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Design and analysis of magneto-rheological relief valve using a permanent magnet

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ABSTRACT

The applications of magneto-rheological fluids have become many, and important. Especially the valves used in dampers and hydraulic systems. Including the pressure relief valve. But all of these valves are type normally open. However, the pressure relief valve should be of the normally closed type. This study presents the concept of a magneto-rheological pressure relief valve using a permanent magnetic, along with a comprehensive analysis. Using FEMM software the design analysis was performed, to determine the efficiency of its performance and work. As a result of the work, the appropriate current value was determined, which is 0.17 amps, along with the number of turns of the electric coil, the best of which was 240 turns, which was applied to open the valve at the appropriate pressure. The maximum pressure was about 2500 kPa, which can be tolerated in the valve also calculated. Through the analysis, it was also determined that 1 mm is the best thickness for the gap. As well as choose the type and dimension of the proper permanent magnet. With this work, the design is considered very suitable and efficient, and it can be developed in the future based on the same principle and method.

Keywords: magnetorheological valve, magnetic flux, strong magnet, pressure relief, FEMM analysis.

INTRODUCTION

Due to the expansion of applications using Magnetorheological fluid technology. Due to the diversity of designs and the development of the composition and quality of the Magnetorheological fluid. Some applications have become commercial. Many researchers and industrial companies have focused on damper magneto-rheological valves [1–4]. Some thought about using it in valves for hydraulic systems, such as directional or flow control valves, and very little thought has been given to the design of the pressure relief valve [5–6]. A Magnetorheological fluid is a fluid affected by a magnetic field. The designs depend on generating magnets through the electric coil. That is, if the valve needs to be closed, a magnetic field needs to be generated. This is generated by the electrical coil, which continues to exist to close the valve [7–9]. There is research using strong magnets in applications that require strong magnetic force. It has proven its strength in these applications. For example, gear applications [10]. This idea encouraged researchers to conduct applied research that takes advantage of the strength of magnetic flux in strong magnets, instead of electromagnets. To make an application it is used in hydraulic valves. The design placed electrical coils to create a field opposite to the field of a strong magnet, to control the opening and closing of the valve according to work requirements. Only a few researchers have addressed it, in their research [11–12]. The nature of the work of pressure relief valves is that they are always closed, opening only at a specific pressure. So there must be a permanent magnetic field. It is only canceled when the valve is requested to be opened. In other words, the relief valve should always be normally closed. The valve should never be normally open, even if it is operated with magneto-rheological fluid technology. This design is important for hydraulic system applications, but no prior work has been done.

This paper proposes a permanent magnet magnetorheological relief valve with a coil-permanent magnet combination, its name is a permanent magnet magnetorheological relief valve. Based on the Bingham plastic model, the pressure drop teaching model of the permanent magnet magnetorheological relief valve is deduced [13]. The simulation, and analysis of the magnetic field intensity in the flow channel of the magnetorheological valve is performed using the finite element method (FEMM). [14]. The key parameters such as gape thickness, permanent magnet size, type, effective current, and number of turns in the coil influence the performance of a permanent magnet magnetorheological relief valve are numerically studied.

Principle of work and structure

The idea of the magnetorheological valve working is based on the principle of the effect of the magnetic field on the magnetorheological fluid, where the magnetorheological fluid changes into a semi-solid under the influence of the magnetic field. In the presence of a magnetic field, the ferromagnetic particles in the magnetorheological fluid quickly form a chain structure arranged in the direction of the magnetic field, and a large number of chain-like structures produce shear stress, as a result, it will affect the pressure drop, and also reduce the path area of the fluid, which changes the rate of magnetorheological fluid flow, at the inlet and outlet of the magnetorheological valve.

The proposal design magnetorheological pressure relief valve has been developed. A model of the magnetorheological pressure relief valve structure is designed to have a permanent magnet, as shown in Figure 1, which consists of a cover made of non-magnetized metal, the valve core, the main valve ring, the valve sleeve, the non-magnetized ring, a coil holder (bobbin), the coil, and a permanent magnet. There are only two fluid flow channels in the structure, the axial fluid flow gap, which has two magnetically affected regions, and the disc gap, through which the magnetic field does not pass. When there is no electrical current in the coil, the effect of the permanent magnet will be on the effective gap. The magnetic field lines are perpendicular to the path of the fluid flow, which will generate a pressure drop at the inlet and outlet of the magnetic valve. When a current is applied to the excitation coil, an opposing magnetic field appears, which reduces the effect of the permanent magnet in the effective gap, this reduces the pressure drop at the inlet and outlet of the magnetic valve. This is the basis of the work of pressure relief valves, meaning that they are closed in the normal position, while they are open in the operating position, here is the presence of an electric current.

In this proposed design of a permanent magnet magnetorheological pressure relief valve. MRF-J25T magnetorheological fluid is selected as the working fluid of the magnetorheological valve. The τ-B relationship curve between the magnetic flux intensity of the MRF-J25T magnetic fluid and the shear stress in Figure 2, shows that the shear stress is stable when the magnetic flux density is approximately 0.5 Tesla. Using the analysis program, the relationship was found in the equation shown in Equation 1. This relationship is not derived from this work, but it is a relationship, taken with modification from several previous studies, some of which were cited in this work. It was put in the form shown in this work. The basic characteristics of the fluid are shown in Table 1 [2, 4 and 7].

$$\tau_y = 1.49834 - 37.6018\,B + 1102.102\,B^2 - \\ -2046.42\,B^3 + 1085.56\,B^4 \quad (1)$$

Design of magnetic circuit

The path and direction of the magnetic field of a proposed magnetorheological pressure relief valve are seen in Figure 3. The permanent magnet only is shown in Figure 3(a). The valve sleeve, the valve core, the permanent magnet, and other magnetic materials are all traversed by the magnetic line of the permanent magnet to create

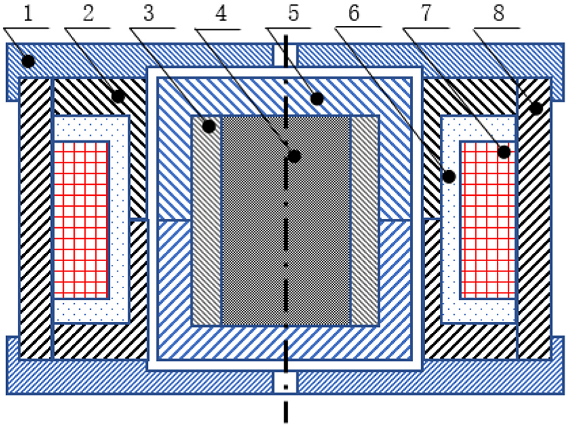


Figure 1. Structure design of relief magnetorheological valve: 1. Non-magnetic end cover, 2. Main valve ring body, 3. Non magnetic ring, 4. Permanent magnet, 5. Valve core, 6. Bobbin, 7. Excitation coil, 8. Valve sleeve

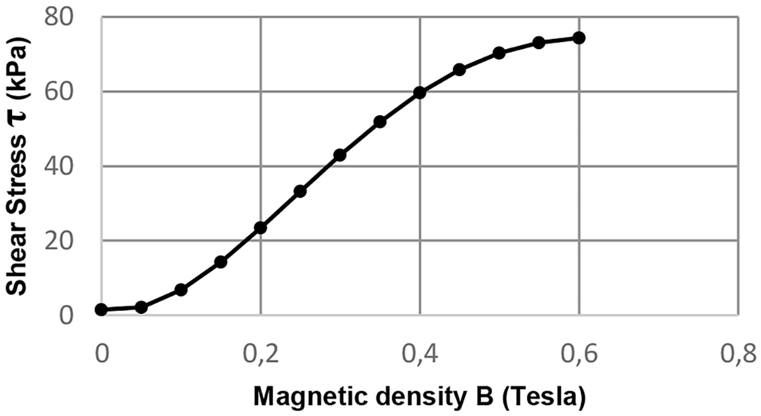


Figure 2. The MRF-J25T relationship curve between τ and B

Table 1. Parameters of MRF-J25T

MRF parameters	Value
Ferromagnetic particles to fluid volume ratio	25%
Career fluid	Hydrocarbon oil
MRF density	2.65 g/m³
Viscosity without magnetic field	0.8 Pa.s
MRF Shear stress	> 50 kPa
Operating temperature	-25~130 °C

a fully closed loop. A permanent magnet and an activated excitation coil act simultaneously to create a magnetic field which reduces the effect of perpendicular magnetic flux density, in the active gap region as seen in Figure 3(b), to create a fully open loop. The magnetic circuit can be divided into many segments of magnetic resistance produced by the magnetic circuit in various materials and positions under the magnetic line of induction [7]. According to the below formula Equation 2, obtained by Kirchhoff can be used to identify the matching magnetic circuit when exciting the coil:

$$N_c I = \oint h dl = \sum_{i=1}^{m} H_i l_i \tag{2}$$

where: N is the number of turns of the excitation coil, I is the current needed to the excitation coil, H is the strength of the magnetic field and l is the length of the portion of the magnetic circuit.

It is a relationship that describes the relationship between the magnetic field intensity (H) and the path length (l) through which the magnetic flux lines pass, with the number of turns and the current of the electromagnetic coil. It can be adopted in simple designs.

The magnetic flux can be obtained as below:

$$\varphi = \oint BdS = B_i S_i \tag{3}$$

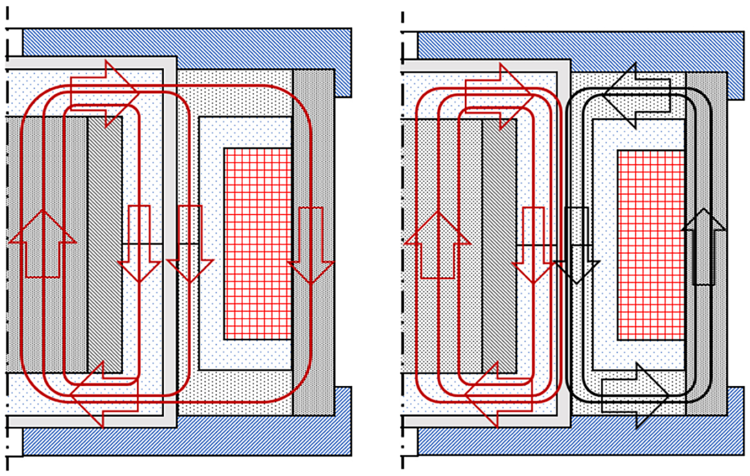

(a) (b)

Figure 3. The path and direction of the magnetic field of the relief magnetorheological valve: (a) when the permanent magnet (PM) is effective only, (b) when electromagnetic is effective in cancelling the PM effect

where: S_i is the center segment of the magnetic circuit's cross-sectional area and B_i is magnetic flux density.

According to electromagnetic theory, the following equation represents the relationship between magnetic field intensity H and magnetic flux density B:

$$B_i = \mu_o \mu_i H_i \tag{4}$$

where: μ_i is the relative permeability of each component of the magnetic substance; μ_0 is the absolute permeability of vacuum, which is $4\pi\times10^{7}$ H/m. The magnetic circuit's reluctance of each part can be found:

$$R_i = \frac{l_i}{\mu_o \mu_i B_i} \tag{5}$$

Manipulate the above equations, it can get as:

$$N_c I = \sum_{i=1}^{m} H_i \, l_i = \sum_{i=1}^{m} \frac{B_i l_i}{\mu_o \mu_i B_i} =$$

$$= \sum_{i=1}^{m} \frac{l_i}{\mu_o \mu_i B_i} \, \emptyset = \sum_{i=1}^{m} R_i \, \emptyset \tag{6}$$

The following formula can be used to express the flux density B of each component of the magnetic circuit, provided it stays within the magnetic material's saturation flux density:

$$B_i = \frac{\emptyset}{S_i} = \frac{N_c I}{S_i \sum_{i=1}^{m} R_i} \leq B_{iset} \tag{7}$$

where: B_i can be $\leq B_{iset}$ for the matching material in the chain's saturation flux density. This is possible due to the symmetrical structure of the magnetic circuit.

The above equations are for coil, while in the proposal permanent magnet magnetorheological pressure relief valve can be applied only equations (3, 4, 5 and 7). The analysis of the valve cannot be done directly mathematically. It can be done only using finite element software. In this work, the complexity of the shape and the fact that the valve is cylindrical, this relationship cannot be applied directly. Therefore, for such cases and due to the difficulty of application, the solution is to use FEMM software, which gives the required results and relationships in detail and by simulation. The presence of the electric excitation coil generates a magnetic force opposite to the force of the permanent magnet present in the valve, and for a short period, only in the case, the valve is opened at the specified pressure. There is no effect on the stability of the valve's operation because the excitation period is short and practically ineffective.

Simulation analysis

To verify the feasibility of the design of the permanent magnet magnetorheological pressure relief valve, the proposed dimensions are shown in Figure 4. The magnetic field in the permanent magnet magnetorheological pressure relief is simulated and analyzed using the finite element method using FEMM open-source software. According to the symmetry of the structure is transformed into a two-dimensional plane. Considering that its section is a regular axisymmetric figure, the half section is selected as the simulation object without affecting the accuracy of the model solution. Figure 5 shows the two-dimensional simulation entity model of permanent magnet magnetorheological pressure relief with addressed all materials.

Automatic mish-generation is performed by FEMM software. The physical model is meshed as shown in Figure 6(a). The analysis result is out as shown in Figure 6(b). A perpendicular and parallel magnetic line of magnetic flux density is seen, without side leakage imposed. As well as electric current can also be applied to the coil circuit to the excitation coil, in case of canceling the effect of PM.

Of course, the finite element method depends on the mesh (type, number, meshing method, and distribution). In this work, the automatic mesh generation method is used. This feature is present

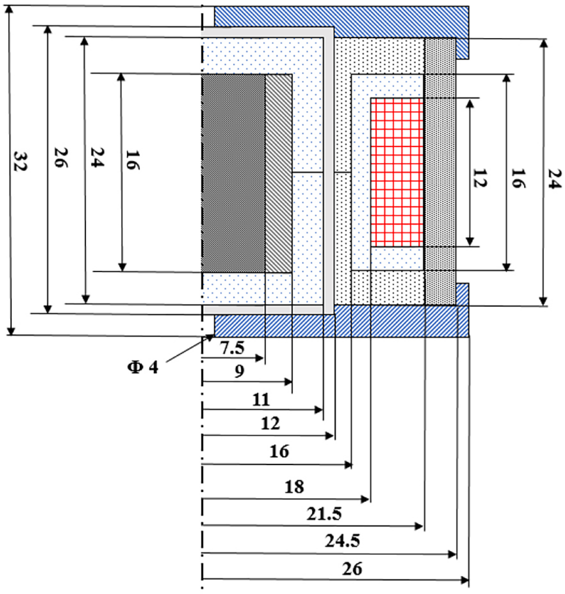


Figure 4. Design model dimensions of proposal Relief magnetorheological valve

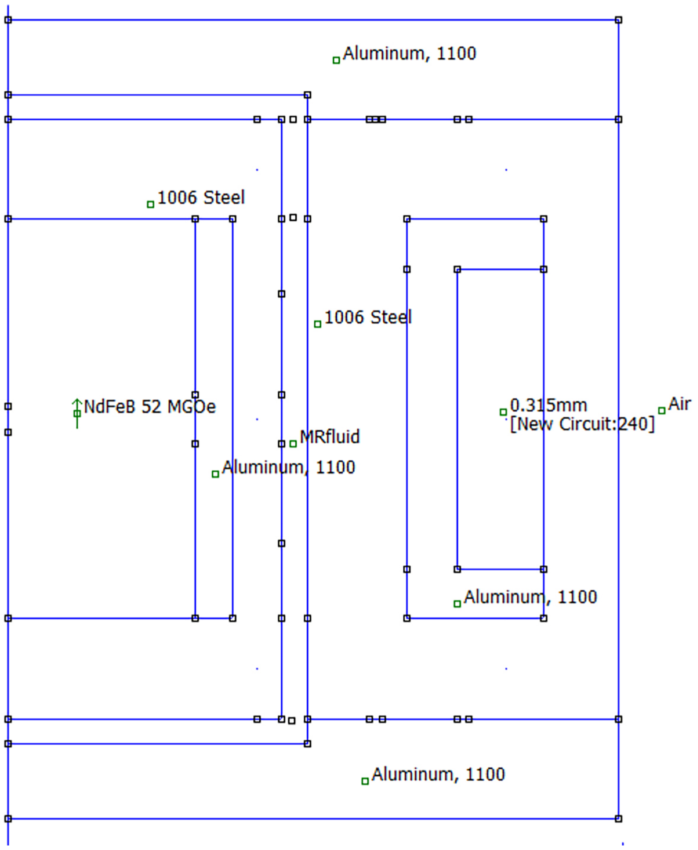
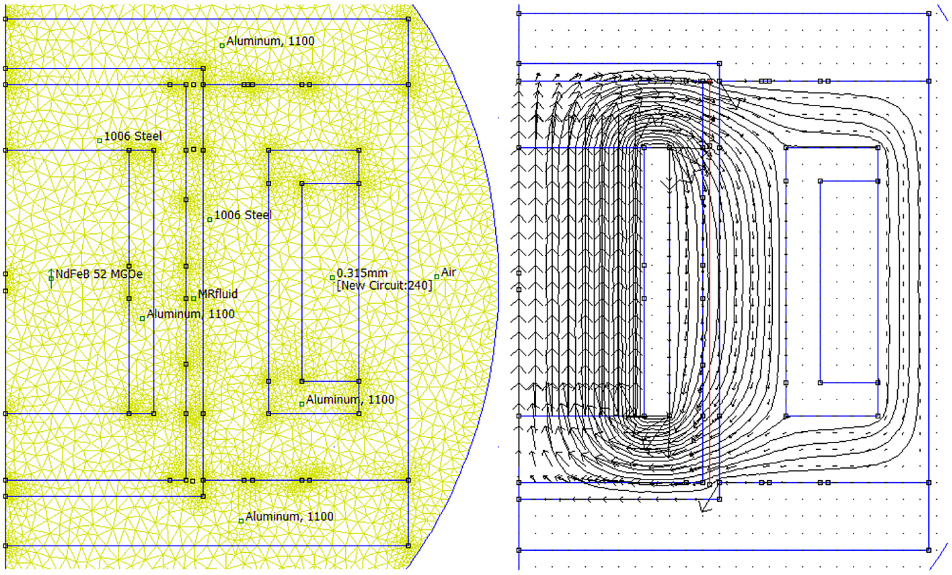


Figure 5. FEMM simulation model of Relief magnetorheological valve



(a) (b)

Figure 6. (a)Finite element mish-generation of the Relief magnetorheological valve. (b)Magnetic flux density path direction and distribution of the Relief magnetorheological valve

in the program. Before that, there was work in previous research, which evaluated this program and compared it with other programs for the same design.

Pressure drop mathematical model

To determine the performance of permanent magnetic pressure relief, the pressure drop can be calculated and performance evaluated. The

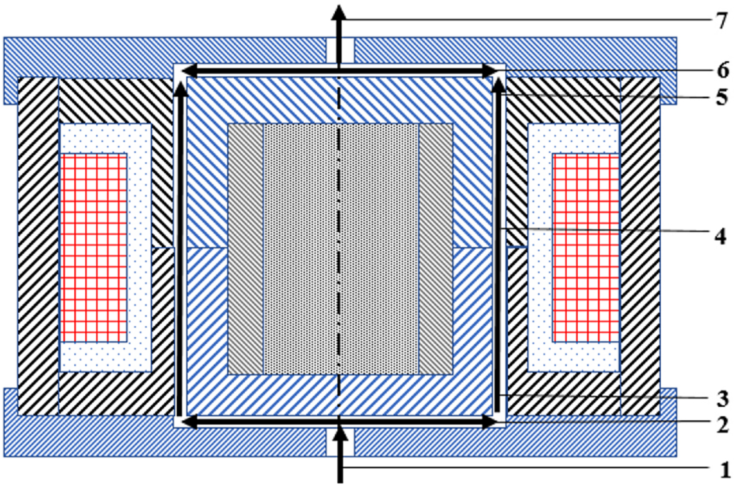


Figure 7. A schematic diagram of the MR fluid path area of pressure drop of the relief magnetorheological valve: 1. Inlet hole-shaped, 2. Inlet disk Area, 3. First MR fluid effective ring-shaped area, 4. Ring-shaped area, 5. Second MR fluid effective ring-shaped area,6. Outlet disk area, 7. Inlet hole-shaped

drop pressure model varies according to the regular axis-symmetry structure of the designed magnetic valve and the different magnetic field strengths in each area of the rheological magnetic valve. Figure 7 shows a simplified diagram of the pressure drop region for permanent magnetic stress relief. Due to its multiple shapes, the fluid flow channels are divided into 7 fluid flow channels, which can be classified into three different regions, namely the perforated region, the disc-shaped region, and the circular region. In the flow mode, the magneto-rheological valve is usually described by the Bingham plastic model, and the total pressure drop at the inlet and outlet is composed of the external viscous pressure drop Δp_η and the magnetic pressure drop Δp_τ. The models are as follows:

1. Pressure drop model at the hole-shaped area – as shown in Figure 7, the hole-shaped area liquid flow channel mainly consists of 1 and 7. Because the flow direction of the magneto-rheological fluid is parallel to the magnetic line of induction. So only the viscous pressure drop Δp_η is generated in these two flow channels. According to the formula for calculating the pressure loss along the path can be considered as the liquid flowing in the hole gap. Therefore, the calculation formula of the viscous pressure drop is [9]:

$$\Delta p_\eta = \frac{8 l_x}{\pi {r^4}_x} \mu Q \tag{8}$$

where: μ is MR fluid viscosity without magnetic field; r is the radius of the fluid flow channel; l is the length of the flow channel; and Q is the flow rate of fluid. Thus regions can be denoted as $\Delta p_{\eta\text{-}1}$ and $\Delta p_{\eta\text{-}7}$.

2. Pressure drop model at the disk area – the fluid flow channels 2 and 6 are disk areas and these channels will produce a viscous pressure drop Δp_η in which the magnetorheological fluid can be calculated as a flat plate model with gradually increasing fluid flow channels and the calculation formula for viscous pressure drop is obtained as follows [13]:

$$\Delta p_\eta = \frac{6\mu Q}{\pi {g^3}_x} \ln\left(\frac{R}{r}\right) \tag{9}$$

where: R is the outer radius of the disc area; r is the inner radius of the disk area; g is disc width; μ is MR fluid viscosity without magnetic field; Q is the fluid flow rate. Thus regions can be denoted as $\Delta p_{\eta\text{-}2}$ and $\Delta p_{\eta\text{-}6}$.

3. Pressure drop model at the annular ring-shaped area – as can be seen from Figure 7, the fluid flow channels 3, 4, and 5 are annular ring-shaped areas. When the magnetic lines of force pass vertically through the liquid flow channel, the fluid flow channel can generate a magneto-induced pressure drop Δp_τ, it is called an effective magnetorheological fluid flow channel. Therefore, channels 3 and 5 are effective magnetorheological fluid flow channels. While generating two pressure drops, a magneto-induced pressure Δp_τ drop and a viscous pressure drop Δp_η. Only a viscous pressure drop Δp_η occurs in channel 4. Which,

using the formula to determine pressure loss along the way, can be thought of as a fluid moving in the annular gap of concentric cylinders. Equation 10 is the simplified viscous pressure drop and Equation 10 is the simplified magneto-induced pressure drop [6].

$$\Delta p_{\eta} = \frac{6 l_x}{\pi r_x g^3} \mu Q \tag{10}$$

where: l is the length of the annular ring-shaped; g is the gap thickness of the effective MR fluid flow channel; r is the inner radius of the annular ring-shaped; Q is the flow rate of fluid; μ is MR fluid viscosity without magnetic field. Thus regions can be denoted as $\Delta p_{\eta\text{-}3}$, $\Delta p_{\eta\text{-}4}$, and $\Delta p_{\eta\text{-}5}$.

$$\Delta p_{\tau} = c\,\frac{\Delta l_x}{g}\,\tau_y\,(B) \tag{11}$$

where: C is the correction coefficient, the coefficient C is obtained by calculating the ratio between field-dependent pressure drop and viscous pressure drop using the approximation function defined [3] in the following equation; τ_y (B) is shear stress generated at the liquid flow channel; Δl is the length of the effective fluid flow channel; g is the gap thickness of the effective fluid flow channel. Thus regions can be denoted as $\Delta p_{\tau\text{-}3}$ and $\Delta p_{\tau\text{-}5}$.

The total pressure drop is:

$$\Delta p = \Delta p_{\eta} + \Delta p_{\tau} \tag{12}$$

Combining three regional pressure drop mathematical models can get the total pressure drop mathematical model of the permanent magnetic pressure relief magnetorheological valve as follows:

$$\begin{aligned}\Delta p = {} & \Delta p_{\eta-1} + \Delta p_{\eta-2} + \Delta p_{\eta-3} + \Delta p_{\eta-4} + \\ & + \Delta p_{\eta-5} + \Delta p_{\eta-6} + \Delta p_{\eta-7} + \Delta p_{\tau-3} + \Delta p_{\tau-5}\end{aligned} \tag{13}$$

RESULTS AND DISCUSSION

The findings that confirm the functionality and performance of the suggested design will be shown in this section. The basic points taken into account when designing are adopting the value of the magnetic flux density B within the limits of 0.5 Tesla, which is perpendicular to the path of the magnetorheological fluid in the gap, since it is only the effective one and not parallel as shown in Figure 8. Also, the best value for the current is not to be high, and the number of turns of the electric coil is appropriate within the dimensions of the valve. The type and size of the permanent magnet must also be selected, as well as the dimensions and thickness of the magnetic-rheological fluid passage gap and the effective gap. Finally, the valve operation and performance were evaluated in terms of pressure. Results were obtained from several experiments and analyses using the FEMM. Figure 8 shows how to display the one case of results as in the FEMM. Displaying the results will be as follows:

Influence of design gap on performance of pressure drop of relief magnetorheological valve

Four dimensions were selected to examine the impact of the gap thickness, that the magnetorheological fluid flows through. They are (0.5, 1, 1.5, and 2 mm). Consider that there will be two places and a 4 mm long effective area. The total length is 24 mm. Measure the value of magnetic flux density B only in the presence of the effect of permanent magnets. It is not measured when there is current in the coil, because it is not needed. Figure 9 shows the influence effect of gap thickness. It is noted that the value of the magnetic flux density at a gap thickness of 0.5 mm, especially in the region between

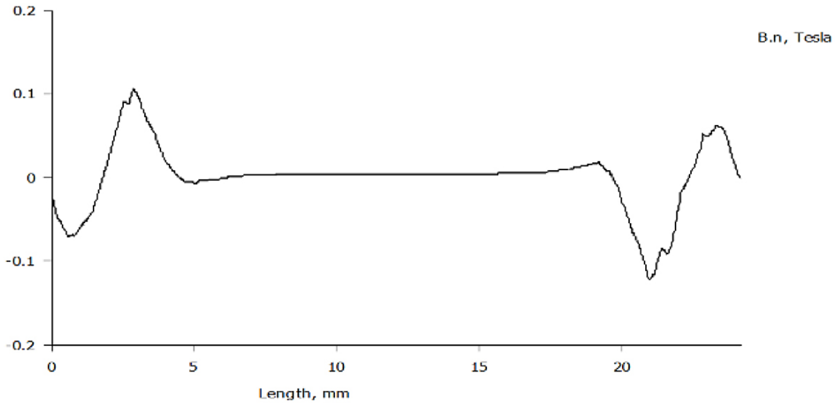


Figure 8. Distribution diagram of the normal magnetic flux intensity B along the MR fluid path

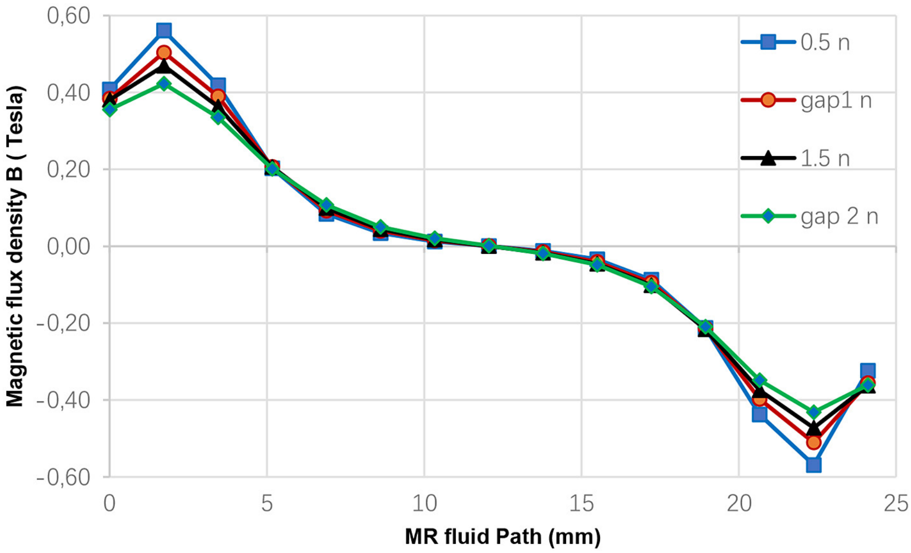


Figure 9. Magnetic flux density with different gap thicknesses along the flow path

(0–4 mm), which is the effective region, was between (0.4–0.55 Tesla). It is considered good, but there is no need for a value higher than 0.5 Tesla, while the value at a gap of 1 mm is between (0.4–0.5 Tesla), which is very appropriate. However, most gaps are less than that and are not suitable. It is also noticeable that the value decreases below that until the next effective gap. But in the opposite direction, this does not affect performance, because the value is absolute. When the gap size is 0.5 mm and the current is present, there is no effect of the magnetic field, high-pressure drop will be generated, especially when the flow increases. This will negatively affect the valve's performance. Figure 10 shows this effect; the valve is open. Analysis and study showed that the appropriate gap thickness to maximize the performance efficiency of this design is 1 mm. Changing the gap thickness generally does not affect the valve's response speed.

Chose the permanent magnet of the relief magnetorheological valve

The proposed design includes permanent magnets. This strong type of magnet is made of

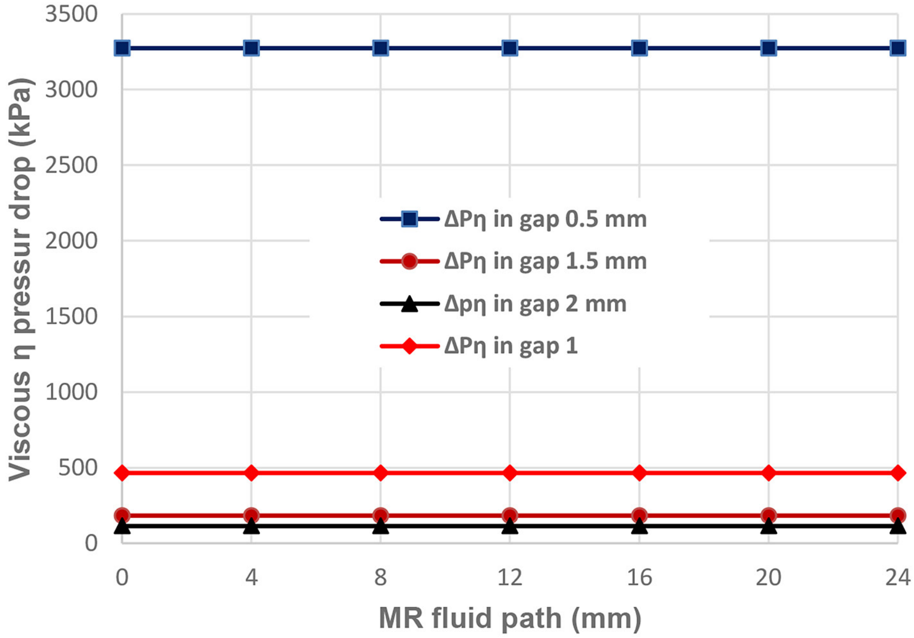


Figure 10. Viscous η pressure drop under different gap thickness

Neodymium. It is in the form of a short shaft. to determine the most appropriate length and diameter. Many experiments were carried out until the most suitable experiment was found to achieve the best magnetic flux density B within the effective gap so that it is perpendicular to the flow path of the magnetic-rheological fluid. Table 2 shows the dimensions of the options, in terms of diameter and length. Figure 11 shows the result of the magnetic flux density value along the gap. Each case has one of the chosen dimensions. It is noted that the most appropriate choice is when the diameter is 15 mm and the length is 16 mm. It gives the most suitable value for the magnetic flux density, which ranges between (0.4–0.5 Tesla). Experiments were also conducted after determining the diameter and length and determining the type of permanent magnet material,

Table 2. Dimensions of permanent magnet

Symbol of PM	PM diameter (mm)	PM length (mm)
D s n	11	16
D m n	13	16
DL l n	15	16
L s n	15	14
L m n	15	15

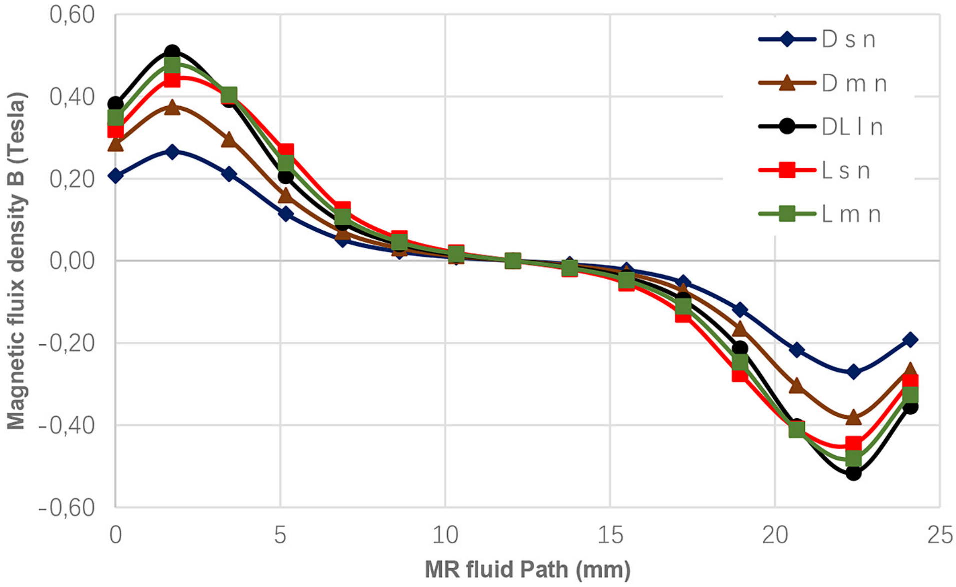


Figure 11. Influence of permanent magnet diameter and length on magnetic flux density B

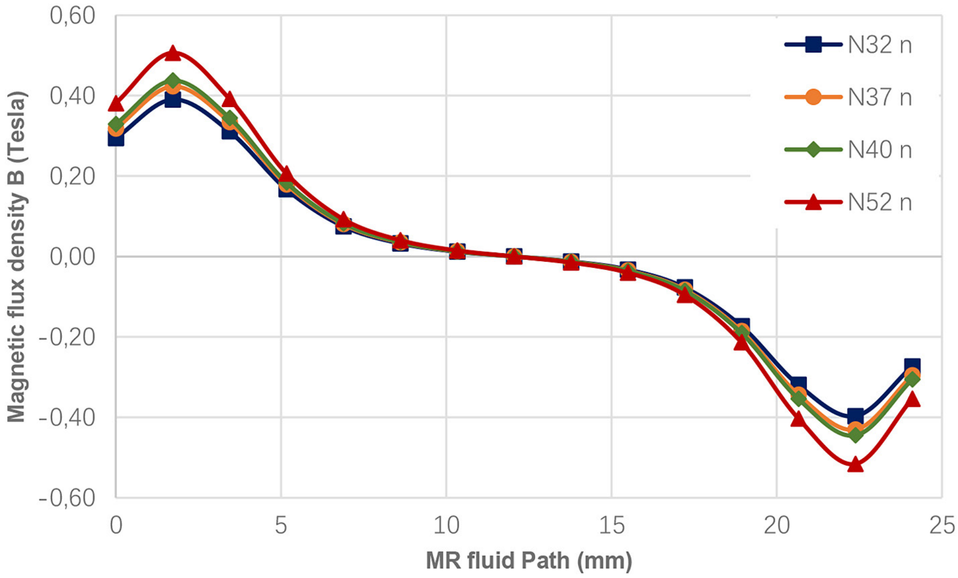


Figure 12. Influence of permanent magnet type on magnetic flux density B

according to what was commercially available. Four types were chosen, which are made of neodymium (N32, N37, N40, and N52). Figure 12 shows the value difference for the magnetic flux density. The most suitable type according to the proposed dimensions of the valve is valve type N52, which gives the most appropriate value, which ranges from (0.4–0.5 tesla).

Influence of coil design on performance of pressure drop of relief magnetorheological valve

The permanent magnet pressure relief magnetorheological valve generates magnetic flux density B to prevent magnetorheological fluid flow. It must be fully opened to the pressure specified for it in the system in which it operates. This is done by generating an opposing magnetic field that cancels out the effect of the permanent magnetic field. This is done using a magnetic coil inside the valve. It is to zero or closer. Each coil consists of several turns of electrical wire with a value for the passing current, according to the Kirchhoff relationship mentioned above in this paper. To calculate the right amount of current and the right number of turns. Experiments were conducted with several coils with a specific number of turns (60, 120, 180, and 240 turns). Also, each type was operated with several currents,

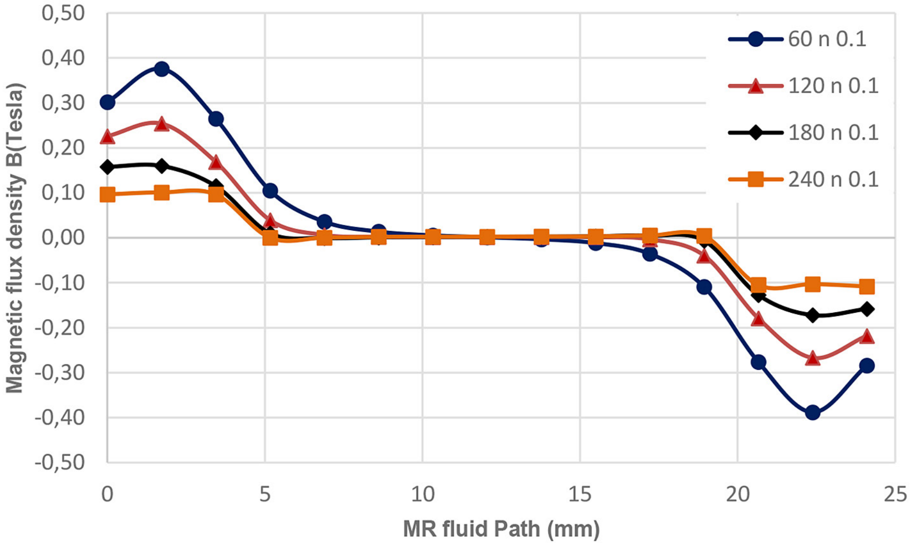


Figure 13. Influence of 0.1 amp with different no. of turns on magnetic flux density B

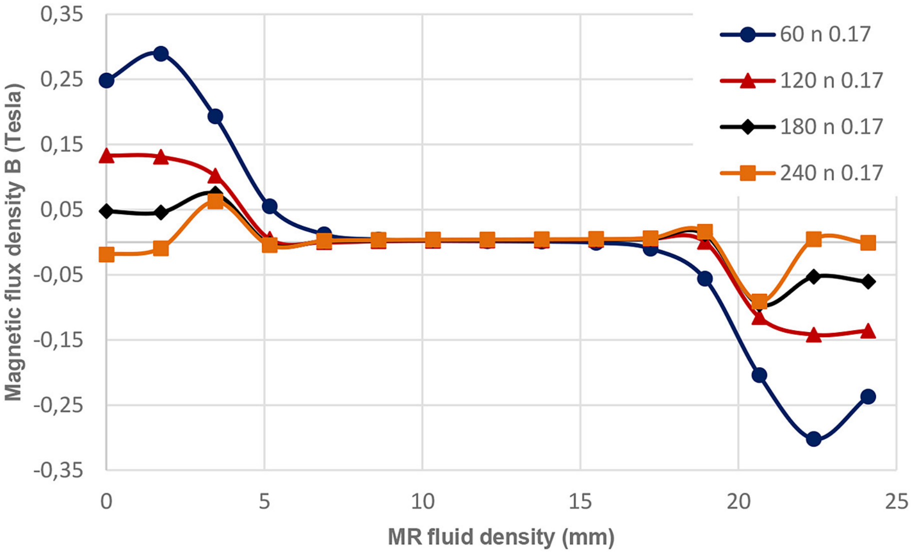


Figure 14. Influence of 0.17 amp with different no. of turns on magnetic flux density B

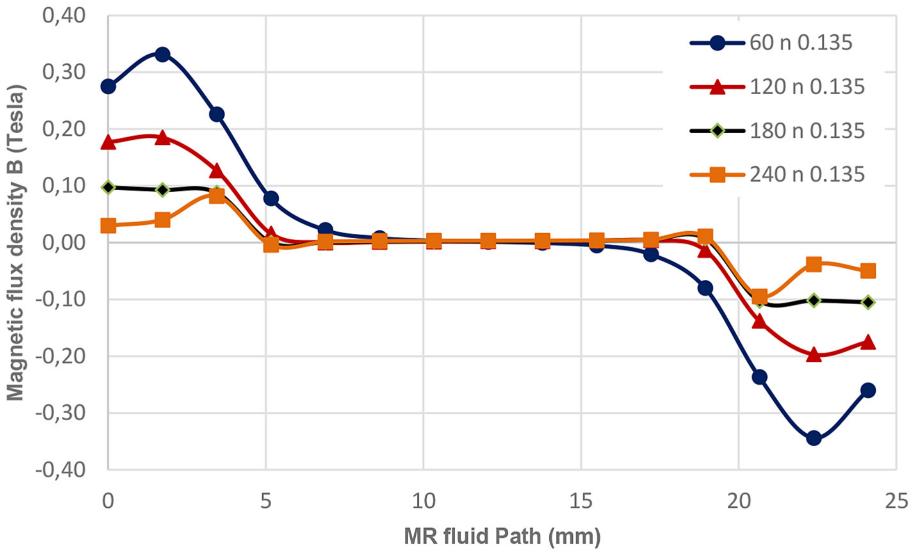


Figure 15. Influence of 0.135 amp with different no. of turns on magnetic flux density B

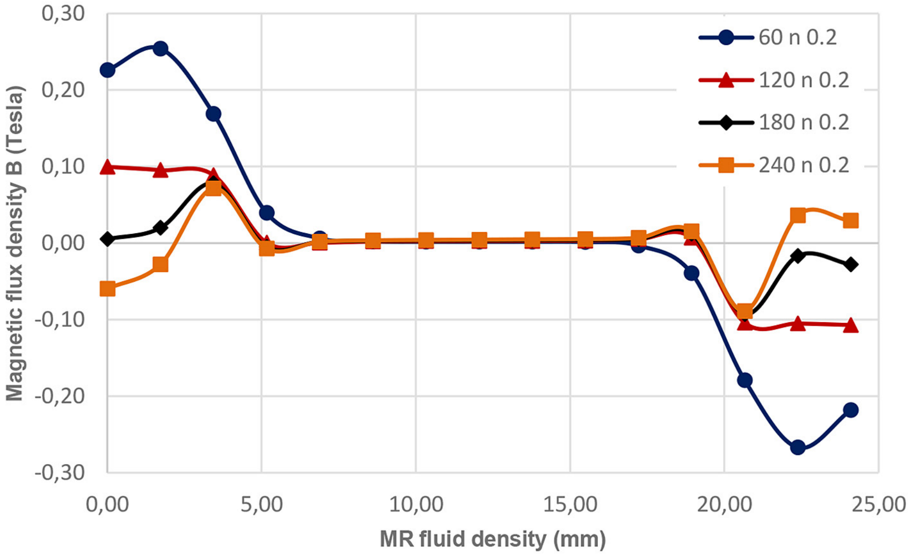


Figure 16. Influence of 0.2 amp with different no. of turns on magnetic flux density B

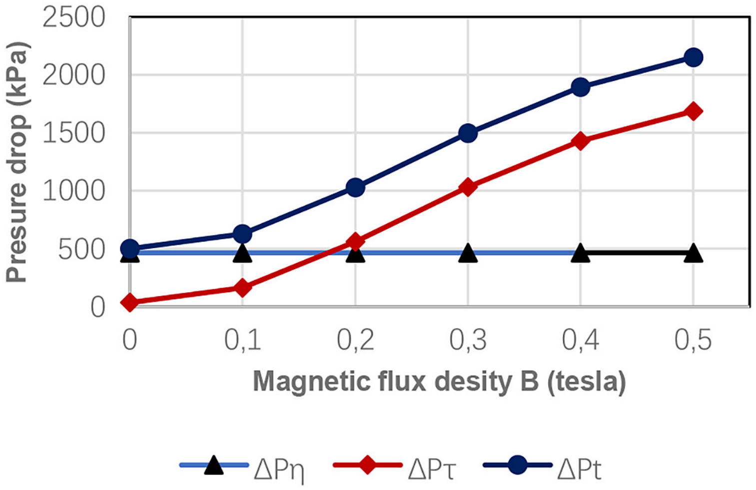


Figure 17. Pressure drop with different magnetic flux density

Table 3. The pressure drop value of the permanent magnet relief magnetorheological valve

Viscous pressure drop Δp_{η} (kPa)	Magnetic pressure drop Δp_{τ} (kPa)	Total pressure drop Δp_{t} (kPa)
500	1650	2150

(0.1, 0.17, 0.135, and 0.2 A), as shown in Figures (13, 14, 15, and 16), respectively. It is noted that the best value for the number of coils and the most suitable current is (240 turns with 0.17 amps). The value of the magnetic flux density B in the active region of the gap is approximately an absolute value (0.02–0.05 Tesla). While in the ineffective region, its value is zero. These values are appropriate for the proposed design of the valve in terms of dimensions and current value.

The effect of coil current on the pressure drop performance of relief magnetorheological valve

The function of the pressure relief valve is to determine the pressure in the system in which it operates. The highest pressure value can be achieved in the proposed design in this work by applying Equations 11, 12, and 13 mentioned above. Figure 17 shows the pressure values and the magnetic flux density B values. It is noted that the highest specific value is approximately (2150 kPa), and this value is specific to this proposed design.

Δp_{η} is a linear and constant equation for each flow and there is no linear change in any of the regions unless the magnetic field affects the viscosity of the magneto-rheological fluid (Table 3). While the effect of Δp_{τ} is non-linear only in the region where the magnetic field is present. In this design of the relief valve, is the annular region. Thus, the total pressure drop is the sum of all the values. According to apply the Equation 13.

CONCLUSIONS

The main conclusion is to achieve the goal on which the work in this research was based. This paper studied and analyzed the performance and operation of the proposed design of the permanent magneto-rheological pressure relief valve. This work is for a proposed design of the valve, in which the basics of analysis and identification of the main parts of the design were established through the FEMM program. The results observed are that it is possible to propose designs according to the system requirements to be worked on. It is not possible to determine the type and size of the magnet. As well as the size and current of the electrical coil. The specific pressure can also be increased. This is done by increasing the surface area for the effective gap. So a value of magnetic flux density B = 0.5 Tesla is achieved. Consideration that the coil generates an opposite field that cancels the effect of the permanent magnetic field, to a value of zero or close to it. This is possible after seeking to propose other designs. Based on what is mentioned in this paper.

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