# Enhanced Pumping Systems: Design and Optimization of Electrorheological and Magnetorheological Micropumps

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## Abstract

Micropumps are essential components in microfluidic systems, widely used in drug delivery, lab-on-a-chip devices, micro-cooling systems, and other applications requiring precise fluid handling in micro-liter volumes. Traditional mechanical micropumps have limitations in performance and adaptability. Smart fluids such as electrorheological (ER) and magnetorheological (MR) fluids offer innovative solutions for enhanced micropump systems with tunable flow rates, bidirectional pumping, and self-priming capabilities. This paper reviews recent advances in ER and MR micropump design and modeling, fabrication techniques, flow rate optimization, and experimental performance. Both valveless and valved pump configurations are analyzed, including key factors like magnetic/electric field strength, channel geometry, flow resistance modeling, and driving methods. Our analysis shows ER/MR micropumps can achieve high backpressures, precision flow control, dynamic flow rate modulation, and bi-directional pumping superior to mechanical designs. We present parametric optimization models and correlations to maximize flow rates and backpressure capabilities. Our findings provide insights into idealized ER/MR micropump geometries, operational parameters, and performance bounds to guide further development and commercialization of enhanced smart fluid-based micro pumping systems.

**Keywords**: micropump, electrorheological fluid, magnetorheological fluid, microfluidics, parametric optimization

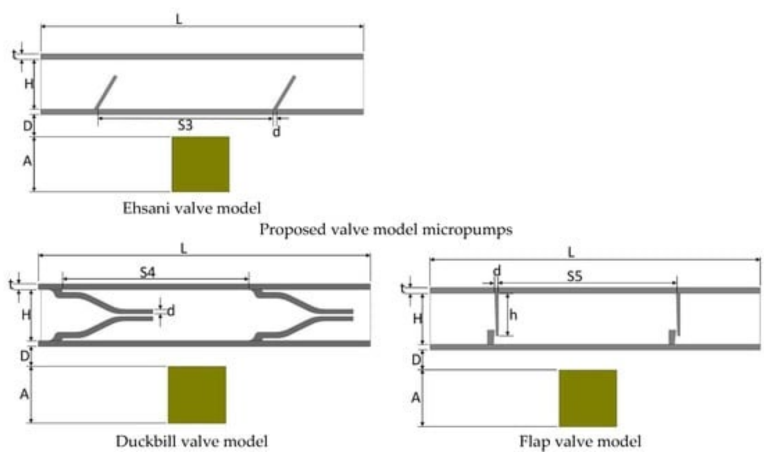
## Introduction

Micropumps are essential microfluidic components widely used in drug delivery systems, lab-on-a-chip devices, micro-cooling systems, and other applications requiring precise fluid handling in micro-liter volumes. Conventional mechanical micropumps utilizing piezoelectric, electrostatic, electromagnetic, hydropneumatics, or shape memory alloy actuators have limitations in performance, adaptability, response time, flow rate controllability, bidirectionality, and integration. Smart fluids such as electrorheological (ER) and magnetorheological (MR) fluids offer innovative solutions for tunable, adaptive micro pumping systems with fast response, precision flow control, and dynamic self-priming capabilities superior to mechanical pumps [1].

ER fluids contain polarizable particles that rapidly and reversibly change viscosity under applied electric fields on the order of kV/mm. MR fluids contain magnetizable particles that undergo field-induced dipole alignment to change viscosity in magnetic fields of 10-100 kA/m. These smart fluids enable "pump walls" that can be electrically or magnetically activated on demand to propel fluids through microchannels. ER/MR micropumps can achieve flow modulation, bi-directional flow control, and self-priming pumping unavailable in conventional mechanical pumps.

This paper reviews recent progress in ER/MR micropump designs, fabrication methods, flow rate modeling and optimization, and experimental performance. Section 2 surveys ER and MR micropump configurations, driving methods, and design considerations. Section 3 analyzes valved and valveless pump modeling approaches and parametric optimization models [2]. Section 4 summarizes key fabrication methods and testing results. Section 5 presents conclusions and opportunities for further enhancing ER/MR micropump performance and commercialization [3].

Figure 1.

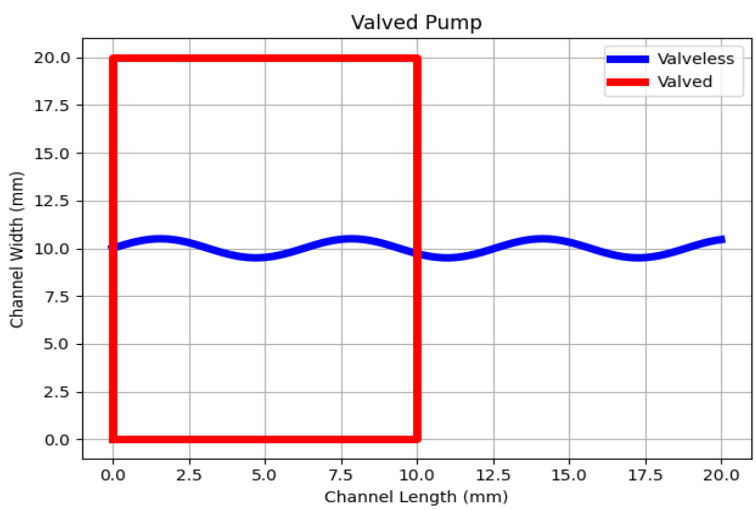



## ER/MR Micropump Design Configurations

***Pump Configurations:*** ER/MR micropumps represent a sophisticated innovation in microfluidics, harnessing the unique properties of electrorheological (ER) and magnetorheological (MR) fluids. These micropumps feature channel walls crafted from ER/MR fluids, which can be activated by integrated electrodes or microcoils [4]. These activation mechanisms induce pumping effects within the channels, facilitating the manipulation and control of fluid flow at the microscale. Within the realm of ER/MR micropumps, two main configurations have emerged as prominent designs: valveless pumps and valved pumps [5]. Valveless pumps are characterized by straight microchannels and rely on the precise timing and waveform of applied electric or magnetic fields to break flow symmetry and direct fluid in a desired direction. Despite their straightforward structural design, valveless pumps demand sophisticated drive systems to effectively control flow patterns. Conversely, valved pumps incorporate check valves and reservoir chambers akin to traditional reciprocating pumps [6]. These pumps operate by alternately activating pump and reservoir chambers, with check valves ensuring the unidirectional flow of fluid. While valved pumps offer simpler drive mechanisms compared to their valveless counterparts, they necessitate additional moving components. Presently, the majority of ER/MR micropumps in operation adhere to the valveless configuration. However, ongoing research explores the potential benefits of valved designs, particularly in achieving higher backpressures and enhancing overall pump performance [7].

The field of microfluidics has witnessed remarkable advancements with the development of ER/MR micropumps, which capitalize on the unique properties of electrorheological (ER) and magnetorheological (MR) fluids. These innovative micropumps feature channel walls constructed from ER/MR fluids, enabling precise control over fluid flow at the microscale. The functionality of ER/MR micropumps is facilitated through the integration of electrodes or microcoils, which activate the fluid and induce pumping effects within the channels. Within this domain, two primary configurations have emerged: valveless pumps and valved pumps. Valveless pumps are characterized by their utilization of straight microchannels and their reliance on the timing and waveform of applied electric or magnetic fields to direct fluid flow. While valveless pumps boast simple structural designs, they require sophisticated drive systems to effectively control flow patterns [8]. In contrast, valved pumps incorporate check valves and reservoir chambers similar to traditional reciprocating pumps. These pumps operate by alternately activating pump and reservoir chambers, with check valves ensuring the unidirectional flow of fluid. Although valved pumps offer simpler drive mechanisms compared to valveless designs, they necessitate additional moving components. Despite the prevalence of valveless pumps in current applications, ongoing research explores the potential advantages of valved designs, particularly in terms of achieving higher backpressures and enhancing overall pump performance [9], [10].

***Driving Methods:*** ER/MR micropumps employ a diverse array of driving methods to control fluid flow within microchannels, each offering unique advantages and applications. One prevalent driving method involves the utilization of traveling waves, where a phase-shifted voltage or current is applied to arrays of electrodes or coils. This application propagates an activation wave along the channel walls, effectively pushing fluid in a desired direction with minimal risk of flow reversals. Another driving method, reciprocating fields, involves alternating the activation and deactivation of pump walls, resulting in oscillatory flow patterns that can be rectified passively or through the integration of check valves. This approach enables precise control over flow dynamics and directionality. Rotating fields present yet another driving method, wherein activation regions continuously rotate within the microchannel. This rotation induces vortex flows or viscous drag pumping effects, offering opportunities for efficient mixing and fluid manipulation. Additionally, gradient fields are emerging as a promising driving method, wherein non-uniform fields are generated perpendicular to the flow direction to create viscosity gradients. These gradients induce internal flow circulation, facilitating enhanced mixing and transport phenomena within the microchannel. While traveling waves are widely regarded as the most efficient driving method, rotating fields offer distinct advantages in producing vortex mixing effects. Gradient methods, although less developed, present intriguing possibilities for further miniaturization and optimization in microfluidic applications. The continuous exploration and refinement of these driving methods contribute to the ongoing advancement of ER/MR micropump technology and its diverse range of applications in fields such as lab-on-a-chip systems, biomedical devices, and microfluidic diagnostics.




***Design Considerations:*** In the meticulous design of ER/MR micropumps, a multitude of factors must be carefully considered to optimize performance and functionality across various applications. Channel geometry stands as a pivotal aspect, with the aspect ratio, or the width-to-height ratio, playing a critical role in determining the distribution of shear stress within the channel. Higher aspect ratios are often correlated with improved efficiency, making them a desirable characteristic in micropump design. The configuration of electrode or coil arrays represents another crucial consideration, with parameters such as the number, size, spacing, and arrangement of field actuators directly impacting field uniformity and pumping power. Denser arrays tend to afford more precise control over fluid flow, enhancing overall performance [11]. Moreover, the strength of the applied electric and magnetic fields is a paramount factor influencing the viscosity changes experienced by ER/MR fluids. While higher field strengths typically induce greater viscosity alterations, they also escalate concerns regarding Joule heating and power consumption. Consequently, striking a balance between field strength and energy efficiency is imperative in micropump design. The characteristics of driving signals, including waveform, amplitude, and phase offsets, are pivotal in determining flow directionality and facilitating flow rate modulation, offering additional avenues for optimizing micropump performance. Furthermore, the integration of passive microstructures such as posts, ridges, and surface patterns within the channels can significantly enhance pumping efficiency by promoting fluid manipulation and flow control. In summary, the overarching goal in ER/MR micropump design is to maximize field strength and channel aspect ratio while minimizing Joule heating, thereby enhancing overall performance and efficacy across diverse applications in microfluidics and beyond.

## Modeling and Optimization

***Lumped Parameter Models:*** Lumped parameter models serve as invaluable tools in the analysis and understanding of the intricate dynamics involved in ER/MR micropumps, simplifying their complex behavior into analogies akin to electrical circuits. In these models, various physical quantities are analogized: flow rate ( $Q$ ) corresponds to current, pressure ( $P$ ) to voltage, and hydraulic or electrical impedances to resistances ( $R$ ). In the context of valveless ER/MR pumps, key components included in such models typically encompass ( $R_{\{\text{channel}\}}$), representing channel flow resistance, ($\frac{R_{\{\text{ER}\}}}{R_{\{\text{MR}\}}}$) denoting activated ER/MR wall flow resistance, ( $L$ ) accounting for inertial effects, and ( $V$ ) representing the applied voltage or current. By conceptualizing the system as an electrical circuit—often resembling an RC (resistor-capacitor) or RLC (resistor-inductor-capacitor) circuit—driven by an alternating current (AC) voltage, these models enable the analysis of pumping performance parameters such as flow rate, backpressure, and power consumption. It is important to note, however, that lumped parameter models come with certain limitations. They typically assume one-dimensional flow and tend to neglect complex viscosity effects, which may limit their accuracy in certain scenarios. Despite these limitations, lumped parameter models provide valuable insights into the fundamental behavior of ER/MR micropumps, facilitating the optimization and refinement of their design and operation for a wide range of applications in microfluidics and beyond.

***Distributed Parameter Models:*** Advanced distributed parameter models represent a significant leap in the complexity and accuracy of modeling ER/MR micropumps, offering detailed insights into the intricate interplay between fluid mechanics and electromagnetic fields. These models go beyond the simplifications of lumped parameter models by solving the Navier-Stokes equations coupled with ER/MR constitutive equations, thus capturing the full multidimensional nature of the flow phenomena. The typical workflow of these advanced models involves several key steps:

1) Solving the distribution of magnetic or electric fields within the pump system, considering the applied voltage or current and the geometric configuration of the electrodes or coils.

2) Determining the induced particle structures within the ER/MR fluid and calculating the resulting viscosity profiles, which are crucial for understanding the fluid's response to the applied fields.

3) Computing the stress tensor within the fluid and deriving the corresponding fluid flow profiles, accounting for the complex interactions between the fluid and the channel walls.

4) Finally, calculating pressure gradients and flow rates throughout the system, providing comprehensive insights into the pump's performance.

These models yield detailed, multi-dimensional flow field data, enabling a thorough understanding of the underlying physics governing ER/MR micropump operation. However, their implementation requires extensive computational resources due to the complexity of the governing equations and the need for high-resolution simulations. Finite element methods are commonly employed to solve the coupled equations efficiently, enabling the accurate prediction of pump behavior under various operating conditions.

Key constitutive parameters play a crucial role in these distributed parameter models, providing insights into the relative importance of different physical effects. The Mason number, defined as the ratio of viscous forces to ER/MR forces, and the Bingham number, representing the ratio of yield stress to viscous forces, are among the most significant parameters. These parameters govern the balance between fluid viscosity and ER/MR effects, influencing the overall performance and behavior of the micropump.

***Flow Rate Optimization:*** To maximize micropump flow rate Q, parametric models are developed based on key variables. For ER pumps, Q can be approximated by :

$$Q \approx \left(\frac{\varepsilon E2wh3}{12\eta L}\right)(1 - e - \alpha) \tag{1}$$

where ε is dielectric constant, E is electric field strength, w and h are channel width and height, η is viscosity, L is channel length, and α depends on fluid properties.

This indicates flow rate increases with higher field strength, larger channels, and lower fluid viscosity. Similar relations can be obtained for MR pumps by replacing E with magnetic field strength H.

More complex models incorporate additional parameters such as driving frequency, wall geometry, particle volume fraction, etc.. Optimization methods like Lagrangian multipliers or genetic algorithms are used to determine optimal design parameters maximizing flow rate or backpressure capabilities.

Table 1. Comparison of driving methods for ER/MR micropumps

| **Driving Method** | **Advantages** | **Disadvantages** |
|---|---|---|
| Traveling wave | Highly efficient unidirectional flow, avoids flow reversals | Requires complex drive electronics with multiple synchronized phases |
| Rotating field | Induces mixing vortex flows | Less efficient for net flow with reversal losses |
| Reciprocating field | Simpler drives with two alternating phases | Flow reversal losses, may need valves for unidirectional flow |
| Gradient field | Potential for greater miniaturization | Significant flow reversal losses, less developed |

## Fabrication and Testing

***ER/MR Fluid Preparation:*** ER/MR fluid preparation is a critical aspect of the manufacturing process, requiring careful attention to ensure the desired properties and performance characteristics of the fluid. Several key methods are commonly employed in ER/MR fluid preparation to achieve the desired particle dispersion and stability.

One fundamental step is milling, which involves the mechanical grinding of particles to obtain uniform micrometer-scale sizes. This process ensures consistency in particle size distribution, which is crucial for achieving predictable rheological behavior in the resulting fluid. Additionally, surfactant treatment of particles is often utilized to inhibit aggregation and promote dispersion within the carrier fluid. By coating the particle surfaces with surfactant molecules, the propensity for particles to clump together is reduced, enhancing the stability of the fluid suspension.

Following particle treatment, dispersion in a carrier oil is performed, typically at volume fractions ranging from 10% to 50%. The choice of carrier oil, whether synthetic or mineral-based, depends on factors such as compatibility with the particles and the desired rheological properties of the final fluid. It's important to note that higher particle loadings generally lead to increased yield stress, which is desirable for generating stronger response to applied fields. However, higher particle concentrations can also compromise fluid stability and increase off-state viscosity, which may affect pump performance.

Commonly employed particles in ER fluids include TiO2, SiO2, or BaTiO3, each offering unique rheological properties and suitability for specific applications. Similarly, carbonyl iron or magnetite particles are frequently used in MR fluids due to their magnetic properties and compatibility with the fluid carrier.

***Pump Fabrication:*** The fabrication of micropump structures involves a series of intricate processes aimed at realizing precise and functional devices capable of manipulating fluid at the microscale. Two primary fabrication techniques commonly employed in the production of micropumps are liquid ER/MR injection and photolithography, each offering distinct advantages and considerations [12]–[14].

In the liquid ER/MR injection method, micropump structures are typically fabricated by etching or molding microchannels into substrates composed of materials such as glass, silicon, or polymers. These substrates serve as the foundation for the micropump architecture, providing the necessary structural support and fluid pathways. Electrodes or coils, essential components for activating ER/MR fluids, are then patterned onto the substrates using techniques such as photolithography or thin film deposition. Once the electrode/coil arrays are in place, ER/MR fluids are injected into the microchannels or deposited as coating layers along the channel walls, depending on the specific design requirements. Finally, the microchannels are sealed using methods such as thermal bonding, adhesive bonding, or laser welding, ensuring the integrity and functionality of the pump structure. On the other hand, photolithographic methods offer a high degree of precision and miniaturization in the fabrication of micropump structures but typically require access to cleanroom facilities due to the sensitive nature of the processes involved. This technique involves the precise patterning of electrode/coil arrays directly onto substrates using photolithographic masks and photoresist materials [15]. Through a series of photolithography steps, intricate features and patterns can be created with exceptional accuracy, allowing for the realization of complex micropump designs.

While both liquid injection and photolithography offer unique advantages, hybrid approaches are also commonly employed in micropump fabrication. For instance, liquid injection techniques may be utilized in conjunction with pre-etched microchannels to achieve a balance between fabrication simplicity and feature resolution, enabling the production of functional micropumps with tailored performance characteristics.

Table 2. Typical performance parameters for ER/MR micropumps

| **Performance Parameter** | **Typical Range** |
|---|---|
| Flow rate | 10 μL/min – 1 mL/min |
| Back pressure | 1 - 10 kPa |
| Response time | < 100 ms |
| Power consumption | 50 mW – 5 W |
| Particle volume fraction | 10% - 50% |
| Electric/magnetic field | 1 – 5 kV/mm <br> 50 – 300 kA/m |

***Performance Testing:*** When evaluating the performance of ER/MR micropumps, a range of critical metrics are considered to assess their effectiveness and suitability for various applications. These metrics encompass aspects such as flow rate characteristics, back pressure limitations, power consumption, dynamic flow rate response, flow directionality, reversibility, and operational stability over prolonged usage cycles. Testing systems designed for evaluating these performance metrics typically involve the application of controlled field signals while simultaneously measuring induced pressures and flow rates within the micropump system. Advanced testing setups may also incorporate visualization techniques to observe fluid flow profiles and measure local viscosities, providing deeper insights into the pump's behavior under different operating conditions.

Recent studies have yielded promising results for an annular ER micropump employing traveling wave driving, showcasing its impressive performance across several key metrics. For instance, the micropump demonstrated a maximum flow rate of 350 mL/min when subjected to an applied field strength of 4 kV/mm at a frequency of 100 Hz. Furthermore, the micropump exhibited a maximum back pressure capability of 11 kPa, indicating its ability to withstand significant resistance while maintaining flow [16]. Notably, the micropump's power consumption was recorded at 0.9 W, which compares favorably to traditional piezoelectric pumps, highlighting its energy efficiency. Additionally, the micropump showcased rapid dynamic flow rate modulation capabilities, underscoring its responsiveness to varying operating conditions.

These results underscore the potential of ER/MR micropumps to outperform conventional mechanical pumps of similar size, offering enhanced performance and versatility in microfluidic applications. However, it is important to note that the performance of these micropumps is highly dependent on driving parameters such as applied field strength and frequency, as well as channel geometry. As such, further research and optimization efforts are necessary to fully harness the capabilities of ER/MR micropumps and address any limitations associated with their operation.

Table 3. Comparison of fabrication methods

| **Method** | **Advantages** | **Disadvantages** |
|---|---|---|
| Liquid filling | Simple process | Limited resolution and feature sizes |
| Photolithography | High resolution, complex structures | Requires cleanroom facilities |
| Hybrid | Combines benefits of both methods | More complex process |

## Conclusions

The exploration of ER/MR micropumps reveals a promising avenue for the development of tunable and adaptive pumping systems utilizing field-responsive smart fluids. Our comprehensive review highlights several key insights and considerations:

Firstly, the existence of both valveless and valved pump configurations offers distinct trade-offs in terms of simplicity, drive requirements, and backpressure capabilities.

Valveless pumps, reliant on traveling wave driving, demonstrate superior efficiency and flow control compared to valved designs, albeit with more complex drive requirements.

Secondly, while lumped parameter models provide a simplified framework for initial analysis, the complex dynamics of ER/MR micropumps necessitate the use of advanced numerical models for accurate multiphysics simulations. These models consider factors such as channel geometry, field strength, and fluid behavior to provide deeper insights into pump performance [17].

Thirdly, micropump fabrication techniques involve either liquid filling or photolithographic patterning methods, each with its own advantages and limitations. Liquid filling enables simpler fabrication but may compromise feature resolution, whereas photolithography offers precise control over electrode/coil arrays but requires access to cleanroom facilities [18],[19].

Despite these challenges, recent advancements have demonstrated the potential for ER/MR micropumps to achieve multifunctional capabilities such as bi-directional pumping, flow modulation, and self-priming [20]. These capabilities pave the way for enhanced versatility and adaptability in microfluidic systems, opening up new possibilities for applications in fields ranging from biomedical devices to lab-on-a-chip technologies.

Looking ahead, further research is warranted to optimize the efficiency and performance of ER/MR micropumps. Improved designs and driving electronics hold the key to unlocking their full potential as next-generation integrated microfluidic systems. With ongoing innovation and refinement, ER/MR micropumps are poised to make significant contributions to advancing microfluidic technology and addressing pressing challenges in fields such as healthcare, environmental monitoring, and beyond. As such, they stand as promising candidates for driving the development of future microfluidic platforms across diverse application domains.

## References

[1] M. El-Hendawi, H. A. Gabbar, G. El-Saady, and E.-N. A. Ibrahim, “Enhanced MG with optimum operational cost of pumping water distribution systems,” in *2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE)*, Oshawa, ON, Canada, 2017.

[2] L. Cremaschi, B. D. Iverson, and S. V. Garimella, “Enhanced electrohydrodynamic pumping at the microscale,” in *Microelectromechanical Systems*, Chicago, Illinois, USA, 2006.

[3] A. Chavez, D. Koutentakis, Y. Liang, S. Tripathy, and J. Yun, “Identify statistical similarities and differences between the deadliest cancer types through gene expression,” *arXiv preprint arXiv:1903.07847*, 2019.

[4] D. L. Dollens, R. L. Becker, and R. L. Adair, “Artificial lift optimization: A case study of ultra long stroke pumping systems performance, enhanced with

modified NEMA C motors," in *Proceedings of SPE Production Operations Symposium*, 1997.
[5] A. E. Hosoi, Y. Liang, I. Bischofberger, Y. Sun, Q. Zhang, and T. Fang, "Adaptive self-sealing microfluidic gear pump." 28-Dec-2021.
[6] X. Wu, Z. Bai, J. Jia, and Y. Liang, "A Multi-Variate Triple-Regression Forecasting Algorithm for Long-Term Customized Allergy Season Prediction," *arXiv preprint arXiv:2005.04557*, 2020.
[7] J. Mazloum and A. Shamsi, "3D design and numerical simulation of a check-valve micropump for lab-on-a-chip applications," *J. Microbio Robot.*, vol. 16, no. 2, pp. 237–248, Dec. 2020.
[8] X.-Y. Wang and Y.-F. Chen, "Innovative design of piezoelectric micropump based on micro-nano additive manufacturing," in *2019 14th Symposium on Piezoelectrcity, Acoustic Waves and Device Applications (SPAWDA)*, Shijiazhuang, China, 2019.
[9] R. Padmanabhan and V. Varghese, "Design and development of an electrostatic-based micropump," *Int. J. Biomechatronics Biomed. Robot.*, vol. 3, no. 4, p. 182, 2020.
[10] Y. Whulanza, A. T. Hakim, S. M. Utomo, R. Irwansyah, J. Charmet, and Warjito, "Design and characterization of finger-controlled micropump for lab-on-a-chip devices," *Evergreen*, vol. 6, no. 2, pp. 108–113, Jun. 2019.
[11] Y. Liang *et al.*, "Solid state pump using electro-rheological fluid." 04-Jun-2019.
[12] K. Aung, N. W. Sein, and N. Nyi, "Design and fabrication of impeller for single suction centrifugal pump," *Int. J. Sci. Res. Publ. (IJSRP)*, vol. 9, no. 8, p. 92110, Aug. 2019.
[13] N. Inomata, K. Kamakura, N. Van Toan, and T. Ono, "Fabrication of on-chip vacuum pump using a silicon nanostructure by metal-assisted chemical etching," *IEEJ Trans. Electr. Electron. Eng.*, vol. 14, no. 6, pp. 954–958, Jun. 2019.
[14] A. Oluwaseun Abiodun, O. Oluwatimilehin Ebenezer, and O. Emmanuel Abidoun, "Design, modeling and fabrication of a portable solar powered suction pump for use in industries and autoclinics," *Int. J. Sci. Res. Sci. Eng. Technol.*, pp. 287–297, Oct. 2019.
[15] E. Vignali *et al.*, "Design, simulation, and fabrication of a three-dimensional printed pump mimicking the left ventricle motion," *Int. J. Artif. Organs*, vol. 42, no. 10, pp. 539–547, Oct. 2019.
[16] Y. Liang, "Design and optimization of micropumps using electrorheological and magnetorheological fluids." 2015.
[17] Z. Mao, K. Yoshida, and J.-W. Kim, "Developing O/O (oil-in-oil) droplet generators on a chip by using ECF (electro-conjugate fluid) micropumps," *Sens. Actuators B Chem.*, vol. 296, no. 126669, p. 126669, Oct. 2019.
[18] Y. Liang, J. R. Alvarado, K. D. Iagnemma, and A. E. Hosoi, "Dynamic sealing using magnetorheological fluids," *Physical Review Applied*, vol. 10, no. 6, p. 64049, 2018.
[19] G. Boyarskii, A. Sorokin, and A. Khaustov, "Experimental pressure-flow characteristics determining of micropumps for orbital station biotechnical

system," *Vestnik Moskovskogo aviatsionnogo instituta*, vol. 26, no. 4, pp. 184–190, 2019.

[20] Z. Mao, K. Yoshida, and J.-W. Kim, "A droplet-generator-on-a-chip actuated by ECF (electro-conjugate fluid) micropumps," *Microfluid. Nanofluidics*, vol. 23, no. 12, Dec. 2019.