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Review Article

A Short Review on Magnetic Micromixers in the Presence of Nanofluids

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ABSTRACT

This short review provides a concise overview of magnetic micromixers operating in the presence of nanofluids, a class of active microfluidic devices that leverage external magnetic fields to overcome the inherent mixing limitations of laminar flow at low Reynolds numbers. Unlike passive micromixers that rely solely on channel geometry, magnetic micromixers employ embedded or externally positioned magnetic elements, such as ferromagnetic wires, magnetic beads, or ferrofluid droplets, to induce localized chaotic advection through contactless actuation, offering tunable performance and reduced risk of contamination. Collectively, these works demonstrate that mixing efficiency can be significantly enhanced, by up to 89% in some cases, through careful optimization of magnet number, spacing, frequency, and nanoparticle volume fraction, as well as through the strategic design of microchannel geometry. However, several research gaps persist, including limited experimental validation, insufficient attention to long-term device reliability, and a lack of integrated lab-on-a-chip systems. Future directions should prioritize hybrid actuation mechanisms, smart magnetic materials, and scalable designs.

1. Introduction

By providing exact control over minuscule quantities, usually in the picoliter to microliter range, microfluidics, the science and engineering of manipulating fluids at the sub-millimeter scale, has transformed several areas [1, 2]. In this field, micromixers are essential for quickly homogenizing many fluid streams, which is difficult due to the laminar flow conditions that are common in microchannels (low Reynolds numbers) [3]. In general, there are two types of micromixers: passive and active. Serpentine and spiral channels [4, 5], convergent-divergent structures [6], feedback patterns [7], T-arrow micromixers [8], and fin- and obstacle-based microchannels [9, 10] are examples of passive micromixers that only use geometric manipulation to produce chaotic advection and diffusion without the need for external energy input, making them straightforward and simple to integrate. In contrast, active micromixers provide adjustable and quick mixing at the expense of more complicated manufacturing by using external fields (such as magnetic [11], acoustic [12, 13], electric [14, 15], etc.) to cause forceful fluid disturbance. Both types are widely used in biochemistry and medicine: in drug delivery systems for nanoparticle synthesis, in lab-on-a-chip devices for cell lysis and DNA hybridization, in point-of-care diagnostics for homogenizing blood samples with reagents, and in chemical synthesis where quick reaction initiation is crucial [16]. Active mixers are recommended where high efficiency and on-demand mixing are crucial, even at low flow

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rates, while passive mixers are preferable for portable, inexpensive systems needing constant flow [17].

In microfluidic systems, where laminar flow predominates due to low Reynolds numbers and effective mixing is difficult without active intervention, micromixers are crucial components. Magnetic micromixers are unique among active mixing techniques in that they use external magnetic fields to provide quick and adjustable fluid agitation. Usually, these devices include magnetic components inside the microchannel, such as revolving magnetic bars, magnetic beads, or embedded ferromagnetic wires. These components move, rotate, or vibrate in response to an oscillating or rotating magnetic field, thereby causing localized chaotic advection and greatly improving the mixing of fluids or suspended particles over short distances [18]. Because magnetic actuation is contactless, it does not require mechanical pumps or on-chip electrodes, which simplifies fabrication and reduces the risk of sample contamination or electrode degradation.

By modifying field characteristics, including frequency, amplitude, and direction, magnetic micromixers' performance may be accurately regulated, enabling customized mixing for various fluid viscosities and flow rates. For instance, high-frequency oscillations encourage strong local stirring close to the magnetic elements, but low-frequency rotating fields can produce large-scale vortex motion. Because of its adaptability, magnetic micromixers are especially useful in lab-on-a-chip applications where quick reagent homogenization is essential, such as medication delivery systems, biochemical tests, and point-of-care diagnostics. Additionally, recent developments have produced soft magnetic elastomers and programmable magnetic microstructures that allow for intricate mixing patterns without the need for moving mechanical components. Magnetic micromixers have better mixing efficiency at low flow rates than passive mixers, which only use channel geometry; nonetheless, careful design is necessary to prevent trapping magnetic particles or producing excessive heat.

Due to its contactless actuation, customizable performance, and simplicity of integration, magnetic micromixers have become a particularly interesting type of active micromixers in light of the increasing interest in lab-on-a-chip applications that require quick and effective mixing at low flow rates. While several research have shown how magnetic fields may improve fluid homogeneity, most of them have only looked at the channel geometry or the magnet design. Particularly when taking into account the non-Newtonian behavior frequently seen in biological and chemical experiments, the interaction between magnetic forces, nanofluid characteristics, and flow conditions is still complicated and poorly understood. Furthermore, existing reviews have largely covered passive and active micromixers in general, with limited attention dedicated specifically to magnetic micromixers operating with nanofluids. By compiling current developments in magnetic micromixers, this brief overview seeks to close that gap, with an emphasis on research utilizing ferrofluids or magnetic nanoparticles. We address the governing physics, highlight important results from experimental and numerical studies, and point out open problems. In the end, this study gives scholars a succinct but thorough summary of the state of the art and identifies promising avenues for future advancement in this quickly developing subject.

2. Governing Equations

The mass transfer equation for the species, the Maxwell equations for the magnetic field, and the continuity and Navier-Stokes equations for the flow field must all be solved in order to model the mass transfer process in the presence of a magnetic field. The following are the Navier-Stokes and continuity equations for steady and incompressible flow [11]:

$$\nabla.\vec{u}_f = 0 \tag{1}$$

$$\nabla\left[-PI + \mu_f(\nabla\vec{u}_f + (\nabla\vec{u}_f)^T)\right] + \vec{F}_{ext} = 0 \tag{2}$$

where

$$\vec{F}_{ext} = \vec{F}_g + \vec{F}_{st} + \vec{F}_m \tag{3}$$

$$\vec{F}_m = \mu_0(\vec{M}.\nabla)\vec{H} \tag{4}$$

where $\vec{u}_f$ is the velocity vector, ρ_f and μ_f are fluid density and dynamic viscosity, respectively. $\vec{F}_{ext}$ is the external force. $\vec{F}_{ext}$ involves the gravitational force $\vec{F}_g$, surface tension $\vec{F}_{st}$, and magnetic force $\vec{F}_m$ [19, 20].

The following formula is used to determine the density and viscosity of nanofluid[21, 22]:

$$\rho_{ff} = (1-\varphi)\rho_{w+}\varphi\rho_{np} \tag{5}$$

$$\mu_{ff} = \mu_w\left(\frac{1}{(1-\varphi)^{0.25}}\right) \tag{6}$$

where ρ_{ff} and μ_{ff} are fluid density and dynamic viscosity, respectively. The mixture density and viscosity are defined as:

$$\rho_{mix} = (1-C)\rho_{w+}C\rho_{ff} \tag{7}$$

$$\mu_{mix} = \mu_w e^{R(1-C)} \tag{8}$$

$$R = Ln(\frac{\mu_w}{\mu_{ff}}) \tag{9}$$

The Maxwell equations are solved in order to determine the volumetric magnetic force[23]:

$$\nabla.\vec{B} = 0 \tag{10}$$

$$\nabla \times \vec{H} = 0 \tag{11}$$

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) \tag{12}$$

$$\vec{B} = \nabla \times \vec{A} \tag{13}$$

$$\vec{M} = \vec{M}_0 C = \chi \vec{H} C \tag{14}$$

where $\vec{B}$ is the magnetic flux, μ_0 is the vacuum permeability. $\vec{H}$, $\vec{M}$, and $\vec{A}$ represent the magnetic field strength, the ferrofluid magnetism, and the electric potential vector, respectively.

The advection-diffusion equation is expressed as follows [24]:

$$\vec{u}_{np}.\nabla c_{np} + \nabla.\left(-D\nabla c_{np}\right) = 0 \tag{15}$$

where D is the diffusion coefficient and $\vec{u}_{np}$ is the particle velocity:

$$\vec{u}_p = \vec{u} + \vec{u}_{mag,np} \tag{16}$$

$$\vec{u}_{mag,np} = \frac{\vec{F}_{mag.np}}{6\pi\eta r_{np}} \tag{17}$$

where

$$\vec{F}_{mag.np} = (\vec{m}.\nabla)\vec{B} \tag{18}$$

$$\vec{m} = V_p.\vec{M} \tag{19}$$

$$\vec{M} = \Delta\chi.\vec{H} \tag{20}$$

$$\vec{F}_{mag.np} = \frac{V_p.(\Delta\chi)(\vec{B}.\nabla)\vec{B}}{\mu_0} \tag{21}$$

Here, $\vec{F}_{mag.np}$ is the magnetic force and $\vec{m}$ is the total momentum exerted on the particle, which depends on the volume of the particle V_p and its magnetism $\vec{M}$. $\Delta\chi$ is the difference in the magnetization of the fluid and the nanoparticles.

Eq. 22 is used to calculate the mixing index, where c is the concentration [25]:

$$\mathrm{MI} = \left(1 - \frac{\int_0^h |c - c_\infty| dy}{\int_0^h |c_0 - c_\infty| dy}\right) \times 100 \tag{22}$$

3. Advances in the Field

Bahrami et al. [11] assessed a two-dimensional active/passive micromixer using a neodymium magnet and sinusoidal microchannel walls (Fig. 1). The micromixer performed 1.16 times better than a straight channel, while the magnetic field enhanced mixing quality by 17.5%. The mixing index increased by 24%, from 0.015% to 0.06%, when the volume percent of magnetic nanoparticles was increased. The mixing index was further enhanced by moving the magnet closer to the microchannel; it peaked at a distance of 13.75 mm from the inlets.

Majumdar et al. [26] presented a Y-shaped micromixer that improved the mixing of ferrofluid and water by leveraging electrokinetic and magnetofluidic transport. They emphasized how zeta potential patches contribute to enhanced mixing performance, along with the careful positioning of neodymium micromagnets adjacent to the microchannel. Using finite element simulations, the authors showed that both the number of magnets and their spacing play a critical role in determining mixing efficiency. The results suggested that with optimal placement of micromagnets and zeta potential patches, a significant increase in the mixing index can be achieved, offering an effective approach for researchers that does not rely on extending channel length.

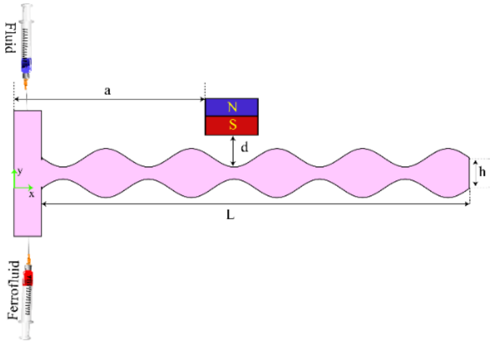

Fig. 1. Schematic of a magnetic micromixer with sinusoidal wall [11].

Wang and Lin [27] evaluated the effects of flow rate, rotation frequency, and magnetic field intensity on mixing efficiency using micro particle image velocimetry, or micro-PIV. The findings showed that while a strong external magnetic field can efficiently spin aggregated chains, it has no discernible influence on mixing efficiency. Rotation frequency, on the other hand, was important. A key number was found where mixing efficiency fluctuates; it was enhanced to this value and falls below it, offering guidance for creating magnetic micro-mixers.

Wei et al. [28] used a nonuniform magnetic field from tapered magnets to achieve high mixing efficiency by a magnetic fluid micromixer. According to numerical calculations, mixing efficiency was increased as the magnets' saturation magnetization increased, resulting in higher magnetic forces acting on the fluid. Furthermore, compared to a symmetric field, an asymmetric magnetic strayed field that created circulation between two fluids improves mixing efficiency.

Sun et al. [29] proposed a magnetic micromixer that combines specially made microwires with a Y-shaped microchannel (Fig. 2). They examined the dynamic behavior of ferrofluid using a 3D Eulerian-Eulerian model and obtained good agreement between numerical and experimental data. The number of microwires was augmented with the enhanced mixing caused by eddies created by longitudinally aligned microwires. However, longer microchannels and mixing durations were required when there were more microwires. They suggested using uniformly magnetic microwires placed horizontally to improve performance, reaching an ideal mixing efficiency of 99.06%. System performance was adjusted thanks to the tunability of the external magnetic field.

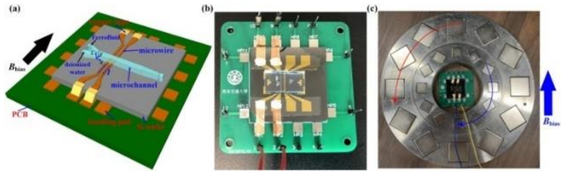

Fig. 2. Schematic of a magnetic micromixer proposed by Sun et al. [29].

The use of oscillating ferrofluid droplets as a programmable actuator to improve mass transfer in a 3D-printed micromixer was investigated experimentally by Haghgoo et al. [30] (Fig. 3). Using these droplets as actuators, they combined two miscible fluids while reducing interaction with biological reactants and influencing the attributes of the finished product. Many factors, including fluid flow rates, magnet movement frequency, and amplitude, affected the motion of magnetized droplets guided by a linear-moving magnet. The mixing index was increased from 0.21 to 0.89 when the magnetic system was activated, according to the results, demonstrating the potential of ferrofluid droplets to greatly improve microfluidic mixing efficiency for biomedical and engineering applications.

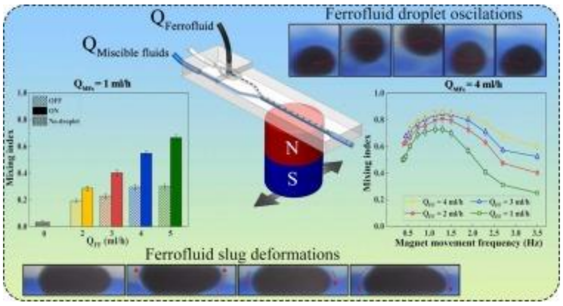

Fig. 3. Schematic of a magnetic micromixer proposed by Haghgoo et al. [30].

4. Research Gaps and Future Directions

Even while magnetic micromixers for nanofluid applications have advanced significantly, there are still a number of research gaps that need to be filled. First, idealized numerical models with simplified assumptions on nanoparticle distribution, agglomeration, and magnetic susceptibility are used in the majority of previous research, including those examined here. Experimental validation under practical working circumstances is conspicuously lacking, especially for multi-phase systems and biocompatible ferrofluids. Second, the synergistic effects of combining magnetic fields with other external stimuli (such as acoustic or electric fields) have not received as much attention as the influence of magnet number, position, and strength; such hybrid approaches could potentially yield mixing efficiencies beyond what is achievable with magnetic actuation alone. Third, there hasn't been a thorough evaluation of the long-term stability and reusability of magnetic micromixers, particularly those that use embedded microwires or magnetic beads. Long-term device dependability may be impacted by problems such particle fouling, mechanical fatigue, and magnetic remanence. Fourth, the scaling laws for magnetic micromixers are still not well characterized; most designs are designed for certain flow rates and channel diameters, which makes it challenging to extrapolate findings to other microfluidic platforms. Lastly, there is still much to learn about integrating magnetic micromixers into full lab-on-a-chip systems, including fluid routing, sample preparation, and on-chip detection. Therefore, the following areas should be the focus of future research: (i) creating standardized experimental protocols for benchmarking the performance of magnetic micromixers; (ii) investigating hybrid actuation mechanisms that combine magnetic fields with other active mixing strategies; (iii) looking into the use of smart magnetic materials (like shape-memory magnetic polymers) for reconfigurable mixer designs; and (iv) moving from single-device studies to fully integrated microfluidic systems for practical applications like drug synthesis and point-of-care diagnostics. up addition to expanding our basic knowledge of magnetofluidic transport, filling up these gaps will hasten the transition of magnetic micromixers from theoretical study to real-world application.

5. Conclusions

This brief paper has given a succinct overview of magnetic micromixers in the presence of nanofluids, highlighting major findings from representative research, governing equations, and current developments. By using external magnetic fields to create chaotic advection without coming into direct touch with the fluid, magnetic micromixers provide a convincing solution to the mixing problem seen in low-Reynolds-number microfluidic flows. The reviewed research show that improving factors like magnet location, number of magnets, nanoparticle volume proportion, and frequency or intensity of the applied magnetic field may significantly increase mixing efficiency. Notable contributions include Majumdar and Dasgupta's use of zeta potential patches to prevent channel stretching, Bahrami et al.'s demonstration of a 24% increase in mixing index by magnet location, and the novel ferrofluid droplet actuator developed by Haghgoo et al., which improved the mixing index from 0.21 to 0.89. Nevertheless, there are still a number of unanswered questions, especially with regard to long-term device dependability, experimental validation, and integration into whole microfluidic systems. Future research should focus on scalable designs that retain high mixing efficiency under a variety of flow conditions, smart magnetic materials, and hybrid actuation techniques. In the end, magnetic micromixers have a lot of potential to advance lab-on-a-chip applications in chemical synthesis, drug delivery, and biological diagnostics—as long as persistent issues with operating stability and manufacturing complexity are resolved. Researchers looking to develop, enhance, or apply magnetic micromixers in next-generation microfluidic systems might use this review as a starting point.

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