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Experimental and Numerical Study of Magnetorheological Clutch with Sealing at Larger Radius Disc

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ABSTRACT

In the existing magnetorheological clutch, there is a problem of improper transmission of torque or inefficiency in the transmission of torque. Research is carried out to improve the design of the magnetorheological clutch. Using simulation techniques and experimental study, a new seal at the outer radius is designed to improve the torque transmission of the magnetorheological clutch. The fluid flow between the input and output shafts are studied using COMSOL Multiphysics v5.3a software. The optimized design of the seal is subjected to experimental study and torque transmitted is measured. The results show an improvement in the torque transmission with the introduction of the new seal.

Keywords: Magnetorheological clutch; Magnetorheological fluid; Seal; Computational fluid dynamics; Particle migration; Transmission torque

1. INTRODUCTION

Magnetorheological (MR) fluid contains carrier liquid, different types of surfactants, additives, and magnetic particles. It shows quick response-ability and easily controllable rheological characteristics[1]. Due to easy controllability and quick response of MR fluid, it has more potential applications[2-3]. The durability of MR fluid devices such as MR brake, MR clutch, and MR damper depends on retaining MR fluid in those devices. Neelakantan[4], *et al.* developed an MR clutch that focused on proper sealing for MR fluid to reduce the centrifugal action at higher rotation. Highly absorbent polyurethane foam was used in this MR clutch. Jianwei[5], *et al.* developed a leak-proof MR damper to improve its damping action. Leakage of MR fluid is an important issue because it affects the working of MR devices[6-7]. Seals play an important role in the durability of MR devices[8-9]. Zhang[9], *et al.* studied the wear characteristics of seals used with MR fluids by a rotary lip seal wear tester. This experiment was taken with and without a magnetic field. They found that wear resistance of the seal was decreased when the magnetic field was applied. But, none has been attempted to do research considering MR fluid with sealing at larger radius disc.

A good quality dynamic seals[10] are used in MR fluid devices, but it increases the cost. Hence it requires developing an effective and economical way for the MR device to control the MR fluid leakage. Our primary concern is retaining MR fluid in the MR clutch at a high rotational speed. In this research work a leak-proof, MR clutch is designed and tested to improve its service life. The required clutching torque of the MR clutch was not studied by the researchers[11] in their work. To develop an economical leak proof MR clutches an attempt has been made to design sealing restrictions to overcome the above problem based on a self-made labyrinth seal[11] type arrangement. Silicon rubber made O-ring has been used because it is flexible, cheaper, and easy to use. It is widely used in the industry to stop the leakage[12]. It provides a fixed flow path for MR fluid. MR clutch based on labyrinth seal type arrangement is tested on various magnetic fields because it plays an essential role while using MR fluid.

In this paper, a leak-proof MR clutch is designed and fabricated. It includes a description of the MR clutch prototype with component design, material selection, and working principle. To stop the flow of iron particles from the disc periphery, a self-made labyrinth type seal has been designed at a larger radius disc. The Bingham model equation is applied to calculate the MR fluid yield stress and simulate the transmission torque of the MR clutch. Then the magnetic field and fluid flow between the input and output shafts are studied using COMSOL Multiphysics v5.3a software. Magnetic flux density and velocity distributions of MR fluid inside the MR gap with the time-dependent flow of iron particles have been simulated by the simulation software. Next, to verify the simulation results an experimental set-up is fabricated and tested. To predict the performance of a self-made labyrinth seal arrangement a time-dependent study of dispersed phase flow has been performed using the simulation software. Simulation and experimental results match well and prove the durability of seal life.

2. DESCRIPTION OF MAGNETORHEOLOGICAL CLUTCH

The main components of designed MR clutch are input shaft (1), an output shaft (2), input disc (3), output disc (4),

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input cover (5), Output cover (6), electromagnetic core (7), coil (8), MR fluid and (9) O-ring. The schematic of the proposed MR clutch with a detailed dimension is shown in Fig. 1. Two different sizes of O-ring are used with thickness 2 mm (O_1 ring) and 3.5 mm (O_2 ring). O_1 ring has an inner diameter of 98 mm and outer diameter 102 mm, whereas the O_2 ring has 106 mm and 113 mm in inner and outer diameter respectively. In this MR clutch, MR fluid is contained in between the input disc and output disc at a fixed gap of 0.5 mm and kept inside the electromagnetic core. Copper wire (SWG 22) with 300 numbers of turns has been mounted to prepare a coil. MR clutch parts with corresponding material are given in Table 1. The working mechanism of the MR clutch in shear mode is presented in Fig. 2. In Fig. 2(a) there is no transmission of torque between the two discs when the magnetic field is “0 T”. It is called “off state” otherwise “on state” due to supply current that forms magnetic flux lines, as shown in Fig. 2(b). Hence it transfers rotational motion from the input disc to the output disc. Table 2 shows the main MR clutch specifications.

During rotation of the disc, particle migration causes leakage of MR fluid through a clearance between the disc and electromagnet. To stop the leakage of MR fluids O-ring based self-made labyrinth seal type arrangement is made, as shown in Fig. 3. The O rings have been arranged according to the configuration of the labyrinth seal. Labyrinth seal has a unique arrangement of faces, mainly called as non-contacting[11]. There is a small gap between two O rings arranged alternatively creates an interlock for effective seal action. Very few fluid particles can escape throughout the length of the seal during rotation.

Table 1. MR clutch components with their materials

Component	Material
Coil	Copper
Core	Aluminum
Bracket	Mild steel
Cover	Low carbon steel
Disc	Low carbon steel
Shaft	Low carbon steel
O-ring	Silicon rubber

Table 2. MR clutch specifications

Variable	Values
The diameter of the disc (mm)	100
Maximum width of the disc (mm)	21
Disc thickness (mm)	3
Number of turns	300
Current supplied in the coil (A)	0-2

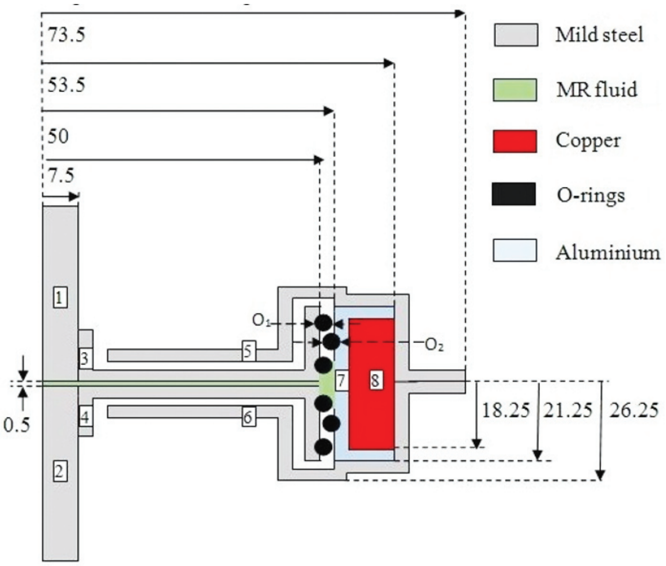
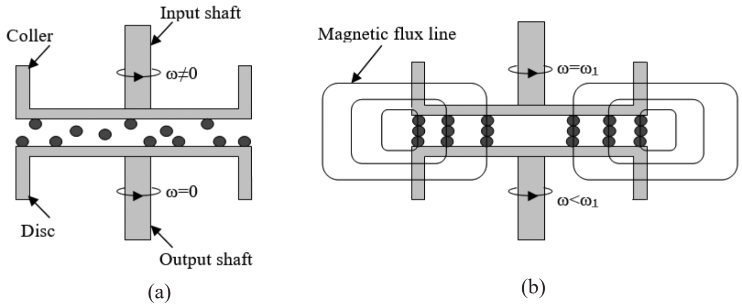
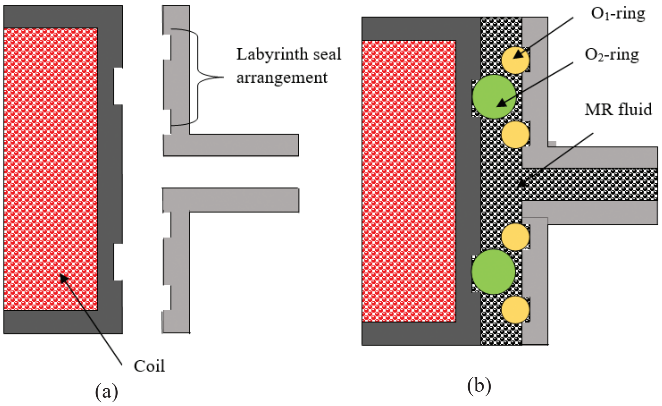


Figure 1. Schematic of the proposed MR clutch with dimensions (in mm).



(a) (b)

Figure 2. Working mechanism of MR clutch in shear mode (a) off state and (b) on the state: ω is the angular velocity.



(a) (b)

Figure 3. Schematic of self-made labyrinth seal arrangement in the MR clutch (a) without O-rings and (b) O-rings with MR fluid.

3. MATHEMATICAL MODELLING OF THE MR CLUTCH

In this present MR clutch, shear stress of the MR fluid is responsible for torque transmission[13]. It is found that the field dependency of shear stress for MR fluid can be explained by Bingham rheology model[14] as shown in Eqn. (1).

$$\tau = \tau_{yd}(B) + \eta_O \dot{\gamma} \tag{1}$$

where $\tau =$ Shear stress, $\tau_{yd}(B)$ = Field dependent yield stress, η_o = apparent viscosity, $\dot{\gamma} =$ Shear rate. Table 3 shows the components of the MR fluid. MR fluid (MRF 80) has been synthesized and characterized. 80 indicate the weight percentage of magnetic or iron particles used in MR fluid.

Table 3. Components of MR fluid

Components	Product no. (Sigma-Aldrich)	Weight percentage (% w/w)	Specification
Carbonyl Iron	44890	80	5-9 µm grain size and density 7.86 g/ml
Silicone oil	50384	19.5	Viscosity 150 mPa.s
Oleic acid	O1008	0.5	Density 0.89 g/ml

Mechanical mixing has been used for the preparation of MRF 80 sample[15-17]. ANTON PAAR Magnetorheometer MCR-102 has been used to characterize the shear stress for the shear rate at 0 T to 0.35 T magnetic flux densities as shown in Fig. 4.

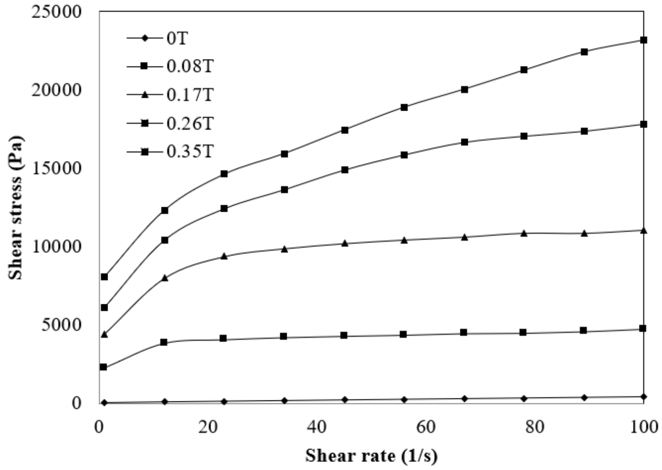


Figure 4. Rheological characterization of MRF 80 from 0 - 0.35T.

For a clutch, the maximum resistant or transmissible torque is thus the function of both $\tau_{yd}(B)$ and $\dot{\gamma}$. The yield stress $\tau_{yd}(B)$ depends on the magnetic field, while $\dot{\gamma}$ depends on both the rotational speed and the fluid gap. The total transmissible torque[16] on the disc surface by the action of MR fluids is given below.

$$T_1 = \frac{2\pi\tau_{yd}(B)r^3}{3} + \frac{\pi^2 \times \eta_O \times RPM \times r^4}{60 \times h} \qquad (2)$$

4. SIMULATION OF THE MR CLUTCH

4.1 Magnetic Field

To find out the yield stress dependency over the magnetic field, and to solve the torque Eqn. (2), simulation has been done in simulation software. It is used to compute the magnetic field and its distributions in the MR clutch domain. A schematic of the proposed MR clutch in 2D axisymmetric geometry is shown in Fig. 5. Simulation software solves Maxwell's equations with magnetic vector potential for every domain. Fig. 5 shows O-ring, electromagnetic core, copper coil, and the surrounding air as domain one (shown in blue color) with relative permeability as corresponding material property. While shafts, discs, cover, and MR fluid used as domain two (shown in light grey color) with the B-H curve as a variable for corresponding materials. Table 4 shows the material properties used in the simulation.

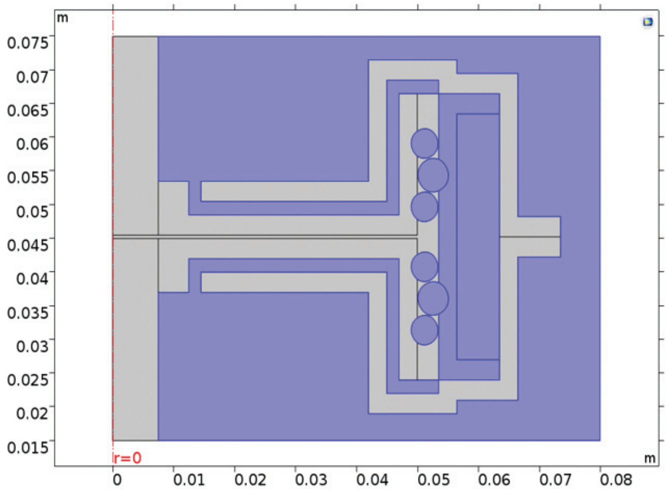


Figure 5. Schematic of a 2D axisymmetric model of MR clutch with different domains: domain 1 (blue) and domain 2 (light grey).

Table 4. Material properties used in magnetic field simulation

Materials	Relative permeability	Relative permittivity
Low carbon steel	1000	1
Copper	1	1
Aluminum	1	9.3
Silicon Rubber	1	7
MR fluid	10	2e5

4.2 Laminar Flow

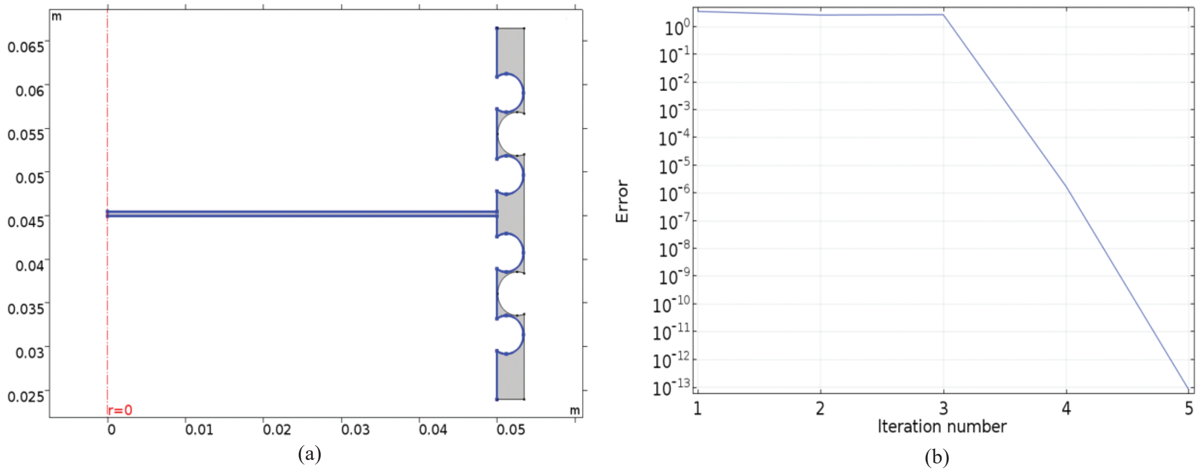
The MR fluid flow is simulated under the single-phase laminar flow study of simulation software[18]. This module utilizes Stokes and the continuity equation. This analysis is started by 2D axisymmetric laminar flow considering initial velocity field component as zero, pressure with 10^5 Pa, and with the two rotating discs as shown with blue color lines in Fig. 6(a). The wall at the end of the MR fluid gap close to the core is treated as a no-slip condition. The PARDISO solver of simulation software is used. However, simulation has been carried out with different mesh sizes. It has been found that the same value of convergence for each mesh size as shown in Fig. 6(b). Thus normal mesh size is used in this simulation for further study. Total numbers of triangular elements are 8222 with 3 nodes per element, 4156 mesh points, and 94 vertex elements. In this physical model section, swirl flow is considered and an inertial term (Stoke flow) is neglected.

Table 5. Material properties of MR fluid used in laminar flow simulation

	MR fluid
Density (kg/m³)	3860
Viscosity (Pa.s)	$\eta_{MRF} = \frac{\tau_{yd}}{\dot{\gamma}} + \eta_O$

5. DESCRIPTION OF THE TEST SET UP

An experimental test set up has been developed to test the clutching action of the MR clutch as shown in the block



(a) (b)

Figure 6. (a) Boundary conditions for MR gap filled in between rotating wall (blue lines) and no-slip wall and (b) convergence plot for normal mesh size.

diagram (see Fig. 7). DC motor (5 hp and 1500 R.P.M) with a speed controller used as a prime mover. It has a DC regulated power supply with output voltage (0-440 V DC) and output supply current (0-10A DC). A torque sensor (100 Nm) is assembled in between the prime mover and fabricated MR clutch through bearing bracket and couplings[19]. A gearbox is connected with the MR clutch by coupling and bearing bracket. A DC power supply with the rating (30V and 2A) is used to control the input supply current to the electromagnet of the designed MR clutch. The fabricated test set up of the MR clutch is shown in Fig. 8.

6. RESULTS AND DISCUSSION

6.1 Magnetic Field Analysis

The magnetic field developed in the proposed MR clutch is shown with magnetic flux lines at 2A coil current in Fig. 9(a). As the MR gap height is considered in the z-direction, the z component of magnetic flux density value is found to vary from -1.82 T (minimum) to 1.87 T (maximum). This negative sign shows that the induced electromagnetic force opposes the change of magnetic flux associated with a surface. If the field points out of the surface (in the same direction as the normal) then the flux is positive; otherwise, it

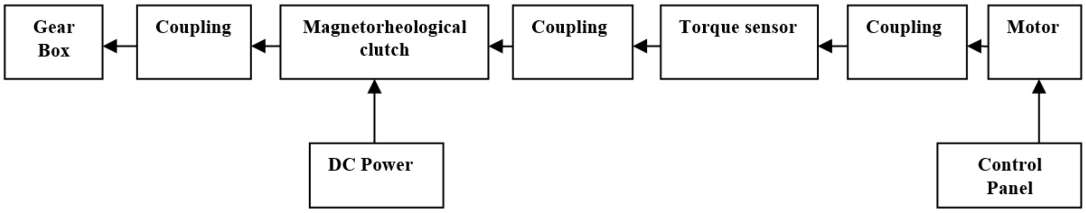


Figure 7. Schematic of a test rig for testing the MR clutch prototype.

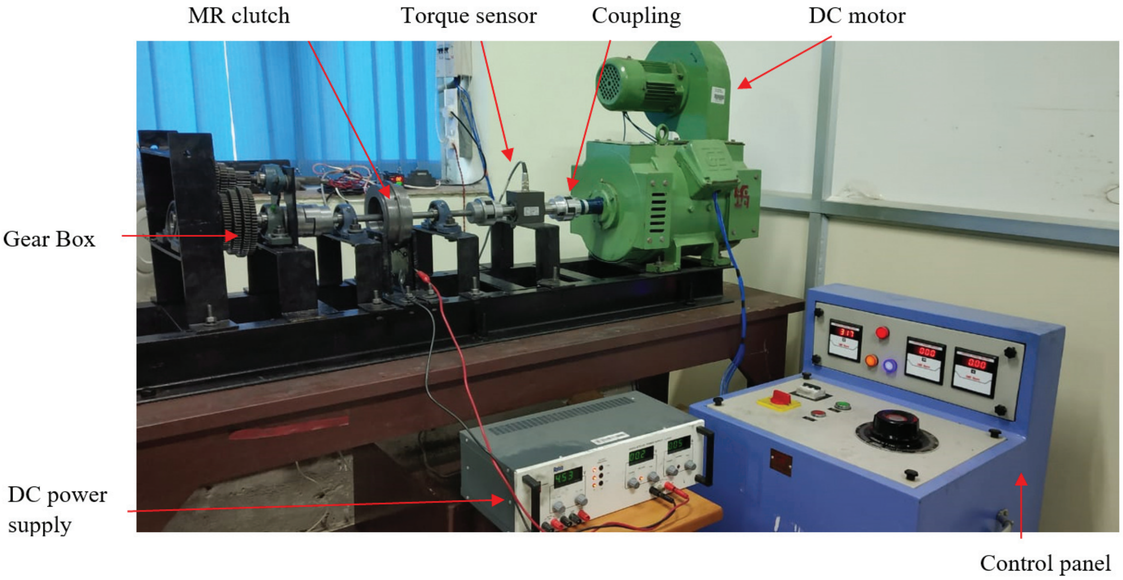
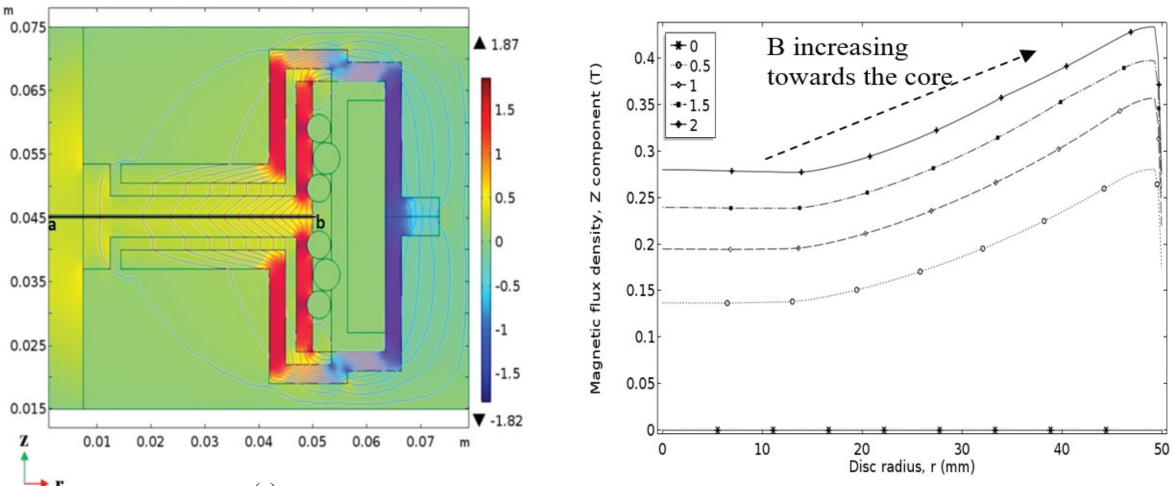


Figure 8. Test set-up for testing the MR clutch prototype.



(a) (b)

Figure 9. (a) Magnetic flux density, z component (T) with streamlines at 2 A and (b) Magnetic flux density in Z-direction with disc radius(r) at cutline ab.

is negative. The red color zone indicates the higher magnetic field and it is shown by streamlines. A horizontal cutline (ab) is drawn, for analyzing the magnetic flux inside the MR gap of the MR clutch as shown in Fig. 9(a). The cutline is taken at height 45.25 mm in the z-direction, starts from zero to 50 mm in the radial direction. The black color line "ab" shows the cutline plotted in the graphical window of simulation software. The line graph of magnetic flux density in the z-direction (mf. Bz) at the horizontal cutline (ab) for various currents (0-2A) with a disc radius is shown in Fig. 9(b). It presents maximum magnetic flux density is 0.43 T at 2A towards the core side, whereas that is 0.28 T close to the shaft side. Since the core side of the clutch disc is nearer to the coil hence it is more affected by the magnetic field.

6.2 MR Fluid Flow Analysis

An equation from literature[20] has been used to find the flow of complex fluid (such as grease). It shows the relation between velocity and r coordinates.

$$u(r) = U_s e^{\alpha(r-r_i)} \left[\frac{\frac{r_0}{r} - \frac{r}{r_0}}{\frac{r_0}{r_i} - \frac{r_i}{r_0}} \right] \tag{3}$$

Here U_s is the rotating speed of the shaft, r_o is the outer radius, r_i is the inner radius, and α is a constant (fitting parameter), which is evaluated experimentally. This equation is used in symmetric or identical geometry. MR fluid is kept in between the two parallel plane discs highlighted by the blue color domain as shown in Fig. 10. Figure 11(a, b) shows the MR fluid flow inside the MR clutch at (a) 250 rpm and (b) 1500 rpm. It shows that the rotational speed of disc affects the MR fluid flow. As the rotational speed increases, the MR fluid flow increases. The maximum value of flow velocity is found close at the core side, which is 1.4 m/s for 250 rpm and 8.39 m/s for 1500 rpm. The velocity increases as moving from the shaft side to the core side due to the centrifugal forces. The MR fluid, which sticks to the surface of the disc, has a higher value of fluid flow as compared to the adjacent surface or core side.

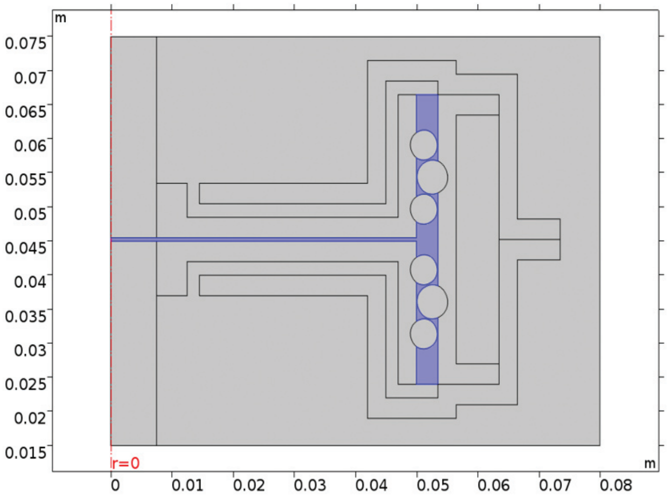


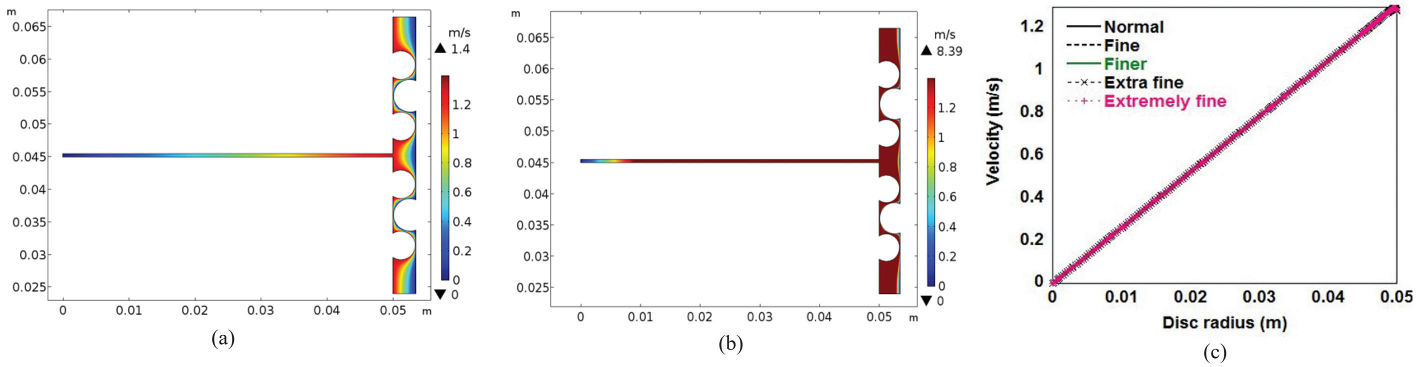
Figure 10. MR fluid flow path through a self-made labyrinth seal arrangement with a 0.5 mm MR gap.

Figure 11(c) shows the MR fluid flow (at "ab" cutline) at 250 rpm with a disc radius at different mesh sizes. The same value of velocity for each mesh size has been observed.

6.3 MR Fluid Particle Migration

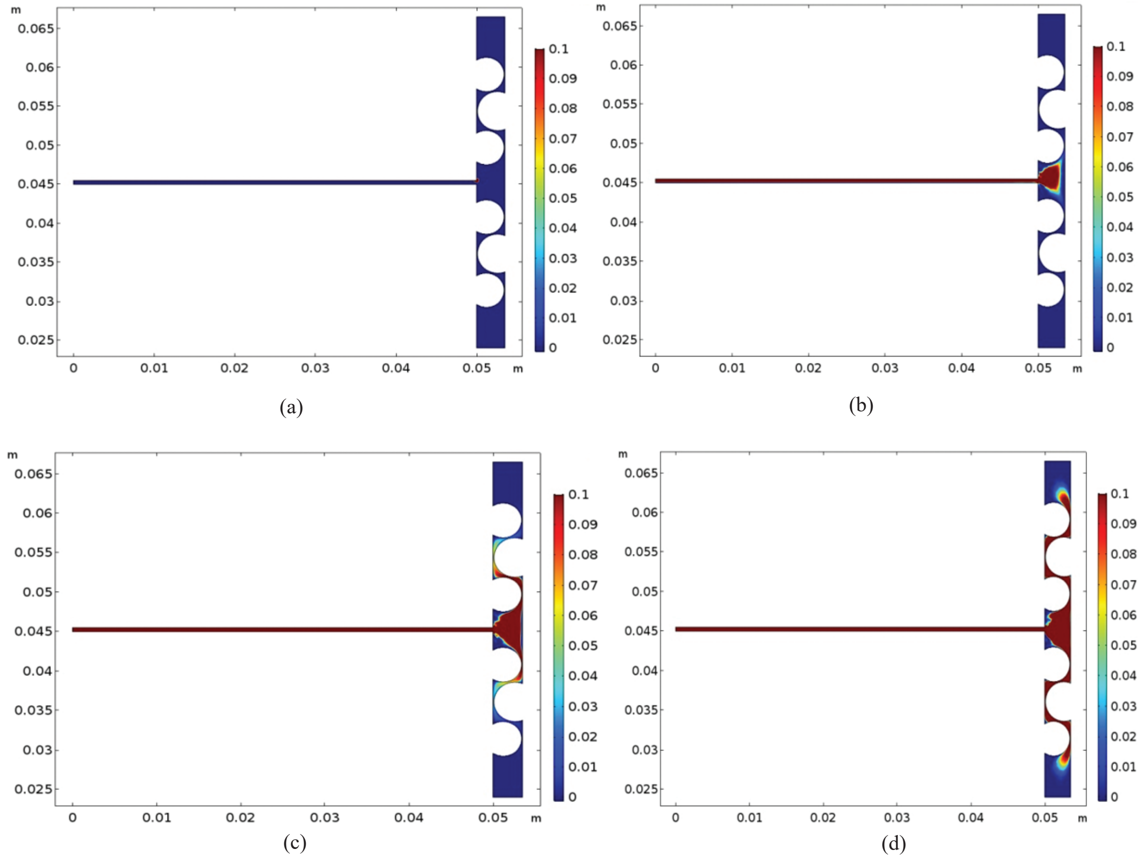
To avoid the leakage of iron particles an attempt has been made to analyze the dispersed phase flow using O-ring based labyrinth seal. A mixture model laminar flow study module of simulation software is used to investigate the MR fluid iron particle migration or leakage through the self-made labyrinth seal clearance. The velocity surface plot at 100 rpm for the above geometry inside the MR gap and clearance is shown in Fig. 12. It shows the MR fluid particle concentration in the MR fluid domain at 100 rpm when time is (a) 0 s (b) 1800 s (c) 3600 s and (d) 6000 s. Simulation gets converged after 6000 s, which indicates that the labyrinth seal can stop leakage effectively.

Density (ρ_{cp}) of continuous phase[21], i.e. MR fluid is 3860 kg/m^3, density (ρ_d) and radius (a) of dispersed phase[22] (iron particles), i.e. 7860 kg/m^3 and 7 µm respectively. At the inlet,



(a) (b) (c)

Figure 11. Surface velocity (m/s) of MR fluid at (a) 250 rpm and (b) 1500 rpm and (c) velocity profile for different mesh sizes.



(a) (b) (c) (d)

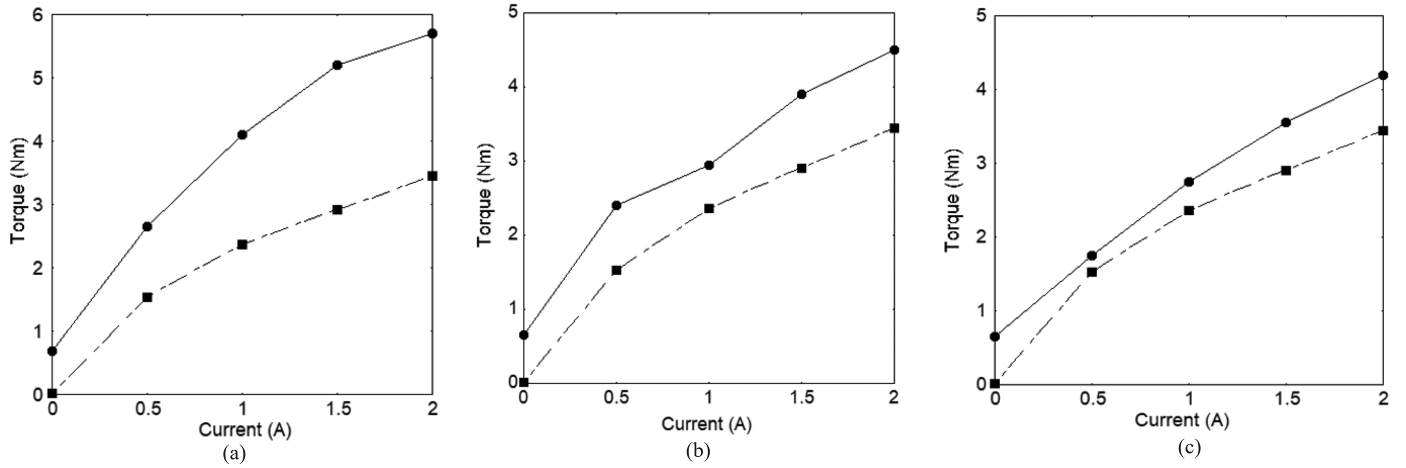
Figure 12. MR fluid particle volume fractions for MR clutch with labyrinth seal at 100 rpm when time (a) 0s (b) 1800 s (c) 3600 s and (d) 6000 s.

the normal inflow velocity is 'u_{in}’ which depends upon volume inflow rate and area of the inlet. Assuming the volume inflow rate is 0.1 ml/min and the dispersed phase fluid domain as a function of the centrifugal forces per unit volume. MR fluid domain[23] expressed as concentration is 0.4 and at outlet suppress backflow has been applied and dispersed phase volume fraction maintains zero. In the MR fluid domain, volumetric force is applied in the phi direction.

$$F_{vol}=\frac{4a^3U_s^2(\rho_d-\rho_{cp})}{3rw(r_{d0}^2-r_{di}^2)} \qquad (4)$$

Here U_s is the rotational speed of the input disc, w is the width of the MR fluid domain, r_{d0} is the disc outer radius and r_{di} is the of the disc inner radius. It is assumed that both input and output discs are rotated. As per the geometry of the self-made labyrinth seal located on the circumference of the clutch discs, a clearance is provided for smooth rotation. The migration of the MR fluid particles towards the end of the core is apparent as time increases from zero to two hours. The volume fraction of solid-phase has maximum packing close to the top and bottom end of the disc surface due to shear-induced migration. Results show that the MR fluid iron particle gets leaked from the clearance between the labyrinth seal and the clutch discs after 6000 s.

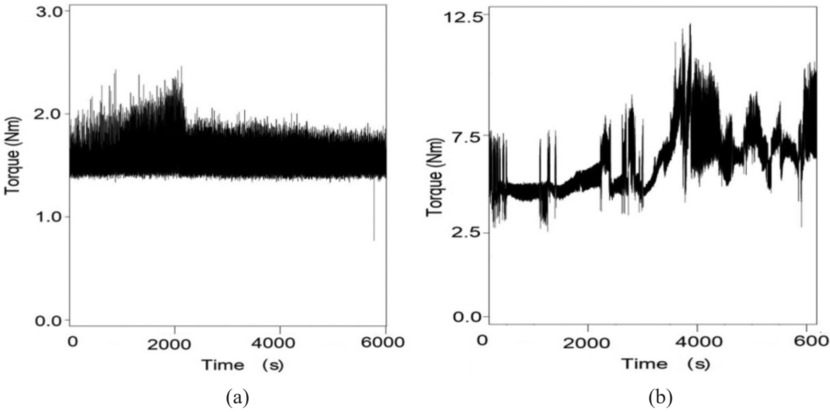
The clutching torque of the fabricated MR clutch is measured in the experimental test rig. The comparison of results found by simulation and experiment at different rpm are shown in Fig. 13. The simulation results show the same trend with



(a) (b) (c)

Figure 13. Transmission torque plots of MR clutch are shown by solid line: experimental torque and dash-dot line: simulation torque at (a) 250 rpm (b) 750 rpm and (c) 1500 rpm.

experimental results. It shows that as the input current changes, the clutching torque also get changes. The value of maximum experimental torque is 5.7 Nm and maximum simulation torque is 3.45 Nm at 2A and 250 rpm, whereas at 1500 rpm maximum experimental torque is 4.2 Nm and maximum simulation torque is 3.45 Nm at 2A. The simulation result is slightly lower than the experimental results at higher rpm. It may be due to the simple Bingham model used in simulation and ignored the shear-thinning action of MR fluid and contact friction of the MR clutch components. The effect of temperature on the MR fluid is also ignored in the simulation. To check the durability of self-made labyrinth seal experimentally, DAQ and HMI software have been used in the experimental test rig. Figure 14 shows the experimental torque results measured with the help of the DAQ. The experiment has been carried out up to 6000 s for 0A and 2A coil current at 100 rpm. It shows the effectiveness and sealing action of the designed seal as predicted in simulation. Figure 14(a) shows constant torque value at 0A current up to 6000 s. While higher transmission torque is found during an experiment in on state condition i.e. at 2A. Thus MR clutch with sealing at a larger radius can be used for torque transmission for a long duration.



(a) (b)

Figure 14. Transient experimental torques of fabricated MR clutch at (a) 0A and (b) 2A.

7. CONCLUSIONS

In the current study, an MR clutch with sealing at a larger radius disc is developed. A numerical study using the CFD method is used for leakage and particle migration analysis through the MR gap in the designed MR clutch. Simulation software has been used to study the magnetic field distribution and MR fluid flow inside the MR fluid gap. CFD approach has been used to study the laminar flow and dispersed phase flow of MR fluid. To stop the leakage rubber made O ring is used in the MR clutch as like labyrinth seal pattern. CFD results are then compared with the experimental results. It shows the effect of CFD analysis on torque transmission in the MR clutch. As there is a change in rpm, the flow velocity also changes, which is maximum at high rpm. Flow velocity changes from one disc to another disc that confirms the torque transmission in the MR clutch. MR fluid particle migration proofs the concept of leak-proof labyrinth seal based MR clutch. Durability and seal life has been predicted by simulation and verified experimentally. This study helps the designer to predict the seal life of the MR fluid-based device.

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In the current study, he checked the manuscript. All the simulation and experimental studies mentioned in the paper was suggested by him.