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Research Article

A Short Overview on Oscillating Feedback Micromixers

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ABSTRACT

This review paper provides a detailed analysis of the fundamental concepts of OFMs and describes the primary mechanisms that control their operation, such as feedback loops, oscillation creation, and their impact on fluid dynamics at the microscale. The discovery of new materials, innovative design techniques, and integration strategies that have improved the functioning and efficiency of OFMs in a variety of microfluidic applications are among the notable advancements in the sector that are also highlighted. The report also discusses current challenges for researchers, such as optimizing mixing efficiency, cutting down on energy use, and addressing scaling issues in commercial applications. The potential for integration with other microfluidic technologies, the exploration of innovative actuation methods, and the growing application of OFMs in cutting-edge fields, including drug delivery systems, lab-on-a-chip devices, and point-of-care diagnostics, are all covered in the review's conclusion. Because of these insights, the paper provides a comprehensive understanding of the state of OFM technology today and its potential in the future.

1. Introduction

To enable effective fluid mixing at the microscale, micromixers are essential components of microfluidic systems [1-4]. In microfluidic channels, where laminar flow dominates and turbulence is absent, achieving efficient mixing poses a significant challenge. Micromixers address this by employing various mechanisms, such as chaotic advection, passive geometric designs, or active methods that utilize external forces like magnetic or acoustic fields [5-8]. They are vital in applications requiring precise and rapid mixing of reagents for reliable outcomes, including chemical synthesis, biomedical diagnostics, and drug delivery. By enhancing system performance, reducing sample and reagent consumption, and accelerating reaction kinetics, micromixers play a pivotal role in advancing microfluidic technology [9-13].

A particular kind of micromixer called OFM uses dynamic oscillations to improve fluid mixing in microfluidic systems. In order to continuously interrupt the laminar flow, these micromixers use periodic motion or oscillations imparted to the fluid, frequently by external actuation or mechanical devices inside the microchannel. By inducing a feedback mechanism, the oscillations greatly enhance the interaction between various fluid layers, resulting in more efficient and consistent mixing. In applications like chemical reactions, lab-on-a-chip devices, and biological experiments where thorough and quick mixing is crucial, OFMs are very helpful. They are a useful tool in microfluidic technology because of their capacity to achieve great mixing efficiency with low energy consumption and device complexity [14].

The basic ideas of OFMs are thoroughly examined in this review study, which also outlines the main mechanisms governing their function, including feedback loops, oscillation production, and their effects on fluid dynamics at the microscale. It also highlights the significant advancements in the field, including the development of new materials, innovative design approaches, and integration strategies that have improved the functionality and

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efficiency of OFMs in various microfluidic applications. The study also addresses the difficulties that researchers are now facing, including maximizing mixing efficiency, reducing energy usage, and resolving scaling concerns in commercial applications. The review concludes by examining the potential for integration with other microfluidic technologies, the investigation of novel actuation techniques, and the expanding use of OFMs in cutting-edge domains such as drug delivery systems, lab-on-a-chip devices, and point-of-care diagnostics. The article offers a thorough grasp of the current status of OFM technology and its prospects for the future, thanks to these insights.

2. OFMs

Because of their high-frequency fluidic oscillation, OFMs are becoming more and more popular. An inlet, two Coanda steps, an oscillating chamber, a splitter, two feedback channels, and an outlet are the standard components of an OFM (Fig. 1) [15]. The Coanda or wall attachment effect is the working concept, in which a fluid jet follows one of the attachment walls, creating a pressure differential that propels fluid circulation. The flow rate entering the OFM determines the oscillation frequency. In an OFM, oscillations cause chaotic advection; greater oscillating frequencies are thought to improve transfer efficiency [16-18]. Therefore, knowing how to raise the oscillation frequency is essential for designing and using OFMs. However, there isn't much research on this topic specifically for micro-scale OFMs; most studies concentrate on macro-scale OFMs. The most important element influencing oscillation frequency, according to Mandane and Ranade [19], is the distance between the feedback channels and the inlet. They discovered that because shorter feedback channels enable the circulating flow to affect the attachment flow close to the oscillating chamber's entrance more rapidly, they result in greater oscillating frequencies. In a similar work, Shakouchi et al. [20] assessed the effects of geometric parameters on oscillating frequency and verified that it rises with decreasing inlet channel height, oscillating chamber entry width (the span of the Coanda steps), and inclined angle of the attachment walls. Stated differently, Mandane and Ranade's conclusion is supported by the fact that oscillations are more likely to occur on smaller scales. These results can be used as useful references for micro-scale OFMs operating in laminar flow conditions, even though they are mainly related to macro-scale OFMs working in turbulent flow.

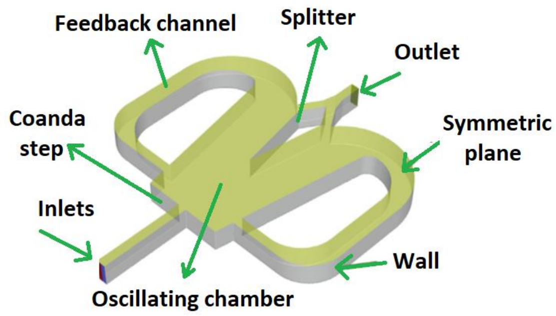

Fig. 1. Schematic of an OFM [15].

3. Applications

3.1. Mixing of miscible liquids

OFMs use their special oscillatory flow dynamics to quickly and evenly blend liquids at the microscale, making them very effective in mixing miscible substances. By upsetting laminar flow patterns, which are typical in microfluidic systems, these micromixers improve mixing efficiency through the use of feedback loops and periodic flow oscillations. This feature is especially useful in chemical and biological applications, such as reagent production, chemical synthesis, and biochemical tests, where accurate and reliable mixing of miscible liquids is essential. Oscillating feedback micromixers guarantee ideal reaction conditions, shorten processing times, and improve the overall performance of microfluidic systems by allowing comprehensive mixing within a small unit. They are essential in procedures needing precise control over liquid composition at tiny scales because of their quick and efficient high mixing performance [21-24].

3.2. Microcrystallization

In continuous microcrystallizers, where exact control over supersaturation and consistent mixing are necessary to produce high-quality crystals, OFMs are crucial. By creating oscillatory flows that disturb laminar patterns, these micromixers improve mixing efficiency by guaranteeing a uniform solute distribution and reducing concentration gradients. This homogeneous mixing encourages regulated crystal nucleation and growth, improving the end product's size distribution, shape, and purity. In the chemical and pharmaceutical industries, where continuous microcrystallization is utilized to create fine compounds, nanomaterials, and active pharmaceutical ingredients (APIs), such skills are essential. Continuous microcrystallizers are a crucial technology for contemporary crystallization processes because they integrate oscillating-feedback micromixers to achieve greater scalability, increased process efficiency, and reduced waste [25-28].

3.3. Microextractors

To improve mass transfer in microextractors, OFMs are essential for quick and complete mixing between immiscible or miscible liquid phases. These micromixers maximize the extraction of target compounds by generating fine interfacial regions through oscillatory flow induction and laminar pattern disruption. Applications where accuracy and efficiency are crucial, such as chemical separations, environmental sample analysis, and pharmaceutical purification, benefit greatly from this capacity. High separation efficiency can be maintained by microextractors using smaller solvent quantities and quicker extraction times thanks to the improved mixing produced by oscillating feedback micromixers. They play a crucial role in developing extraction methods for a range of industrial and analytical applications due to their smooth integration into small, scalable microfluidic devices [29-34].

4. Advances in the field

Xu and Chu [35] used the Coanda effect to passively mix two immiscible liquids in a microextractor with asymmetric feedback channels (Fig. 2). The asymmetric feedback channels demonstrated more noticeable oscillation, recirculating flows, and non-recirculating flows when experimentally examined at high Reynolds numbers. The asymmetric microextractor produced stronger oscillations and efficiently distributed the aqueous phase. Extraction efficiency in mass transfer tests was 97.1%, indicating the efficacy of asymmetric feedback systems.

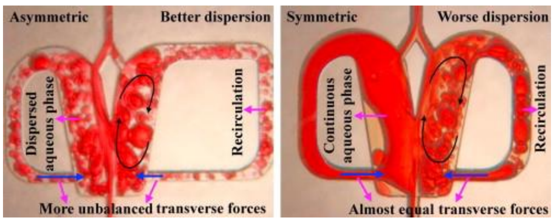

Fig. 2. Schematic of an OFM employed by Xu and Chu [35].

A selected scaling-out method for expanded passive OFMs was introduced by Li et al. [36] in order to generate superior $BaSO4$ nanoparticles at a high throughput of 281.4 mL/min (Fig. 3). The rate of NP production can surpass published rates, reaching 538.4 g/h.

The response surface approach and computational fluid dynamics are used by Jafari Ghahfarokhi [37] to maximize the performance of a high-throughput recycle micromixer (Fig. 4). It evaluated the effects of geometrical parameters on the mixing index (MI) and pressure drop (Δp) by simulating the mixing of DI water and blood plasma. MI and Δp are strongly influenced by channel depth, with MI increasing as channel depth increases. An ideal recycling micromixer for biological and clinical applications is produced by the RSM's mathematical correlations for MI and Δp.

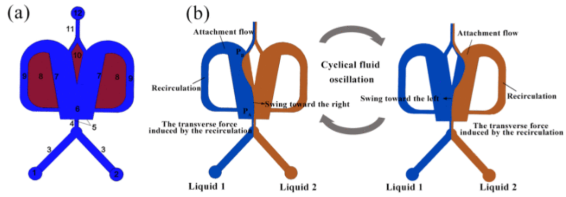

Fig. 3. Schematic of an OFM used by Li et al. [36]: (a) structure, and (b) micromixing mechanism.

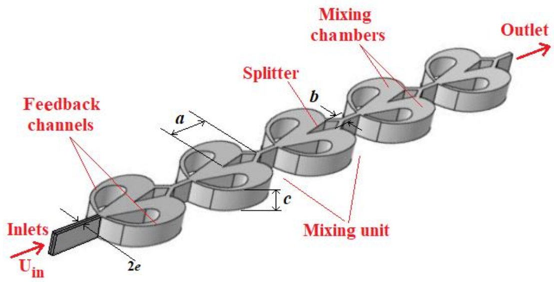

Fig. 4. Schematic of an OFM used by Jafari Ghahfarokhi et al. [37].

Yang et al. [38] suggested a passive oscillating micromixer that combines the time-varying flow properties of an active micromixer with a passive micromixer to improve mixing through chaotic convection. Re raises the oscillation frequency, which encourages convective mixing and permits a mixing index of up to 0.8. The flow oscillation is easily scaled up and has a good effect on the residence time distribution (RTD).

The Coanda effect was taken into consideration when designing an oscillating feedback micromixer by Xie and Xu [39] (Fig. 5). The effects of Reynolds number on oscillation frequency, pressure drop, and chaotic mixing were investigated using two-dimensional unsteady simulations. Mixing caused by chaotic advection was observed and measured using Lagrangian particle tracking indicators. According to the results, mixing efficiency rose as Reynolds number grew, reaching 75.3% at Re

= 100. The simulation results were validated through experimental testing.

Using Lagrange particle tracking techniques, Wang et al. [15] examined the vertical performance of oscillating feedback micromixers (OFMs). The entire micromixer can be traversed by tracer particles, according to the results, which encourages general mixing. Additionally, the study shows that effective mixing can be carried out at different elevations along the whole vertical area, even close to the top and bottom walls.

Although they have limited processing capability, oscillating feedback micromixers (OFMs) show potential in microchemical engineering. Wang et al. [40] investigated mixing performance for a range of OFMs with varying enlargement factors using the Villermaux-Dushman reaction. The findings demonstrate that selective scaling of OFMs can achieve 14.4L/h with a manageable pressure decrease while maintaining the benefits of micromixing. In order to provide universal scaling-up design principles, the study also identifies three scaling requirements for OFM scaling.

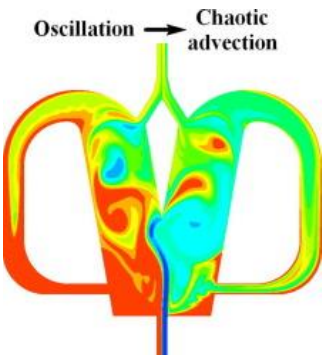

Fig. 5. Schematic of an OFM used by Xie and Xu [39].

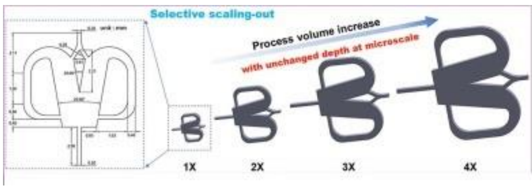

Fig. 6. Schematic of an OFM used by Wang et al. [40].

5. Challenges and future directions

The following challenges arise from simulation and experimentation when designing oscillating feedback micromixers (OFMs):

OFMs need the employment of sophisticated simulation methodologies and significant computer resources due to their complex fluid dynamics, which are characterized by transitional flows, multiphase interactions, and non-Newtonian fluid behavior. To properly capture the oscillatory feedback mechanisms in these intricate flow regimes, highly complicated turbulence models, sophisticated meshing, and sophisticated algorithms are needed. As a result, simulations become much more expensive and complex, requiring not only a large amount of processing power but also the adoption and advancement of sophisticated modeling techniques. To produce accurate and predictive simulations, these approaches must take into account the non-linearities and transitory behaviors seen in OFMs. Validation of Computational Fluid Dynamics (CFD) simulations against experimental data is crucial to their accuracy. However, because OFMs are complex and dynamic, it is very difficult to gather adequately detailed and accurate experimental data. To accurately duplicate the conditions depicted in simulations, experimental sets for validation must be carefully designed. Monitoring flow patterns and mixing efficiency requires high-speed sensors and imaging systems that can record data at millisecond or even microsecond durations. These sensors also need to be able to function in the harsh environments found in OFMs, which include temperature gradients, fluctuating pressures, and high oscillation frequencies. The development cycle of OFMs is further complicated by the time-consuming and resource-intensive nature of the design and optimization procedure for these tests.

Future directions can be expressed as follows: Future OFMs are expected to change from single-purpose micromixers or microreactors to multipurpose platforms that can carry out a variety of activities as microfluidic technology develops. These could include temperature management, pH monitoring, biological analysis, and even more sophisticated features like optical analysis and real-time chemical detection. With these improvements, OFMs could function as genuine Lab-on-a-Chip systems, providing automated, compact, and effective solutions for complex biochemical processes. These integrated systems have the potential to transform industrial process optimization, environmental monitoring, and healthcare applications, including drug screening and point-of-care diagnostics. Improvements in microfabrication technology will enable the creation of increasingly complex and effective OFM designs. The creation of robust and incredibly complex micromixer geometries will be made possible by innovations like 3D printing and two-photon polymerization as well as new materials, including ceramics, composites, and high-temperature-resistant polymers. More customization is made possible by these technologies, which also cut production costs and time, increasing the accessibility and appeal of OFMs for a range of applications. Additionally, large production may be made possible by scalable manufacturing techniques, expanding its use beyond research labs to broad industrial and therapeutic applications.

Sensors and microprocessors are anticipated to be incorporated into future OFM systems, allowing for adaptive control and real-time monitoring of fluid flow velocity, mixing efficiency, and other crucial parameters. In response to real-time feedback, these intelligent systems might dynamically modify operating parameters, like oscillation frequency and flow rates, to maximize performance for particular applications. Using artificial intelligence and machine learning, OFMs might potentially learn from past data to increase productivity and anticipate any problems before they happen. OFMs would become more dependable and functional with this level of intelligence, making them essential instruments for advanced industrial and research activities.

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