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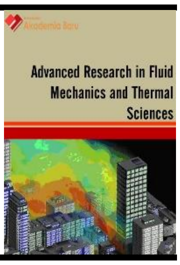

Design and Performance Analysis of Magnetorheological Valve for Upside-Down Damper

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ABSTRACT

Magnetorheological (MR) fluid-based devices are being developed widely due to controllable properties according to its external force. In addition, the upside-down damper is highly demanded by the automotive industry, due to its advantages compared to the conventional damper. MR damper is categorized as semi-active suspension and mainly used in the automotive industry for its performance and fail-safe feature. MR valve is the primary component for being developed, as for different shape and design may offer different performance. This article proposed a semi-active damper by using MR valve design with flow mode and meandering flow path, which have been researched to have a positive effect on increasing the performance of the MR valve. The main purpose of this article is to analyze the performance of the proposed valve. The magnetic field prediction was simulated using Finite Element Method Magnetics (FEMM). The pressure drop of the valve was 0.02 kPa at 50 mm/s at off-state and up to 2.5 MPa at on-state with 1A current on the same valve velocity. With the upside-down damper combined with MR fluid, it offers better performance compared to passive suspension and lower cost and safer than the active suspension. Therefore, this device is very suitable to be developed for future automotive industry.

Keywords:
Magnetorheological; damper; upside-down; valve; semi-active

1. Introduction

MR fluid can change form in an instant response, and its properties are proportional to the strength of the magnetic field [1, 2]. The form and properties change of the MR when induced on magnetic field is reversible [3, 4]. Because of these typical properties of MR fluid, it has been developed and applied in many devices such as the adjustable dampers for automotive industry [5, 6]. The elimination of moving parts inside these devices proposes a faster response and reduces the wear and tear of the components, thus the durability of the system can be increased [7, 8, 9].

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The MR valve is the main component that has the most effect on the performance of the MR damper [10, 11]. Numerous types of MR valve concepts have been developed within the last decade. The original concept of a stand-alone annular MR valve was designed by Yokota *et al.,* [12], which involved an annular flow channel and an electromagnetic coil fitted adjacent to the flow channel. A different approach was proposed by Wang *et al.,* [13] to the MR valve by using the radial concept for a large-scale seismic damper application in a bypass configuration. The radial type MR valve can be arranged in a multi-stage arrangement thus giving an advantage in the pressure drop. Wang *et al.,* [14] proposed a combination of both annular and radial flow path to increase the performance of the MR valve. Recently, the meandering flow path structure has been developed and utilized in the MR valve which combines the annular and radial flow path [15, 16]. The study results of the meandering type MR valve presented that the performance of the MR valve can still be improved through the extension of an effective area in the meandering flow path structure.

Given the importance of the MR valve, various designs for MR valves have been proposed and analyzed. As an example, the annular type MR valve is the most common type of valve used in an MR damper and has already been tested for several design variations such as the inner coil [17], the outer coil [18, 19] and the multiple-coil design [16] and the performance of each design has been evaluated. Radial-type MR valves have also been presented as an option to the annular type MR valves, with the potency of increasing the pressure drop by providing modular stages [13]. The latest development for MR valve is a combination of annular and radial flow path [13, 20], which has demonstrated promising performance and has already been applied in engine mount designs to raise the vibration suppression force [21]. Figure 1 shows the basic concept of the MR valve with a meandering flow path.

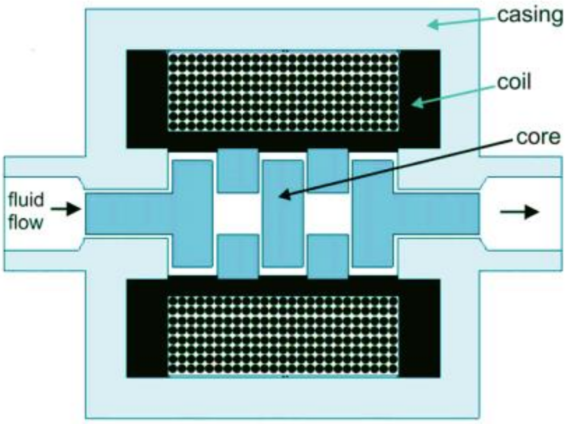


Fig. 1. The basic concept of the MR valve with a meandering flow path [15]

Common monotube damper structures have limited strokes and the strength to resist buckling [22, 23]. Therefore an alternative solution is to adopt an upside-down the structure to lengthen strokes and strengthen resistance to buckling. There are still a few types of research about the MR for the upside-down damper, even though its high market demand and advantages it provides compared to passive or even active suspension. Thus, the purpose of this paper is to understand the design of an MR valve for an upside-down damper with a meandering flow path and to verify its performance of each zone with electric current variation by analytical assessment and magnetic simulation using FEMM. This paper consists of four sections, beginning with the introduction in section 1, followed by the methodology of the MR valve analysis in section 2, which defines the calculation and boundary conditions of simulation of the proposed valve. Section 3 shows the result of the calculation and analysis of the MR valve through modeling and simulation of the pressure drop that can be generated by the valve, while the last section concludes the work.

2. Methodology

There are some measures to increase the pressure drop of the MR valve. Some design increases the effective area, i.e., along with the fluid channel. However, the space required will increase. Another way to improve the pressure drop is to increase the strength of the magnetic flux density, and yet the MR fluid has a peak point which instead decreases its performance.

The design of the valve consists of two annular gaps and one annular gap. This construction will maximize the performance while minimizing the space needed. The materials of the valve are various, so it may result in the magnetic flux to be perpendicular to the MR flow to increase the efficiency of the magnetic flux density. The coil used in this design is the 26 AWG copper coil. Figure 4 shows the construction and material selection of the valve using the FEMM meshing image, and Figure 2 shows the 3D model of the proposed MR valve.

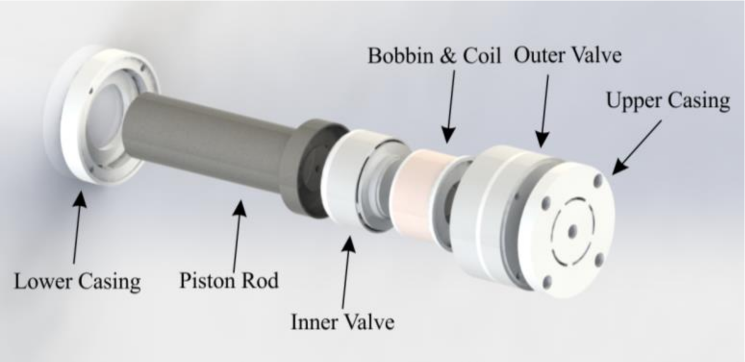


Fig. 2. Exploded view of the proposed MR valve

The calculations are divided into two sections, namely the off-state condition and on-state condition. The off-state condition is the condition in which pressure drop is only caused by the viscous effect, which means no magnetic field induced. The on-state condition is a condition which electric current induced to the coil, thus creating an electromagnetic field and affecting the MR fluid, so the pressure drop was added by the yield stress of the MR fluid.

The calculation of the off-state condition consists of two formulas, which is the pressure drop for the annular and radial gap. These formulas are expressed by the following equation [20].

$$\Delta P_{viscous,annular} = \frac{6\eta Q L}{\pi d^3 R} \tag{1}$$

$$\Delta P_{viscous,radial} = \frac{6\eta Q}{\pi d^3} \ln\left(\frac{R_1}{R_0}\right) \tag{2}$$

where η is the viscosity of the fluid, Q is the fluid flow rate, L is the annular channel length, d is the flow channel gap size, R_1 is the outer channel radius, and R_0 is the inner channel radius. These are the variables that determine the viscous pressure drop. The flow rate of the fluid needs to be calculated first by using the following equation.

$$Q = \frac{\pi D^2 v}{4} \tag{3}$$

The calculation for the magnetic field effect on MR fluid consists of three steps. The first step was to determine the yield stress of the MR fluid in the effective area. In this case, MRF-132DG from Lord Corp. is used. This MR fluid was chosen due to its resistance to heat degradation, which is required for this type of use. The yield stress of the MR fluid is expressed by the following polynomial equation [24].

$$\tau_y(B) = \begin{cases} -58.92B^3 + 74.66B^2 + 35.74B - 3.387, \text{for } \tau_y(B) > 0 \\ 0, \quad \text{for } \tau_y(B) \leq 0 \end{cases} \tag{4}$$

where τ_y is the yield stress of the MR fluid, and B is the flux density in Tesla. The magnetic simulation was conducted by FEMM to determine the flux density of each zone. After the simulations being conducted, the average magnetic flux density on each zone was determined to be the function of this equation on each zone, respectively.

The next step was to determine the pressure drop caused by the yield stress of the MR fluid. There are two formulas used in this case, which is the pressure drop for the annular gap and the pressure drop for the radial gap. The following equation is used to determine the yield stress of the MR fluid [20].

$$\Delta P_{yield,annular} = \frac{c\tau_y(B)L}{d} \tag{5}$$

$$\Delta P_{yield,radial} = \frac{c\tau_y(B)}{d}\,(R_1 - R_0) \tag{6}$$

where c is the flow function coefficient, which is obtained by calculating the ratio between the field-dependent pressure drop and viscous pressure drop. The formula used to determine the flow function coefficient was expressed by the following equation [25].

$$c = 2.07 + \frac{12Q\eta}{12Q\eta + 0.8\pi R d^2 \tau(B)} \tag{7}$$

The final step was to add the off-state condition with the yield stress of the MR fluid, so the final pressure drop was obtained. To be used in the analytical assessments, these equations were calculated for each zone and to be summed up for the final pressure drop. The parameters used in that equation will be illustrated by Figure 3.

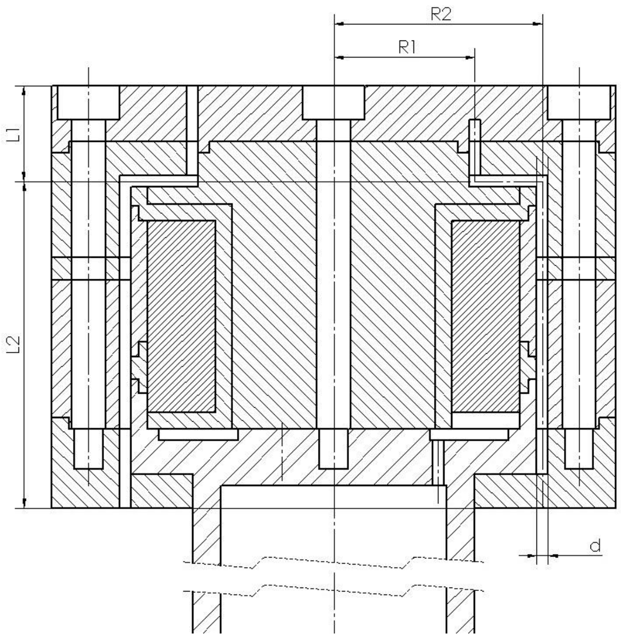


Fig. 3. Parameters of the MR valve

3. Results

The parameters of the proposed MR valve are shown in Table 1. These parameters are to be used for further calculation, which will be provided in two subsections. The first section explained the magnetic flux simulation, while the second section explained the pressure drop prediction of the proposed design.

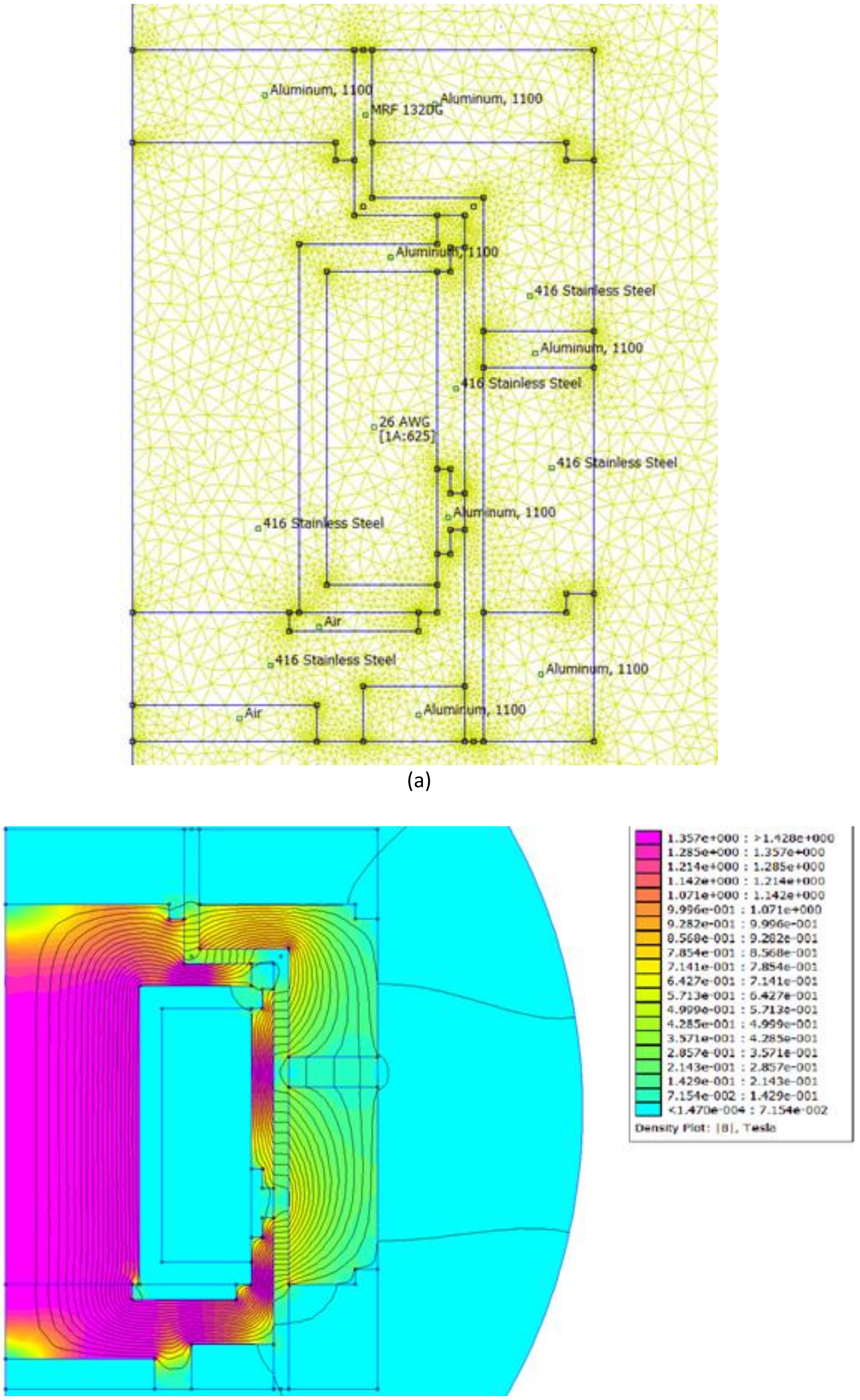
The result of the calculations is determined with variations of the current input and piston velocity. The current input will vary between 0.5, 0.75, and 1 A at the peak, while the piston velocity will vary between 20, 50, 100, 300, and 600 mm/s. These variations are selected to observe the controllability of the damper itself.

Table 1
Parameter of the MR valve

Parameters	Description	Units	Value
η (*MRF-132DG*)	Fluid Viscosity	Pa-s	0.112
d_a	Annular gap size	mm	1
d_r	Radial gap size	mm	1
L_1	Annular 1 gap length	mm	8.5
L_2	Annular 2 gap length	mm	29
R_1	Outer radius radial	mm	12.5
R_0	Inner radius radial	mm	18.5
D	Piston diameter	mm	50

3.1 Magnetic Flux Simulation

This subsection discusses the magnetic flux density simulation of the proposed MR valve using FEMM. The simulation was configured for the two-dimensional and axis-symmetric condition to obtain the most accurate result. Figure 4 shows the meshed model and magnetic flux density of the MR valve when induced by 1A electric current.



(a)

(b)

Fig. 4. (a) Meshed model and (b) magnetic flux density of the MR valve on 1A electric current induced using FEMM

From the figure above, it can be observed that the inner side of the valve has a dense flux magnetic while the outer of the valve has a sparse flux magnetic. This occurence is caused by the inner side of the valve has a smaller space than the outer side, and caused the flux density to be limited by the radius of the coil to the center of the valve. Another result of the simulation was the flux density vs. flow path distance plot and shown in Figure 5.

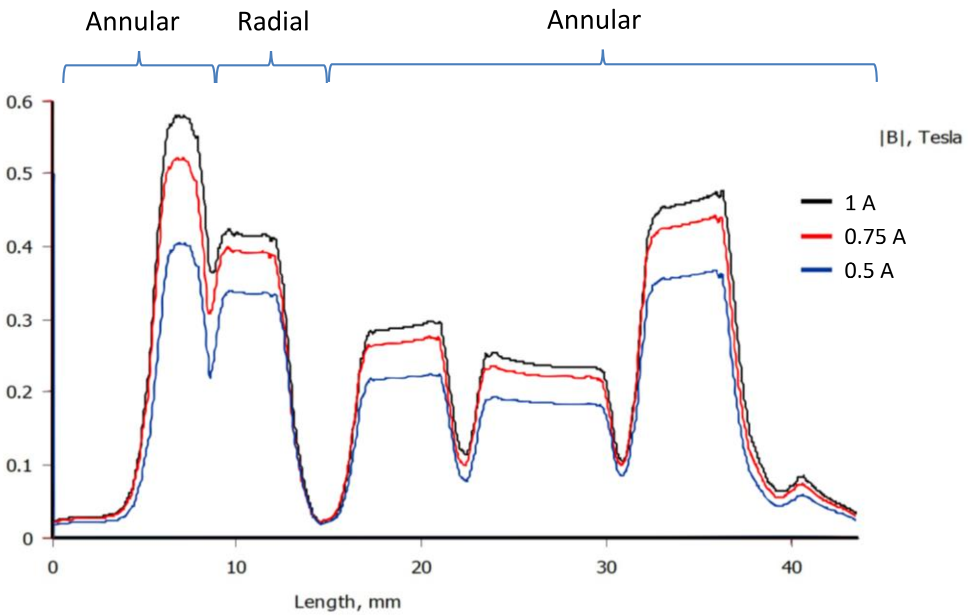


Fig. 5. Flux density vs. gap length plot using FEMM

3.2 Pressure Drop Prediction

3.2.1 Off-state condition

The calculation of this conditions used Eq. (1) for annular gap and Eq. (2) for the radial gap. Piston velocity variation will be applied to these calculations. The result of the calculations is presented in Figure 6. The figure shows that the pressure drops of the off-state condition proportional to the piston velocity.

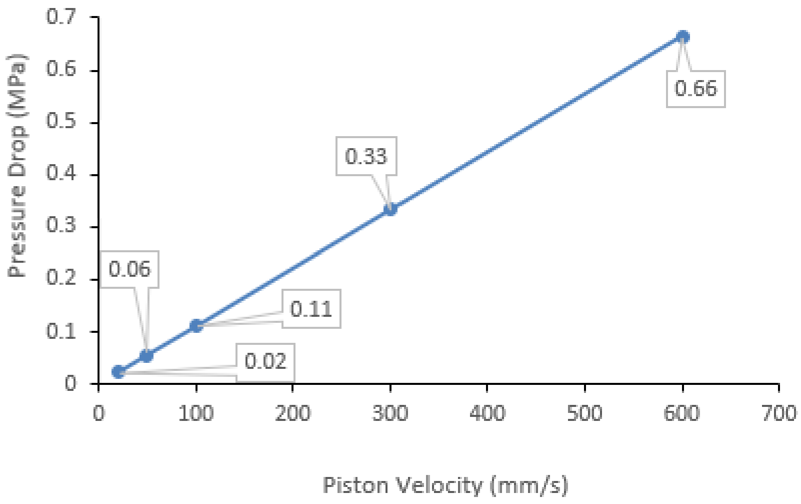


Fig. 6. Off-state pressure drop vs. piston velocity of the MR valve

3.2.2 On-state condition

For the on-state condition, the formulas used are Eq. (4) through Eq. (7). The results of the calculation are shown in Figure 7 in the form of pressure drop vs. piston velocity for each electric current induced. From the figure, it can be deduced that the pressure drop of the on-state condition which has been calculated is much higher than the off-state condition. It is also can be concluded that the pressure drop is proportional to the electric current induced, respectively.

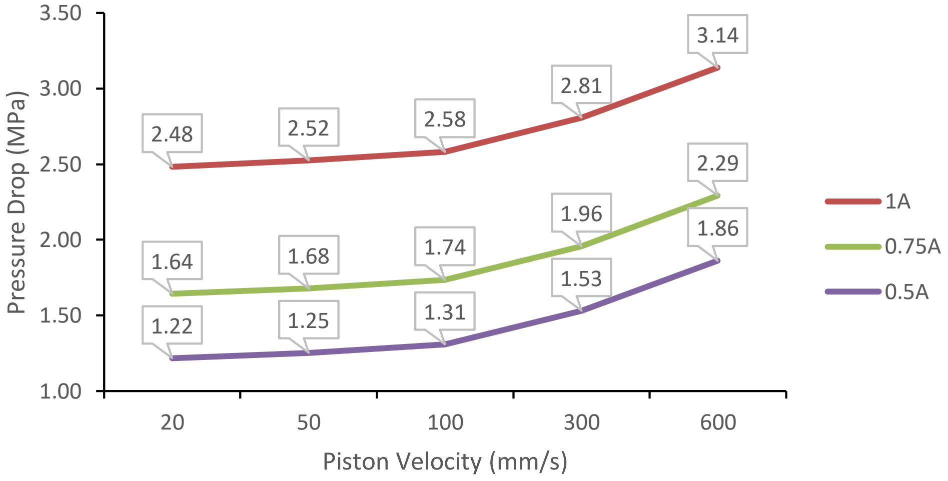


Fig. 7. On-state pressure drop vs. piston for various electric current induced

Meanwhile, the performance of each zone is shown in Figure 8. The result shows that the pressure drop of each zone is constant for every piston velocity given. The result also shows that the most affecting zone is the Annular 2 zone, due to its large effective area. The pressure drop of the Radial zone is also higher than the Annular 1, even though the Annular 1 has a larger effective area and magnetic flux density compared to the Radial zone. Thus, this result demonstrates that the radial gap indeed has better performance than the annular gap.

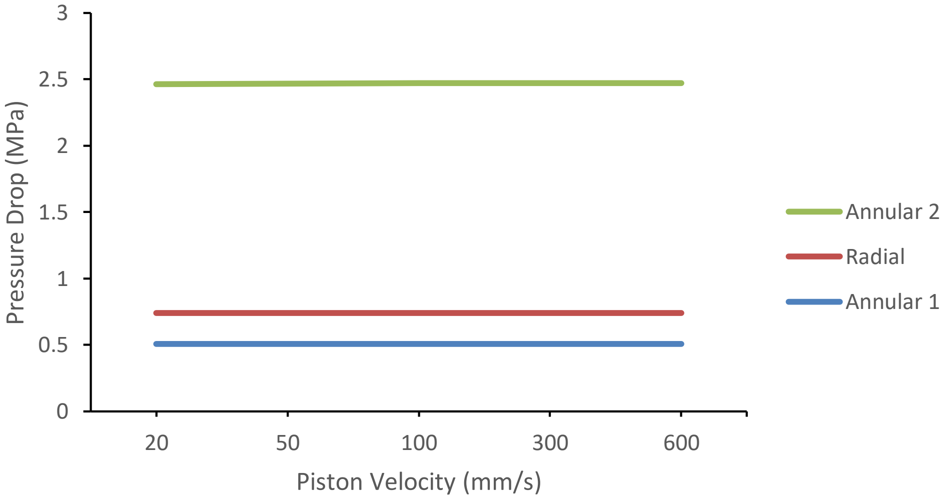


Fig. 8. Pressure drop vs. piston velocity for each zone at 1A

4. Conclusions

The analysis of the proposed MR valve has been done with several results, including the magnetic field analysis and analytical assessment of the pressure drop predictions. The magnetic field simulation shows that the magnetic flux has to be designed in such a way that it is perpendicular to the MR fluid flow path to improve the MR valve performance. Aluminum is an excellent option to bend the magnetic flux due to its paramagnetic properties. The pressure drop calculation shows that the electric current input is proportional to the yield stress of the MR fluid, thus capable of adjusting the pressure drop by changing the current input. The pressure drop on the annular gap is lower than the radial gap. This proves that the radial gap indeed more efficient than the annular gap.

Acknowledgment

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