

Research Article

# Thermal Thinning of Magnetorheological Fluid and its effect on MR brake performance

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## Abstract

*The aim of this paper is review the viscosity of magnetorheological (MR) fluid as function of temperature. A rheological model of shear stress dependent on temperature has been established. MR fluid has been characterized at various temperatures for different magnetic fields to observe the thermal thinning of MR fluid. In order to confirm the thermal thinning behavior of MR fluids, experiments have been conducted in MR brake test rig. The results show that with increase in temperature, there is decrease in braking torque.*

**Keywords:** MR fluid, MR brake, Thermal Thinning.

## 1. Introduction

Magnetorheological (MR) suspensions are known for dramatic change in their apparent viscosity. Due to their variable viscosity, MR fluids are used in engineering applications requiring controllable dynamic performance. One such application is magnetorheological brake in which MR fluid is treated as a brake lining material. This material does not wear-away and provides desirable friction resistance by just controlling the magnetic field passing through it. As MR brake involves electromagnetism and magnetisable friction material, this system can be named as electromagnetic brake (Gupta and Hirani, 2011). It is interesting to note that this brake in off state condition can work as bearings (Hirani, 2009, Hirani *et al*, 2000, Hirani *et al*, 1999, Hirani *et al*, 1998, Muzakkir *et al*, 2011, Hirani, 2005, Hirani *et al*, 2001, Muzakkir *et al*, 2013, Hirani 2004, Muzakkir *et al*, 2015, Hirani, Verma, 2009, Hirani, Suh, 2005, Hirani *et al*, 2001, Rao *et al*, 2000, Hirani *et al*, 2000, Hirani *et al*, 2002, Hirani *et al*, 1997, Hirani *et al*, 1999).

A typical MR fluid consists of 20-40 volume percentage of pure-iron (purity > 99%) particles (size: Ø3-10 micrometers), suspended in a carrier liquid such as mineral oil, synthetic oil, water or glycol. A variety of proprietary additives to avoid gravitational settling, to elude wear and to promote particle suspension, are added to MR fluids. To model the behavior of MR fluids, the Bingham plastic model (Ginder and Davis, 1994) is used. MR fluids exhibit maximum yield strengths of 50-100 kPa for applied magnetic fields of 150-250 kA/m. The performance of MR-based devices is relatively

insensitive to temperature over a broad temperature range (Ginder and Davis, 1994).

MR brake has been studied by various researchers (Muzakkir and Hirani, 2015, Muzakkir and Hirani, 2015, Muzakkir and Hirani, 2015, Sarkar and Hirani, 2015), (Sarkar and Hirani, 2013), (Sukhwani, *et al*, 2009), (Sukhwani and Hirani, 2008), (Sukhwani and Hirani, 2008), (Hirani and Manjunatha, 2007), (Sukhwani, *et al*, 2007), (Sukhwani, *et al*, 2006), (Gupta and Hirani, 2011). In their research, thermal thinning behaviours of MR fluid (theoretical model and experimental data) are missing. Therefore in the present study, the thermal thinning behaviour of MR fluid and effect of temperature on the braking torque exercised by MR brake have been presented.

## 2. Viscosity-temperature model of MR fluids

Most liquids show decrease in the value of viscosity with increase in temperature. This can be understood by associating liquid-operating temperature with the average kinetic energy of the molecules. Higher temperature shows higher average kinetic energy of the molecule. The higher average kinetic energy of the molecules overcomes the cohesive forces between the molecules that tend to hold the molecules together. Therefore, thermal thinning effect is observed. There are several viscosity-temperature models available. Some of them are purely empirical whereas others are derived from theoretical models. The most commonly used equations are summarized in Table 1.

The viscosity variation of MR fluids with temperature is not given much emphasis in literature. As temperature is very important aspect and all base oil used in synthesis of MR fluid show thermal thinning

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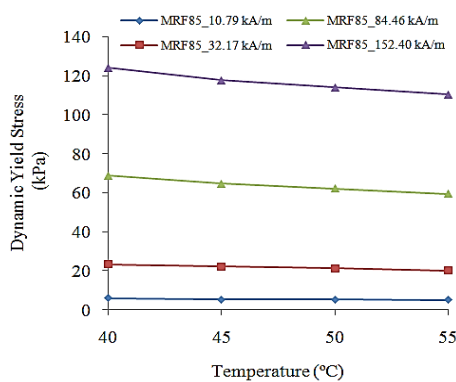
**Table 1.** Various Viscosity Temperature Model

Name	Equation	Comment
Reynolds [Stachowiak and Batchelor, 2001]	$\eta = be^{-aT}$	Early equation; accurate only for limited range of Temperature.
Slotte [Stachowiak and Batchelor, 2001]	$\eta = \frac{a_1}{(b+T)^c}$	Reasonable; useful in numerical analysis
Walther [Stachowiak and Batchelor, 2001]	$\left(\frac{\eta}{\rho} + a_1\right) = bd\left(\frac{1}{T}\right)^c$	Forms the basis of the ASTM viscosity-temperature chart.
Vogel [Stachowiak and Batchelor, 2001]	$\eta = a_1 e^{\frac{b}{T-c}}$	Very useful in engineering calculations
Andrade-Eyring equation [Larson, 1999]	$\eta = a_1 e^{\frac{b}{T}}$	Valid over wide range of temperature. Derived from the hypothesis that small molecules move by jumping into unoccupied sites.

behaviour, it is very important to know the effect of temperature on the viscosity of MR fluid.

The shear stress flow curve of MR fluid (85% by iron particles) have been measured in ANTON PAAR modular compact rheometer MCR-102 at different magnetic fields in controlled shear rate (CSR) mode. The measurement was performed in a parallel plate system with a diameter of 20 mm at a gap of 1 mm for various input currents (0.1 to 4.8 A). The resulting flow responses have been examined as a function of magnetic field strength ranging from 0 to 152.4 kA/m. The magnetic field strength (A/m) has been calculated from the magnetorheological cell 70/1T MRD. Temperature was varied between 30°C to 55°C.

To observe the effect of temperature on shear stress, experiments have been performed and results at various magnetic fields are plotted in Figure 1. There is a common trend of reduction in shear stress of MR fluid with increase in temperature. In other words, the MR fluid undergoes thermal thinning behaviour due to increase in temperature.

**Figure 1** Thermal Thinning of MR fluids

MR fluid exhibits Newtonian fluid-like behavior in absence of the external magnetic field, and the constitutive equation (Chen, *et al*, 2014) is given as

$$\tau = \eta(T)\dot{\gamma} \quad (1)$$

The rheological performance of MR fluid under shearing flowing model in presence of the external

magnetic field can be described through Herschel-Bulkey model

$$\tau = \tau(H) + \eta(T)\dot{\gamma}^n \quad (2)$$

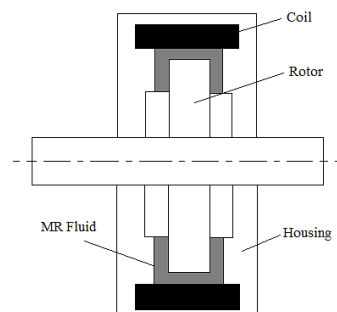
Where,  $\tau(H)$  represents the dynamic yield stress of MR fluid, which varies along with the strength of the external magnetic field,  $\eta(T)$  represents the viscosity of MR fluid as function of the operating temperature  $T$ ,  $\dot{\gamma}$  represents the shear strain rate of MR fluid, and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

Therefore, variation in the apparent viscosity as function of temperature and magnetic field can be modelled as follows:

$$\eta(T, H) = [\tau(H) + \eta(T)\dot{\gamma}^n] / \dot{\gamma} \quad (3)$$

### 3. Analysis of thermal thinning on MR Brake

To understand the rheological behavior of the MR fluid, an experimental study was performed on MR brake. The analysis specially involves study of braking torque vs. temperature at different magnetic field.

**Figure 2** MR brake (Seval, 2002)

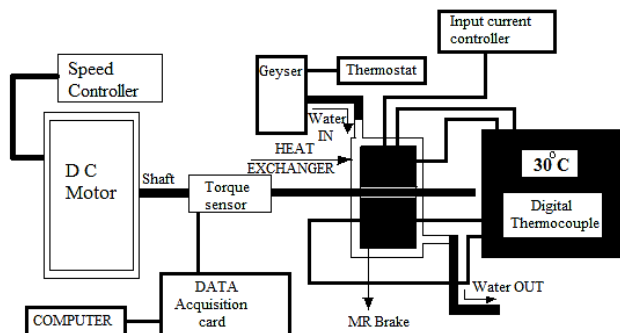
#### 3.1. Construction of MR brake

Construction of brake is shown in Figure 2. It consists of rotor fixed to the shaft, which is placed in bearing and can rotate in relation to housing. Between rotor and housing plate, there is a gap filled with MR fluid. Theoretically, a smaller gap will be better because the

magnetic flux density in the gap decreases sharply with increasing air gap. In addition, a smaller constant gap can easily maintain a uniform distribution of the magnetic flux in the gap. Practical gap generally range from 0.25 to 2 mm.

Current in the coil, supplied with 12 VDC, creates magnetic field in the gap. Magnetic field strength depends on the current in the coil. Value of the current can be set from 0 to 1 A. Viscosity of the fluid influences torque. When the current in the coil is equal to zero, no magnetic field is generated and brake torque equal to minimum  $M_{min}$  is exerted on the shaft. The  $M_{min}$  is equal to the torque caused by bearing, seal and viscosity of the carrier liquid. When current is the maximum (1A) then magnetic field is created and brake has highest possible value of the torque  $M_{max}$ , that is limited only by maximum current in the coil  $I_{max}$  and the construction of the brake.

A heat exchanger was designed and mounted on the circumference of the MR brake to analyze temperature effect on the dynamic viscosity of the MR fluid. The outer diameter of 110 mm was kept and the water was used a circulating coolant to take away heat from MR brake. A schematic block of the experimental set up is shown in Figure 3.



**Figure 3** Schematic block of the experimental set up (Sukhwani, et al, 2006)

3.2. Experimental set up

An experimental apparatus for evaluating the performance of the MR brake (Lord Corporation MRB 2107-3) was set up. The schematic block diagram is shown in Figure 3. The system is composed of four main parts: DC motor (with associated analog speed regulator), Torque sensor, MR brake and the Heat Exchanger. Torque sensor is connected through a data acquisition card to a computer where values are obtained. The number of samples taken for each reading was 2000 data.

The inlet of water supply was connected to the geysers to have better and precise control over the temperature. Temperature scanner was used to measure the surface temperature of the MR brake. Four points were connected to the four corners of the outer surface of the brake and readings were taken subsequently.

3.3 Procedure

A testing procedure, listed below, was followed

- (1) Rotate shaft of MR brake at speed of 200 RPM for 1 min as an initial condition, which stirs the MR fluid in the brake to distribute it evenly. Circulate water at partial opening through the nozzle control gap.
- (2) Supply the required current using the 12 VDC power supply source to provide the required current for flux generation.
- (3) Control the operating temperature is to the desired level between room temperature to 70°C. For analyzing Temperature thinning affect, five set of reading i.e. 25 °C,30 °C,35 °C,40 °C,45 °C,50 °C were planned. Each reading was taken with at stable temperature value. Almost 10-20 minutes are required for stability of the each reading.
- (4) Measure the torque from the torque sensor. Repeat all sets of reading at all five temperatures by keeping the speed constant. While taking reading it is necessary to check the presence of noise present in the reading. The required values are obtained by averaging all the points.

3.4 Results

Table 2 results show the braking torque at various temperatures keeping speed and current constant. The value of torque decreases with increase of temperature. However, percentage increase in torque with increase in magnetic field as well as temperature is noticed.

**Table 2.** Experimental results at different operating conditions (Accuracy of the torque sensor is 0.25%)

Temp. (°C)	Torque (Nm) (at 0 A current)	Torque (Nm)(at 0.2 A current)	Increase in torque value (%)
25	0.1765	0.1788	1.30
30	0.1673	0.1703	1.79
35	0.1610	0.1659	3.04
40	0.1571	0.1630	3.76
45	0.1550	0.1602	3.35
50	0.1505	0.1582	5.12

Conclusions

In this study performance of a MR fluid brake has been evaluated to investigate its thermal thinning behavior of MR fluid. Following conclusions can be drawn from this study:

1. With increase in temperature there is decrease in braking torque.
2. With increase in magnetic field, thermal thinning of carrier fluid shows more dominant results compared to particle chain formation of MR fluid.

References

S. Gupta, H. Hirani, (2011), Optimization of magnetorheological brake, *ASME/STLE 2011 International Joint Tribology Conference*, pp 405-406.  
 Hirani, H., Athre, K., Biswas, S. (1998), Rapid and Globally Convergent Method for Dynamically Loaded Journal Bearing Design, *Proc. IMechE (UK), Journal of Engineering Tribology*, vol. 212, pp. 207-214.

- Hirani, H., Athre, K., Biswas, S. (1999), Dynamic Analysis of Engine Bearings, *International Journal of Rotating Machinery*, vol. 5, no.4, pp. 283-293.
- Hirani, H., Athre, K., Biswas, S. (2000), A Hybrid Solution Scheme for Performance Evaluation of Crankshaft Bearings, *Trans. ASME, Journal of Tribology*, vol. 122, no. 4, pp. 733-740.
- Hirani, H., Athre, K., Biswas, S. (2000), Transient Trajectory of Journal in Hydrodynamic Bearing, *Applied Mechanics and Engineering*, vol. 5, no. 2.
- Hirani, H., Athre, K., Biswas, S. (2001), A Simplified Mass Conserving Algorithm for Journal Bearing under Dynamic Loads, *International Journal of Rotating Machinery*, vol. 1, pp. 41-51.
- Hirani, H., Athre, K., Biswas, S. (2001), Lubricant Shear Thinning Analysis of Engine Journal Bearings, *STLE, Journal of Tribology Transaction*, vol. 44, no. 1, pp. 125-131.
- Muzakkir, S.M., Hirani, H., Thakre, G.D., Tyagi, M.R. (2011), Tribological Failure Analysis of Journal Bearings used in Sugar Mill, *Engineering Failure Analysis*, vol. 18, no. 8, pp. 2093-2103.
- Hirani, H., Athre, K., Biswas, S. (2002), Comprehensive Design Methodology for Engine Journal Bearing, *IMEchE (UK), Part J, Journal of Engineering Tribology*, vol. 214, pp. 401-412.
- Hirani, H. (2004), Multi-objective Optimization of a journal bearing using the Pareto optimal concept, *Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology*, vol. 218, no. 4, pp. 323-336.
- Hirani, H. (2005), Multiobjective optimization of journal bearing using mass conserving and genetic algorithms, *Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology*, vol. 219, no. 3, pp. 235-248.
- Hirani, H., and Suh, N. P. (2005), Journal Bearing Design using Multi-objective Genetic Algorithm and Axiomatic Design Approaches, *Tribology International*, vol. 38, no. 5, pp. 481-491.
- Hirani, H., and Verma, M. (2009), Tribological study of elastomeric bearings of marine shaft system, *Tribology International*, vol. 42, no. 2, pp. 378-390.
- Muzakkir, S.M., Hirani, H., Thakre, G.D., (2013), Lubricant for Heavily-Loaded Slow Speed Journal Bearing, *Tribology Transactions*, vol.56, no. 6, pp. 1060-1068.
- Muzakkir, S.M., Lijesh, K. P., Hirani, H., Thakre, G.D. (2015) Effect of Cylindricity on the Tribological Performance of Heavily-Loaded Slow Speed Journal Bearing, *Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology*, 2015, vol. 229, no.2, pp.178-195.
- Muzakkir, S.M. and Hirani, H. (2015), A Magnetorheological Fluid Based Design Of Variable Valve Timing System For Internal Combustion Engine Using Axiomatic Design, *International Journal of Current Engineering Research*, Vol.5, No.2 (April 2015), pp 603-612.
- Rao, T. V. V. L. N., Hirani, H., Athre, K., Biswas, S. (2000), An Analytical Approach to Evaluate Dynamic Coefficients and Non-linear Transient Analysis of a Hydrodynamic Journal Bearing, *STLE Tribology Transactions*, vol. 23, no.1, pp. 109-115.
- Muzakkir, S. M., and Harish Hirani. (2015) Maintenance Free Bearings. *International Journal of Engineering Research*, vol. 4, no.3, pp.133-136.
- Muzakkir, S. M., Harish Hirani, and G. D. Thakre. (2015), Experimental Investigations on Effectiveness of Axial and Circumferential Grooves in Minimizing Wear of Journal Bearing Operating in Mixed Lubrication Regime. *International Journal of Current Engineering and Technology*, vol.5, no.1, pp.486-489.
- Muzakkir, S. M., K. P. Lijesh, and Harish Hirani. (2015). Effect of Base Oil on the Anti-Wear Performance of Multi-Walled Carbon Nano-tubes (MWCNT), *International Journal of Current Engineering and Technology*, vol.5, no.2, pp.681-684.
- H Hirani, T Rao, K Athre and S Biswas, (1997), Rapid performance evaluation of journal bearings, *Tribology international*, vol. 30, no.11, pp. 825-834.
- H Hirani, K Athre, S Biswas, (1999), Dynamically loaded finite length journal bearings: analytical method of solution. *Journal of tribology*, vol. 121, no. 4, pp. 844-852.
- Hirani, H. (2009), Root cause failure analysis of outer ring fracture of four row cylindrical roller bearing, *Tribology Transactions*, vol.52, no.2, pp.180-190.
- Lijesh, K. P., S. M. Muzakkir, and Harish Hirani. (2015), Failure Analysis of Rolling Contact Bearing for Flywheel Energy Storage Systems., vol.5, no.1, pp. 439-443.
- Lijesh K.P. and Harish Hirani, (2015), Shaft Alignment Systems: A Comparative Study, vol.5, no.2, pp. 1009-1014.
- Lijesh, K. P., Hirani, H., (2014), Stiffness and Damping Coefficients for Rubber mounted Hybrid Bearing, *Lubrication Science*, vol. 26, no.5, pp. 301-314.
- Lijesh, K. P., Hirani, H., (2015), Development of Analytical Equations for Design and Optimization of Axially Polarized Radial Passive Magnetic Bearing, *ASME, Journal of Tribology*, vol. 137, no. 1, (9 pages).
- Lijesh, K. P., Hirani, H., (2015), Optimization of Eight Pole Radial Active Magnetic Bearing, *ASME, Journal of Tribology*, vol.137, no.2.
- Lijesh, K. P. and Hirani, H. (2015), Design and Development of Halbach Electromagnet for Active Magnetic Bearing, *Progress In Electromagnetics Research C*, vol. 56, 173-181.
- Muzakkir, S.M., Lijesh, K. P. and Hirani, H. (2014), Tribological Failure Analysis of a Heavily-Loaded Slow Speed Hybrid Journal Bearing, *Engineering Failure Analysis*, vol. 40, pp.97-113.
- Samanta, P., Hirani, H., (2007), A Simplified Optimization Approach for Permanent Magnetic Journal Bearing, *Indian Journal of Tribology*.
- Samanta, Pranab, and Harish Hirani. (2008), Magnetic bearing configurations: Theoretical and experimental studies. *Magnetics, IEEE Transactions on* vol. 44, no. 2, pp. 292-300.
- Shankar, S., Sandeep, Hirani, H. (2006), Active Magnetic Bearing, *Indian Journal of Tribology*, pp 15-25.
- Hirani, H., Samanta, P. (2007), Hybrid (Hydrodynamic + Permanent Magnetic) Journal Bearings, *Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology*, vol. 221, no.18, pp. 881-891.
- Lijesh, K. P., and Harish Hirani. (2015), The Performance of Hybrid Journal Bearing under Extreme Operating Conditions. *International Journal of Current Engineering and Technology*, vol. 5, no.1, pp. 277-282.
- Lijesh, K. P., and Hirani, H. (2014). Design of eight pole radial active magnetic bearing using monotonicity. In *Industrial and Information Systems (ICIIS), 2014 9th International Conference on IEEE*, pp. 1-6.
- Lijesh K.P., Harish Hirani, Samanta P., (2015), Theoretical and Experimental Study for Hybrid Journal Bearing, *International Journal of Scientific and Engineering Research*, Volume 6, Issue 2, pp. 133-139.
- Lijesh K. P, Harish Hirani, (2015), Magnetic Bearing Using RMD Configuration, *Journal of Tribology*.
- C. Sarkar, H. Hirani, (2013), Theoretical and experimental studies on a magnetorheological brake operating under compression plus shear mode, *Smart Materials and Structures*, 22, art. no. 115032.
- C. Sarkar, H. Hirani, (2013), Synthesis and characterization of antifriction magnetorheological fluids for brake, *Defence Science Journal*, 63, pp. 408-412.
- C. Sarkar, H. Hirani, (2013), Design of a squeeze film magnetorheological brake considering compression enhanced shear yield stress of magnetorheological fluid, *Journal of Physics: Conference Series*, 412, 012045.
- C. Sarkar, H. Hirani, (2015), Transient thermoelastic analysis of disk brake, *International Journal of Current Engineering and Technology*, 5, pp. 413-418.
- C. Sarkar, H. Hirani, (2015), Magnetorheological smart automotive engine mount, *International Journal of Current Engineering and Technology*, 5, pp. 419-428.
- C. Sarkar, H. Hirani, (2015), Finite element analysis of magnetorheological brake using ANSYS, *International Journal of Current Engineering and Technology*, 5, pp. 725-732.
- C. Sarkar, H. Hirani, (2015), Design of Magnetorheological Brake using Parabolic Shaped Rotating Disc, *International Journal of Current Engineering and Technology*, 5, pp. 719-724.
- C. Sarkar, H. Hirani, (2015), Synthesis and characterization of nano-copper-powder based magnetorheological fluids for brake, *International Journal of Scientific Engineering and Technology*, 4, pp. 76-82.
- C. Sarkar, H. Hirani, (2015), Effect of particle size on shear stress of magnetorheological fluids, *Smart Science*, (in press).
- C. Sarkar, H. Hirani, (2015), Development of magnetorheological brake with slotted disc, *Proc. IMechE, Part D: Journal of Automobile Engineering*, pp 1-18. DOI: 10.1177/0954407015574204.
- G. Seval, (2002), Synthesis and properties of Magnetorheological fluids, Dissertation, University of Pittsburgh.
- H. Hirani, C. S. Manjunatha, (2007), Performance evaluation of magnetorheological fluid variable valve, *Proc. of the Institution of Mechanical Engineers, Part D, Journal of Automobile Engineering*, 221, pp. 83-93.
- J. M. Ginder, L. C. Davis, (1994), Shear Stresses in Magnetorheological fluids: Role of Magnetic Saturation, *Applied Physics Letters*, 65, pp. 3410-3412
- R. G. Larson, (1999), The structure and rheology of complex fluids, Oxford University press, New York.
- S. Chen, J. Huang, K. Jian, J. Ding, (2014), Analysis of Influence of Temperature on Magnetorheological Fluid and Transmission Performance, *Advances in Materials Science and Engineering*, Article ID 583076, pp 1-7.
- V. K. Sukhwani, V. Lakshmi, H. Hirani, (2006), Performance evaluation of MR brake: an experimental study, *Indian Journal of Tribology*, pp. 67-52.
- V. K. Sukhwani, H. Hirani, T. Singh, (2007), Synthesis of magnetorheological grease, *Greasetech India*.
- V. K. Sukhwani, H. Hirani, (2007), Synthesis and characterization of low cost magnetorheological (MR) fluids, *The 14th International Symposium on: Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring*, 65262R-65262R-12.
- V. K. Sukhwani, H. Hirani, (2008), A comparative study of magnetorheological-fluid-brake and magnetorheological-grease-brake, *Tribology Online*, 3, pp. 31-35.
- V. K. Sukhwani, H. Hirani, T. Singh, (2008), Synthesis and performance evaluation of MR grease, *NLGI Spokesman*, 71.
- V. K. Sukhwani, H. Hirani, (2008), Design, development and performance evaluation of high speed MR brake, *Proc. Institute Mech. Engineers., Part L, Journal of Materials: Design and Applications*, 222, pp.73-82.
- V. K. Sukhwani, H. Hirani, T. Singh, (2009), Performance evaluation of a magnetorheological grease brake, *Greasetech India*, 9, pp. 5-11.