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Analysis of Magnetorheological Normally Close Directional Control Valve

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Abstract

This valve is intended for use in valves for steering movement, using the qualities of the Magneto-rheological (MR) fluid to regulate the fluid, direct contact without the utilization of moving parts like a spool, a connection between electric flux, and fluid power was made, The simulation was done to employ the" finite element method of magnetism (FEMM)" to arrive at the best design. This software is used for magnetic resonance valve finite element analysis. The valve's best performance was obtained by using a closed directional control valve in the normal state normally closed (NC) MR valve, with simulation results revealing the optimum magnetic flux density in the absence of a current and the shedding condition, as well as the optimum pressure. Finally, the MR valve proved successful in proportionally dominant in the direction and the quickness of the hydraulic actuators, and the new model allows hydraulic valves to be replaced with smaller valves while also lowering complexity.
(Some of the figures in this article are only available in color in the online edition.)

Keywords: *Magneto-rheological (MR) fluid, MR valve, FEMM magnetic programming, normally close (NC)MR valve.*

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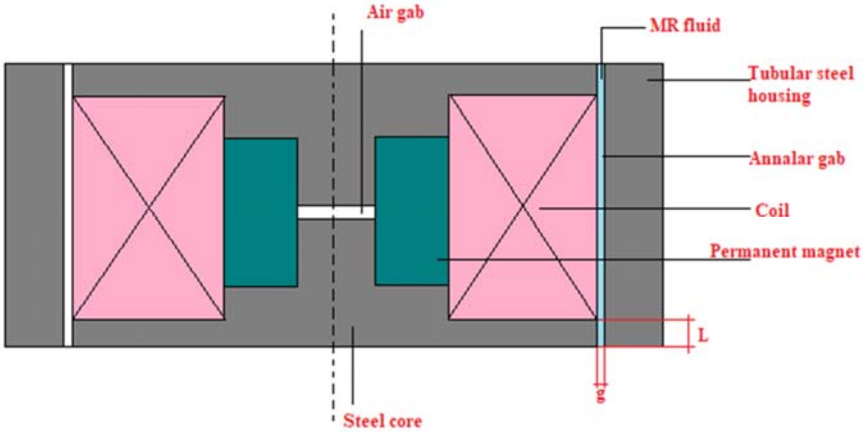
1. Introduction

The directional control valve is the most important components of the hydraulic system. The directional control valve has a sophisticated design, with a moving spool controlling the actuator's direction for the desired speed. One of the controlled fluids is a magneto-rheological (MR) fluid. Without the usage of moving parts, direct contact between the fluid power and magnetic field can be established using the properties of MR fluid.

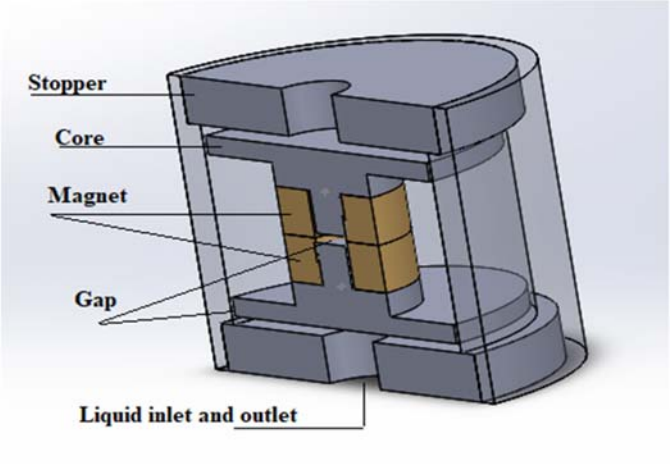
Shaju et al. [1] have constructed a “Wheatstone bridge hydraulic power circuit” using four MR valves to operate a hydraulic actuator using a gear pump as the source of hydraulic power. The output load and driving current to the MR valve determined the hydraulic system's performance. An MR directional control valve with no moving parts was recently built using the rheological properties of MR fluid. Salloom and Samad came up with the new compact design. They recommended integrating a series of singular MR valves into a small unit that makes the design and manufacturing process easier. They demonstrated how the MR directional control valve is built and how it works. As a result, the primary goal of this work is to provide the results of an experimental test of a newly built MR directional control valve [2]. At 0.6 A of current, an annular resistance slot of 1 mm in width, and a radial resistance slot of 0.5 in width, an optimal magnetic field distribution, and a higher pressure fall of 24.5 bars were achieved. Theoretical calculations, analysis, simulation, and experimental tests were used to calculate valve performance, particularly pressure drop. At 1.2 A of current, the pilot pressure fall can reach. 26.5 bars, which is consistent with simulation results. FEMM software is being used by other researchers for analysis [3]. Salloom and Samad [4] described the construction and present the individual directional control (3/4 MR valve), in which finite element analysis with FEMM software was used to achieve the optimal design, and this design achieved good results for the intensity of magnetic flux in the effective gap, and then an inverse relationship between the current and the flow of intelligent liquid. The design was distinguished by the valve's tiny size and length. If enough of the coil outside the functional area if is damaged, it can be easily and quickly replaced. For hydraulic actuator control, the “(4/3 MR valve)” can replace various types of spool directional control valves. Three variants of the magnetic resonance MR damper valve structure were created, built, and tested as part of this research. The volume of the MR damper, the volume of the MR fluid, and the number of coil turns were measured. These variables were compared, and it was discovered that the proposed MR damper with the concentric valve structure has a higher dynamic range of damping force with a less massive and lower price in terms of easy assembly, direct maintenance, and MR fluid volume (where the serpentine settled valve on the bypass channel of the damper). neglected to focus on the variation of the damping force, as it was proven that this force can be increased from 20 N to 600 N at a current of 0.3A, the simulation results were completely consistent with the experimental results when the friction force and the accumulating force were Neglecting neglected to focus on the variation of the damping force, as it was demonstrated that this force can rise from 20 N to 600 N at a current of 0.3A [5]. The terms “magnetic resonance fluid” (MR fluid) and “magnetic resonance elastomer” (MR elastomer) have steadily gained popularity. MR fluid is a type of characteristic fluid that is transient when the magnetic field intensity changes. When there is no external magnetic field, the magnetic particles are uniformly dispersed in the base fluid, and the MR fluid is in a fluid state; The ferromagnetic particles form a chain structure parallel to the magnetic field line when an external magnetic field is applied, and the magnetic fluid changes from a liquid to a semi-solid in microseconds [6]. The radial MR valve with a single-coil was simulated using ANSYS software, which works on a decrease in pressure by changing the internal structure (increase in dimensions to easily block the internal channel), where the response time with the current was tested as well as the change in pressure under variable loads. The overall pressure loss of the primary valve is 1.842 MPa when the applied current is 1.8 A, whereas the total pressure drop of the optimum valve is 2.58 MPa, indicating a 40.07 percent increase. Meanwhile, at a current of 1.25 A, the greatest damping force of the better cylinder system controlled by the radial MR valve can reach around 3.6 kN [7]. The objectives of this research are to create and refine an "MR directional valve" that is adequate for use in hydraulic monitoring systems that use the MR fluid. As a result, the fundamental goal of this paper is to suggest a squeezed design of MR valves for use in directional control valves that use MR fluid. This valve's structural design and operating principles are explained, along with a functional experiment. "A simulation using the finite element method of magnetism (FEMM) is also used to analyze the valve's fulfillment".

2. Construction of a Normally Close MR Valve

For controlling the direction of movement of the MR, a normally close (NC) valve was created to be small and simple to install. A body, double covers, and four singular MR valves make up this valve. The valve's body was prepared to hold four singular valves. The active portion is a single MR valve (element). The last includes a pulley, double cores, two magnets, and a return route through which the magnetic flux can pass, as indicated in Figure 1. Low carbon steel was selected for the steel rail because of its low relative permeability (1018), the coils are straightforward to change because they are placed outgoing of the active area. The coil's parties are simply fed via the body's opening. The single MR valve has a short length (19 mm). It can be utilized in MR valves with 4/3 directional control, making it smaller than the exemplary one.



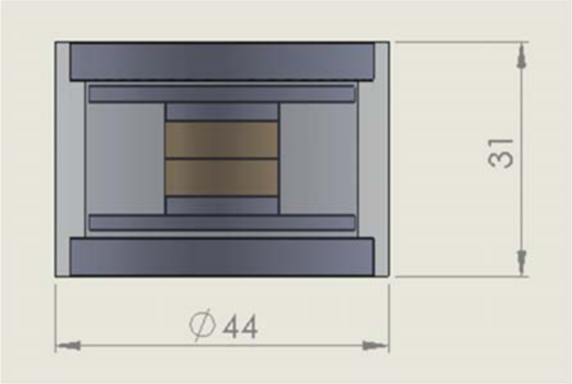
(a) Schematic of the single coil MR valve.



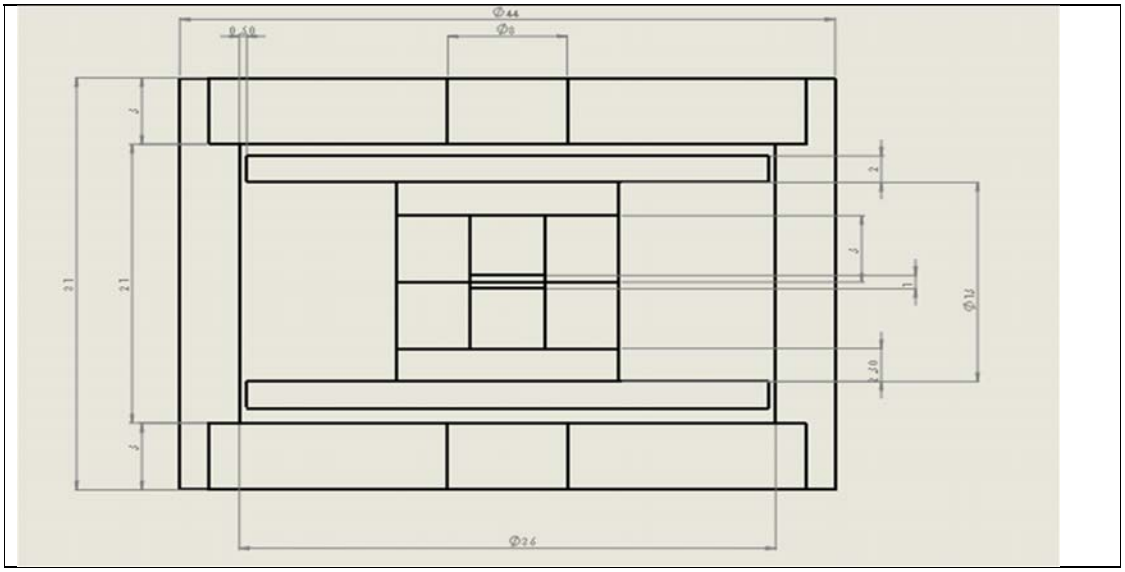
(b) MR Valve (element) construction

Fig. 1. Assembly of singular MR Valve (element).

The valve body's magnets are one of the most powerful sorts of magnets, they are made of neodymium (N35). The inner contents are surrounded by a low carbon steel cylinder with a 0.5 mm gap. The valve body is sealed on both ends with Teflon insulating material, with a hole on each end for the smart MR fluid to enter and depart. The dimensions of this valve are shown in Figure 2.



(a) 3D of MR Valve



(b): 2D of MR Valve

Fig. 2. The Dimension (in mm) of the MR valve.

3. The Precept of Work

The presence of a magnetic field due to the presence of permanent magnets in the valve body, the iron particles in the MR fluid line up in the form of chains, forming a solid substance that prevents the fluid from passing through, the valve is completely closed in its normal state, preventing the fluid from passing through without shedding any current.

When an electric field is activated DC on the valve coil, an electric field opposite the magnetic field is generated, cancelling the magnetic field's effect on the valve. This causes the solid chains to disintegrate with the liquid, allowing the liquid to pass through and the valve to become completely open. An increase or decrease in the current is provided to the coil to adjust the amount of fluid flow through the current. Depending on which position of the valve is chosen, this can be accomplished utilizing various coil connections with certain electrical circuits. The circuit's purpose is to supply variable current to the valve's coils while also selecting the valve's operation position.

The circuit is provided with a 12 V DC input and produces a variable current of 0–2.5 A as an output. A variable current is achieved by connecting a rheostat to the valve's coil in series, and the selected position is achieved by connecting a three-position select switch to relays.

4. Modeling

The following methodology was used to evaluate the NC MR valve's functionality. “Based on the MR fluid flow and rheological stress, the pressure mode was employed as a playback mode in a singular MR valve, as shown schematically in Figure3.

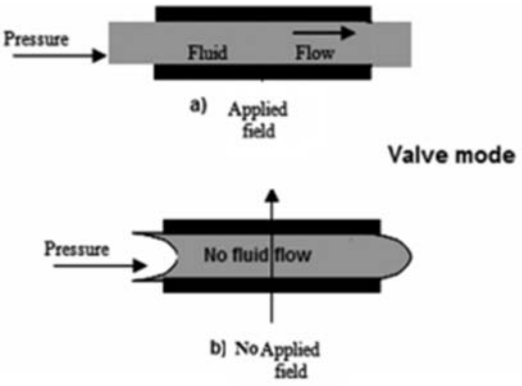


Fig. 3. Representation of the pressure mode of the NC MR fluid flow.

The MR fluid's yield shear stress reduced as the magnetic field increased, and vice versa." The MR fluid behaved like Newtonian fluids in the existence of a magnetic field". As a result, the MR fluid follows the Bingham plastic's flow in the existence of a magnetic field, with variable yield strength. Bingham's equation in this scenario is as follows (Jolly et al., 1998):

$$\tau = \eta\dot{\gamma} + \tau_y(H) \qquad \tau > \tau_y \qquad \dots (1)$$

where τ is shear stress, η is the dynamic viscosity, $\gamma^{\cdot}$ is the fluid shear rate, $\boldsymbol{\tau}_y$ is magnetic-field-dependent shear yield stress, and H is the magnetic field (H=0). This equation was utilized to create a gadget that could work with MR fluid.

The pressure decrease in valve mode is caused by the sum of the viscous (pure rheological) component and the magnetic-field-dependent (MR) components The value of this pressure drop is calculated using the following approximation: (Li and colleagues, 2003):

$$\Delta P = 2\left(\frac{6\eta QL}{g^3 w} + \frac{c\tau_y L}{g}\right) \qquad \dots (2)$$

The viscous component of this equation, whereas the dynamic viscosity is η (Pa s), the flow rate is Q (m3/s), and the geometric length, width, and gap size of the flow rectangle channel are L, w, and g (m), respectively.

Theoretically, this component of the equation is correct. The other half of the equation, on the other hand, is reliant on the magnetic field ingredient. In reaction to the applied magnetic field, the yield shear stress $\tau_y(\mathrm{N/mm^2})$ is promoted. In the rheological pressure drop, the geometric values L and g in the unit (m) are the same. Many considerations were crucial during the design period of single MR valves. The fluid gap, the number of wire turns, the bobbin diameter, the flux length, the core, and the flux return thickness, were all considered. Other factors may influence the pressure drop, and the empirical factor ‘c’ represents the influence of these other factors. To build an efficient MR valve, the flux density in the fluid gap should be constant. The relative permeability of the MR fluid is significantly lower than that of low-carbon steel (such as two cores, bobbin, and flux return). In this investigation, the distance is reduced to 0.5 mm.

5. Analysis

Except for yield shear stress (τ_y), all resolve elements on the right-hand side are known, according to equation 2. An analysis is required to deem the pressure drop of a singular MR valve. The yield shear stress(τ_y)of MR fluid in valve gaps is studied using the magnetic flux density acquired from the analysis. Equation 2 can be used to compute the pressure drops. In the magnetic analysis, the cylindrical shape of the MR valve has a complex structure. Only FEMM can be used for the analysis. It is insufficient to evaluate the MR valve as a 2-D axisymmetric pattern due to symmetry as illustrated in figure 4. The magnetic circuit was modeled using a finite element method, as illustrated in the diagram. Figure 5 shows the model created with the FEMM software.

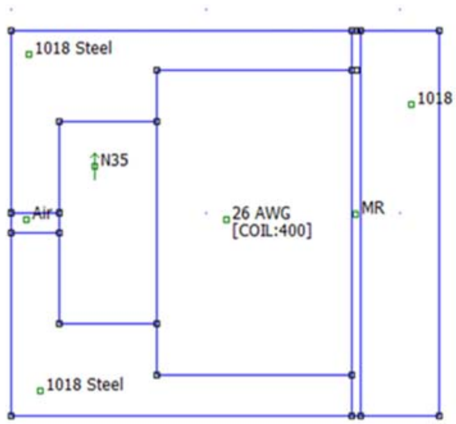


Fig. 4. The dimensions of MR valve in FEMM software

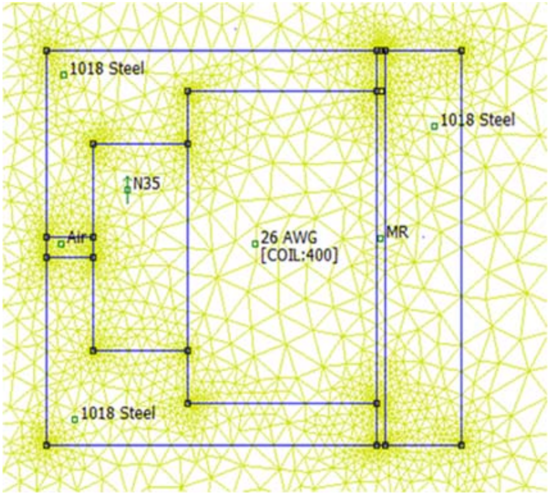


Fig. 5. FEMM model of NC MR valve

Figure 6 depicts the magnetic field direction in the MR valve. The MR fluid ownership was chosen by the MRF-132DG standard [8]. From the magnetic flux density (B) vs. magnetic field strength (H) (BH) curve of the MR fluid, point H and B belong to the MR fluid as data for novel nonlinear material introduced to the FEM analysis. The magnetic coils had a total of 400 turns. During the simulation, a current of 0 to 2.5 A was delivered to the coil. To model an MR valve, MR fluid was used. Nguyen et al. (2007, 2008) have approximated a polynomial equation to obtain the shear stress.

$$\tau_y(kPa) = 52.962B^4 + 176.51B^3 + 158.79B^2 + 13.708B + 0.1442 \quad \ldots(3)\ [9]$$

B is magnetic flux density in tesla calculated along the valve gap by finite element analysis by FEMM software.

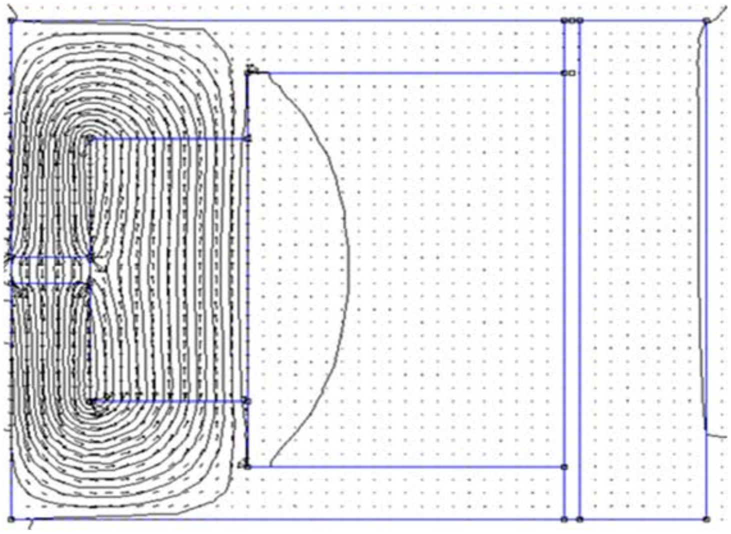


Fig. 6. The NC MR valve magnetic field direction.

6. Results and Discussion

The FEMM software was used to perform a finite element study on the NC MR valve. The MR valve's performance is restricted by the MR fluid's finite yield stress. A magnetic strength of 340–390 kAmp/m is ideal. The shear stress in the yield zone is about 47 kPa.

Figures 7 and 8 illustrate the magnetic density and magnetic field results of the MR valve’s resolve test using the FEMM software, respectively. When there is no current (I=0A), the findings are expressed in the nomenclature of magnetic strength in the valve's active gap. The “magnetic strength intensity(H)” was found to be 300 kAmp/m according to the proposed design of the MR valve. The proposed MR valve provided an optimal H value. The $\tau_y$was calculated using equation 3 and the B acquired from the FEMM program (τ_y=47kpa).

Figure 9 and table 1 illustrate the emulation results for the MR valves. When the puncture thickness (g) is 0.5 mm, as a function of valve gap distance, figure 9 shows the “magnetic flux density induced by various currents in MR valve coils. The magnetic flux lines are perpendicular to the MR fluid’s flow in this case”. The magnetic flux density was practically constant at the valve gap distance and dropped as the current of the valve coils increased. The styling of the valves was considered to maximize the magnetic domain’s controllability. The maximal magnetic domain did not transcend the magnetic field's saturation strength.

Table 1 depicts the influx in MR valves as a function of current variation beneath various pressure reductions. The flow rate of MR valves increases as the current increases, indicating that they are primarily impacted by magnetic domains, which are specified by the coil current. It's worth noting that the flow rate rises in lockstep with the current until it reaches 2.5 A. By looking at pressure decline curves, it's clear that when the pressure drop is 650 kPa, the MR fluid isn't flowing at a current 2.5 A. As a result, because the valve can open at maximum current, a 650 kPa operational pressure decrease is adopted (2.5 A). By adjusting the current value, the MR valve can be controlled with a variable flow rate (Q): a high current for a high flow rate, and a low current for a low flow, as shown in figure 10. The experiment explained how a valve works and how the proposed electrical connection can be used to change the flow direction.

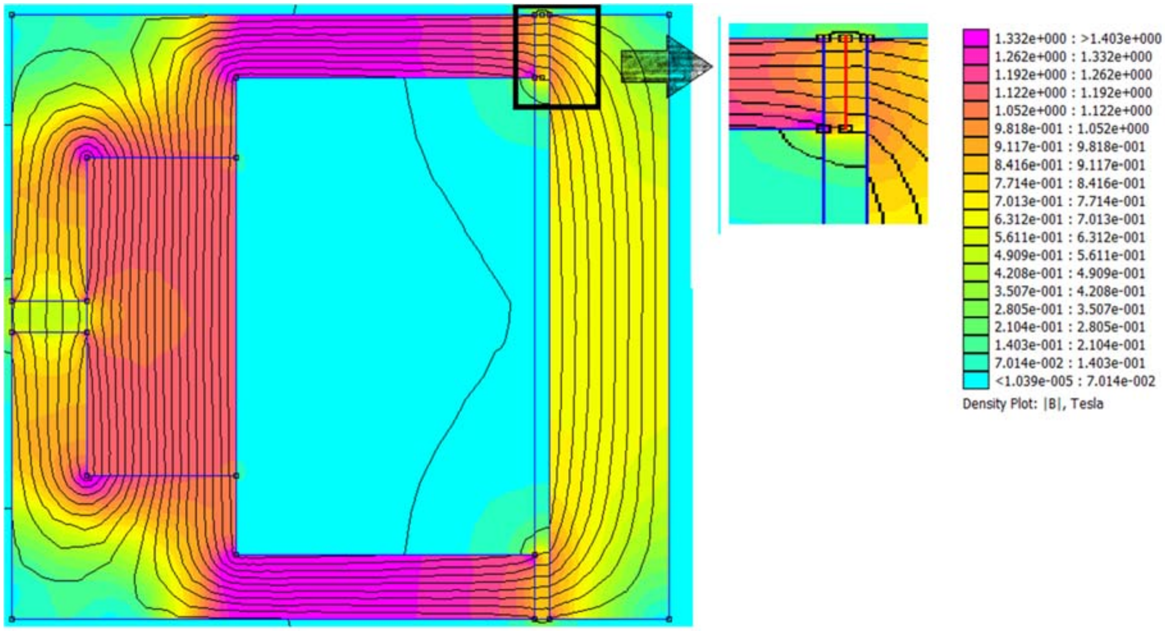


Fig. 7. The NC MR valve magnetic flux intensity result.

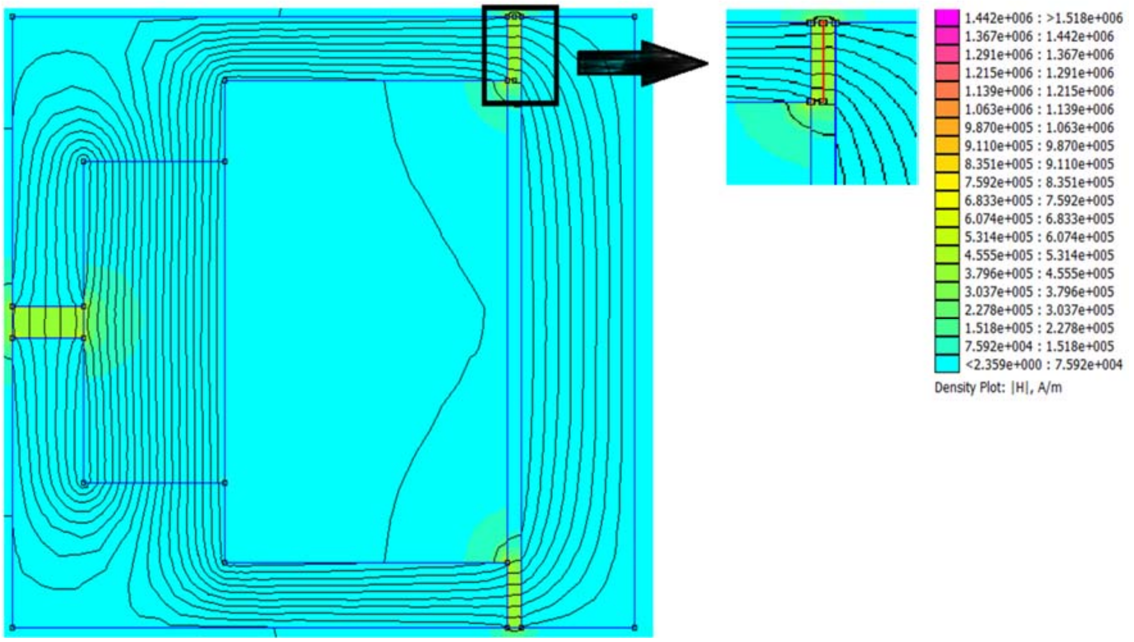


Fig. 8. The NC MR valve magnetic field strength result.

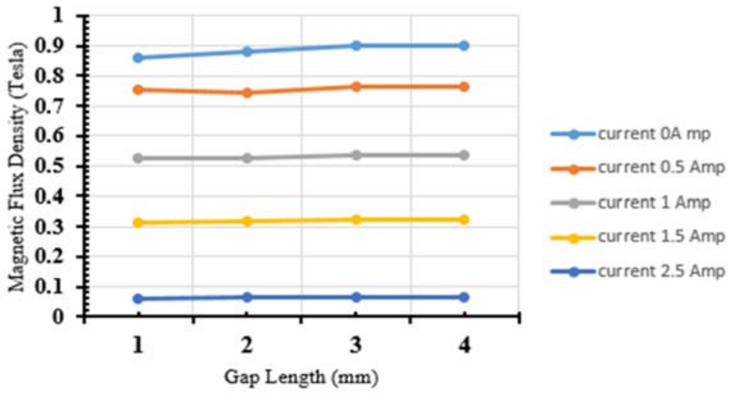


Fig. 9. The magnetic flux intensity (B) along the MR valve gap.

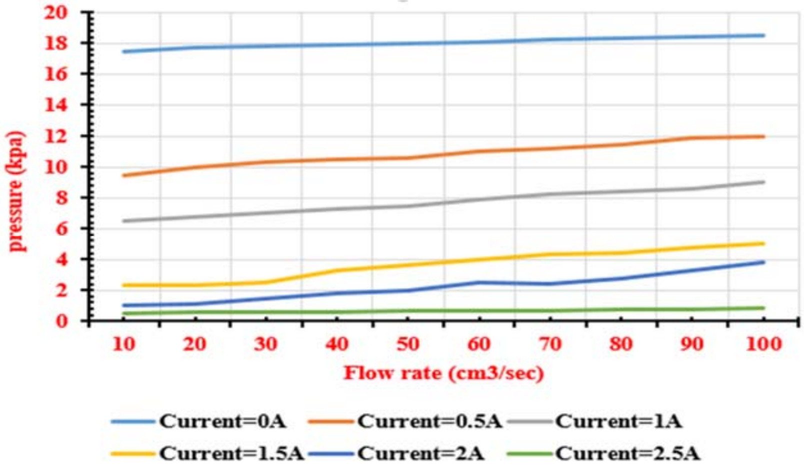


Fig. 10. Relation between flow rate and pressure drop for different currents.

Table 1,
The relation between current, magnetic flux intensity, pressures, and shear stress to MR Valve

Current (A)	Magnetic Flux Density (B) (Tesla)	Shear stress τ_y	Pressure (bar)
0	0.899	47.1488	18.8
0.5	0.765	38.4553	17.07
1	0.535	30.23	12.09
1.5	0.325	15.9	6.36
2.5	0.064	1.626	0.65

The MR valve has a changeable flow rate (Q) that is controlled by adjusting the current value; a high current equals a high flow rate and vice versa. When the current is 0 A, the valve closes due to the magnetic field generated by the permanent magnet, and the magnetic flux intensity value is a maximum of 0.9, preventing it from flowing. When the current is 2.5A, the B 0.325, which allows the MR fluid to flow. The magnetic flux values that were acquired from the FEMM software are given in figures 11,12, and 13, and show a reasonable relation between the current and flow rate and pressure drops.

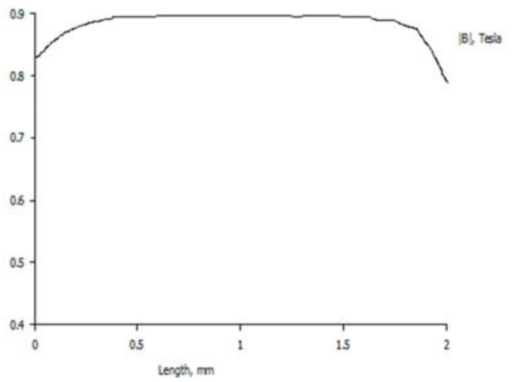


Fig. 11. Magnetic flux density(B) in FEMM software when I=0A.

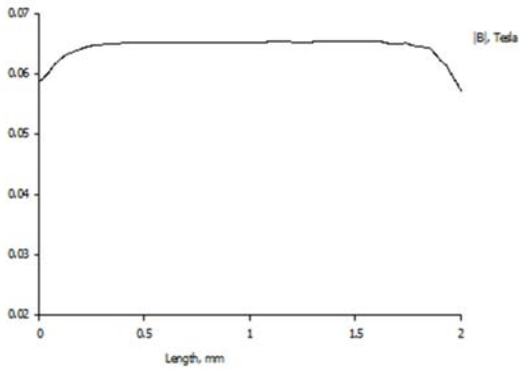


Fig. 12. Magnetic flux density(B) in FEMM software when I=2.5A.

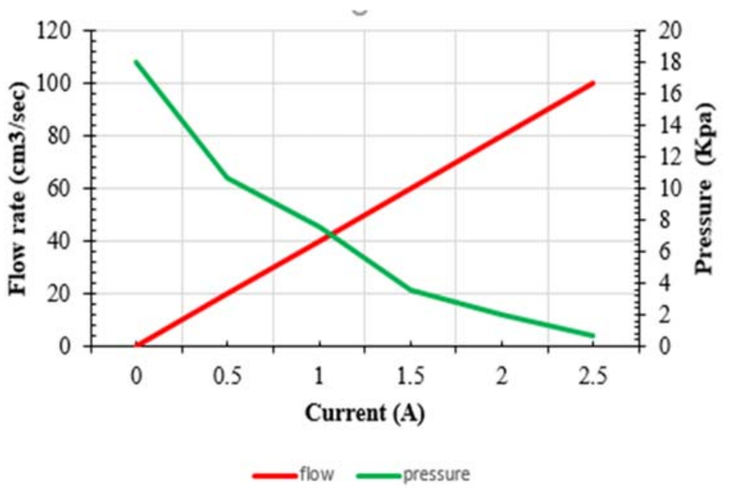


Fig. 13. Reasonable relation between current and flow rate and pressure drops.

7. Conclusion

The structure and operating norms of a singular valve that is generally closed without moving components and can be controlled by the properties of the magnetic fluid are covered in this paper. The valve has a total length of 19 mm. It has a 400-turn coil, a powerful Neodymium (Ni) magnet, and a 2 mm effective gap along its length. The magnetic flux density (B) is obtained when applying different values of the current, as the flow rate increased with the increase in the value of the current and the relationship was proportional between current and flow rate, and the value of the pressure decreased with the increase in the current, implying that the pressure and the current had an inverse relationship. The valve was tiny in size, and the valve coil was outside the effective region, allowing it to be easily replaced if it was damaged. Different values of the magnetic flux in the gap of 2 mm were determined from the simulation using the finite element analysis in the FEMM program. When the valve is closed and the current value is zero, an ideal magnetic flux density (B) of around 0.9 Teslas is obtained. When the current is 2.5 A, the valve is fully open and has maximum flow, where the magnetic flux density (B) value is 0.0653 Teslas.

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تحليل صمام تحكم اتجاهي مغناطيسي مغلقاً في حالة الطبيعة لا يسمح بمرور السائل

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الخلاصة

تم العمل في هذا البحث عن طريق تحليل العناصر المحدودة للوصول الى أفضل تصميم لصمام تحكم اتجاهي مغلقاً في حالة الطبيعية لا يسمح بمرور السائل دون الحاجة الى اجزاء متحركة، من خلال صفات السائل المغناطيسية الريولوجية تم خلق مجال بين كثافه التدفق المغناطيسي وقوة السوائل ، ان الهدف الرئيسي من هذه الدراسة هو الوصل لكثافة فيض مغناطيسي مناسبه تتسبب في تصلب السائل المغناطيسي عند غياب التيار الكهربائي، حيث اظهرت النتائج التجريبية ان الصمام قادر على التحكم في جريان السائل تدريجيا عند زيادة التيار مما وفر هذا التصميم امكانيات لتصغير حجم الصمامات الهيدروليكية، الغاء الاجزاء المتحركة، بالإضافة الى قدره على استخدامه للتحكم في اتجاه وسرعة المشغلات الهيدروليكية.