluid [12], Weiss and Wu researched the influence rule of temperature on yield stress of MR fluid respectively [13, 14], Patil analyzed

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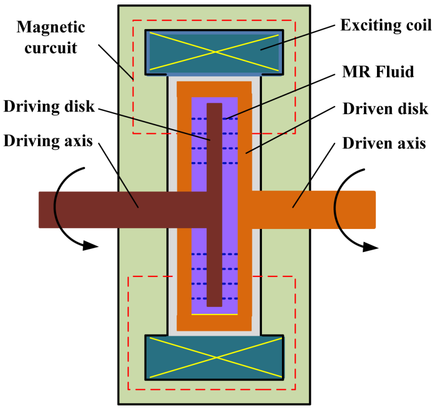
the temperature field of a MR brake for automotive application [15]. At present, it is still lacks of system research on influence mechanism of temperature. In this paper, firstly, a MR transmission device and its test-bed are established, and then, the thermal expansion, temperature pressure effect, heat volatilization, viscosity temperature characteristic, magnetic temperature characteristic and other related temperature characteristics are experimented systematically to obtain the influence principle of temperature on torque transmission of MR fluid.

2. Establishment of MR Fluid Transmission Test-bed

2.1. Experimental prototype

The single disc structure is adopted to analysis the torque transmission stability of MR fluid, and the corresponding transmission prototype is designed and manufactured as shown in Fig. 1, where the Fig. 1(a) is the transmission principle and the Fig. 1(b) is the prototype. It can be seen that the transmission prototype is mainly composed of exciting coil, driven disk and axis, driving disk and axis, and MR fluids, and when there is current in the exciting coil, the driving disk can drives the driven disk to rotate by the MR fluids. The physical parameters of the prototype are shown in Table 1.



(a) Transmission principle

(b) Prototype

Fig. 1. (Color online) MR fluid transmission prototype.

Table 1. physical parameters of the prototype.

Parameters	Value
Maximum torque	6 N.m
Maximum rotation speed	3000 r/min
Radius of driving disk	55 mm
Maximum input voltage of exciting coil	90 V
Wire diameter of exciting coil	0.85 mm
Resistance of exciting coil	27 Ω
The material of main parts	steels 20

2.2. Experimental test-bed

An experimental test-bed for MR fluid torque transmission is set up, as shown in Fig. 2. It consists of AC servo motor, coupling, experimental prototype, torque sensor and display, servo driver, current source, infrared thermograph device, Pt100 thermal resistance, pressure sensor, signal recorder, etc. The speed of AC servo motor is adjusted by servo driver, and the speed regulation range is 0-3000 r/min. The working magnetic field of the MR fluid is adjusted by current source. The transmittable torque value is measured by the torque sensor. Pt100 thermal resistance and infrared thermal imager are used to measure disc temperature. The temperature pressure effect of MR fluids is measured by pressure sensor.

The main technical parameters of testing equipments are as follows: The servo motor power is 1.8 kW, the rated torque is 6 N.m, the peak torque is 18 N.m, and the rated speed is 3000 r/min. The torque sensor adopts static torque sensor with a range of ± 20 N.m and an accuracy of 0.3 %. The infrared thermal imager adopts AVIO S30W series and is connected to a computer through S30 Remote Program software to quickly obtain temperature

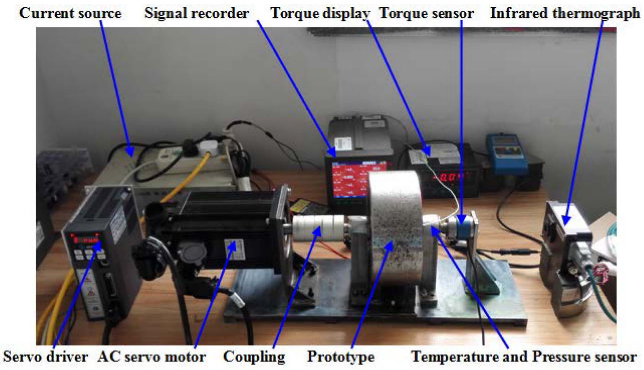


Fig. 2. (Color online) Experimental test-bed for MR fluid torque transmission.

distribution images. Pt100 thermal resistor adopts three-wire connection method and has high testing accuracy. The measurement range of pressure transmitter is 0-50 kPa, and the signal output mode is 4-20 mA current. The signal recorder has the highest sampling speed of 0.1s, which is convenient to collect and store a variety of signals such as current, voltage, thermal resistance and thermocouple.

3. Results and Discussions

3.1. Thermal expansion characteristic of MR fluid

The thermal expansion of MR fluid will appear when working temperature rises, in this section, two kinds of MR fluids with a mass fraction of 30 % and 50 % are prepared and placed in a vacuum drying oven respectively, and then, adjusts the temperature from 20°C to 220°C to observe the thermal expansion.

For the convenience of comparison, the same volume of silicone oil is also taken into the drying oven, and the thermal expansion rates of three types of liquid are obtained, as shown in Fig. 3.

It shows that the thermal expansion rate of MR fluids increases approximately linearly with temperature, which is consistent with the thermal expansion coefficient law of material. The thermal expansion rate of the 30 wt% MR fluid is 6 % and 18 % respectively as the temperature is 120°C and 220°C. Actually, in the real working process, the temperature of the MR fluid exceeds 120°C easily which will cause the overpressure phenomenon. Therefore, it is necessary to design thermal expansion compensation device.

It can also be found that the particles mass fraction has weak influence on thermal expansion rate, and the thermal expansion rate of 50 wt% MR fluid is slightly lower than that of 30 wt%. The reason is that the main component of MR fluid is silicone oil, and the volume of which is similar between the two types of MR fluids. Furthermore, the expansion rate of silicon oil is slightly higher than that of MR fluid, which indicates that the thermal expansion of the MR fluid is mainly caused by silicone oil.

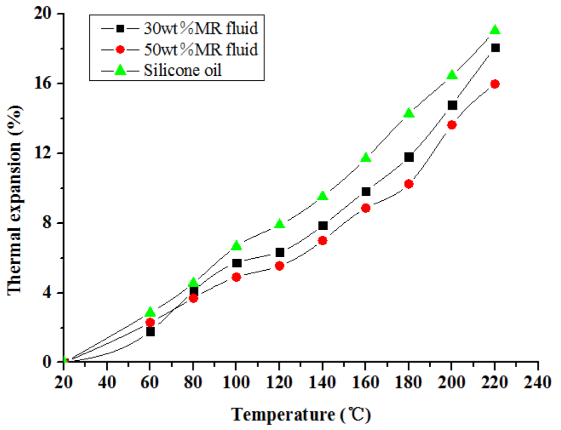


Fig. 3. (Color online) Thermal expansion characteristic of MR fluids.

3.2. Temperature vs. pressure effect of MR fluid

MR fluid has higher thermal expansion coefficient, in this section, the relationship between temperature and pressure will be determined by experiment, as shown in Fig. 4.

It can be seen that the workspace pressure enhances rapidly with the increase of temperature. The mechanism can be explained by the state equation of ideal gas: $PV=NRT$, where P is pressure, V is volume, N is amount of substance, T is absolute temperature, R is constant, and there is a linear relationship between pressure and temperature. When the temperature rises from 32°C to 63°C, the working space pressure reaches 13 kPa and the pressure increment is 10.6 kPa, which easily exceeds working pressure range of the rotary seal and causes the leakage of MR fluid. In addition, it can also be seen from the torque curve that, due to temperature and leakage effects, the transmission torque of MR fluid decreases with the increase of temperature..

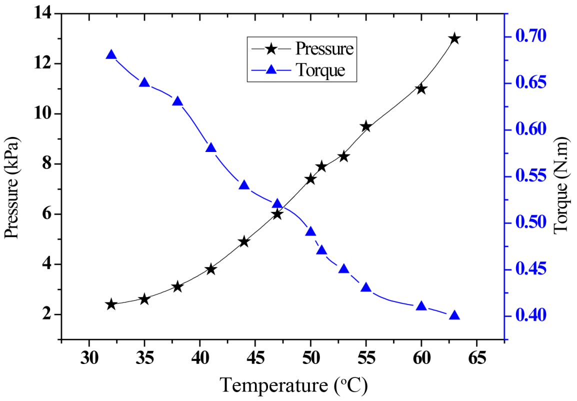


Fig. 4. (Color online) Temperature and pressure effect of MR fluids.

3.3. Thermal volatilization characteristic of MR fluid

There is no thermal volatilization for the particles, and the content of additives is very small. Therefore, the thermal volatilization of MR fluid is caused mainly by the carrier liquid. Four types of MR fluids with same volume are placed in the measuring cylinder, and the viscosity of the base carrier fluid is 100cSt, 350cSt, 500cSt and 1000cSt respectively. The test temperature is kept at

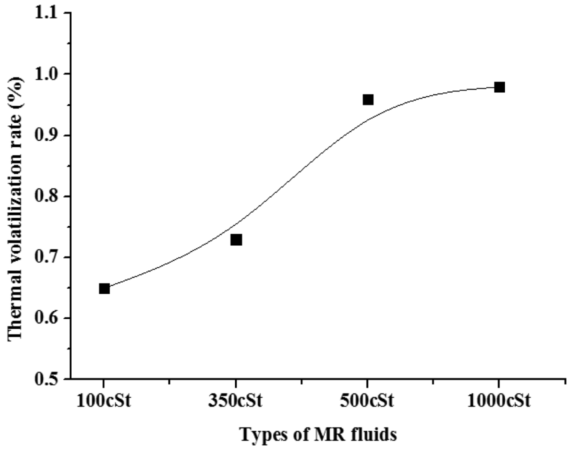


Fig. 5. (Color online) Thermal volatilization characteristics of MR fluids.

200°C, and the volumes of MR fluids are recorded after 8 hours. The volatilization rates of MR fluids are obtained, as shown in Fig. 5.

It can be seen from Fig. 5 that the thermal volatilization rate of each MR fluid is relatively small, below 1 % at 200°C for 8 hours. Therefore, it is not necessary to consider the loss of heat volatilization in MR fluid transmission. In addition, the volatilization rates of different carrier fluids are different, and the higher the viscosity is, the stronger the volatilization is.

3.4. Viscosity vs. temperature effect of MR Fluid

Two types of MR fluids with silicone oil based (350cSt) and mineral oil based (50cSt) are prepared respectively, and the viscosities at different temperatures are tested as shown in Fig.6, where the temperature range is 20°C-240°C.

As can be seen from Fig. 6, the apparent viscosity of MR fluid gradually decreases with the increase of temperature. It changes more sharply in the initial temperature stage, but slowly at high temperature. Furthermore, the viscosity reduction rate of silicone oil based MR fluid is 78 %, which is lower than that of mineral oil, and has better viscosity temperature characteristics at the temperature range of 20°C-240°C.

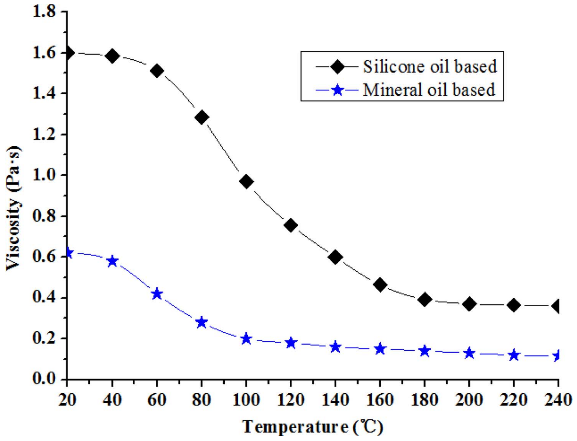


Fig. 6. (Color online) Viscosity vs. temperature effect of MR fluids.

In order to clearly reveal the influence of temperature on viscous torque, according to the reference 16, the relative relationship between viscous torque T_η and magnetic torque T_H can be obtained by:

$$\lambda = \frac{T_\eta}{T_H} = \frac{3\eta\Delta\omega(R_2^4 - R_1^4)}{4h\tau_0(H)(R_2^3 - R_1^3)}$$

Where, λ is the ratio of viscous torque and magnetic torque, R_1, R_2 is the inner and outer radius of disk, h is the distance between two disks, $\Delta\omega$ is the difference of rotation speed between two disks, $\tau_0(H)$ is the yield stress due to applied magnetic field H.

In this prototype, the inside radius of disk is 0mm, the outer radius of disk is 0.055 mm, the working gap of MR fluid is 2 mm, and the apparent viscosity is 1.6 Pa.s as the temperature is 20°C, the maximum yield stress of the MR fluids due to applied magnetic field is 50 kPa, when the difference of rotation speed is 500 r/min, the viscous torque is only 3.45 % of the magnetic torque, which means that the variation of viscous torque due to temperature has little effect on the overall maximum torque. However, when the magnetic torque is small, the influence of temperature on viscosity torque can not be ignored.

3.5. Influence of temperature on the magnetic properties

Magnetic properties of carbonyl iron particles are measured by vibrating sample magnetometer (VSM). To

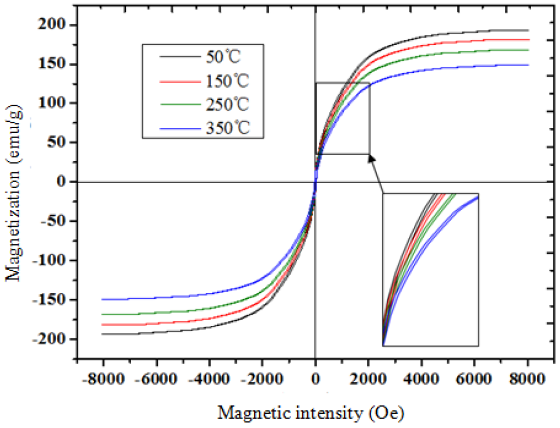


Fig. 7. (Color online) Magnetic properties of MR fluids and particles.

obtain the magnetization characteristics of particles at different temperatures, the test temperature is adjusted to 50°C, 150°C, 250°C and 350°C respectively, and the result is shown in Fig. 7.

It can be seen from Fig. 7 that the magnetization of the carbonyl iron powder decreases with the increase of temperature. Comparing with 50°C, the saturation magnetization decreases by 6.2 %, 13 % and 23 % respectively at 150°C, 250°C and 350°C, indicating that the carbonyl iron powder has good thermal magnetization stability within 150°C, when the temperature exceeds 250°C, the saturation magnetization decreases rapidly.

3.6. Influence of temperature on the stability of torque transmission

(1) Experiment on temperature distribution

The right magnetic yoke of MR transmission device is removed to observe the surface temperature distribution of disk, and the serve motor speed is adjusted to 1000 r/min, the current of the excitation coil is 0.4 A. The infrared thermal imager is used to observe the distribution of the temperature field of the disk during the working process, as shown in Fig. 8.

It can be seen that the highest temperature is distributed around the disc, which indicates that the area outside the disc is more serious. Furthermore, according to the temperature distribution at different time, it can also be found that the temperature increases with time gradually, but due to the small thickness of the disk, the temperature spreads slowly to the radial direction. Therefore, in the design of MR fluid transmission device, the problem of heat dissipation in the outer diameter area should be mainly solved.

(2) Influence of temperature on torque transmission stability

To improve the temperature rise, the motor speed is adjusted to 3000 r/min, and the transmittable torque of MR fluid under exciting current of 0.4 A and 0 A is measured respectively, as shown in Fig. 9.

From Fig. 9, it can be seen that the transmission torque of MR fluid decreases approximately linearly with the increase of temperature. When the exciting coil current is

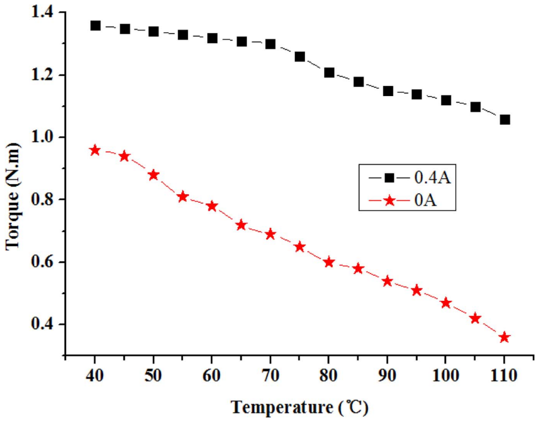
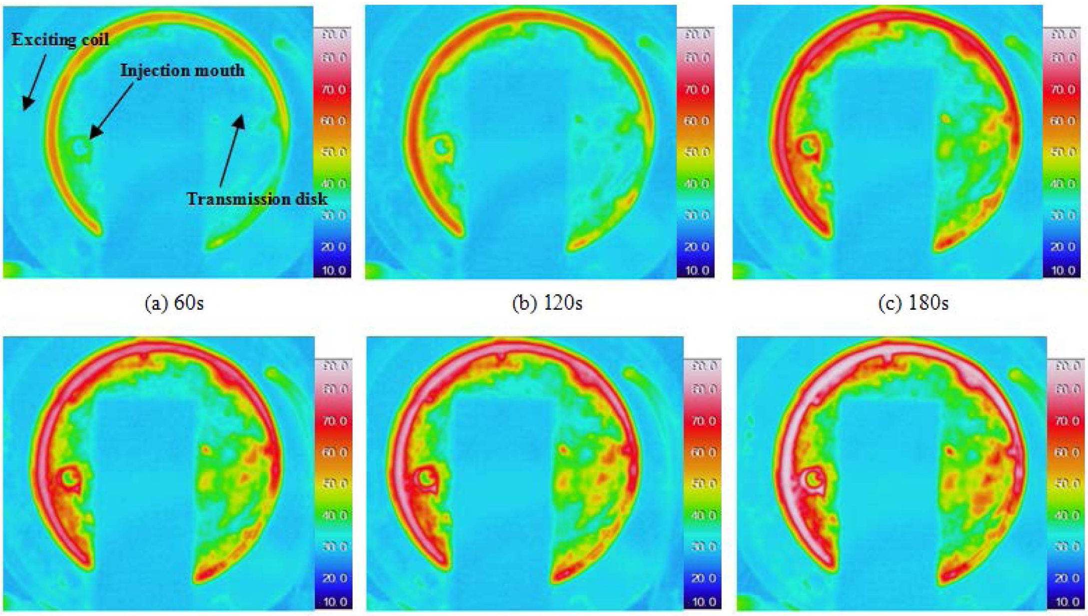


Fig. 9. (Color online) Influence of temperature on torque transmission stability of MR fluid.



(a) 60s (b) 120s (c) 180s

(d) 240s (e) 300s (f) 360s

Fig. 8. (Color online) Surface temperature distribution of disk.

0 A, the transmittable torque reduces by 60 % in the range of 40°C-110°C. While the exciting coil current is 0.4 A, the transmittable torque only reduces by 20 % due to the magnetic torque. According to the test results of section 3.5, at the range of 50°C-150°C, the magnetic torque reduction due to magnetization variation of carbonyl iron particles is only 6.2 %, while the total transmission torque variation of MR fluid is related with the proportion between viscous torque and magnetic torque. In this experiment, the torque variation at the time of 0.4 A is still higher because of the relatively low magnetic torque. If the MR fluid reaches the maximum transmission torque, the temperature induced torque fluctuation is only slightly higher than 6.2 %.

(3) Influence of temperature and rotation speed on torque transmission stability

Most of MR fluid transmission devices operate under variable rotation speeds. According to Newton's law of friction, the transmittable torque enhances with the increase of rotation speed, while decreases with the increasing temperature as shown in Fig. 9, Therefore, it is necessary to analyze the transmittable torque variation under different temperatures and rotation speeds simultaneously, and obtain the main factor that affecting the torque fluctuation, the result is shown in Fig. 10. Among them, the exciting coil current is 0.8 A, the rotation speed is 0 r/min, 600 r/min, 1200 r/min, 1800 r/min, 2400 r/min and 3000 r/min respectively, and the corresponding temperature is 30°C, 32°C, 45°C, 70°C, 90°C and 120°C respectively.

As can be seen from Fig. 10, when the prototype runs, temperature of MR fluids increases slowly at low rotation speed, while enhances rapidly at high rotation speed. Due to the combined effect of temperature effect and rotation speed, the transmittable torque appears fluctuation. Within the range of 30°C-45°C and 0-1000 r/min, the transmission torque of MR fluid enhances with increasing rotation speed, which means that torque reduction due to temperature is less than the torque increase due to rotation speed, and the rotation speed is the main influence factor on the torque fluctuation. While the temperature is higher than 45°C, the temperature effect enhances, causing the reduction of transmittable torque of the MR fluid, even if the rotation speed reaches 1800 r/min (70°C), 2400 r/min (91°C) or 3000 r/min (120°C). Commonly, the working rotation speed of MR fluid transmission device is less than 1800 r/min and the working temperature is higher than 45°C. Therefore, compared with the rotational speed, temperature is the main factor affecting the torque fluctuation of MR fluid.

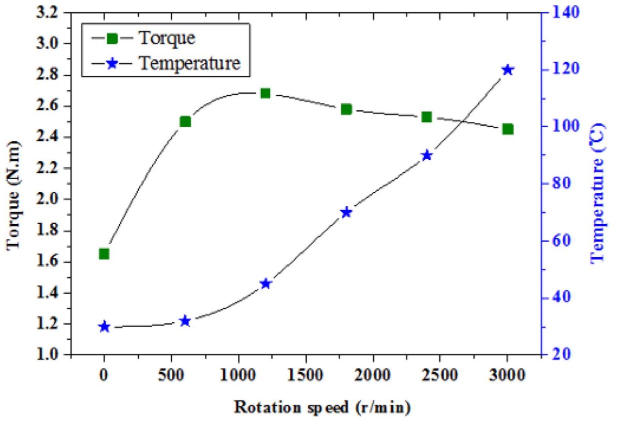


Fig. 10. (Color online) Influence of temperature-rotation speed on torque transmission stability of MR fluid.

4. Conclusions

The influence mechanism of temperature on torque transmission of MR fluid is described, and the thermal expansion, temperature pressure effect, heat volatilization, viscosity temperature characteristic, magnetic temperature characteristic and other related temperature characteristics are experimented and analyzed systematically. The results indicate that the thermal expansion rate is very high, and the 30 wt% MR fluid is 6 % and 18 % respectively at 120°C and 220°C. The working space pressure due to thermal expansion is 13 kPa when the temperature rises from 32°C to 63°C, which easily exceeds working pressure range of the rotary seal and causes the leakage of MR fluid. The thermal volatilization rate is lower than 1 % at 200°C for 8 hours. The viscosity of the silicone oil based MR fluid decreases by 78 % when the temperature increases from 20°C to 240°C, and the saturation magnetization decreased by 6.2 %, 13 % and 23 % respectively at 150°C, 250°C and 350°C. Furthermore, the temperature field distribution experiment shows that the highest temperature region is at the outer diameter of the disk and expands slowly along the radial direction. In general, temperature is the main factor affecting the torque fluctuation of MR fluid.

Acknowledgment

The support of the Fundamental Research Funds for the Central Universities (2017QNA14) and the Priority Academic Program Development of Jiangsu Higher Education Institutions in carrying out this research is gratefully acknowledged.

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