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CFD Analysis of Magnetorheological Fluid Clutch

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***Abstract*—Magnetorheological (MR) fluid is a type of smart fluid, in which magnetic particles are suspended in a non-magnetic carrier liquid, such as silicone oil. MR fluid is versatile, and caused a significant advancement in actuator technology. When subjected to an external magnetic field, MR fluids exhibit significant and reversible changes in their rheological properties, offering superior control compared to traditional hydraulic actuators while being lighter and more cost-effective. The MR fluid (MRF) clutch is one of the most essential types of actuators for torque transmission in rotating systems. Its reliability stems from the absence of mechanical contacts, which minimizes wear and enhances durability. Most research on MRF clutches has focused on their physical principles and optimization, and often using experimental setups. However, detailed investigations into MR fluid behavior within complex clutch geometries, particularly at high particle volume fractions, remain limited. This study uses a finite-volume based solver and solves the conservative equations for a single-phase highly concentrated MR fluid, to simplify the modeling. The numerical model shows first an excellent agreement with experiments in terms of torque. The influence of the magnetic flux density on the MRF's dynamic viscosity and velocity profiles is then quantified up to 0.5 T. The magnetic field drastically affects both the fluid flow and properties by inducing large spatial variations in the small rotor-stator gaps.

***Keywords-component*—Magnetorheological Fluid, Clutch, Numerical Simulation, Torque**

I. INTRODUCTION

Magnetorheological fluid was first invented by Jacob Rabinow in 1948 [1]. It can change its apparent viscosity almost instantly when exposed to a magnetic field. Its behavior changes from free-flowing liquid to a solid-like state upon the application of a magnetic field (Fig.1).

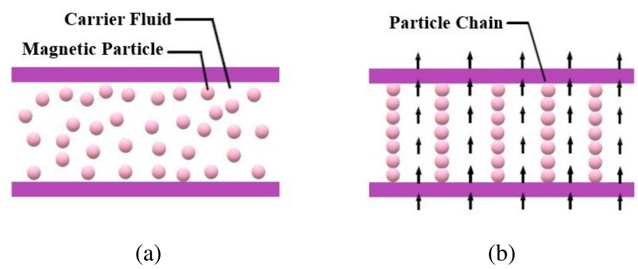


Figure. 1: Operating principle of MR fluid: (a) off-state, (b) on-state

In recent decades, an increasing fascination for magnetorheological fluids (MRF) has led to substantial research and development efforts. Due to their adaptability and quick responsiveness, MRFs have emerged as fundamental components in contemporary technology, fostering innovations in industrial applications and leading the progress of magnetically-responsive materials. Within the aerospace sector, MRF clutches are receiving increased attention. They provide a reliable, efficient, and environmentally friendly alternative to hydraulic systems for the aerospace industry to support the More Electric Aircraft program. The MRF clutch is a typical MR transmission device that is based on direct shear mode [2]. However, MRF clutches face some challenges, especially under high operational stress. Over time, the particles can also degrade or settle, reducing the effectiveness of the fluid. Another important issue is sedimentation in small-gap flows, which may influence the suspension of magnetic particles and thus directly impact torque transmission. Therefore, comprehension of MR fluid behavior is the key to optimize clutch efficiency and reliability. To better understand their behavior, researchers have applied two main numerical approaches, discrete and continuum, to analyze the dynamics of MR fluids in various configurations, disclosing important results about their performance and efficiency.

Discrete numerical methods have been used to investigate particle-level interactions in MR fluids. For instance, Zhao et al. [3] performed molecular dynamics simulations to study the cylindrical particle-fluid interface. Their findings emphasized that an increased carrier fluid viscosity enhances the performance of MR fluids by increasing shear strength, chain entanglement, and stability. Similarly, Yu et al. [4] used DEM (discrete element model) - LBM (lattice Boltzmann method) coupled with the immersed moving boundary (IMB) method to simulate 2D numerical domains. Their study confirms that higher particle volume fractions accelerate chain formation, affecting MRF rheology. Their numerical framework also offers a validated method for analyzing MRF microstructure. In a related study, Wang et al. [5] investigated the MR fluid dynamics by using a dipole-based force model for cube-shaped domains and found that the stronger the magnetic fields, the longer the particle chains and the higher the chain density.

Given the need to analyze the macroscopic performance of MRF clutches, various continuum approaches have also been adopted. Thakur and Sarkar [6] conducted a study on radial MR clutches with various groove profiles, and found that radial grooves increase the torque, whereas circular grooves decrease it. They also pointed out that the torque increases with radius and becomes uniform at a higher rotational speed. In a similar work, Song et al. [7] studied drum-type magnetorheological clutches, showing that the optimized design parameters significantly improve torque, thereby offering a compact and efficient solution with a fast response time. In addition, the interaction of magnetorheological fluids in clutch applications has been studied regarding their torque dynamics and rheological behavior. Binyet and Chang [8] investigated single-plate MR clutches, showing that at low rotational speeds, the torque is high, while at high speeds, the torque decreases. Furthermore, Kozubková et al. [9] studied the flow of MR fluids between concentric cylinders, indicating that due to the non-Newtonian nature of MR fluids, as strain rate increases, the viscosity decreases, which affects the torque produced. These studies confirm that continuum modeling effectively captures the macroscopic behavior of MR fluids in clutches, where the primary focus is on torque transmission and bulk flow behavior rather than individual particle interactions. This makes the continuum approach the most appropriate choice for the present study.

The next key consideration is the selection of the appropriate rheological model, which plays a crucial role in accurately interpreting MR fluid behavior in clutches. Many studies, including those by Thakur and Sarkar [6] and Song et al. [7], applied the Bingham plastic model for the yield-stress behavior under magnetic fields in MR fluids. On the other hand, Kozubková et al. [9] utilized the power-law model for solving specific flow conditions, thus making the MR fluid adaptable to different operational regimes. Furthermore, Pei and Peng [10] analyzed the prediction errors of various parametric constitutive models for MR fluids using data from their research and prior studies across various conditions such as magnetic field, current, temperature, and shear rate. They showed that Zhang's model (6 parameters) achieves the lowest error (3.9%), while the Bingham model (2 parameters) exhibits the highest (91.8%) due to its inability to capture non-linear behaviors like shear-thinning.

The present study employs a continuum approach to explore the magnetorheological fluid flow in a cylindrical MRF clutch system. Unlike previous studies, it provides a detailed numerical investigation of MR fluid behavior within a complex clutch geometry, considering a high particle volume fraction. The simulation model implemented in ANSYS Fluent is based on a laminar viscous model to accurately depict the MR fluid behavior under different magnetic flux densities ($B = 0, 0.3$, and 0.5 T). The Herschel-Bulkley model is selected to represent the rheological properties of the MR fluid, as it provides a balance between accuracy and complexity by capturing field-dependent changes in viscosity and yield stress [10].

II. NUMERICAL MODEL

A. *Computational domain and materials*

The original geometry of the MRF clutch (Fig.2) was first simplified using DesignModeler within ANSYS Workbench to create a modified version (Fig.3a) by removing redundant components from the complex design. Then, the fluid domain was defined to focus only on the essential clutch features (Fig.3b). All rotating and stationary walls are considered as no-slip walls. The three cylinders attached to the rotating disc are set to rotate at a constant rate fixed to 188 rpm. The main clutch dimensions are presented in Table I.

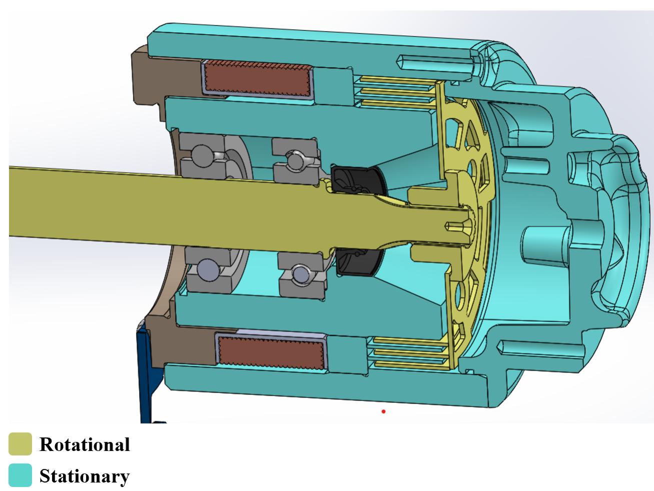
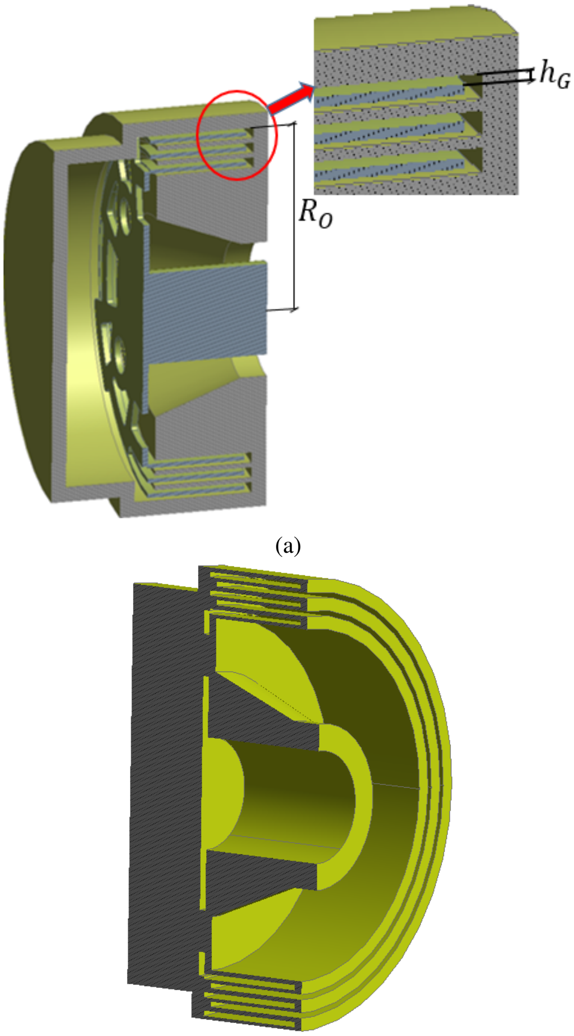


Figure. 2: Original geometry of MRF clutch



(b)

Figure. 3: Cross sections of MRF clutch: (a) solid components and (b) fluid domain

TABLE. I: MRF properties and clutch parameters

Property/Parameter	Description
Radius of outer cylinder, R_O	26 mm
Gap Height, h_G	0.45 mm
Carrier fluid	Hydrocarbon-based
Particle type	Carbonyl Iron Powder (CIP)
MRF's density	3650 kg/m^3
Particle size	1-10 μm
Volume fraction	40%
Magnetic flux density, B	0-0.5 T
Rotor speed	188 rpm

The MR fluid (MRF) used in this study is a hydrocarbon-based magnetorheological (MR) fluid with a 40% volume fraction of Carbonyl Iron Powder (CIP) microparticles. The particles are spherical with a diameter ranging between 1 and 10 μm. The mixture density is measured at 3650 kg/m^3. It is noteworthy that the model assumes a single-phase mixture, where the size and concentration of CIP particles are accounted for in the mixture's density and dynamic (molecular) viscosity, which quantifies its resistance to shear-driven flow.

In this study, the fluid motion is governed by the incompressible Navier-Stokes equations:

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla P + \nabla \cdot \tau \quad (1)$$

where ρ is the fluid density, $\mathbf{u}$ is the velocity field, P is pressure, and τ is the stress tensor. Since the applied magnetic field B is uniform, no explicit magnetic force term appears in the momentum equation. Instead, the effect of B is incorporated indirectly through the rheological properties of the magnetorheological (MR) fluid, which follows the Herschel-Bulkley (H-B) model:

$$\tau = \tau_0(B) + k(B)\dot{\gamma}^{n(B)} \quad (2)$$

where τ is the shear stress (Pa), τ_0 the yield stress (Pa), k the flow consistency ($Pa.s^n$), $\dot{\gamma}$ the shear rate (s^{-1}) and n the flow index $(-)$. The field-dependent parameters for the MR fluid, namely $\tau_0(B)$, $k(B)$, and $n(B)$, have been determined from internal experimental tests conducted at various magnetic field strengths B, as presented in Table II.

TABLE. II: MR Fluid power-law parameters

Magnetic flux density B (T)	**Yield stress** τ_0 (Pa)	**Consistency index** k (Pa·s^n)	**Flow index** n (-)
0	0	4.51	0.5444
0.3	17400	596.83	0.001
0.5	33000	795.77	0.001

B. Numerical modeling

The conservation equations for mass and momentum were solved for an incompressible single-phase fluid in the laminar steady-state regime using the finite-volume approach. In this study, the magnetic field data B was obtained from finite element (FE) simulations. Then, the shear rate, shear stress, and yield stress were derived from experimental tests under obtained magnetic fields. The three H-B model parameters (Eq. 2) were calculated from these experimental data (Tab. II) and implemented in the fluid solver. This approach links the external magnetic field's influence to the Navier-Stokes equations via the shear stress term, enabling accurate representation of the MR fluid's behavior under varying magnetic flux densities.

The simulations were conducted using ANSYS Fluent 2023 R2. A pressure-based solver was employed with the SIMPLE algorithm to overcome the pressure-velocity coupling. The gradient calculation method was set to Least Squares Cell-Based. Spatial discretization for pressure and momentum was achieved through second-order schemes, ensuring high accuracy for the laminar flow regime. Under-relaxation factors were configured as follows: 0.3 for pressure, 1 for density and body forces, and 0.7 for momentum. Convergence was reached when all residuals for continuity and velocity components fell below 10^{-3} and 10^{-6}, respectively.

C. Grid generation

The mesh, created using Fluent Meshing, consists of 1,895,303 cells, with polyhedral cells in the volume and polygonal faces on the surface, forming a hybrid unstructured mesh (Fig. 4). This configuration was determined after testing various mesh densities to achieve an optimal balance between computational efficiency and accuracy.

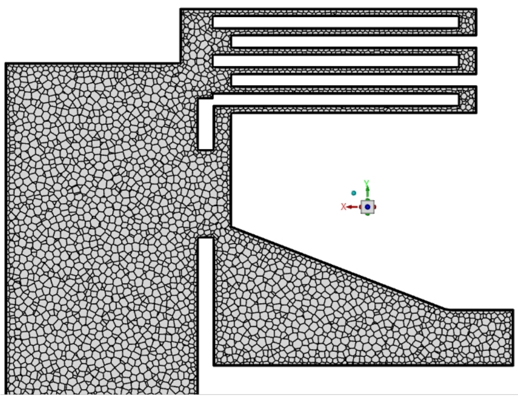


Figure. 4: Cross-sectional view of the mesh grid

III. RESULTS AND DISCUSSION

A. Validation

To confirm the accuracy of the employed numerical model, the obtained CFD results were compared against the experimental data for transmission torque of the MR fluid in the MRF clutch. The torque values for $B = 0.3$ T and $B = 0.5$ T for both experimental and numerical methods, along with the errors between them, are shown in Table III. It can be concluded that the validation procedure was satisfactory which proves the capability of CFD model to predict the MR fluid behavior.

TABLE. III: Comparison between the experimental and numerical torque values for two magnetic flux densities

Magnetic flux density, B (T)	**Experimental torque (N.m)**	**Numerical torque (N.m)**	**Error (%)**
0.3	4.49	4.34	3.34
0.5	8.00	8.16	2

B. Influence of the magnetic flux density on the fluid flow

Without a magnetic field $B = 0$, the fluid dynamic viscosity remains constant and uniform within the clutch (results not shown here for sake of brevity). However, when a magnetic field is imposed, as shown in the viscosity contours (Fig.5), the dynamic viscosity increases dramatically, particularly near the stationary surfaces, leading to enhanced resistance to flow. This increase becomes more pronounced as B rises from 0.3 to 0.5 T, reflecting the adjustable rheological properties of the fluid that are critical for torque generation in MR fluid clutches. More importantly, the magnetic field creates a nonuniform distribution of viscosity in the rotor-stator gaps at the periphery of the clutch.

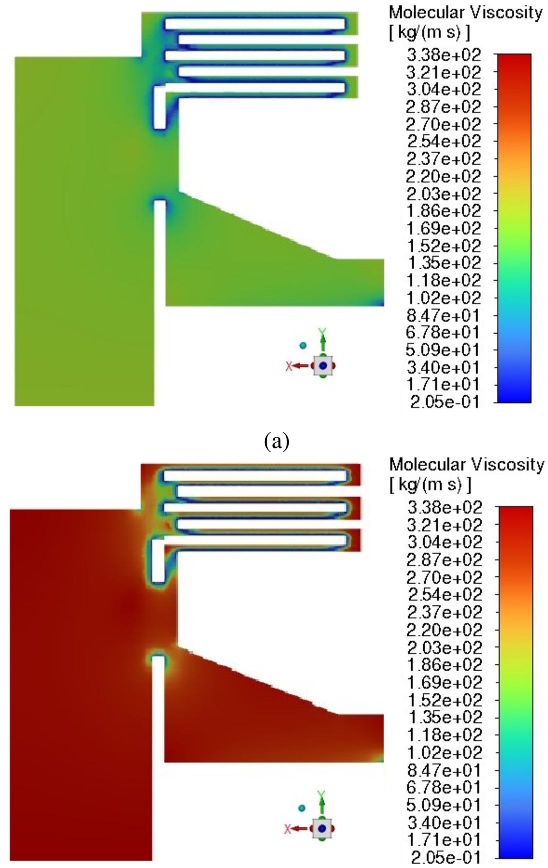
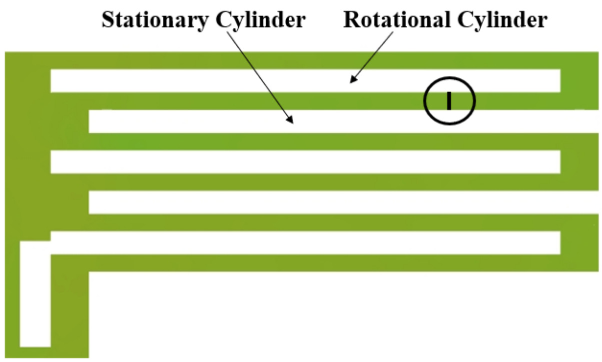


Figure. 5: 2D contours of the dynamic viscosity under two magnetic flux densities: (a) $B = 0.3$ T, (b) $B = 0.5$ T

To explain this nonuniform distribution of the dynamic viscosity, radial profiles of the dynamic viscosity and tangential velocity are displayed in Figure 6 for $B = 0$ and 0.5 T. The profiles are extracted along a radial line in the second rotor-stator gap (Fig.6a). Without magnetic field ($B = 0$), the dynamic viscosity remains constant (Newtonian behavior) and quite low (0.114 Pa.s) and the main flow is a pure Couette shear flow as highlighted by the linear profile of the tangential velocity (Fig.6c). For $B = 0.5$ T, the flow transits to a rotor-stator with two boundary layers, one along each wall (Fig.6c). In between, the tangential velocity increases almost linearly when approaching the rotating wall, which is characteristic of a laminar rotor-stator flow. A steep velocity gradient near the stationary wall indicates a thinner boundary layer. Thus, the shear rate is no more constant, which induces large variations of the dynamic viscosity following a shear-thinning behavior ($n = 0.001 < 1$) (Fig.6b). High viscosity regions are observed near the stationary and rotating walls corresponds to low shear regions, where the fluid remains in a pre-yield state. In contrast, a sharp drop in viscosity in the central region indicates a shear-thinning zone, where the fluid has yielded under higher shear rates.



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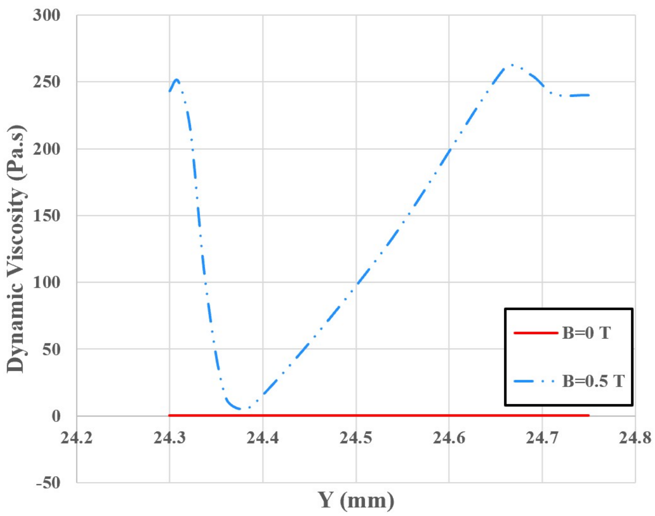

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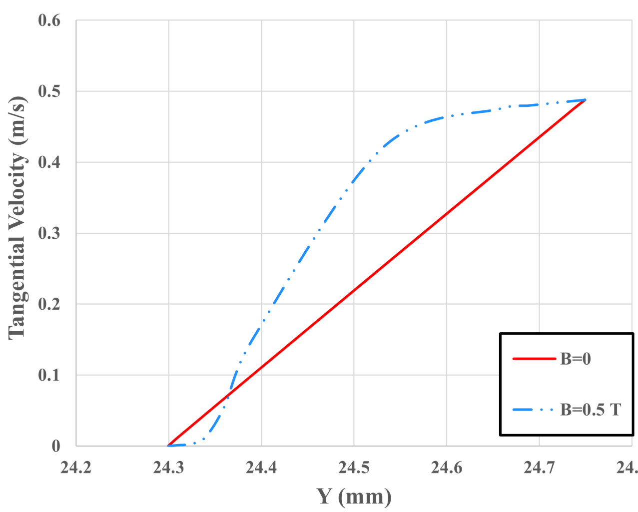

(c)

Figure. 6: (a) Definition of the extraction line in the second rotor-stator gap; Corresponding (b) dynamic viscosity and (c) tangential velocity profiles for $B = 0$ T and $B = 0.5$ T

Figures 7 and 8 display the contours of static pressure and tangential velocity, respectively, for $B = 0$ and 0.5 T. The pressure distribution also responds significantly to the imposed magnetic field. At $B = 0$, the pressure is uniformly distributed within the rotor-stator gaps. By increasing B, the pressure near the rotating cylinders rises significantly, enhancing shear stress and torque transmission. The pressure variations along the x direction within the gaps may be explained by the influence of the endwalls: the right endwall is stationary, while the left one is rotating (see Fig.2). These changes demonstrate the magnetic field's role in shaping the pressure field and its impact on torque generation within the clutch system. Figure 7c displayed the corresponding streamline patterns for $B = 0.5$ T, indicating that the base flow is mainly tangential.

As shown by comparing Figures 8a and b, the tangential velocity is less affected by the magnetic field as the two fields for $B = 0$ and 0.5 T are quite comparable. In rotor-stator gaps, for Batchelor flow profiles (two boundary layers with a core in solid body rotation), the tangential velocity profile should be proportionnal to the radial pressure gradient. From the velocity profile on Figure 6c, the deviation from the Batchelor profile is evident and explains the moderate influence of the magnetic field on that quantity.

IV. CONCLUSIONS

A single-phase numerical model has been developed to model the MRF fluid flow in a clutch by focusing on the accurate prediction of the rheological properties. The results demonstrated that this level of modeling is adequate to predict torque for flux densities up to $B = 0.5$ T. Comparisons with new experimental data showed indeed that the maximum discrepancy reached 3.3 % at $B = 0.3$ T.

The results confirm the significant influence of magnetic flux density on the MR fluid's rheological and flow behavior. At fixed geometry and rotation rate, as B increases, nonuniform distributions of dynamic viscosity, static pressure and tangential velocity appear in the rotor-stator gaps. More importantly, the mean flow in these gaps transits from a pure Couette shear flow for $B = 0$ to a rotor-stator flow with two boundary layers. From $B = 0.3$ to 0.5 T, the mean torque increases by a factor 1.88.

For future works, it would be valuable to analyze the relationship between rotational velocity up to 10^3 rpm and MR fluid behavior in the current MRF clutch system under different magnetic fields. For some specific applications, the stationary walls can rotate in the same direction but with a different rotation rate than the present rotating walls, which will be also considered.

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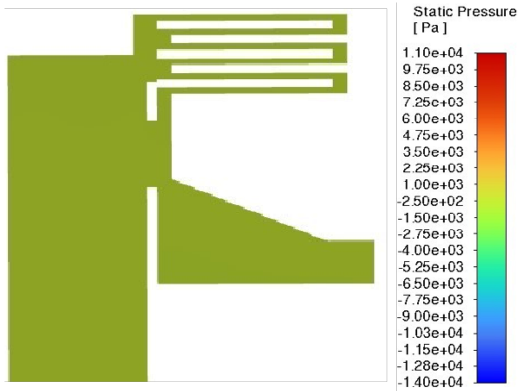

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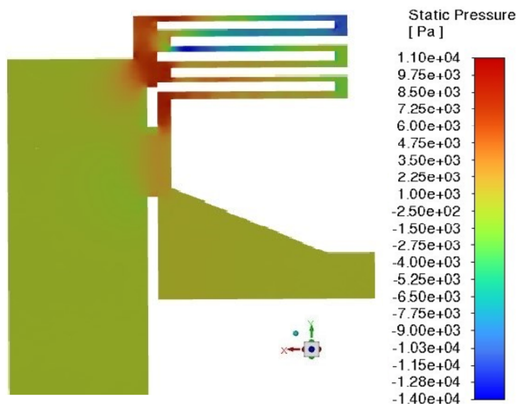

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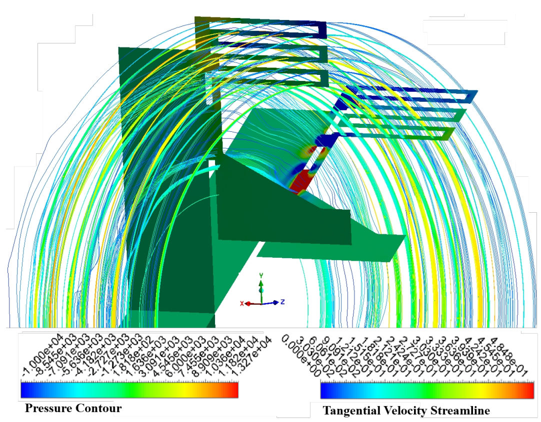
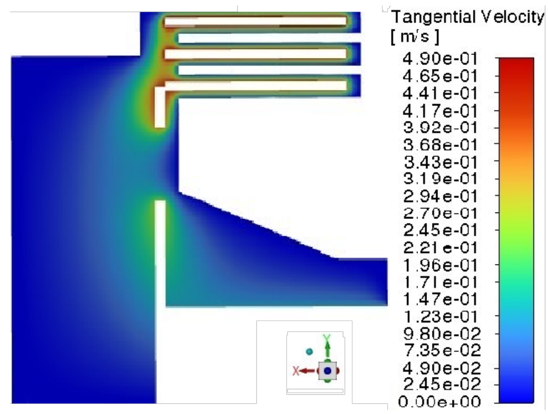
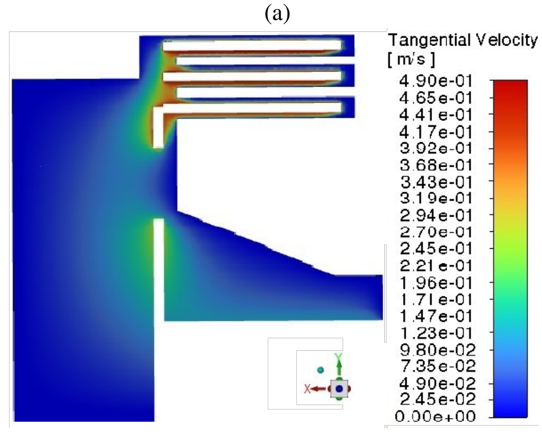


(c)

Figure. 7: 2D contours of static pressure for (a) $B = 0$ T and (b) $B = 0.5$ T; (c) Streamlines colored by the tangential velocity and static pressure contours along two planes for $B = 0.5$ T



(a)



(b)

Figure. 8: 2D contours of the tangential velocity for: (a) $B = 0$ T and (b) $B = 0.5$ T

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