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Research Article

Analysis of Influence of Temperature on Magnetorheological Fluid and Transmission Performance

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Magnetorheological (MR) fluid shows different performances under different temperature, which causes so many problems like the reduction of rheological properties of MR fluid under a high temperature condition, the uncontrollability of shear stress, and even failure of transmission; on that basis, the influence of temperature on the performance of MR fluid and the cause of the rise in temperature of MR transmission device are analyzed in this paper; the shearing transmission performance of the MR transmission device under the effect of an external magnetic field and the influence of temperature on the shearing stress and transmission performance are analyzed. The study results indicate that temperature highly influences the viscosity of MR fluid, and the viscosity influences the shear stress of the MR fluid. The viscosity of MR fluid gradually declines when temperature rises from 100°C. Once the temperature exceeds 100°C, the viscosity would increase and the temperature stability would decline. Temperature obviously influences the characteristics of MR transmission, and particularly, highly influences the characteristics of MR transmission once being higher than 100°C. The chaining of the material in the magnetic field is influenced, which causes the reduction of the rheological properties, the uncontrollability of the shear stress, and even the failure of transmission.

1. Introduction

MR fluid is suspension fluid, which is prepared by small magnetic particles (microlevel) dispersing in insulated carrier fluid, and shows specific noncolloid nature MR characteristic as the external magnetic field varies. MR fluid is the material related to the external magnetic field and shows the nature of common fluid in the absence of magnetic field. Once there is an external magnetic field, the rheological properties would vary along with the external magnetic field; namely, the yield stress increases linearly along with the external magnetic field, and the variation is characterized in that the speed is fast, the variation process is reversible, and the variable range is wide. With such unique mechanical properties, the MR fluid can be widely used. However, the mechanical properties of MR fluid are directly related to temperature, which means that MR fluid shows different performances under different temperature. The viscosity of base fluid of MR fluid is sensitive to the variation of temperature, and the variation of temperature would cause the variation of the viscosity; the variation of the viscosity may cause the variation of the shear stress, and, as a result, the performances of MR device vary. Additives are also sensitive to temperature, some are decomposed at about 100°C, and some even cause irreversible changes of MR fluid after cycling under high or low temperature, which influences the chaining of the material in the magnetic field, resulting in the reduction of the rheological properties and the uncontrollability of the variation of the shear stress.

Based on the mechanical characteristics of MR fluid, there are many studies on performance [1, 2] and applications such as brake [3] and damper [4] during recent years, but relatively few studies were performed for the influence of temperature on the performance of MR fluid and transmission performance. Li and Du performed study on the influence condition of temperature for the viscosity and the shear stress with experiment [5]. Nagaya et al. and Erol et al. carried out study on the temperature characteristics and temperature distribution condition of the MR transmission device [6, 7]. The material performance of MR fluid is highly influenced by the temperature and also limits the application in phase type engineering. Therefore, the analysis of the temperature distribution condition of MR fluid and the variation of the material performance under different service states is of a great significance.

2. Analysis of Viscosity-Temperature Characteristics of MR Fluid

Temperature highly influences the viscosity of MR fluid, and the viscosity influences the shear stress, and, as a result, the transmission performance of MR fluid is influenced. Therefore, the viscosity-temperature characteristics of MR fluid must be carried to obtain the influence rules of temperature on the viscosity of MR fluid.

The zero-field viscosity of the typical MR fluid under room temperature is less than 1.5 Pa·s; the zero-field viscosity, the shear stress, and the volume fraction are proportional; the shear stress under 0.5 T magnetic flux density is higher than 60 kPa. The influence of the temperature on MR fluid is mainly expressed in form of the viscosity; namely, the viscosity of carrier liquid is sensitive to the variation of temperature and declines as the temperature rises, which meets the viscosity variation rule of most of the fluid, and the viscosity of carrier liquid also brings large influence on the performance of MR fluid. Additives are also sensitive to temperature, some would be decomposed at about 100°C, and some are even thickened when in use after cycling under high or low temperature, which influences the chaining of the material in the applied magnetic field, resulting in the reduction of the shear stress and the sudden variation and uncontrollability of the variation of the shear stress of MR transmission device. The Curie temperature of the ferromagnetic suspended phase particles is always up to 770°C, and the temperature of obvious oxidization is also higher than 300°C, so that the influence from the service temperature of MR fluid can be ignored. The surface treating agent may improve the properties of solid phase and liquid phase interfaces, improve the rheological properties, and be relatively stable under temperature variation [8]. Therefore, the influence of temperature on the performance of MR fluid is expressed through the influences on the carrier fluid and additive.

According to the molecules, liquid is composed of a large number of random-motion molecules, and its viscidity performance is closely related to the molecule state. The viscosity of liquid is the comprehensive manifestation of intermolecular attraction and momentum transfer; the intermolecular attraction will sharply decline as the space between molecules rises, and the molecular momentum depends on the velocity of movement. There is small space between liquid molecules, and the average velocity of random motion is low, so intermolecular force mainly determines the viscidity performance. Once temperature rises, the average velocity of MR fluid molecular motion rises, and the space between molecules also rises. Therefore, the viscosity of liquid decreases as temperature rises. The temperature-based variety rule of the viscosity of MR fluid and the temperature-based variation level (viscosity index) of the viscosity is the important index of the temperature characteristic of MR fluid [9].

It is very important to understand the relation between viscosity of MR fluid and temperature during analyzing the influence of temperature on MR fluid. International and domestic academics have made a large number of studies on the viscosity and temperature characteristics of synthetic oil. Reynolds, Andrade-Erying, Slotte, Vogel, and Walther-ASTM et al. put forward some formulas for expressing the relation between viscosity and temperature; some formulas were on the basis of the analysis of the liquid flowing model and some were on the basis of the collation of experience data. Therefore, all formulas have some advantages and limitations on application. Under normal temperature (0~100∘C), suspension liquid flows in form of particles with directional alignment by shearing manner along a certain angle, and such flowing does not produce any mutual interference. According to the nature and working characteristics of carrier liquid, this study adopted the relation formula put forward by Reynolds for showing the relation between viscosity of MR fluid and temperature,

$$\eta(T) = be^{-aT}, \tag{1}$$

wherein a and b are constant, T is temperature in degrees Klvin, and $\eta(T)$ represents viscosity.

The viscosity index (VI) represents the temperature-based variation level of viscosity of various kinds of oil. If the viscosity index is large, the influence of temperature on viscosity of liquid is small, so it is clear that the viscosity is not sensitive to temperature. VI of most of industrial oil ranges from 0 to 100, but it must always be beyond 100 in case of applying to synthetic oil and multilevel oil. The carrier liquid of MR fluid is characterized in that polymer is added to the base oil and its viscosity rises, but the viscosity and temperature characteristics vary gently just like those of the base oil, so that the viscosity index obviously rises.

According to the variation relation formula of temperature and viscosity under normal temperature and the analysis of influence of temperature on components of MR fluid, in light of the existing relevant studies [5, 9, 10], and on the basis of $b = 143$ and $a = 0.0143$, the temperature-based variation curve of the viscosity of MR fluid within the temperature range of −40~140°C is obtained, and the theoretical value and experimental value of viscosity versus temperature are shown in Figure 1. Figure 1 shows that temperature highly influences the viscosity of the carrier fluid of MR fluid. If the temperature is −40~0°C, the viscosity is highly influenced by the temperature. If the temperature is 0~100°C, the viscosity is relatively stable and would slightly decline as temperature rises. If the temperature is higher than 100°C, the viscosity would gradually increase. The analysis result indicates that the carrier fluid of MR fluid is solidified and settled under −40~0°C, and as a result, large viscosity appears. The viscosity gradually declines as the temperature rises from 0 to 100°C; it is because of the fact that the thermal motion of molecule of carrier fluid is aggravated when temperature rises that

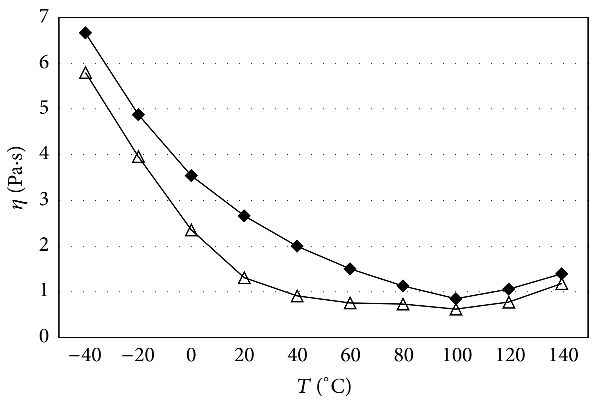

Figure 1: The curve of viscosity of MR fluid versus temperature.

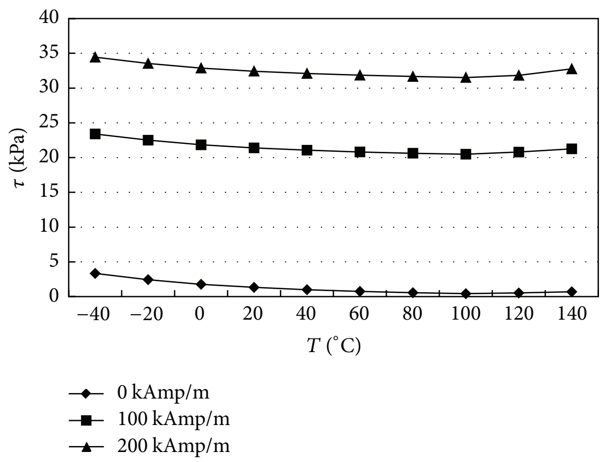

Figure 2: The curve of the shear stress versus temperature.

both attraction and internal friction decline; on that basis, the shear stress produced by shear deformation correspondingly decreases, and as a result, the viscosity declines. In addition, this phenomenon is reversible under such temperature range. Once the temperature is higher than 100°C, the carrier fluid would be volatilized and the additives would be decomposed, which make the viscosity gradually increase. If the temperature is higher than 100°C, some additives may cause irreversible thickening of MR fluid after cycling under high and low temperature, which influences the chaining of the material in the applied magnetic field, resulting in the reduction of the shear stress and uncontrollability of the variation of the shear stress, the reduction of the transmission stability, and even the failure of transmission.

3. Influence of Temperature on Rheological Property of MR Fluid

The MR characteristics of MR fluid are highly influenced by the viscosity, and the viscosity is sensitive to temperature, so that the influence of temperature on the viscosity of MR fluid and the shear stress can be taken into major account in the study on the influence of temperature on MR fluid. If there is really a big influence of temperature on the viscosity and shear stress, the study on the influence rule of temperature on the viscosity and shear stress and the study on the corresponding compensation measures must be carried out; otherwise, the practical application of MR fluid would be seriously restricted.

MR fluid exhibits Newtonian fluid-like behavior in absence of the external magnetic field, and the constitutive equation is that

$$\tau = \eta(T)\,\dot{\gamma}. \quad (2)$$

The rheological performance [10] of MR fluid under shearing flowing model in presence of the external magnetic field can be described through Herschel-Bulkey model,

$$\begin{aligned} &\tau = \tau(H) + \eta(T)\,\dot{\gamma}^n, \quad \tau \geq \tau(H), \\ &\dot{\gamma} = 0, \quad \tau < \tau_y(H), \end{aligned} \quad (3)$$

wherein $\tau(H)$ represents the dynamic yield stress of MR fluid, which varies along with the strength of the external magnetic field, $\eta(T)$ represents the viscosity of MR fluid, which varies along with the temperature T, $\dot{\gamma}$ represents the shear strain rate of MR fluid, and n is constant.

In general, the yield stress of MR fluid increases as the magnetic field strength rises before reaching magnetic saturation, and the yield stress is the function $\tau(H) = C \cdot 271700\phi^{1.5239} \cdot \tanh(0.00633H)$ of the magnetic field strength [11], wherein $\tau(H)$ represents the yield stress, ϕ represents the volume percentage of the magnetic particles, H represents the magnetic field strength, and C represents the constant related to the carrier fluid of MR fluid. According to the temperature-based variation relation of viscosity of MR fluid and the constitutive equations of MR fluid and on the basis of shear strain rate of $\dot{\gamma} = 1000\,\text{s}^{-1}$ and $n = 0.93$, the influence of temperature on shear stress can be calculated. If the flux magnetic field strength is 0 kAmp/m, 100 kAmp/m, and 200 kAmp/m, the temperature-based variation of the shear stress is calculated within −40~140°C (calculated based on the temperature of −40°C, −20°C, 0°C, 20°C, 40°C, 60°C, 80°C, 100°C, 120°C, and 140°C), and the curve of the shear stress versus temperature is as shown in Figure 2.

Figure 2 shows that the shear stress under the absence of magnetic field is relatively smaller than the shear stress under the external magnetic field and is only about 1/10 of the shear stress in presence of magnetic field. The shear stress gradually increases as the current rises; namely, the magnetic field strength rises. The shear stress gradually decreases as the temperature rises. However, the shear stress gradually increases as the temperature increases from 100°C, but the variation is gradually irregular; it is to be studied. The shear stress of MR fluid varies a lot along with the temperature

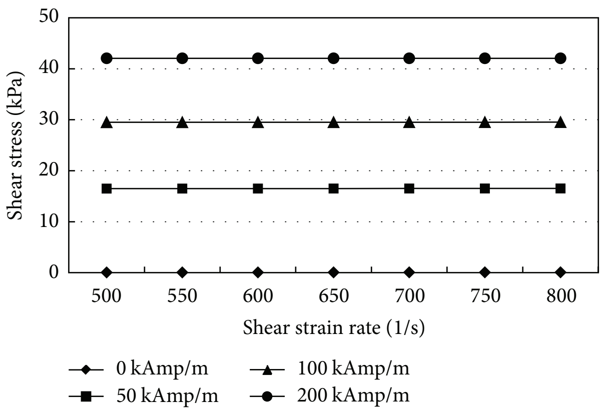

Figure 3: The curve of shear stress versus shear strain rate.

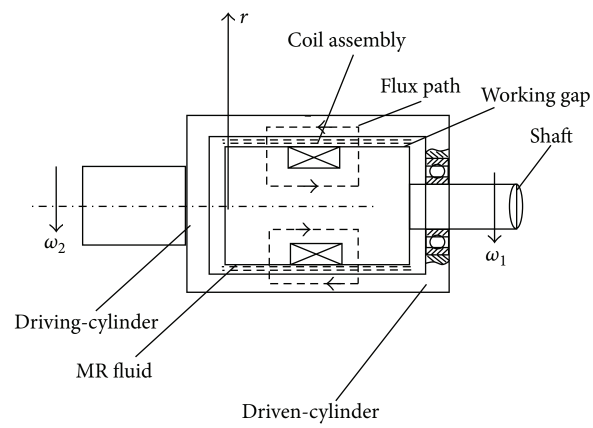

Figure 4: Shear transmission principle of MR fluid between two cylinders.

under the absence of magnetic field (the variation trend is mainly determined by the carrier fluid); the shear stress lowers down to be about 1/10 of the original to the maximum. The shear stress decreases along with the relative variation of the temperature in presence of the external magnetic field, and the shear stress only lowers down to be about 1/7 to the maximum.

When the zero-field viscosity of MR fluid is 0.86 Pa·s, the strength of the external magnetic field is 0 kAmp/m, 50 kAmp/m, 100 kAmp/m, and 200 kAmp/m, and the shear strain rate is 500 (1/s)~800 (1/s), and the curve of the shear stress versus shear strain rate may be calculated, as shown in Figure 3. According to Figure 3, we can know that the shear stress increases slowly with the increase of shear strain rate; but the shear stress obviously increases with the increase of strength of external magnetic field, and it keeps steady as the increase of shear strain rate. The shear stress in the absence of magnetic field is very small compared with that when there is applied magnetic field, and the rheological properties of MR fluid are subject to Bingham model.

The result shows that the shear stress of MR fluid gradually increases as the current rises; namely, the magnetic field strength increases under the same temperature condition. The shear stress gradually declines as the temperature rises within −40~100°C under the same magnetic field strength. The shear stress slightly increases as the temperature rises beyond 100°C and is gradually uncontrolled.

4. The Influence of Temperature on Transmission Performance of MR Fluid

4.1. Shear Transmission Principle of MR Fluid between Two Cylinders. MR transmission device is widely applied to various control systems. Such transmission devices using MR fluid as the working medium have the advantages of being simple in structure, low in energy consumption, fast to respond, and easy to control. The transmission devices are of multiple structural forms, including shear mode, pressure flow mode, extruding mode, or the combination of all based on the working mode. The cylinder type MR transmission runs under the shear mode. Just like the power transmission characteristics of the common transmission devices, the transmission ratio of the driving shaft to the driven shaft is realized by controlling the shear stress of MR fluid, and the shear stress of MR fluid is controlled through the current of the electrified coil. The electrified coil produces the magnetic field between the inner cylinder and outer cylinder of the cylinder, and MR fluid between the inner cylinder and the outer cylinder is magnetized. MR fluid shows high shear yield stress under the applied magnetic field, and the shear yield stress is power exponential to the external magnetic field, and the torque of the driving shaft and the driven shaft of MR transmission device is transmitted through the shear stress of MR fluid [12–14]. The shear transmission principle of MR fluid between the two cylinders is as shown in Figure 4.

Some of the mechanical property and electric energy are converted into heat during operating MR transmission device, which inevitably causes the temperature variation. The heat source of MR transmission device is mainly produced by the rise of temperature of MR fluid under the effect of high shear stress, the heat produced by the electric power loss of the magnet exciting coil, the frictional heating of bearing and rotating sealing ring, high temperature service environment of MR device, and so forth. All the factors above may cause irreversible variation of the zero-field viscosity of MR fluid. In general, the bearing and rotating sealing ring produce little heat which can be ignored. The metal coil for producing magnetic field always produces large heat under electrifying condition (the electromagnetic coil always works at about 75°C). MR device always services in an environment with high temperature (e.g., the upper limit of the working temperature of the transmission device running close to the autoengine is always higher than 100°C; the Jetta of FAW-Volkswagen is 115°C, and FUKANG car is 118°C), and as a result, the influence of the environmental temperature on the performances of MR fluid and device cannot be ignored. In case of partial yield of MR fluid, there is a difference between the rotating speeds of the driving-cylinder and the driven-cylinder of MR transmission device; sliding difference also appears among MR fluids, and thus magnetic particles at each level produce frictional heat to cause the rise in temperature

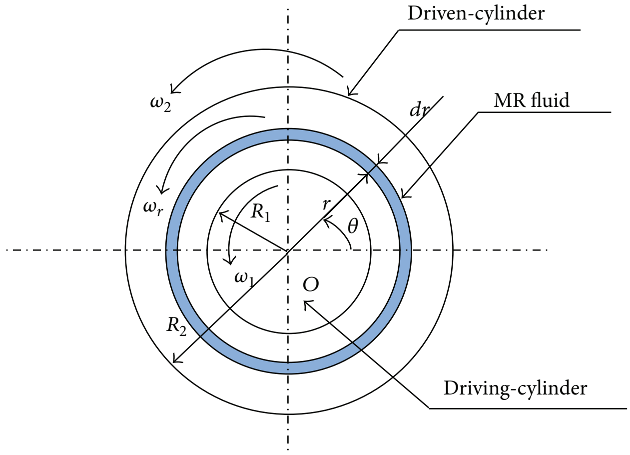

Figure 5: Shear transmission model of cylinder type MR fluid.

of MR fluid, which also seriously influences the transmission performance [15, 16]. MR fluid in the transmission device shows serious heating under sliding difference conditions [6, 7]; the frictional heating of particle layers can reach about 260°C within a short time once the sliding power reaches 10 kW.

4.2. Analysis on Transmission Performance of MR Fluid. MR transmission between two coaxial cylinders is of the shear transmission mode as shown in Figure 5. The transmission device is of axial symmetry mode. It is assumed in calculation that MR fluid is continuous and uniform medium and meets the mass conservation principle; namely, MR fluid is constant-flowing incompressible viscous non-Newtonian fluid; the density does not vary along with the time and place; MR fluid does not flow in axial and radial directions and only shows tangential velocity.

The sector infinitesimal face shear transmission model [11, 17] of MR fluid under cylindrical coordinate was established based on the assumption above, and the following can be obtained according to Newton's second law:

$$2\tau_{r\theta} + \frac{\partial \sigma_{\theta\theta}}{\partial \theta} + \frac{\partial \tau_{r\theta}}{\partial r} r = \rho r \frac{d\omega}{dt}, \quad (4)$$

wherein $\sigma_{\theta\theta}$ represents positive tangential stress, $\tau_{r\theta}$ represents tangential stress, ρ represents density of MR fluid, and ω represents tangential speed.

MR fluid model is of axial symmetry, $\sigma_{\theta\theta}$ is only the function of radius r, $\partial\sigma_{\theta\theta}/\partial\theta = 0$. $\tau_{r\theta}$ only represents the function of radius, the flow speed does no variation tangentially, and formula (4) can be shown as

$$2\tau_{r\theta} + \frac{d\tau_{r\theta}}{dr} r = 0. \quad (5)$$

According to the working state of the transmission device, the solid state and liquid state, rather than the coexistence state of solid and liquid, of MR fluid, are taken into account. MR fluid is in form of Newton liquid and completely in yield state in absence of the external magnetic field. According to formula (5),

$$\tau_{r\theta} = \frac{c}{r^2}. \quad (6)$$

According to $\dot{\gamma} = dv_\theta/dr$, $v_\theta = \omega(r)\cdot r$, and $\tau = \eta(T)\dot{\gamma}$,

$$r\frac{d\omega}{dr} + \omega = \frac{c}{\eta(T)}\frac{1}{r^2}, \quad (7)$$

wherein $\eta(T)$ represents the viscosity of MR fluid in absence of the external magnetic field and $\dot{\gamma}$ represents the shear strain rate.

The boundary conditions shown as $r = R_1$, $v_\theta = \omega_1 R_1$, $r = R_2$, and $v_\theta = \omega_2 R_2$ are substituted to obtain

$$c = \frac{[\eta(T)(\omega_1 R_1 - \omega_2 R_2)] R_1 R_2}{R_2 - R_1}. \quad (8)$$

MR fluid is in solid state in presence of external magnetic field, the transmission shaft does not relatively rotate, and the torque is transmitted between the driving shaft and the driven shaft without any loss,

$$\omega = \omega_1 = \omega_2. \quad (9)$$

The transmission torque of MR fluid is

$$M = \int_{R_1}^{R_2} dM = 2\pi l \int_{R_1}^{R_2} \tau_{r\theta} r^2 dr, \quad (10)$$

wherein R_1, R_2 represent the radius of the inner cylinder and outer cylinder of the transmission device and l represents the axial length of the transmission device.

4.3. Experimental Research on Force Transfer Performance

4.3.1. The Test of MR Transmission Performance. To measure the impact of temperature on force transfer performance of MR transmission device, the experiment table for MR transmission is built (as shown in Figure 6). The experimental table mainly comprises AC electromagnetic variable-speed motor, worm reducer, torque sensor, DC power supply, digital thermometer, coupling, transmission gear, heating ring, and temperature sensor. MR fluid used during the test is self-prepared MR fluid sample; the magnetic particle is carbonyl iron powder (volume fraction: 25%); the carrier fluid is shock absorber oil; the additives include thixotropic agent, surface active agent, and solid lubricant (additive content: 1.4%); the viscosity in absence of the magnetic field is 0.86 Pa·s; the used temperature range is −20°C~100°C; and the performance will reduce if the temperature exceeds 100°C. The inside and outside diameters of the transmission gear are, respectively, $R_1 = 50$ mm, $R_2 = 52$ mm; the working clearance length is 120 mm; and the maximum input angular velocity is $\omega_{1\,\max} = 100$ rad/s. During the experiment, MR fluid was injected into the MR transmission device; current is provided via excitation coil; torque sensor was used to measure the torque; temperature produced by heating ring was measured by temperature sensor. The temperature sensor was installed at the 50 mm radius position at the two ends of the transmission gear.

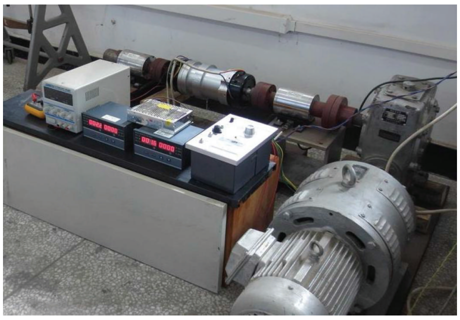

Figure 6: Test system of MR transmission performance.

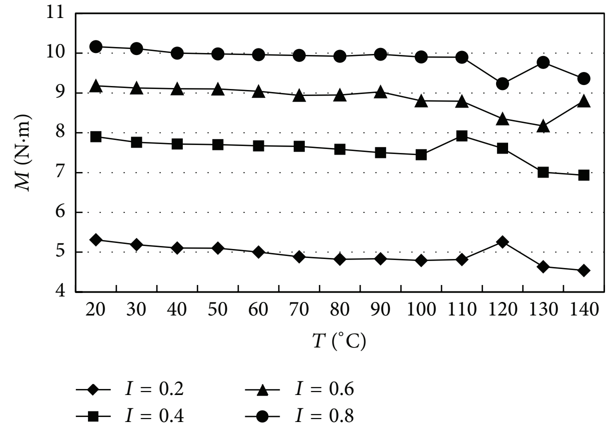

Figure 7: The curve of torque versus temperature.

4.3.2. Experimental Result Analysis. When the input revolution of the transmission gear is 60 r/min and the exciting current is 0.2 A, 0.4 A, 0.6 A, 0.8 A, make the temperature increase gradually from room temperature. As shown in Figure 7 for the change relationship between experimental value of transmission torque of transmission gear and temperature, when the temperature rises to 100°C from room temperature, the torque transferred by MR fluid slightly reduces with the increase of temperature. The main reason is that, during this temperature range, the impact of temperature on MR fluid is mainly characterized by viscosity, and the change of viscosity has very small impact on torque. However, after the temperature exceeds 100°C, the torque transferred by MR fluid is discontinuous as temperature change; it is wavy and has irregular change, causing unstable transmission performance. The main reason is that the "use of multiviscosity" of MR fluid and the discontinuous and uncontrollable yield stress of MR fluid under high temperature condition cause the irregular and unstable torque to be transferred.

Figure 7 shows that the torque transferred by MR fluid gradually declines as temperature rises under the same magnetic field strength and rotating speed, but the variation is continuous and uniform. Once the temperature is higher than 100°C, the torque transferred by MR fluid gradually increases and varies irregularly, which cause instability of the transmission performance. It is mainly caused by the fact that MR fluid is thickened when in use after the temperature is higher than 100°C, and the temperature-based variation of the shear stress is uncontrollable, and as a result, the transmission stability and efficiency are low. The specific influence rules need further study.

5. Conclusions

(1) The influence of temperature on MR fluid is mainly shown as the influence on the viscosity, and the viscosity influences the shear stress. The temperature nearly does not influence the viscosity and shear stress of MR fluid under normal temperature (0~100°C) but influences the viscosity a lot under low temperature and high temperature because of carrier fluid and additive, and as a result, the mechanical property of MR fluid is influenced.

(2) Because of the obviously raised temperature of MR device under the effect of high shear stress, lots of heat produced by the electric power loss of the magnet exciting coil, and the influence of the environmental temperature, MR fluid always services in high temperature environment, so that the temperature effect of high temperature on transmission device cannot be ignored.

(3) Temperature obviously influences MR transmission device and, particularly, highly influences MR transmission device once being higher than 100°C. The mechanical property of MR fluid is highly influenced; the chaining of the material in the magnetic field is influenced, which causes the reduction of rheological properties, the uncontrollability of the shear stress, and even the failure of transmission. Once the influence rules of temperature on the transmission device under high temperature environment are mastered, the resulting unstable transmission can be compensated by other ways in the practical application, so as to improve the transmission performance.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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