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PINCH MODE MAGNETORHEOLOGICAL FLOW BENCH: FLUID FLOW ANALYSIS

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Abstract. Magnetorheological (MR) fluids are known smart materials. In the presence of magnetic field the material develops a yield stress. The technology has been used in the automotive industry, for example, or high quality optical finishing applications. In the (existing) conventional flow-mode valves the MR fluid is energized by magnetic flux perpendicular to the fluid flow path. The effect is an increase in the material's effective resistance-to-flow. The so-called gradient pinch mode (GPM) follows a different principle – the flux in the flow channel is directed to activate the fluid in the areas adjacent to the channel walls. Then, high yield stresses are induced in the material in the adjacent zones and low yield stresses are achieved in the middle of the channel, the yield stress distribution is non-uniform. As a result, a Venturi-like contraction is formed solely by material means, i.e. without changing the flow path geometry. This may lead to a new category of controlled semi-active valves. However, a fundamental research is still required to characterize the rheology of MR fluids in this mode. In the study the authors explore opportunities for building a pinch mode valve assembly for the experimental work with MR fluids. The authors propose a solenoid assembly that can be integrated into a flow bench, and then proceed with a CFD steady-state study of the fluid flow through the valve. The results are then presented in the form of velocity plots and pressure maps as well as averaged pressure drop vs volumetric flow rate, respectively, at various levels of ampere turns.

Key words: Computational Fluid Dynamics, Flow Bench, Analysis, Magnetorheological, Pinch Mode

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1 INTRODUCTION

To begin with, magnetorheological (MR) fluids are well-known representatives of smart materials. While in the presence of magnetic field the material develops a yield stress [1]. The magnitude of the effect is sufficient to utilize it in real-life applications, namely, semi-active suspension systems in passenger cars or high-quality optical finishing [2, 3]. Many other application concepts were either studied or prototyped [4, 5]. By principle, MR devices feature solenoids for magnetizing a control volume of the MR fluid. The material operates in at least one of the so-called operating modes: flow, shear, squeeze and gradient pinch [6, 7]. Of the four modes, the so-called gradient pinch mode has been researched and studied to the least extent. In pinch mode the material is magnetized in a different manner in comparison with the other modes. With the flow, shear or squeeze mode devices the magnetic flux path is designed in such a way to travel across the flow path in the direction perpendicular to the fluid flow. In this case the flux is forced to travel in the flow channel in parallel to the fluid flow across a relatively small distance between the neighbouring magnetic poles. As a result, the flux gradient is the highest in the regions near the walls of the channel (lowest reluctance), and the smallest in the center of the gap (highest reluctance). This makes the material to operate in a manner similar to a conventional variable area orifice. However, the contraction effect is realized by material means without changing the geometry of the flow path.

Both the empirical and modeling knowledge on the behaviour of MR fluids in pinch mode are scarce. The credit for discovering the effect goes to Goncalves and Carlson [7]. Still, the reference record counts few publications, i.e. analysis of the behaviour of MR fluid in a pinch mode valve and a presentation of a semi-analytical solutions for calculating the pressure drop across the valve [8] and magnetostatic analyses of pinch mode valve concepts [9, 10]. It is complemented by the experimental study [11] of the behaviour of several fluid formulations in pinch mode for which the pressure drop vs flow rate relationships were extracted. The present study is an attempt to build on the findings of [11] and to extend the results of the previous study with steady-state flow simulations. In brief, Section 2 reveals the details of a flow bench prototype and the solenoid valve. In Section 3 the authors present the CFD (Computational Fluid Dynamics) model. Section 4 highlights the results, and conclusions are provided in Section 5.

2 FLOW BENCH

This study is based on the flow bench concept previously developed by the authors and described in [10, 11], and the reader should refer to prior art for a detailed description of the test rig. Briefly, the rig illustrated in Fig. 1 features a thru-hole flow path, a coil assembly of $N = 300$ wire turns and a magnetic core. The fluid flows through the thru-hole and is subjected to the magnetic field induced by the control coil's current up to $I = 3$ A (or $NI = 900$ A, NI – ampere turns). The size of the thru-hole is $D = 3$ mm, and its length $L_g = 30$ mm. The adjacent magentic poles are separated by a non-magnetic spacer; the distance between the poles is $w = 1$ mm. The assumed fluid's properties are that of a 22 % Fe vol. MR fluid (see Fig. 2), and the core material properties correspond to a low carbon steel alloy (grade SAE1010).

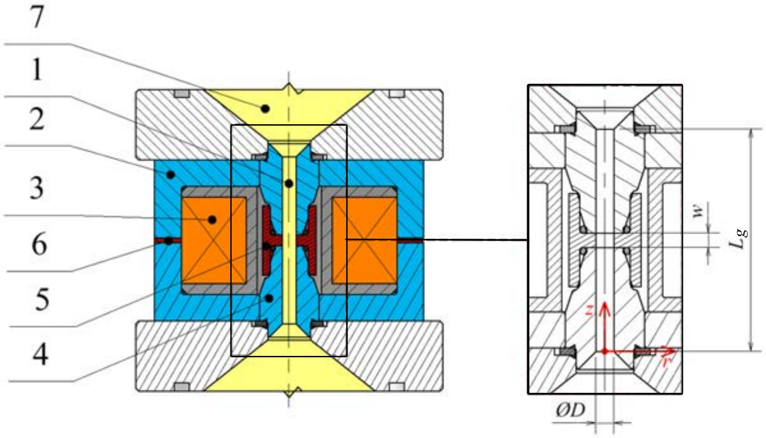
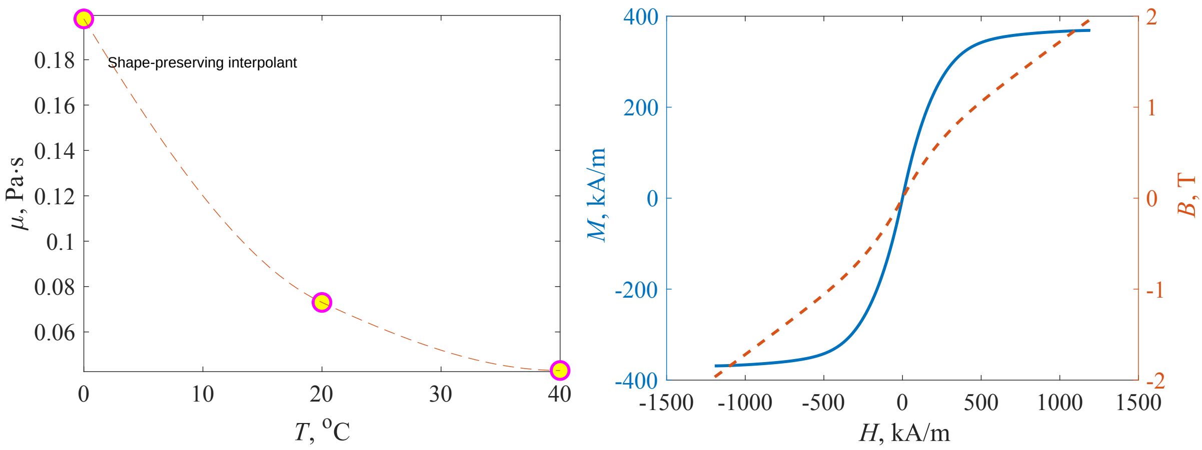


Figure 1: MR valve concept [11]; 1 – flow channel, 2 – core, 3 – coil assembly, 4 – core inserts, 5 – non-magnetic spacer, 6 – magnetic flux measurement gap , 7 – inlet(s)



(a) (b)

Figure 2: MRF material properties: a) viscosity vs temperature, b) $B - H$ & $M - H$ curves

3 CFD MODEL

As mentioned, for the purpose of the modeling study the authors assumed the material properties of the MR fluid MR-122EG developed by Lord Corp. All the necessary material properties were determined experimentally. Specifically, the variation of the material's viscosity μ against the temperature T revealed in Fig. 2(a) was determined using Anton Paar rheometer type MCR 302, and its magnetisation curve $B - H$ (B – flux density, H - magnetic field strength) or $M - H$ (M - magnetisation) obtained via LakeShore vibrating sample magnetometer type 7407 measurements – see Fig. 2(b). Finally, the density of the measured sample was $\rho = 2.33$ g/cc. Finally, Fig. 3 shows the yield stress vs magentic flux density data.

To begin with, the model developed by the authors is a one-way coupled CFD-EM (CFD

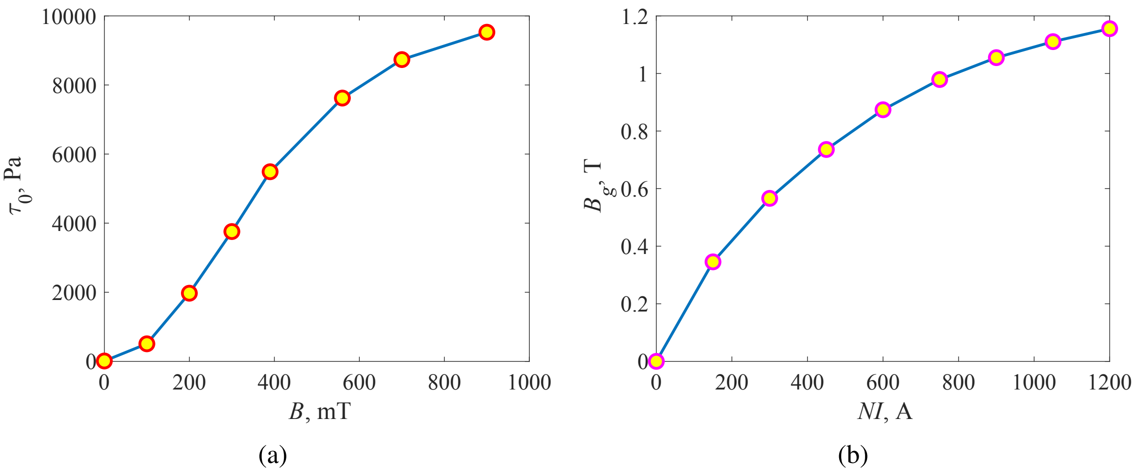


Figure 3: MRF material properties (cont'd): a) $\tau_0 - B$, b) $B_g - NI$

– computational fluid dynamics, EM - electromagnetic) model. This type of multi-domain analyses cannot be conducted using flow models alone, and need to be complemented by solving the problem first in the magnetic domain. As such, using the geometry in Fig. 1 a magnetostatic EM model was developed in Ansys Maxwell R2020 (see Fig. 4), and the magnetic flux density spatial distributions obtained within the ampere turns range up to $NI = 900$ AT. The obtained solutions were then imported into the CFD model for the complementary $\tau_0 - B_g$ mappings.

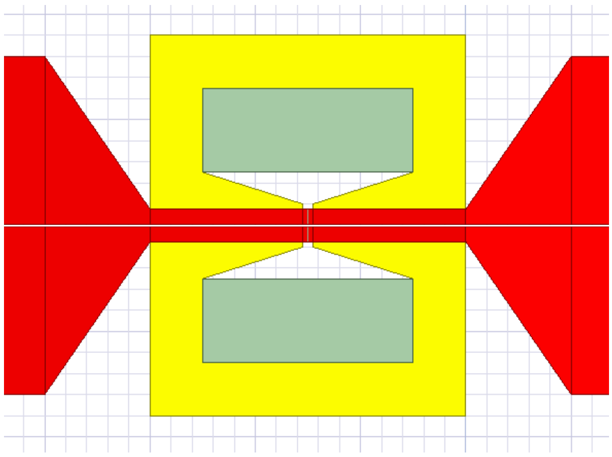
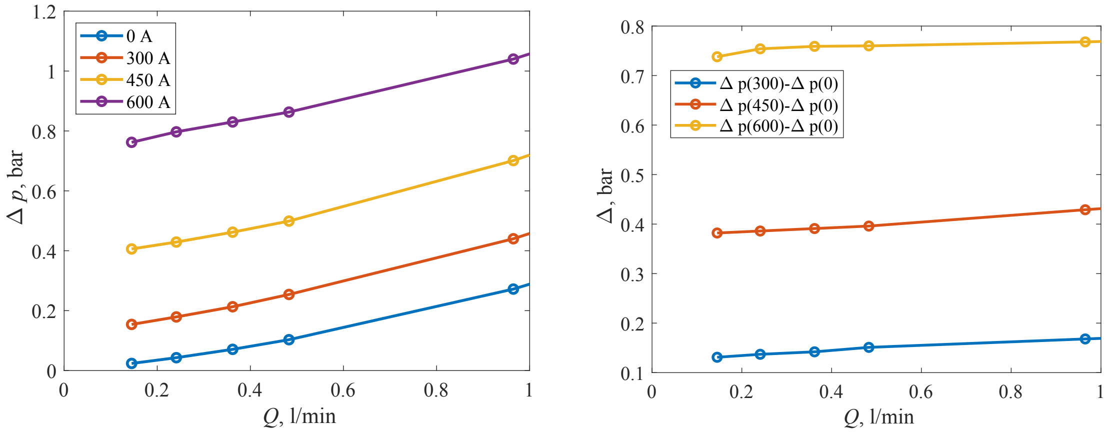


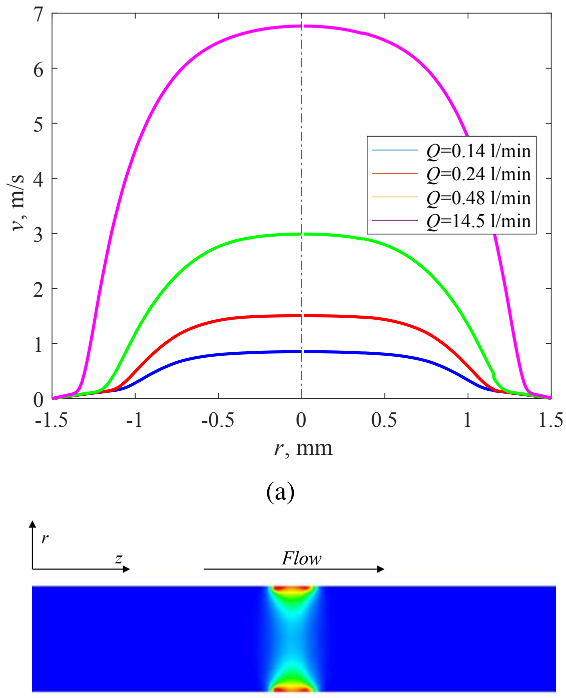
Figure 4: Magnetostatic model geometry

The geometry of the CFD model in Ansys Fluent R2020 corresponds to the MR fluid domain of the FE model in Fig. 4. Solving such coupled problems via CFD usually impose numerical problems. First, the commonly used Bingham model's apparent viscosity representation requires handling the singularity at zero shear rate. Second, the obtained flux density map must be imported into the flow model and interpolated across the entire domain. As a result, the



(a) (b)

Figure 5: CFD results: plots of $\Delta p - Q$

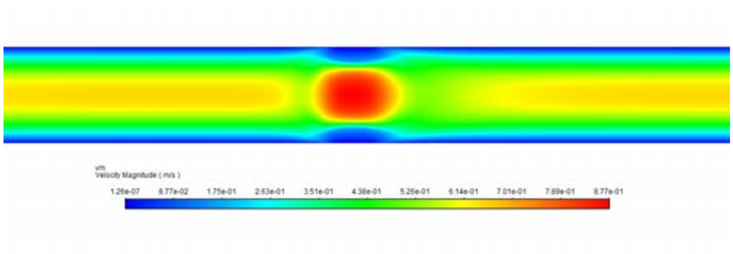


(a)

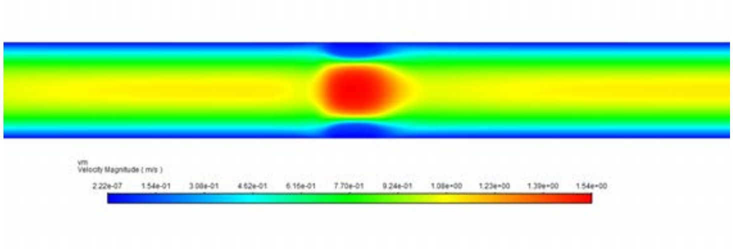
(b)

Figure 6: Velocity profiles & yield stress distribution in the flow channel, NI=450 A

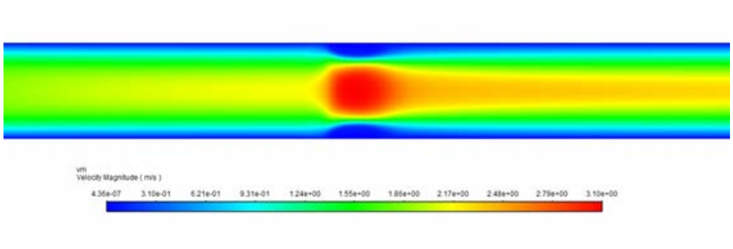
apparent viscosity model is not capable of predicting the flow field at high yield stress levels and low flow velocities (or at low Reynolds numbers and high Hedstrom numbers [12]). To handle the discontinuity the authors followed the procedure highlighted in [12]. The approach, however, is not without drawbacks. It reduces the Bingham model to a bi-viscous one with the above consequences on the obtained flow field solutions as described in the section below.



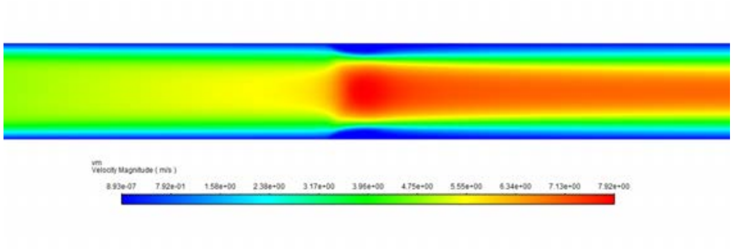
(a) $Q = 0.14$ l/min



(b) $Q = 0.24$ l/min



(c) $Q = 0.48$ l/min



(d) $Q = 1.45$ l/min

Figure 7: Velocity magnitude contours: $NI = 450$ A

4 RESULTS

The obtained CFD results are presented in Figs. 5 to 7. As highlighted above, the flow simulations were preceded by computing the magnetic flux distribution in the solenoid, and then imported in the CFD code. In particular, the summary of the data is illustrated in Fig. 5(a) as plots of the pressure drop Δp vs the inlet flow rate Q at selected levels of the coil ampere turns NI up to 600 A and flow rates up to 1 l/min. The prescribed flow rate range at the inlet corresponded roughly to the one used in the experiments [11]. Next, Fig. 5(b) reveals the calculated dynamic range plot. The dynamic range Δ was calculated as $\Delta = \Delta p(NI) - \Delta p(0)$. To complement the analysis, selected exemplary flow profiles ($NI = 450$ A) can be observed in Fig. 6, and the corresponding velocity magnitude contours in Fig. 7.

The obtained results allow the authors to draw several conclusions. First of all, the developed model is capable of raw predictions of the pressure drop across the flow channel only. The pressure drop magnitude at the off-state and the maximum ampere turns level are predicted, however, the distinct behaviour of the fluid in pinch mode (the $\Delta p - Q$ curve slope increase with magnetic field strength) is not well captured by the model as seen in Fig. 5. Instead, the obtained $\Delta p - Q$ data are representative of a typical Bingham-like material. Analyzing the flow profiles and the flow velocity contours in Figs. 6 and 7 reveals, however, the presence of the pseudo-contractions near the walls of the channel due to the high magnetic flux concentration and the resulting yield stress increase there. At $NI = 450$ A and the lowest flow rate the size of the contraction approaches nearly 1/3 of the channel size. As the flow rate at the inlet increases (and so the resulting pressure drop) the contractions gradually degrade towards the channel walls. Note, however, that the flow is not completely blocked in the observed contractions due to the above-mentioned defficiencies of the apparent viscosity model.

5 CONCLUSIONS

The CFD study reveals the results of a preliminary analysis towards obtaining a convincing model. The analysis has succeeded in part. It is true that application of the modified Bingham model allows to extract pinch mode's some specific features such as the contractions in the regions with the highest flux (yield stress) concentration as demonstrated in the presented velocity profiles and contours. At the same time, the field-dependent $\Delta p - Q$ slope change cannot be captured by the model. It is most likely that the steady-state analysis cannot handle the local accumulation of the particles in the high flux concentration zones between the adjacent poles. As a result, the model is likely to underestimate the material's local yield stress increase. Therefore, in order to gain insight into the fluid's behaviour on the micro scale as well as to improve on the present model, the Dense Discrete Phase Model (DDPM) will be employed for tracking the individual particle trajectories and collisions.

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