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NUMERICAL ANALYSIS OF MIXING IN A MULTIFUNCTION ELECTROMAGNETIC MICROPUMP

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ABSTRACT

This work presents numerical study on the feasibility of implementing a newly introduced electromagnetic pump for mixing fluids in microscales. It also introduces an interesting energization scheme that can be used to adjust the mixing length until obtaining complete mixing. The electromagnetic gentle pump was proposed for biomedical applications. It consists of an annular fluidic channel, set of solenoids, two permanent magnets and a cover. The pumping concept depends on controlling the rotation of the two hard magnets placed in an annular channel in opposing polarity under the influence of an electronically controlled moving electromagnetic field. This concept is currently under development for microfluidic applications using polymer micromachining. Results have been visualized through plotting mass fraction contours along the channel length. Results are motivating and showed higher mass fraction of H_2O at low channel widths.

INTRODUCTION

Due to the rapid increase in demand on biomedical applications, continuous efforts have been directed toward developing efficient microfluidic devices (i.e. pumps, mixers and separators) (1 - 3). The fluid in such devices flows at low Reynolds numbers and is mainly laminar (4). Under such conditions, turbulence eddies are missing and mixing is inefficient where the main mixing mechanism is diffusion and the intermolecular diffusion of macromolecules is too slow to have effective mixing in small length of time scales. To overcome this problem several designs of passive and active micromixers have been investigated recently (5).

Active mixers employ external forces (e.g., electro-osmosis, magnetic-stirring and ultrasonic) to perform mixing. These designs may add complexity to the microfluidic chip fabrication process where the external actuator should be integrated into the system (6). On the other hand, passive mixers can be easily fabricated as part of the microfluidic chip since they have no external forces. However, such devices need longer mixing length in order to achieve uniform mixing (7).

Recently, a new electromagnetic pump has been introduced [8, 9]. This pump offers interesting concept that can be electronically controlled to achieve high mixing efficiency. In this work, the suggested mixing behaviour in the multifunction electromagnetic micropump will be introduced and the mass fraction of H_2O due to one cycle of pumping action at different rotational speeds and geometrical parameters will be presented numerically. Mixing can be achieved by allowing two fluids to enter through the inlet port using a T-junction.

MIXING CONCEPT AND OPERATION

The mixing concept will be presented by first introducing the electromagnetic micropump and followed by the proposed energization mixing scheme that will allow efficient mixing. The pumping concept shown in Fig. 1 depends on controlling the rotation of two magnets placed in an annular channel under the influence of a moving electromagnetic field [8, 9].

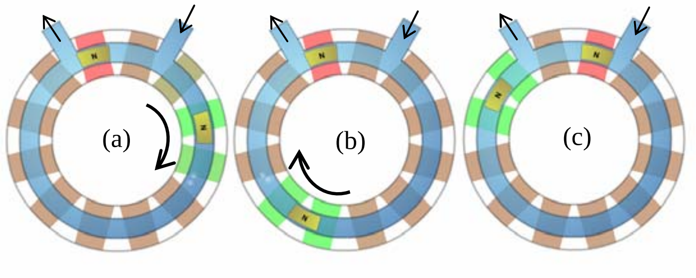

Fig. 1. The electromagnetic micropump concept

The permanent magnets are placed inside the microfluidic channel and their movements are controlled through electronically energizing a set of coils arranged below the fluid channel. One of the magnets hold between the inlet and outlet ports to isolates the inlet flow from the outflow, while the rest create a magnetic field on the free magnet to drag the fluid from the inlet to the outlet (Fig. 1a). The free magnet rotates along the channel through successive activation of the coils that attract it due to their magnetic force (Fig. 1b); the fluid is pushed out through the outlet and withdrawn into the channel from the inlet. As the free magnet reaching the outlet (Fig. 1c), the magnets begin to exchange their roles and move together, where the hold magnet is accelerated and attracted along the channel and the free one is decelerated until it stops between the inlet and outlet ports and acts as a valve. Simultaneous exchange of roles results in a pumping action.

For mixing purposes, it can be noted that, in one pumping cycle, the fluid is subjected to a mixing length equal to the channel length between the inlet and outlet ports. This length is also a function of the circular channel average radius and distance between the inlet and the outlet ports.

In microscale, diffusion is the main mixing mechanism where mixing length plays an important role. To satisfy obtaining a controllable wide range of mixing lengths, the pump energization scheme can be modified to allow pumping and mixing according to the required application. This can be realized electronically through modifying the pump energization scheme.

As shown in Fig. 2, after dragging the fluids into the channel, the two magnets continue to rotate together through the channel (Fig. 2b, c). This means that the fluids will rotate with the magnets in the channel and no further pumping action is occurred. The mixing length in this case can be adjusted according to the number of magnets rotation cycles and diffusion will take place more efficiently.

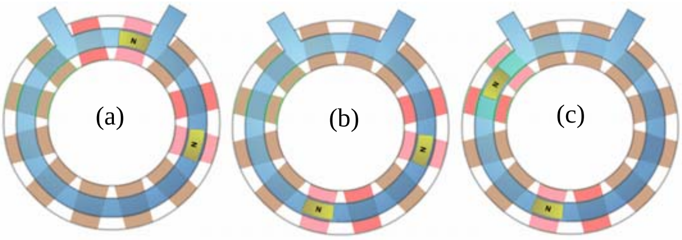

Fig. 2. **Mixing concept in the electromagnetic micropump**

NUMERICAL SIMULATIONS

Three dimensional numerical models (Fig. 3) of the pump circular channel have been simulated using the CFD program Fluent. Hexahedral structured grid was used in the meshing scheme and grid independent solution was ensured by increasing the number of grids.

Fluent uses a finite volume technique to solve for the three dimensional equations of momentum and continuity. The pressure, momentum, and pressure-velocity coupling were achieved through the simple scheme. The model is defined to be transient, viscous laminar, species transport, with considering the energy equation. Water with 998.2 kg/m^3 density, 0.001 Pa·s viscosity and methyl-alcohol-liquid with 785 kg/m^3 density and 0.0005495 Pa·s viscosity were used as working fluids.

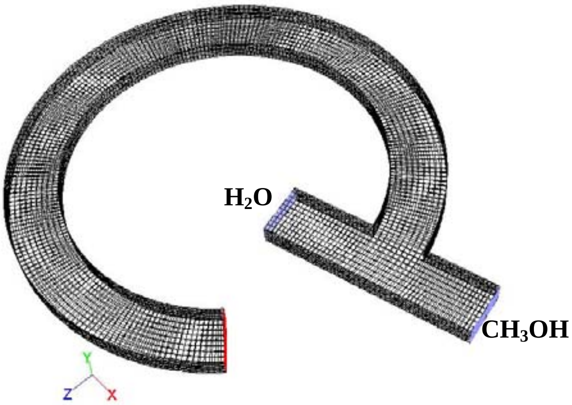

Fig. 3. **The numerical 3D – flow domain.**

For the convergence criterion, the solver iterated the equations until the scaled residuals were less than 10^{-5} or until it stabilized at a constant value, which is still small enough to ensure convergence. This can be best viewed by plotting the scaled residuals of the simulation versus the iterations for the continuity equation and the velocity components as appeared in Fig. (4).

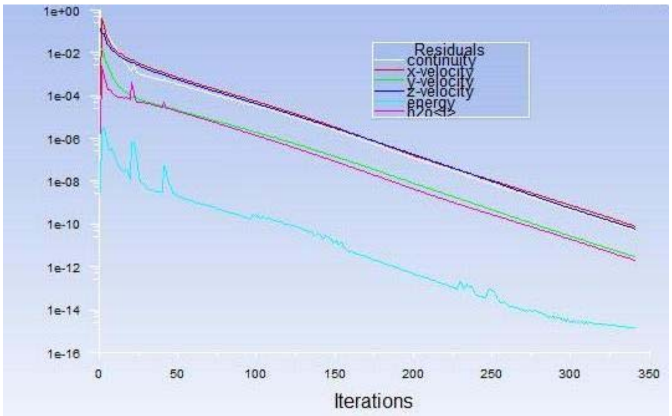

Fig. 4. **Scaled residuals Versus iterations (*w*=1500 µm, *h*=380 µm).**

RESULTS AND DISCUSSION

The mixing concept has been previously experimentally investigated in a meso-scale model (10). Water with different colors (yellow and blue) as in Fig. 5a, were driven from two inlet reservoirs through a mixing T-junction and transferred through the circular channel due to the electromagnetic pumping action between the inlet and the outlet ports.

As shown in Fig. 5b, the two fluid streams first flow in laminar profile like two independent layers along the inlet channel. Here the mixing process begins; however, it is very slow and is mainly due to diffusion according to the low flow speed. This mixing process is continued in the pump channel and as shown at the outlet, a new relatively homogeneously mixed layer is obtained. This supports the validity of using this pumping concept for mixing.

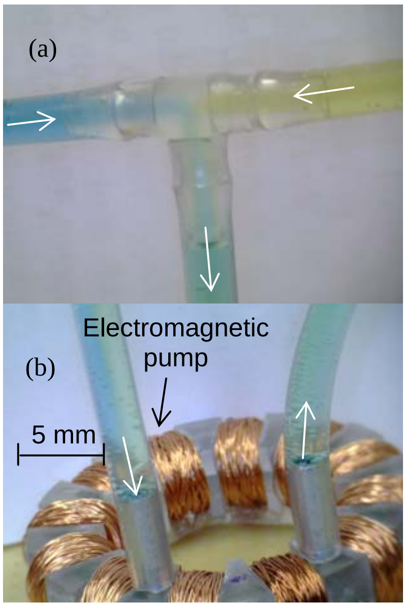

Fig.5. Experiments on mixing in the electromagnetic pump (10).

For the microscale pump, numerical results of one rotating cycle (pumping cycle) have been simulated first. Water and methyl-alcohol-liquid were considered as working fluids. Schematic of the micropump channel is plotted in Fig. 6 and simulated dimensions are summarized in table 1.

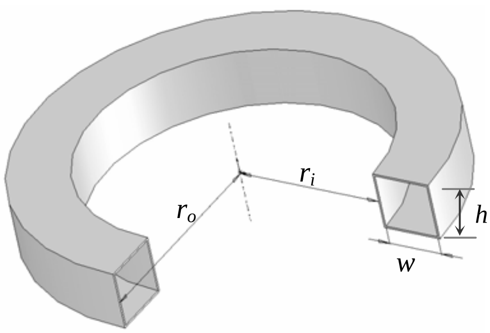

Fig. 6. Circular channel geometrical dimensions

The fluid mixing process has been visualized through plotting the mass fraction of H_2O contours for all models at different channel widths. The mixing process has also been monitored with time, as shown in Fig. 7 for channel width of 500 µm. The two fluids enter the channel through a T-junction. The mass fraction of H_2O is plotted after 100 ms and 350 ms where mixing reaches a constant fraction of 42.5 %.

Table 1. Simulated microchannel dimensions

Channel width (µm)	Channel height (µm)	Average radius (µm)
500	380	3525
1000	380	3525
1500	380	3525

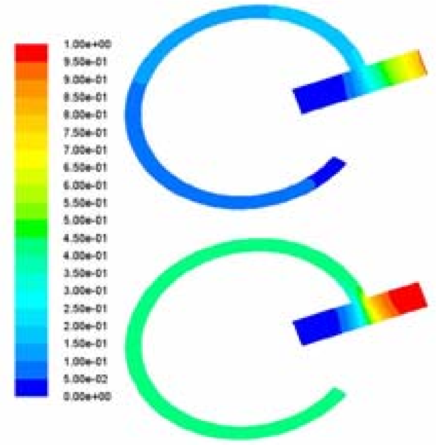

Fig. 7. Mass fraction contours of methyl-alcohol-liquid at average fluid velocity of 3.7 mm/s, *w*=500 µm

Increasing the channel width (*w*) at constant height (*h*) results in a reduction in the H_2O mass fraction. For example, at constant average fluid speed of 3.7 mm/s, for channel width of 1000 µm (Fig. 8) the mass fraction of H_2O at the outlet is in the range between 35% - 40%, while between 20%- 55% at channel width of 1500 µm (Fig. 9). All presented visualization contours are taken at the middle plane of the fluidic channel. This reduction in mass fraction is related to the reduction in diffusion rate between the two fluids, where the planar diffusion area that should be covered is increased with increasing the width.

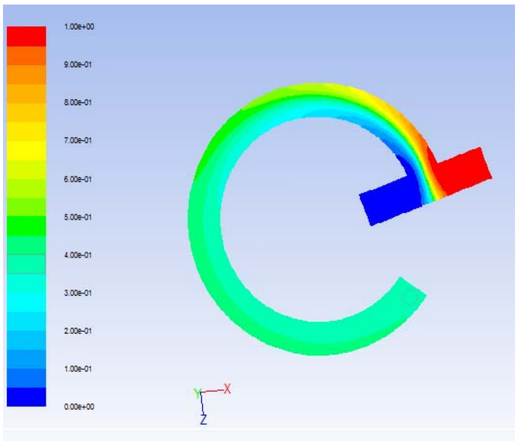

Fig. 8. Mass fraction contours of methyl-alcohol-liquid at average fluid velocity of 3.7 mm/s, *w*=1000 µm

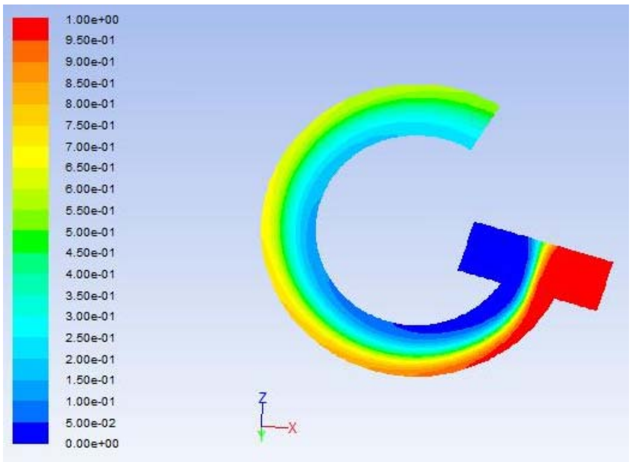

Fig. 9. Mass fraction contours of methyl-alcohol-liquid at average fluid velocity of 3.7 mm/s, *w*=1500 µm

Obtained results support the validity of using the electromagnetic micropump for mixing purposes. However, the mass fraction ratio can be increased by increasing the number of mixing cycles and then allow more mass diffusion.

CONCLUSIONS

This work presents a numerical visualization study on the feasibility of using the electromagnetic micropump for micro mixing. The pump showed good mass fraction of H_2O at low channel widths and offers the possibility of controlling the mixing length through changing the number of mixing cycles electronically. This allows flexible micro mixing of different fluids at a wide range of geometrical parameters and rotational speeds according to the application requirements.

In addition this pump is intended for handling fluids carrying particles and this makes it suitable for lab-on-a-chip applications.

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