NANOMATERIALS
SCIENCE & ENGINEERING
Vol. 3, No. 2, pp. 47-53 (2021)

RESEARCH ARTICLE

https://doi.org/10.34624/nmse.v3i2.26269

Magnetic field, heat transfer and rheological analysis of a magnetorheometer using finite element method

Chandra Shekhar Maurya*, Chiranjit Sarkar

Department of Mechanical Engineering, Indian Institute of Technology, Patna, 801103, India
**Corresponding author, e-mail address: 1821me19@iitp.ac.in*

Received 19 October 2021; accepted 14 December 2021; published online 30 December 2021

ABSTRACT

Magnetorheological (MR) fluids show changes in apparent viscosity under an applied magnetic field. As a result, dramatic and reversible changes in rheological properties occurred, which permits many electromechanical devices to have potential utility in the aerospace, automobile, medical, and another field. Therefore, there is a need to investigate the rheological properties and heat developed due to changes in the rheological properties of MR fluids under the uniform magnetic field. This work presents the numerical simulation of magnetostatic, laminar fluid flow, and thermal field distribution of a plate-plate magnetorheometer using the finite element method. We analyzed the magnetic field distribution and magnitude of the magnetic field along the radius of the plates. We obtained a better uniform magnetic field along the radius of the plate with enhanced the magnitude of the magnetic field at a particular applied current compared to the other existing design of the rheometer. The maximum magnetic flux density at 4A of coil current is 1.3T. Laminar flow simulation gives the shear stress at the applied magnetic field as a function of the shear rate. We obtained the maximum velocity of the magnetic particles at the outer radius between plates. The heat generated due to the electromagnetic coil and slippage heating between the plates (i.e., MR region) is 302.5K and 308.5K at 3A current after 40 minutes of working time of magnetorheometer. The maximum temperature generated due to the combined effect of the electromagnetic coil and slippage is about 318K after 40 minutes of working time of magnetorheometer, much below the operating temperature of MR fluids. Here we enhanced the magnetic field density profile and magnitude of magnetic flux density along the working radius of the plate and minimized the effects of resistive coil heating in the MR fluid region by the coil and location design.

1. INTRODUCTION

Magneto-rheological fluids (MRF) are a suspension of iron particles in base oil (synthetic oil, water, etc.) that exhibit magnetic effects when a magnetic field is applied to it. When a magnetic field is applied to MRF, it causes significant and reversible changes in their rheological behavior [1][2].MRFs generally act like Newtonian fluids (shear-thinning) in the absence of a magnetic field, but the relationship between shear stress and shear rate is balanced by yield stress in the presence of a magnetic field [3][4]. Yield stress depends on the increasing viscosity due to the formation of the chain-like structure of the magnetic particles[5][6]. MR fluid is used in clutches, brakes, dampers, and actuators for transmission control, vibration control, and damping[7][8]. There are several magnetic, and heat transfer simulation works that were done on brakes and clutches, but few on the rheometer. Laun et al. (2008)[9] and Laun et al. (2010)[11] present the work on rheometer and obtained o.74T and 1.37T at 3A of coil current respectively, but less work was performed on the heat transfer analysis of a rheometer. We provide a hybrid magnetorheometer model in this research that produces a magnetic flux of 1.3T at 4A along the whole working radius. We also go overheat

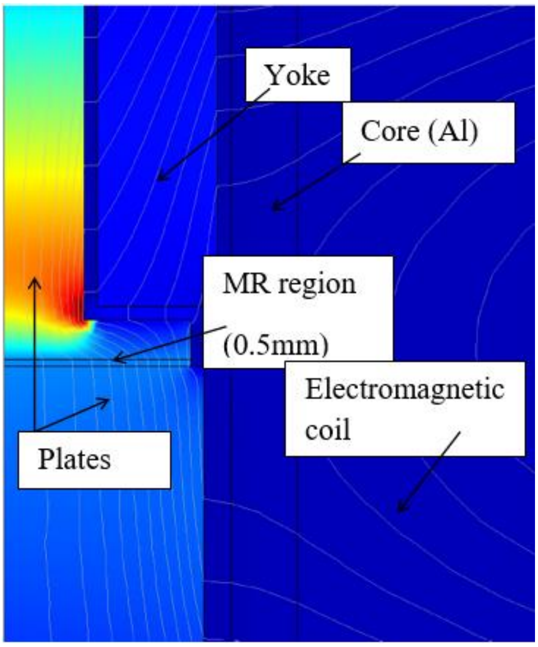

Figure 1. 2-D Axis symmetric magnetic field simulation of hybrid magnetorheometer.

creation from the electromagnetic coil's resistive heating and MR fluid slippage between the plates.

2. SIMULATION HYBRID MAGNETORHEOMETER

This research uses COMSOL's 2-D axisymmetric space to simplify the model and increase its accuracy. Figure 1 shows a 2-D axisymmetric schematic cross-section of the plate-plate magnetorheometer.

2.1. Magnetic Field Simulation

A "magnetic field" module in Comsol Multiphysics 5.3a software is used to simulate the magnetic field of the 2D axis-symmetric model. The magnetic field simulation is carried out using Ampere's Law, with the MUMPS solver and the air border acting as magnetic insulation. Except for the magnetic coil, Ampere's law applies to all border domains. The model is divided into two sections: solid and MR

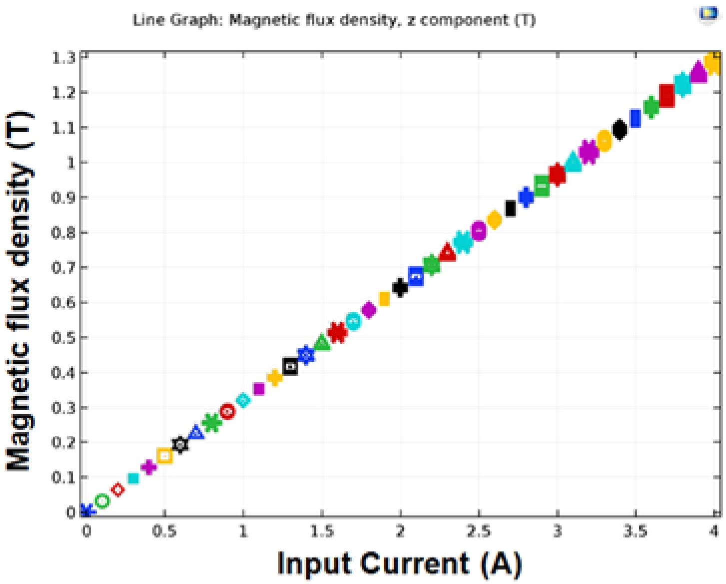

Figure 2. Magnetic flux density versus coil current at 0.5mm gap of MR region.

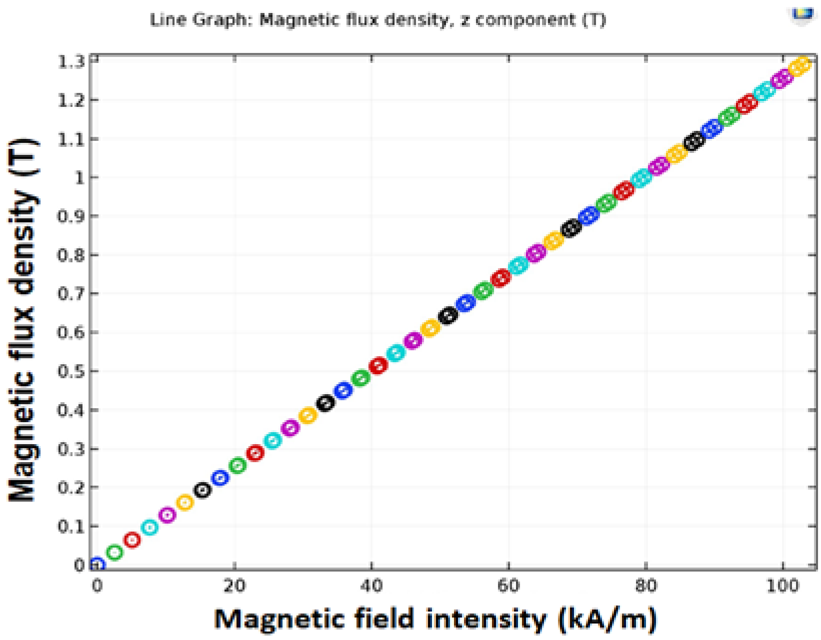

Figure 3. Variation of magnetic flux density versus magnetic flux intensity up to 4A input current.

fluid. The mesh size that was chosen was quite fine. The precision of the magnetic field is determined by the mesh quality of the MR region, which has a major impact on the simulation's computational outcomes. There are 2576 triangular elements and 399 geometric entity indices in this set. The plates and top yoke are made of low carbon steel 1010, which has a larger magnetic flux density than non-magnetic materials. The component materials are selected for their high relative permeability (μ_r) and low coercivity(H_c)The property, advantageous of low-coercivity material is this minimizes the remnant field that is retained within the fixture upon removal of the magnetic field [12][13]. Components with low magnetic permeability that are not part of a magnetic circuit are generally chosen to reduce the magnetic leakage.MRF85, a self-prepared magnetorheological fluid made up of iron particles and silicone oil (viscosity 0.15 Pas) as base oil, was used in this simulation. The magnetic z-components of lines pass perpendicularly through the 0.5mm gap of sample space in Fig. 1, a 2-D axisymmetric simulation of the magnetic field of a hybrid magnetorheometer. The red zone in Fig 1 shows the maximum intensity of the magnetic field

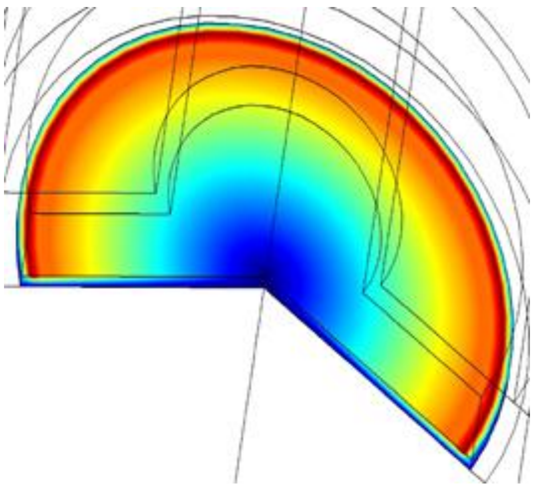

Figure 4. Distribution of velocity of MR fluid between the plates.

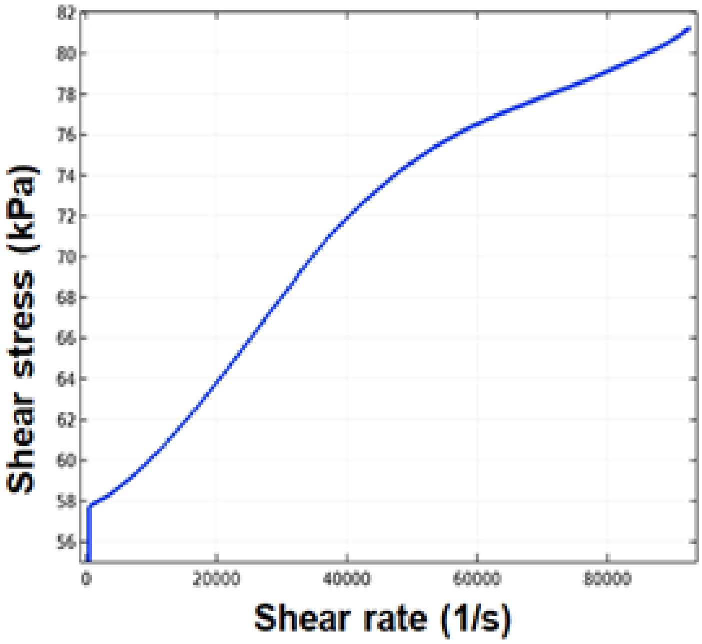

Figure 5. Variation of shear stress with shear rate.

in that area of plates. As the input current rises, the magnetic flux density rises to a certain point, after which the magnetic field begins to get saturated as the current rises. As demonstrated in Fig. 2, the highest magnetic flux density at 4A coil current is 1.3T. Figure 3 shows that the magnetic flux density between parallel plates grows as the magnetic flux strength increases.

2.2. Laminar Flow Simulation

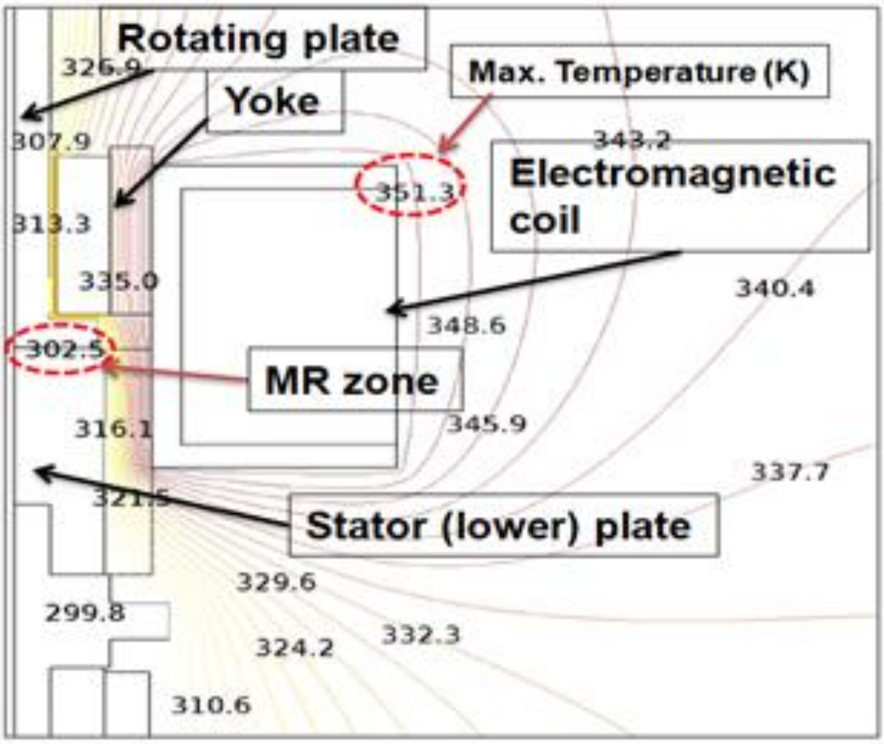

Figure 6. Distribution of temperature due to the resistive heating of the electromagnetic coil after 40 minutes of working time of magnetorheometer.

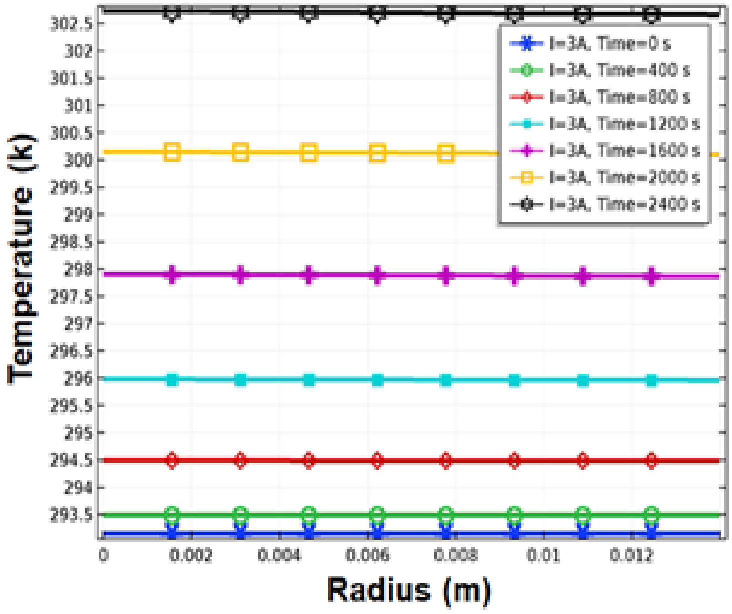

Figure 7. Variation of temperature through the radius of MRF region due to the resistive heating of the electromagnetic coil after 40 minutes of working time of magnetorheometer.

The shear stress at the applied magnetic field is calculated using laminar flow simulation and the shear stress impacts on shear stresses. MR fluid is placed between two parallel rotational plates with a 0.5mm gap between them, with the upper plate rotating while the lower plate remains fixed. The MR fluid particles rotate over stationary plates as the upper plates revolve. As shown in Fig. 4, the maximum velocity of MR fluid particles is away from the center of plates (the red zone area over the plates), which has an impact on MR particles collected away from the center. This can now be reduced by raising the magnetic flux density, because a strong chain forms among the particles under a high magnetic field, and the viscosity of the MR fluid rises. MRF85 yield stress is a function of magnetic flux density, with a value of 57.4KPa for 4A coil currents. An approximate polynomial equation was developed using Anton Paar MCR102, which shows the relation between magnetic flux intensity (B) and shear stress for MRF85, as shown in equation 1 [10].

$$\tau_y(kPa) = -603.78 \times B^4 + 1084.7 \times B^3 - 663.91 \times B^2 + 227.11 \times B + 2.5967 \quad (1)$$

Bingham model applied to describe post-yield behavior of MR fluid, while in the post-yield region a constant viscosity is assumed at a given magnetic field. Bingham model equation is given below[6]:

$$\tau = \tau_y + \eta_0 \dot{\gamma} \quad (2)$$

Where $\tau$is the shear stress, τ_y is the yield stress, $\dot{\gamma}$ is the shear rate,$\eta_0$is the viscosity of base - dynamic viscosity (η)As in equation 3. The shear stress of MR fluid increases with increasing the shear rate, as shown in Fig. 5.

$$\eta \dot{\gamma} = \tau = \tau_y + \eta_0 \dot{\gamma} \quad (3)$$

2.3. Hear Transfer Simulation

The temperature is controlled by the hybrid magnetorheometer, which is generated primarily by two sources: (1) resistive heating of the electromagnetic coil, and (2) slippage of MR fluid between the plates. In regards to the physical working conditions, the simulation was performed for 40 minutes of working time of magnetorheometer, and the maximum temperature generated in the MR fluid zone as a result of the combined effects of resistive electromagnetic coil heating and slippage was approximately 318K.

2.3.2. Effect of Slippage

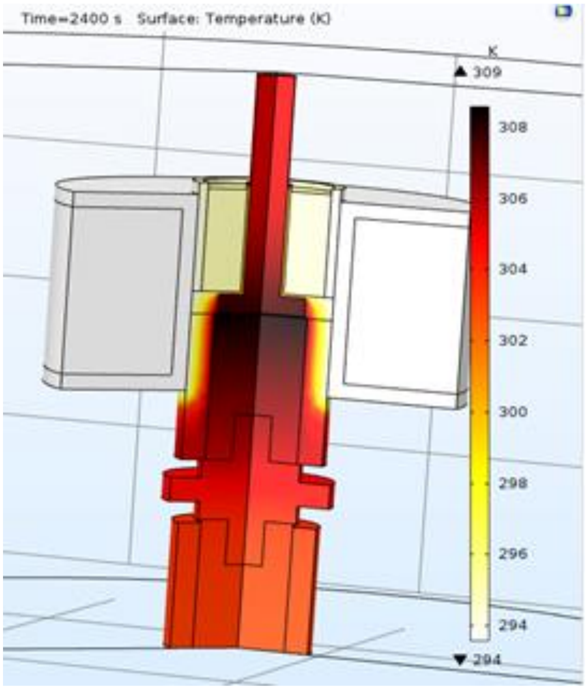

Figure 8. Distribution of temperature over the surface of rheometer due to slippage after 40 minutes of working time of magnetorheometer.

Due to the increased viscosity of MR fluid in the presence of the magnetic field, it becomes tough to break the chains when the rheometer plates begin to slip. The simulation is based on the idea that viscosity between the plates causes shear stress, which is then transformed into heat flow. The heat produced by slippage in the current magnetic field is more than the heat produced by slippage in the absence of a magnetic field. The temperature generated by MR fluid slippage in the presence of a magnetic field is 308.5K, which is higher than the temperature generated by the resistant coil. After 1 hour of working time of magnetorheometer, the maximum temperature generated is 313K, which is relatively low. As indicated in Fig. 8, the largest quantity of heat generated by slippage is near the MR sample. When compared to slippage heating, the temperature generated by resistive heating of the electromagnetic coil is lower. Slippage heating has a greater impact on the MR sample zone, thus we must keep it under control for the duration of the project. The maximum operating temperature limit of the MRF85 is 443k, which is significantly higher than the combined temperature impacts of the coil and slippage heating during 40 minutes of working time of magnetorheometer, as illustrated in Figs. 7 and 8.

4. CONCLUSIONS

The magnetic field over the MR sample was enhanced in this study; the magnetic flux density was 1.3T at 4A of input coil current. A homogeneous magnetic field is generated over the MR sample using this hybrid magnetorheometer model. Because the temperature created by the sum of electromagnetic coil heating and slippage heating is around 318K, which is well below the operating temperature of MR fluid, there is no requirement for water cooling for the 40 minutes of working time of magnetorheometer. Temperature variation is similarly constant around the radius, as seen in Figs. 7 and 8, and no temperature gradients occurred over the MR sample as a result. Now in this way, we improved the design of the magneto rheometer by enhancing the magnetic flux density and controlling the temperature over the MR sample.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the smart material and machines lab at the Department of Mechanical Engineering at IIT Patna, Patna, for supplying a rotational rheometer

(Anton Paar MCR102) and all other resources utilized in this study.

REFERENCES

[1] D. Susan-Resiga, "A rheological model for magneto-rheological fluids," *J. Intell. Mater. Syst. Struct.*, vol. **20**, no. 8, pp. 1001–1010 (2009).

[2] C. S. Maurya and C. Sarkar, "Effect of Fe3O4 Nanoparticles on Magnetorheological Properties of Flake-Shaped Carbonyl Iron Water-Based Suspension," *IEEE Trans. Magn.*, vol. **56**, no. 12, pp. 1–8 (2020).

[3] C. S. Maurya and C. Sarkar, "Synthesis and characterization of novel flake-shaped carbonyl iron and water-based magnetorheological fluids using laponite and oleic acid with enhanced sedimentation stability," *J. Intell. Mater. Syst. Struct.*, vol. **32**, no. 14, pp. 1624–1639 (2021).

[4] A. Farjoud, M. Ahmadian, N. Mahmoodi, X. Zhang, and M. Craft, "Nonlinear modeling and testing of magneto-rheological fluids in low shear rate squeezing flows," *Smart Mater. Struct.*, vol. **20**, no. 8, p. 14 (2011).

[5] C. S. Maurya and C. Sarkar, "Rheological and creep and recovery behavior of carbonyl iron water- based magnetorheological gel using laponite as an additive and oleic acid as a surfactant," *Rheol. Acta*, vol. **51** (2021).

[6] C. S. Maurya and C. Sarkar, "Rheological response of soft flake-shaped carbonyl iron water-based MR fluid containing iron nanopowder with hydrophilic carbon shell," *Rheol. Acta*, vol. **60**, no. 5, pp. 277–290 (2021).

[7] C. S. Maurya and C. Sarkar, "Dynamic and creep and recovery performance of Fe3O4 nanoparticle and carbonyl iron microparticle water-based magnetorheological fluid," *J. Intell. Mater. Syst. Struct.*, (2021).

[8] J.D. Carlson and M.R. Jolly, "MR fluid, foam and elastomer devices," *Mechatronics*, vol. **10**, no. 4-5, p. 555-569, (2000).

[9] H. M. Laun, G. Schmidt, C. Gabriel, and C. Kieburg, "Reliable plate-plate MRF magnetorheometry based on validated radial magnetic flux density profile simulations," *Rheol. Acta*, vol. **47**, no. 9, pp. 1049–1059 (2008).

[10] H. M. Laun, C. Gabriel, and C. Kieburg, "Twin gap magnetorheometer using ferromagnetic steel plates—Performance and validation," *J. Rheol.*, vol. **54**, no. 2, pp. 327–354 (2010).

[11] C. Gabriel and H. M. Laun, "Combined slit and plate-plate magnetorheometry of a magnetorheological fluid (MRF) and parameterization using the Casson model," *Rheol. Acta*, vol. **48**, no. 7, pp. 755–768, (2009).

[12] C. S. Maurya and C. Sarkar, "Magnetic and Transient Temperature Field Simulation of Plate – Plate Magnetorheometer Using Finite-Element Method," *IEEE Trans. Magn.*, vol. **56**, no. 4, pp. 1–9 (2020).

[13] M. Ocalan and G. H. McKinley, "High-flux magnetorheology at elevated temperatures," *Rheol. Acta*, vol. **52**, no. 7, pp. 623–641 (2013).