Defence Science Journal, Vol. 65, No. 3, May 2015, pp. 252-258, DOI : 10.14429/dsj.65.7879

Synthesis and Characterisation of Nano Silver Particle-based Magnetorheological Fluids for Brakes

Chiranjit Sarkar* and Harish Hirani!

*Mechanical Engineering Department, Delhi Technical University, India
!Mechanical Engineering Department, IIT Delhi, India
*E-mail: chiranjit.ju@gmail.com

ABSTRACT

Magnetorheological (MR) fluids can be used as brake friction materials subject to heat transfer properties of the fluids to dissipate the heat generated during braking action. The aim of this manuscript is to synthesise MR fluids having higher heat transfer properties than that of the conventional MR fluid. The coating of nano-silver-particles, having thermal conductivity more than five-times than that of iron particles used in the MR fluids, has been tried to enhance the heat dissipation rate of MR fluids. To perform feasibility study on usage of silver particles, three composition of MR fluids (without any silver particles, with 0.25 per cent weight and 0.50 per cent weight silver particles) were synthesised. The scanning electron microscopic photographs and EDX analysis of the iron particles have been presented. Shear strengths of all three different compositions of MR fluids were measured using magnetorheometer and the results have been plotted. The effect of silver particles on shear stress of MR fluids has been described. A flywheel-based MR brake experimental setup was developed to analyse the performance of synthesised MR fluids. 'T' type thermocouples were used to avail the temperature distribution of the fabricated MR brake. The results of temperature distribution of brakes containing three different compositions of MR fluids have been presented and compared.

Keywords: Magnetorheological fluids, braking torque, synthesis of MR fluid, heat dissipation

1. INTRODUCTION

Magnetorheological (MR) fluid consists of micron-sized magnetically permeable (i.e. soft iron) particles dispersed in the non-magnetic fluid carrier. In the presence of the magnetic field, particles form chains in the direction of magnetic flux and increase its shear strength. Most of carbonyl iron-based MR fluids have an issue with sedimentation of suspended particles. To overcome sedimentation, many methods, such as applying polymer coating on iron powder, adding surfactant, and adding magnetic nano particle have been attempted[1,2]. Some researchers used ferro fluid to reduce the settling rate of micron-sized particles in MR fluid[3-7]. The ferro-fluid nano sized particles help to make a kind of colloidal nano bridge (CNB)[8-10]. Mahesh[11], *et al.* prepared F-MRFs with varying volume percentage of ferro-fluid nano particles and observed an enhancement in viscosity of MRFs with an increase in the number density of particles. Some researchers have prepared MR fluids as suspensions of polymer-coated nano size (diameter ~30 nm) ferrite particles[12], iron-cobalt alloy particles[13], and meso-scale carbonyl iron and nickel-zinc ferrites[6], carbonyl iron and nano scale magnetic particle additives (Co-γ-Fe_2O_3, CrO_2)[14]. Phule and Ginder[6] reported the effectiveness in stabilization of nano-scale additives such as silica, fibrous carbon, and other polymers, forming a coating layer on the MR particles or making a thixotropic network. In MR brake[15], increase in fluid's shear stress restricts the rotational movement of disk and increases braking torque on the disk. Under braking conditions, kinetic energy gets converted to heat and thermal thinning of MR fluid occurs.

Various researchers have studied temperature distribution of MR brake devices. Karakoc[16], *et al.* found an increase of 25 °C temperature in 20 s of continuous braking at 200 rpm. Wiehe[17], *et al.* indicated possibility of 150 °C as the maximum temperature of the MR brake. Liao[18] found sharp decay in the damping force on increasing operating temperature from 20 °C to 80 °C.

To solve heat dissipation problem of MR devices, cooling methods have been proposed by researchers. Dogruoz[19], *et al.* employed radiating fins in the shell to accelerate heat dissipation from the MR fluid damper. Tian and Hou[20] proposed a rotating fan to achieve forced air cooling of a MR clutch. Zheng[21], *et al.* utilised rotary heat pipes to achieve forced cooling of the MR transmission device. Wang[22], *et al.* proposed water cooling method for a high power MR brake. In the present study, mixing of nano-silver particles has been tried to increase the heat dissipation of MR fluids. Three different compositions of MR fluid samples were synthesised and characterized using MCR-102 magnetorheometer. To find the effect of synthesized MR fluid on braking torque and temperature distribution, a MR brake test rig has been designed and experiments have been performed. MR brake surface temperature has been measured

Received 27 July 2014, revised 5 May 2015, online published 29 May 2015

using seven thermocouples, placed on the surface of the MR brake housing. The comparison between temperature rise and braking for three different compositions of MR fluids samples has been presented.

2. SYNTHESIS AND CHARACTERISATION

Normally MR fluid consists of carbonyl iron (CI) particles (diameter 3 µm - 10 µm, 20 per cent - 40 per cent by volume), additives and base oil[23]. In this study, three different compositions of MR fluid samples were synthesized using 99 per cent pure iron particles having micron sizes (2 µm to 212 µm) purchased from Sigma Aldrich. An attempt has been done to observe the particle size distributions using HORIBA laser scattering particle size distribution analyzer LA-950. Iron particles were dispersed in water and used in the funnel of the analyzer LA-950. Sonication was done to disperse the particles thoroughly. The form of distribution was set at 'auto' mode. Particle size distributions calculations were made on the volume basis. Refractory index of iron and water were kept 3.500 i – 3.800 i, and 1.333, respectively. Figure 1 shows the probability volume density graph of iron particles. The mean size and standard deviation of the iron particle distributions are 87.86 µm and 67.03µm, respectively.

Impurities contain *As*: ≤ 5 mg/kg, *Cu*: ≤ 100 mg/kg, *Mn*: ≤ 1000 mg/kg, *Ni*: ≤ 500 mg/kg, *Pb*: ≤ 20 mg/kg and *Zn*: ≤ 50 mg/kg. To avoid settling of particles, 3-10 microns sized particles[24] were preferred, but to increase the shear stress, larger sized particles have been recommended. MR applications having relative rotating bodies (such as brakes, clutches), settling of particle does not arise and larger sized particles may be permitted. Nonetheless, the added silver-nano particles could improve its sedimentation problem.

First MR fluid sample MRF 85 contains 14.5 per cent by wt silicone oil, 0.5 per cent by wt oleic acid, and 85 per cent by wt carbonyl iron powder. Second sample MRF85_0.25Ag is made of 14.25 per cent by wt silicone oil, 0.25 per cent by wt silver nano-particle, 0.5 per cent by wt oleic acid, and 85 per cent by wt carbonyl iron powder. Third sample MRF85_0.5Ag was composed of 14 per cent by wt silicone oil, 0.50 per cent by wt silver nano-particle, 0.5 per cent by wt oleic acid, and 85 per cent by wt carbonyl iron powder, as shown in Table 1.

Silver nano-particles were purchased from EPRUI Nanoparticles and Microspheres Co. Ltd. The average silver particle size was 50 nm. Nearly spherical silver particles are black in colour with some impurities (Impurities are *Sb*: 0.0065 per cent, Bi: 0.0086 per cent, *Fe*: 0.0076 per cent, *Zn*: 0.0043 per cent, *Cu*: 0.0074 per cent, *In*: 0.0043 per cent, *Ni*: 0.0015 per cent and *Cd*: 0.0001 per cent).

To mix in carrier fluid (silicone base oil), silver nano-particles, and silicone oil were homogenized in homogenizer which was set at 35 per cent pulsation power and 70 °C temperature for duration of 2 h. The homogenized mixture of silicone base oil and silver nano-particles was blended in the mixture of CI powder and oleic acid to prepare MR fluid samples.

In the present work, silicone oil was selected due to its superior qualities, such as: Good temperature-stability, good heat-transfer characteristics, oxidation resistance[11,12], very low vapour pressure, and high flash points. In other words, Silicone oil experience only a little change in physical properties over a wide temperature span (40 °C to 204 °C[13,14]); whereas, the vegetable oil is bio-degradable[15,16] and its properties are temperature-sensitive.

MR brake during braking action generates high heat, which increases the temperature of MR fluid. To improve the performance of MR brake, fluids needs to have high heat dissipation capability, and that is why silver nano-particles of high thermal conductivity were utilised to increase the heat

Table 1. MR fluid compositions

MR fluids samples	Silicone oil (per cent by wt.)	Iron particle (per cent by wt)	Oleic acid (per cent by wt)	Silver particles (per cent by wt)
MRF85	14.50	85	0.50	0
MRF85_0.25Ag	14.25	85	0.50	0.25
MRF85_0.50Ag	14	85	0.50	0.50

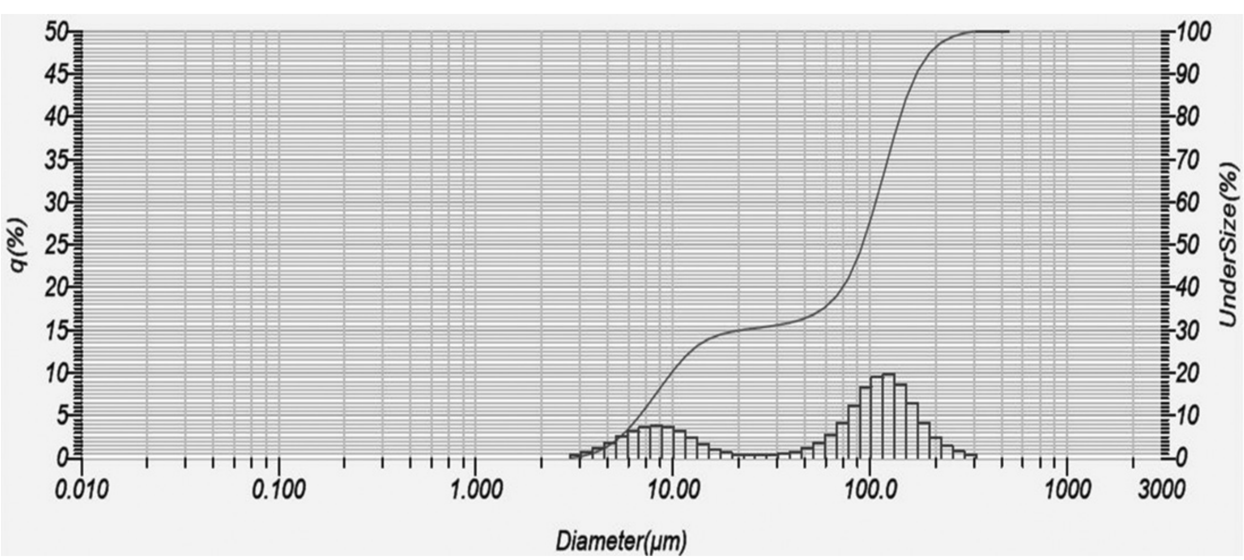


Figure 1. Probability volume density graph of iron particles.

dissipation rate of MR fluids.

Due to the di-magnetic property of silver nano-particles, shear stress of MR fluid may decrease. However, Fig. 2 shows that there is not much difference between the shear stress of MRF85 and MRF85_0.25*Ag*. The shear stress of MRF85_0.50*Ag* is relatively low compared to the shear stress of MRF85. These results discourage usage of silver nano-particles from magnetic effect (shear stress) point of view. On other hand, it is important to find effect of silver particles on temperature distribution, which is the aim of using nano-particles.

To observe the effect of temperature on shear stress, experiments were performed and results at various magnetic fields are plotted in Fig. 3. There is a common trend of reduction in shear stress of MR fluid with increase in temperature. In other words, the MR fluid undergoes shear thinning behaviour due to increase in temperature.

From Fig. 3, it can be said that at 30 °C temperature, the average shear stress of MRF85 is higher than the shear stress of MRF85_0.25*Ag* and MRF85_0.50*Ag*. From temperature 35 °C to 45°C, the average shear stress of MRF85 and MRF85_0.25*Ag* are the same and average shear stress of MRF85_0.5*Ag* is lower than that of MRF85 and MRF85_0.25Ag. From temperature 45°C to 55°C, the shear stress of MRF fluids decreases due to temperature increase.

The scanning electron microscope photographs of iron particles (Sigma Aldrich) are shown in Fig. 4(a). These iron particles are spherical in shape with various sizes. The iron particles were extracted from MRF85_0.50*Ag*, and the scanning electron microscopic photographs of these iron particles has been captured and shown in Fig. 4(b). The EDX analysis of iron particles extracted from MRF85_0.50*Ag* is shown in Fig. 5. It shows that there is some presence of *Ag* nano particles with the iron particles.

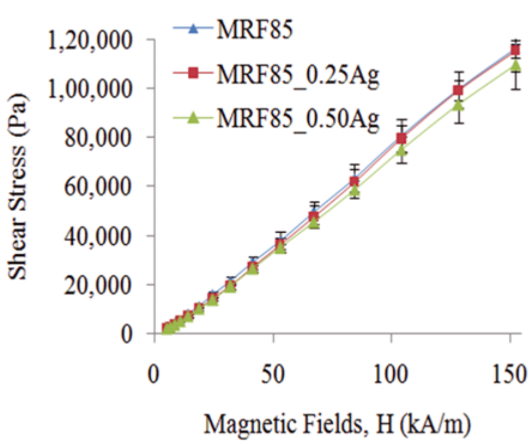


Figure 2. Shear stress of MRF85, MRF85_0.25*Ag* and MRF85_0.50*Ag* with magnetic field (kA/m) at 100 s^{-1} shear rate.

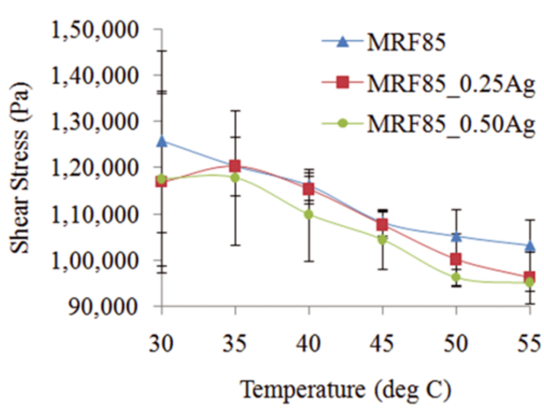
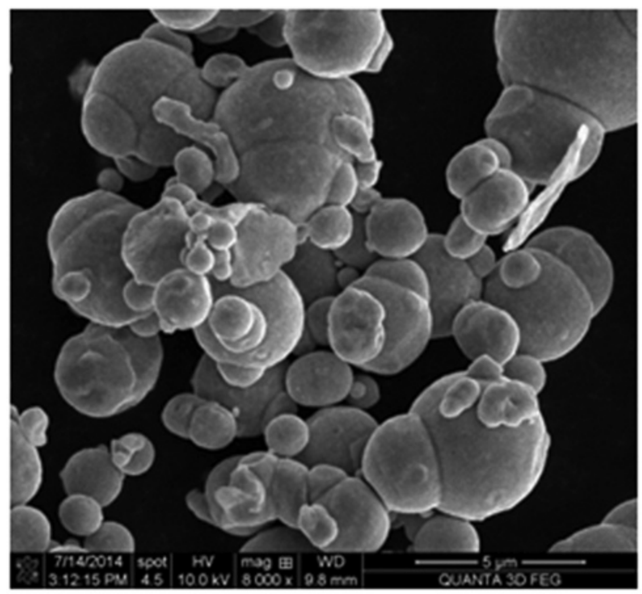
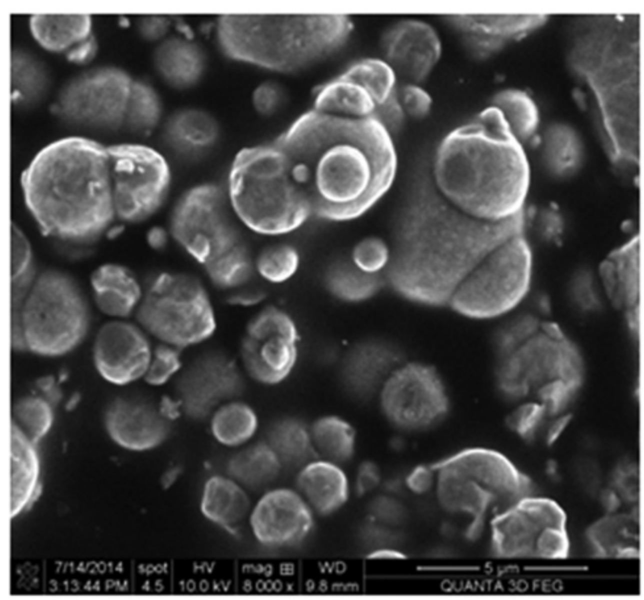


Figure 3. Shear thinning of MR fluid due to temperature increase at 152.4 kA/m magnetic field.



(a)



(b)

Figure 4. Scanning electron microscopic photograph: (a) Iron particles (Sigma Aldrich) and (b) *Ag*-nano particles make a layer on the Iron particles.

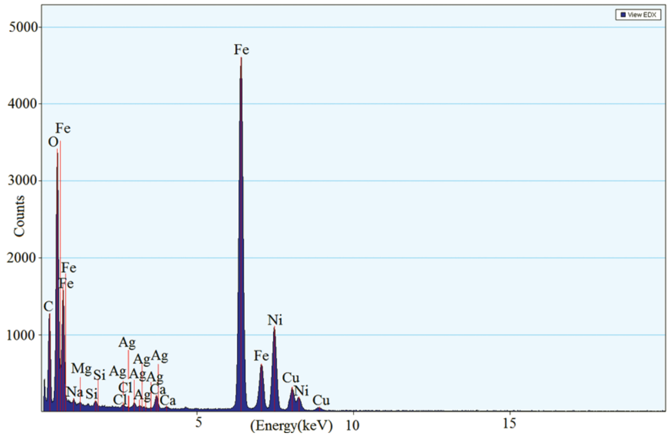


Figure 5. EDX analysis of extracted particles from MRF85_0.50*Ag*.

3. EXPERIMENTAL STUDY ON TEMPERATURE MEASUREMENT OF MR BRAKE

The block diagram of the MR brake test rig is shown in Fig. 6. It consists of 3 phase 5 HP dc motor with speed controller. A flywheel (20 kg) is connected between the dc. Motor and MR brake through bearing brackets and jaw couplings. A dc power supply (30 V and 5 A) to control the current to the electromagnet of MR brake; a tachometer to measure the rotational speed; and eight thermocouples to measure the surface temperature of the MR brake housing have been used. However during measurement, one thermocouple was broken.

To find the temperature profiles at various operating conditions, a number of experiments for various combinations of magnetic field, H (0 kA/m to 350 kA/m) and speed (200 rpm and 600 rpm) of brake shaft were planned. After completing each experiment, time to cool MR brake to the room temperature is relatively large. To reduce this time, a table fan was used to cool the MR brake back to its normal condition.

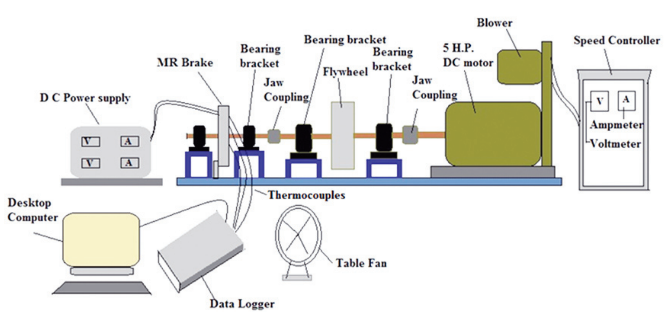


Figure 6. Schematic diagram of the MR brake test rig.

Figure 7 shows the photograph of the MR brake test rig. Figure 8 shows the position of the thermocouples on the surface of the MR brake housing. The volume of MR fluids in MR brake is $2\pi\left(r_2^2 - r_1^2\right)h = 2\times\pi\times\left(0.044^2 - 0.010^2\right)\times 0.001 = 1.15\times10^{-5}$ m^3 or 11.53 ml where, r_1 and r_2 are the inner and outer radius of the disk and h is the MR gap.

Braking torque and surface temperatures in each experiment, were measured by adopting following step-by-step procedure:

- Run the dc motor at constant rpm using speed controller.
- Note down the reading of the voltmeter and ammeter of

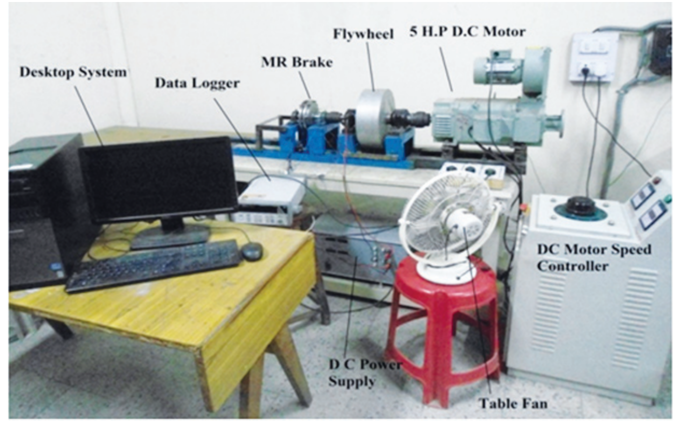


Figure 7. Photograph of MR brake test rig

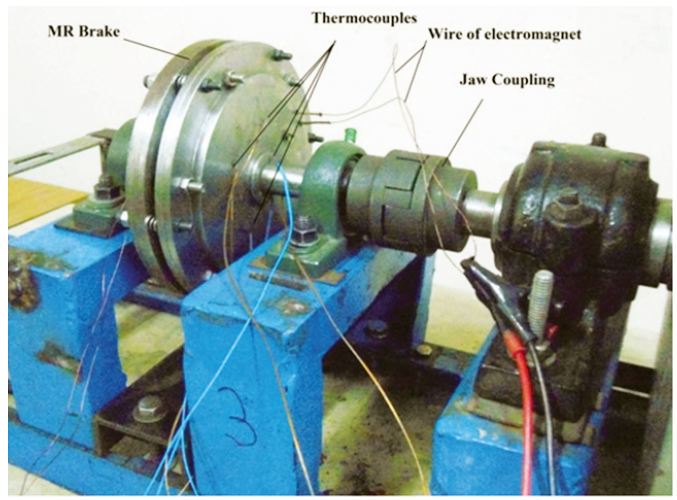


Figure 8. Position of thermocouples on the surface of the MR brake.

the speed controller of the dc motor.
- Estimate the power loss. Supply current in the electromagnet of MR brake.
- In the presence of magnetic field, brake actuation happens and the speed of the disk of MR brake reduces. Therefore, regulate the voltage using the speed controller to maintain the same speed (rpm) of the MR brake shaft.
- Record the reading of the voltmeter and ammeter of the dc motor speed controller. Calculate the power loss. Braking torque (BT) is calculated using following formula

$$BT = \frac{PW_f - PW_i}{\omega} \tag{1}$$

where PW_i and PW_f are the initial and the final power losses; ω is constant angular speed.
- Record temperatures using thermocouples after the stabilisation of temperature in the desktop computer using data logger.
- After completing temperature reading, switchoff the power supply to the electromagnet and reduce the rpm of the dc motor to zero.
- Switch on the table fan to cool the MR brake to get back to initial temperature.

Repeat the same procedure for another experiment (different current electromagnet and different motor speed). Each experiment was performed thrice.

4. RESULTS AND DISCUSSIONS

Figure 9 shows the braking torque of the MR brake using three different compositions of MR fluid (MRF85, MRF85_0.25Ag and MRF85_0.50Ag) at 200 rpm. As current in the central electromagnet increases, braking torque and surface temperature of MR brake housing increase. Figure 10 shows the maximum temperature of surface of MR brake housing at 200 rpm. Temperature of the MR brake using MRF85 is more than that of MRF85_0.25Ag and MRF85_0.50Ag as shown in Fig. 10. It can be said that the silver nano-particles helps heat dissipation and reduces the temperature of MR brake.

To observe the effect of silver particles at relatively higher speed, experiments were performed at 600 rpm. Figures 10 and 11 are renumbered as Figs. 11 and 12. Figure 11 shows the results of braking torque of three compositions (MRF85, MRF85_0.25Ag, MRF85_0.50Ag) of MR fluids at initial speed of rotating disc as 600 Rpm. These results show a decreasing trend from 7.8 Nm to 6.8 Nm with increase in Ag percentage from zero to 0.5 per cent. On comparing these results with torque results obtained at 200 Rpm, it can be said that performance of the silver nano particles is sensitive towards the rotational speed. Figure 12 shows the MR brake housing surface temperature at 600 Rpm. The surface temperature of MR brake using MRF85_0.50Ag is least among the temperatures obtained all three compositions of MR fluid.

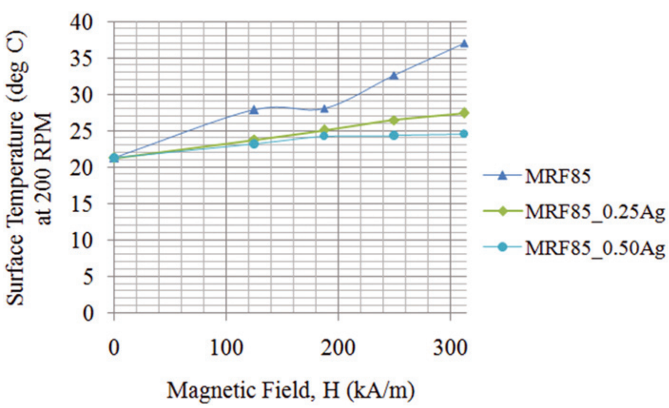


Figure 9. Braking torque at 200 Rpm.

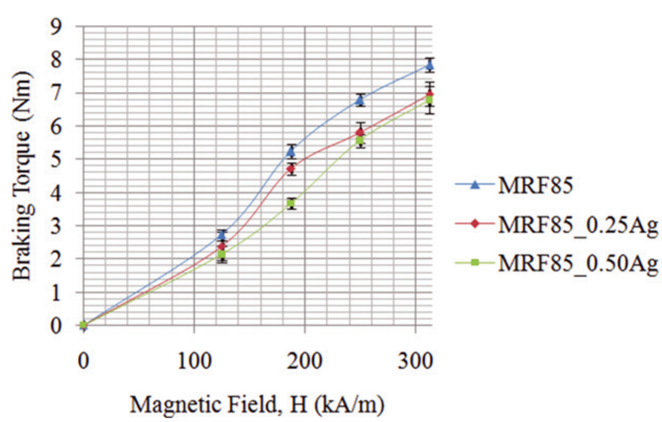


Figure 10. Surface Temperature at 200 Rpm.

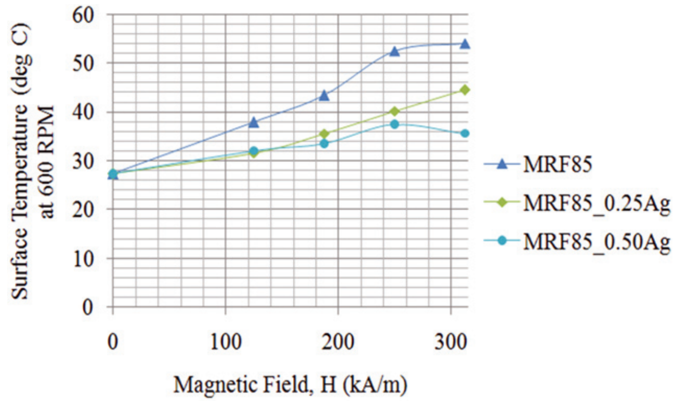


Figure 11. Braking torque at 600 Rpm.

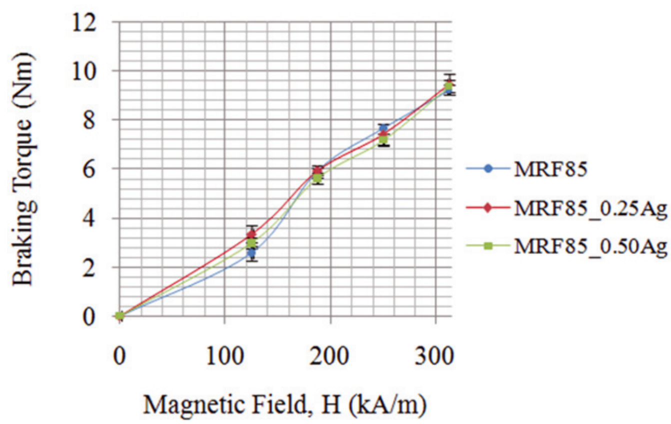


Figure 12. Surface Temperature at 600 Rpm.

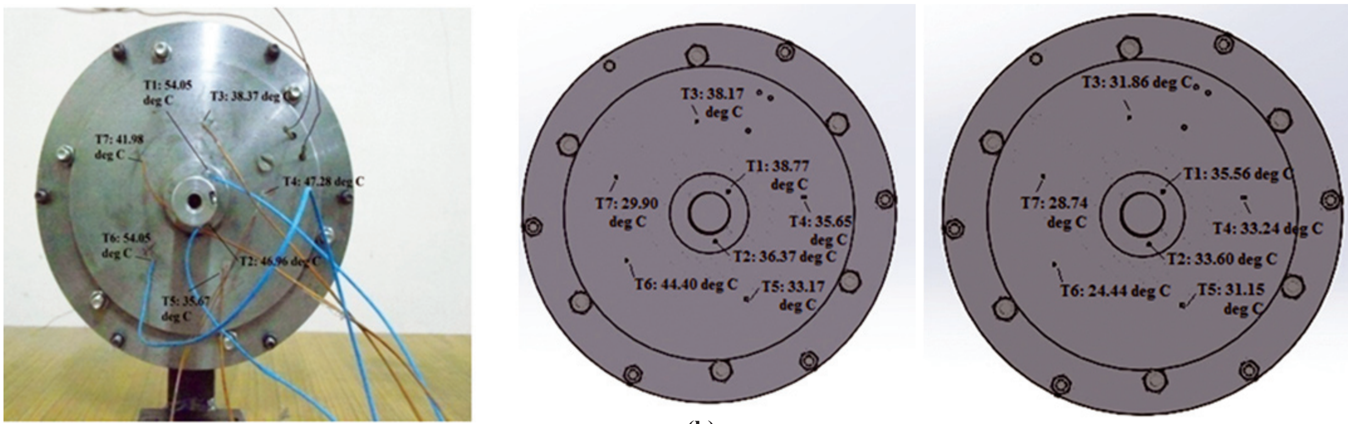
It confirms that the rate of heat dissipation of MR brake as MRF85_0.50Ag > MRF85_0.25Ag > MRF85.

On comparing Figure 9 and Figure 11, it can be said that with increase in Rpm, braking torque of MR brake decreases. MR fluid containing silver nano particles is sensitive toward the shear thinning behaviour of MR fluids.

Figure 13 shows the maximum temperature on the MR brake housing surface, using three different compositions MR fluids. Thermocouples T3, T4, T5, T6, and T7 are placed on the same pitch circle diameter of MR brake housing surface. The temperature difference (maximum temperature reading – minimum temperature reading) for MRF85, MRF85_0.25Ag, and MRF85_0.50Ag are 18.38 °C, 14.50 °C, and 8.80 °C, respectively. Therefore increase in silver nano particle percentage helps in uniform temperature distribution on the MR brake. The difference in temperature around the periphery of the disk of MR brake may be due to misalignment between the disk and the MR brake housing.

Based on the results of MRF85_0.25Ag and MRF85_0.50Ag at 200 rpm and 600 rpm, following can be stated:

- Braking torque at 200 rpm: The braking torque using MRF85_0.25Ag and MRF85_0.50 Ag are within the error bar. Therefore, 0.25 per cent Ag particle can be used as far as economical point of view.
- Surface temperature at 200 rpm: The percentage difference of MR brake housing surface temperature between MRF85_0.25*Ag* and MRF85_0.50*Ag* is 10.5 per cent.



(a) **(b)** **(c)**

Figure 13. Thermocouples reading (maximum temperature) using different MR fluids at 600 Rpm; (a) MRF85, (b) MRF85_0.25Ag, and (c) MRF85_0.50Ag.

This is mainly due to decrease in braking torque on the use of MRF85_0.50*Ag*, which results in lesser effective braking. Therefore, 0.25 per cent *Ag* particles is preferred compared to 0.5 per cent *Ag* particles.

- Barking torque at 600 rpm: The braking torques for MRF85_0.25Ag and MRF85_0.50*Ag* are 7 Nm and 6.8 Nm, respectively. The percentage decrease in braking torque indicates 0.25 per cent *Ag* particles is a better option.
- Surface temperature at 600 rpm: The percentage difference of MR brake housing surface temperature between MRF85_0.25Ag and MRF85_0.50Ag is 19.9 per cent. As surface temperature is decreasing by 19.9 per cent at the cost of decrease in torque by 2.8 per cent, 0.5 per cent Ag may be preferred at higher speed operations.

5. CONCLUSIONS

Three different compositions of MR fluid samples (No silver, with 0.25 per cent weight and 0.50 per cent weight silver particles) were synthesised. Shear stress and torque performance were characterised using MCR-102 magnetorheometer and developed experimental setup respectively. From the research performed on three different compositions of MR samples, following conclusions can be drawn:

- Shear stress of MR fluids reduces with an increase in percentage in silver nano-particles.
- Shear stresses of all three different compositions of MR fluids decrease with increase in operating temperature.
- At 200 rpm, braking torque of three different compositions of MR fluid samples is within the error bar. No noticeable change in braking torque occurs, but reduction in temperature rise with increase in silver particles has been observed.
- At 600 rpm, 0.25 per cent particles silver-based MR fluid give better performance as compared to 0.50 per cent particles silver based MR fluid. MRF85_0.25*Ag* provides lesser temperature compared to MRF85, while provides higher shear stress compared to MRF85_0.50*Ag*.
- MR fluid containing low particle percentage (0.25 per cent) of silver nano-particles is preferred for MR brake applications.

REFERENCES

1. Lim, S.T.; Cho, M.S.; Jang, I.B.; Choi, H.J. & Jhon, M.S. Magnetorheology of carbonyl iron suspensions with submicron-sized filler. *IEEE Trans. Magn.*, 2004, **40**, 3033-3035. http://dx.doi.org/10.1109/TMAG.2004.830400
2. Wereley, N.M.; Chaudhuri, A.; Yoo, J.H.; Jhon, S.; Kotha, S.; Suggs, A.; Radhakrishnan, R.; Love, B.J. & Sudarshan, T.S., Bidisperse magnetorheological fluids using Fe particle at nanometer and micron scale. *J. Intell. Mater. Syst. Struct.*, 2006, **17**(5), 393-401. http://dx.doi.org/10.1177/1045389X06056953
3. Rosenfeld, N.; Wereley, N.M.; Radakrishnan R. & Sudarshan, T.S. Behavior of magnetorheological fluids utilizing nanopowder iron. *Int. J. Mod. Phys. B*, 2002, **16**, 2392-2398. http://dx.doi.org/10.1142/S0217979202012414
4. Patel, R. & Chudasama, B. Hydrodynamics of chains in ferrofluid-based magnetorheological fluids under rotating magnetic field. *Phys. Rev. E: Stat. Nonlinear, Soft Matter Phys.*, 2009, **80**, 012401.
5. Wereley, N.; Chaudhuri, A.; Yoo, J.H.; John, S.; Kotha, S.; Suggs, A.; Radhakrishnan, R.; Love, B. & Sudarshan, T. Bidisperse magnetorheological fluids using Fe particles at nanometer and micron scale. *J. Intell. Mater. Syst. Struct.*, 2006, **17**, 393–401. http://dx.doi.org/10.1177/1045389X06056953
6. Phule, P.P. & Ginder, J.M. Synthesis and properties of novel magnetorheological fluids having improved stability and redispersibility. *Int. J. Mod. Phys. B*, 1999, **13**, 2019–2027. http://dx.doi.org/10.1142/S0217979299002095
7. Lopez-Lopez, M.; Vicente, J.D.; Bossis, G.; Caballero, F.G. & Duran, J. Preparation of stable magnetorheological fluids based on extremely bimodal iron–magnetite suspensions. *J. Mater. Res.*, 2005, **20**, 874–881. http://dx.doi.org/10.1557/JMR.2005.0108
8. Hagenbuchle, M. & Liu, J. Chain formation and chain dynamics in a dilute magnetorheological fluid. *Applied Optics*, 1997, **36**, 7664–7671. http://dx.doi.org/10.1364/AO.36.007664
9. Patel, R. Mechanism of chain formation in nano fluid based MR fluids. *J. Magn. Magn. Mater.*, 2011, **323**, 1360–1363.

http://dx.doi.org/10.1016/j.jmmm.2010.11.046

10. Butter, K.; Bomans, P.; Frederik, P.; Vroege, G. & Philipse, A. Direct observation of dipolar chains in iron ferro fluids by cryogenic electron microscopy. *Nat. Mater.*, 2003, **2**, 88–91. http://dx.doi.org/10.1038/nmat811
11. Chand, M.; Shankar, A.; Noorjahan; Jain, K. & Pant, R.P. Improved properties of bidispersed magnetorheological fluids. *RSC Adv.*, 2014, **4**, 53960 - 53966.
12. Kormann, C.; Lama, H. M. & Richter, H. J. MR fluids with nano-sized magnetic particles. *Int. J. Mod. Phys. B*, 1996, **10** (23-24), 3167. http://dx.doi.org/10.1142/S0217979296001604
13. Margida, A.J.; Weiss, K.D. & Carlson, J.D. Magnetorheological materials based on iron alloy particles. *Int. J. Mod. Phys. B*, 1996, **10**(23-24), 3335. http://dx.doi.org/10.1142/S0217979296001781
14. Chin, B.D. & Park, O.O. Rheology and microstructures of electrorheological fluids containing both dispersed particles and liquid drops in a congruous phase. *J. Rheo.*, 2000,**44** (2), 397. http://dx.doi.org/10.1122/1.551091
15. Sarkar, C. & Hirani, H. Theoretical and experimental studies on a magnetorheological brake operating under compression plus shear mode. *Smart Mater. Struct., 2013,* **22**(11)**,** 115032 (12pp).
16. Karakoc, K.; Park, E.J. & Suleman, A. Design considerations for an automotive magnetorheological brake. *Mechatronics*, 2008, **18**(8), 434–47. http://dx.doi.org/10.1016/j.mechatronics.2008.02.003
17. Wiehe, A.; Noack, V. & Maas, J. A model of heat dissipation for MR based brake. *J. Phys.: Conf. Ser.,* 2009, **149**(1), 012084 (4pp).
18. Liao, C.R. Study on magnetorheological fluid damper for automobile suspension system. (Chongqing: Chong Qing University), 2001.
19. Dogruoz, M.B.; Gordaninejad, F.; Wang, E.L. & Stipanovich, A. J. Heat transfer from fail-safe magnetorheological fluid dampers. *Proc. SPIE Conf. Smart Mater. Struct.,* 2001, **4331**(355)**,** 343–53.
20. Tian, Z.Z. & Hou, Y.F. A double-disk magnetorheological clutch, CN Patent Application 201110041597, 2011.
21. Zheng, J.; Zhang. G. H. & Cao, X.J. Design and experiment for magnetorheological transmission device with heat pipes. *Chin. J. Mech. Eng.,* 2009, **45**(7), 305–11. http://dx.doi.org/10.3901/JME.2009.07.305
22. Wang, D.M.; Hou, Y.F.; & Tian, Z.Z. A novel high-torque magnetorheological brake with a water cooling method forheat dissipation. *Smart Mater. Struct.,* 2013, **22**(2), 025019 (11pp).
23. Carlson, J.D.; & Jolly, M.R. MR fluid, foam and elastomer devices. *Mechatronics.,* 2000,**10**(4-5), 555-69. http://dx.doi.org/10.1016/S0957-4158(99)00064-1
24. Park, B.J.; Fang, F.F.; & Choi, H.J. Magnetorheology: materials and application. *Soft. Matter.,* 2010, **6**(21), 5246-53. http://dx.doi.org/10.1039/c0sm00014k
25. Shetty, B.G.; & Prasad, S.S. Rheological Properties of a honge oil-based magnetorheological fluid used as carrier liquid. *Def. Sci. J.*, 2011, **61**(6), 583-589. http://dx.doi.org/10.14429/dsj.61.331
26. Choi, J.S.; Park, B. J.; Cho, M.S.; & Choi, H. Preparation and magnetorheological characteristics of polymer coated carbonyl iron suspensions. *J. Magn. Magn. Mater.*, 2006, **304**(1), 374-376. http://dx.doi.org/10.1016/j.jmmm.2006.02.055
27. Genc, S. Synthesis and properties of magnetorheological (MR) fluids. University of Pittsburg, 2002. (PhD Thesis)
28. Gonclaves, F.D. Characterizing the behavior of magnetorheological fluids at high velocities and high shear rates. Virginia Poly-technic Institute and State University Blacksburg, Virginia, Jan. 2005. (PhD Thesis)
29. Kumbhar, B.K.; Patil, S.R. & Sawant, S.M. Synthesis and characterization of magnetorheological (MR) fluids for MR brake application, 2015 (in press). doi:10.1016/j.jestch.2015.03.002
30. Oommen, T.V. Vegetable oils for liquid-filled transformers. *IEEE Electr. Insulation Magazine*, 2002, **18**(1), 6-11. http://dx.doi.org/10.1109/57.981322

CONTRIBUTORS

Dr Chiranjit Sarkar did the experimental studies of synthesis and characterization of MR fluids. He did the experiments on the temperature measurement of MR brake. He plotted all the graphs and photographs. He had written the draft paper.

Prof. Harish Hirani had checked the draft paper. All the experimental studies mentioned in the paper was suggested by him.