MICROFLUIDIC MIXING BY FLUIDIC DISCRETIZATION

Kin Fong Lei and Wen J. Li*
Centre for Micro and Nano Systems, The Chinese University of Hong Kong, Shatin, Hong Kong SAR
*Contact Author: wen@acae.cuhk.edu.hk

ABSTRACT

A new concept of microfluidic mixing based on fluid "discretization" is proposed in this paper. Polymer based micropumps, micromixer and microchannels have been designed and integrated in a single PMMA chip microfluidic system. The optically transparent and biocompatible material used to fabricate the microfluidic system will enable many biomedical and chemical analysis applications. The idea of "discretized" microfluidic mixing is to manipulate fluids as "discretize" volumes by pumping fluids by two micropumps into a microchamber alternatively in order to increasing the interfacial surface area. Hence, the diffusion between fluids can be completed in a shorter time and fluids can be mixed instantly without external energy in the chamber. The design, implementation and experimental results are presented in this paper.

Keywords: Microfluidic mixing, micropump, micromixer

INTRODUCTION

Microfluidic mixing plays an important role in BioMEMS and micro total analysis system. For achieving the accurate diagnosis results in a reasonable period of time, efficient and precise mixing of reagents is required. Furthermore, most of the microfluidic components are fabricated in planar microfabrication processes, fluid mixing method in macro world such as mechanical actuation is inapplicable at microscopic level. And because of the low Reynolds number in the microchannel flow, turbulent mixing is not a possible method for microfluidic mixers. Hence, most of the microfluidic mixing is obtained by diffusion mechanism. A pure diffusion based mixing process in a microfluidic system often takes a long time. Thus, to enhance the micromixing process, some special mechanisms must be used to manipulate fluids for increasing the interfacial surface area, which will allow the diffusion be completed in the micromixing process in a shorter time. A number of micromixing devices can be found in the literatures. Two categories roughly conclude these micromixing devices: 1) active micromixers [1][2] that provide some active mechanisms such as moving parts or varying pressure gradients over the flow field; 2) passive micromixers [3][4] that utilize no energy input except the fluid driving mechanism (pressure head or pump). Examples of active micromixer were developed by Z. Yang *et al.* [1] and L. H. Lu *et al.* [2]. The former used ultrasonic traveling waves generated by PZT and applied to the fluids in a mixing chamber. The latter used the magnetic rotating microstirrer array to generate turbulent flow. Both micromixers require the use of external energy and most of the active mixing schemes are relatively complex then the passive mixing. Other examples of passive micromixer were developed by R. Miyake *et al.* [3] and J. Branebjerg *et al.* [4]. The mixing structures of both passive micromixers are complex and require multi-layers. For an integrated microfluidic system, the ease of fabrication and compatibility of integration with other components become important. Furthermore, to commercialize of a microfluidic system, a cost effective microfabrication technique is necessary. Details of the basic polymer base microfluidic devices fabrication processes developed by our group were presented in [5][6].

In this paper, we propose a novel micromixer fabricated by micro molding replication technique. To perform the mixing of two fluids in a microchannel, two vortex micropumps [7][8] were used to "discretize" fluid flow in a microchannel. The micromixer was integrated with micropumps and microchannels in a single PMMA chip. The actual design, implementation and experimental results will be described in the following sections.

VORTEX MICROPUMP

The fluid manipulation of our proposed microfluidic mixing system is driven by vortex micropump. Detailed fabrication and modeling results developed by our group were discussed in [7][8]. The vortex micropump uses kinetic energy to move fluid through the use of an impeller and a circular pump chamber. The fundamental design concept is illustrated in Figure 1. The fluid enters the pump near the center of the impeller and is moved toward to the outer surface of the pump chamber by the rotating motion of the impeller. Because of the boundary of the pump chamber, the fluid is guided to enter the microchannel and the pumping flow is created. Since the generation of pumping flow is due to the rotating motion of the impeller, by changing the rotational speed of the impeller, the pumping flow rate can be controlled smoothly.

As mentioned earlier, microfluidic devices are required to be optically transparent and bio-compatible for bio-optical detection and chemical applications. For our vortex micropump, we choose polymethyl methacrylate (PMMA) as the structural material. The SU-8 fabricated

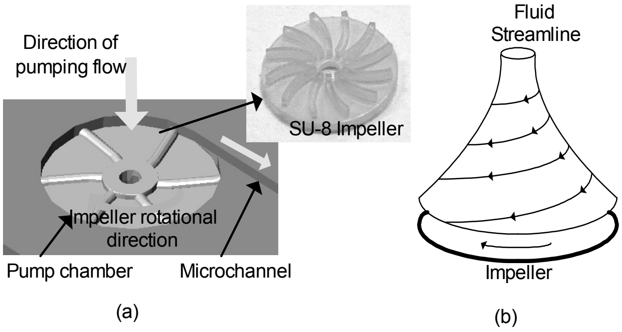

Figure 1. (a) Illustration of the vortex micropump working principle. (b) Fluid streamline inside the pump chamber.

micro impeller is placed inside the pump chamber. When the fluid enters the micropump from the center of impeller, the rotational motion of impeller, driven by a DC motor, can induce a fluid pressure gradient and thus create a continuous flow. In our vortex micropump design, two structural layers are needed. The lower layer includes pump chamber and microchannels, while the upper layer is a cover layer providing fluidic connection. A completed vortex micropump with microchannel is shown in Figure 2. The diameter of pump chamber is 5mm. The fluid is pumped through an output microchannel of 300μm in width and 200μm in depth.

The experimental and simulation results of the pump rate as a function of rotational speed of impeller is plotted in Figure 3. In the figure, we also compared the pump performance of two different sizes of the pump chamber, which are 3mm and 5mm in diameter. In general, due to the operating principle of the vortex micropump, the produced fluid flow rate is proportional to the impeller rotational speed. That is, the pump rate increases with the applied voltage of the DC motor. From the comparisons of two different sizes of the pump chamber, the difference in pumping performance is evident. Larger pump chamber can produce higher fluid flow rate and pressure. From the measurement data, the minimum pump rate is 0.11ml/min at the startup voltage (0.75V) of the DC motor. The maximum pump rate is 9.5ml/min at the applied voltage of 2.5V.

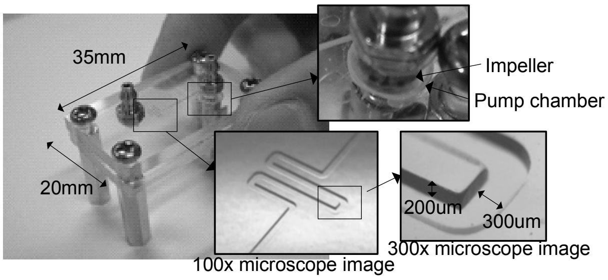

Figure 2. Photo of a vortex micropump with microchannel. The chip size is 20mm × 35mm. The diameter of pump chamber is 5mm. The output microchannel is 300μm in width, 200μm in depth.

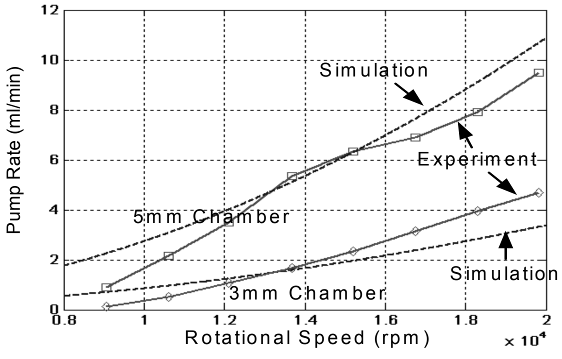

Figure 3. Comparison of the experimental (solid line) and simulation (dotted line) results. The relationship of the pump rate (water as pump medium) and rotational speed of impeller at zero back pressure.

MICROFLUIDIC DISCRETIZED MIXING

A. Working principal

Fluid mixing plays an important role in microfluidic systems for biological and chemical applications. A new concept of fluid mixing is proposed in this section. The idea is to manipulate fluids as "discretized elements" to increase the interfacial surface area such that the diffusion between fluids can be completed in a shorter time. That is, two vortex micropumps can be programmed to pump alternately high and low flow rate, and thereby force fluids coming from two different inlets into a single channel with "chunks" of alternating fluidic mass ("discretized fluid"). When these chunks of fluids are forced into a sudden expansion chamber ("mixing chamber"), their interface increases dramatically, causing the fluids to mix downstream. Using this working principal, as the swapping frequency of the two micropumps increases, the volume of a single segment of discretized fluid decreases. The diffusion between two small volumes of fluid can be completed in a shorter time. Furthermore, to enhance the mixing performance, special geometry of the mixing chamber can also improve the diffusion of fluidic mass.

B. Experimental setup

The discretized mixing phenomenon was demonstrated on an integrated microfluidic mixing system, as shown in Figure 4(a). Two inlets of the system were connected to the beakers that served as liquid reservoirs. To test the mixing performance, one of the beakers was filled with water; another was filled with red ink. The experimental setup is illustrated in Figure 4(b). The microfluidic mixing system was placed under a microscope for observation. The pumping sequence was controlled by the computer program.

C. Discretized fluid

Due to the advantage of fast response and controllability of the vortex micropumps, we can program the pumping sequence and flow rate of the vortex micropumps by a computer software. Two vortex micropumps could pump fluids alternatively by programming the applied voltages as shown Figure 5(a). In order to eliminate the backward fluid flow, the micropumps were controlled as either having a high pump rate (applied voltage was about 1.5V) or a low pump rate

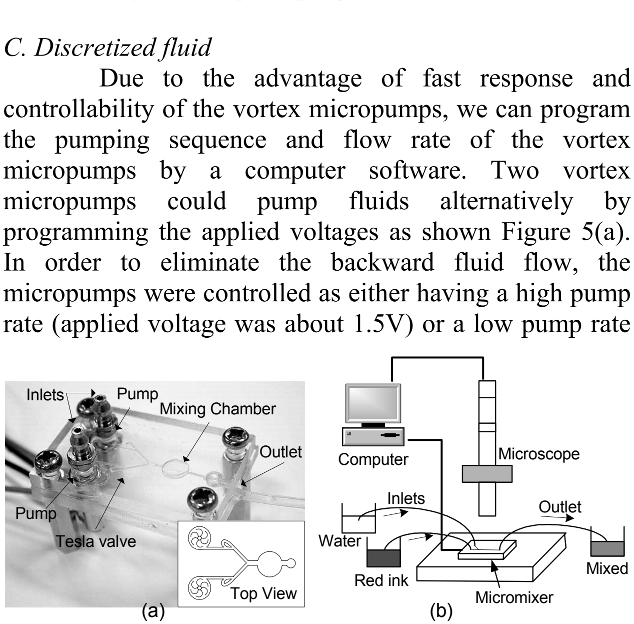

Figure 4. (a) The integrated microfluidic mixing system. The chip size is 30mm × 40mm. (b) Schematic of the experimental setup.

(the applied voltage was about 1V). That is, when micropump 1 was in the high pump rate mode, micropump 2 was controlled to be in the low pump rate mode in order to balance the backward pressure of the micropump 2. This technique can be used to swap the pumped fluid as shown in Figure 5(b). The illustration and microscopic image of this "fluid swapping" concept is shown in Figure 5(c). It is shown that the discretized fluid, i.e., alternating water layer and red ink layer, flow in the microchannel from left to right direction. The volume of these discretized fluid mass is related to the swapping frequency of the pumps, and can be estimated by an analytical solution. A comparison of the theoretical and experimental results for the volume of the discretized fluids (in a 600μm wide, 200μm deep channel) is plotted in Figure 6.

D. Discretized mixing results

The discretized fluid can be delivered to the mixing chambers of different geometries using the "fluid swapping" process as described earlier. When these chunks of fluids were forced into a sudden expansion chamber, their interface increased dramatically, causing the fluids to mix downstream. In our experiment, two different geometric types of mixing chambers, as shown in Figure 7, were utilized to demonstrate this discretized mixing phenomenon. The first one was an expansion rectangular chamber (3000μm wide, 300μm height) with obstacles (424μm and 212μm rectangular grid, 300μm height). The second one was an expansion circular chamber (5000μm diameter, 300μm height) with special microchannels (600μm wide, 300μm height) linked to it. In Figure 8, fluids (DI water and red ink solution) were pumped into the expansion (mixing) chamber at approximately the same impeller rotational speed, i.e., same flow rate. It was shown that two fluids left the mixing chambers separately as the velocities of two fluids were almost equal entering the chambers. This configuration will not initiate any mixing even if the interfacial surface of the separated fluid varies inside the circular chamber.

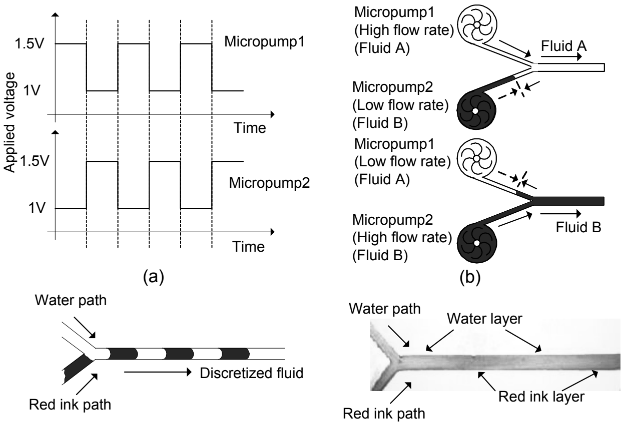

Figure 5. (a) Applied voltage sequence of two vortex micropumps. (b) Illustration of the backward fluid flow elimination mechanism. (c) Illustration and microscopic image of the discretized fluid in a microchannel.

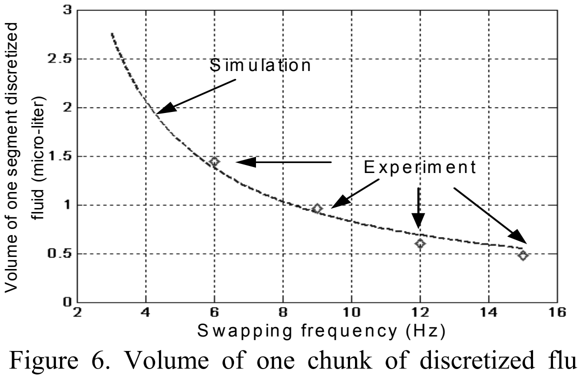

Figure 6. Volume of one chunk of discretized fluid versus the swapping frequency of two vortex micropumps.

However, as shown in Figure 9 and Figure 10, when two fluids were discretized by the vortex micropumps at the swapping frequency of 6Hz and then expanded in the mixing chambers, a very interesting phenomenon was observed: the fluidic interface length, i.e., the mixing performance, is a function of the swapping frequency of the micropumps. In Figure 9, the discretized fluid flowed from the left to right direction. It was shown that the fluid was blocked by the rectangular obstacles such that the flow field inside the mixing chamber becomes complex to enhance the mixing performance. Then, a mixed fluid can be generated before leaving the mixing chamber. Again, in Figure 10, the discretized fluid flowed into the mixing chamber from left to right direction. In this geometry, the fluid flow direction was forced to turn around in the circular chamber and this motion will improve the mixing performance.

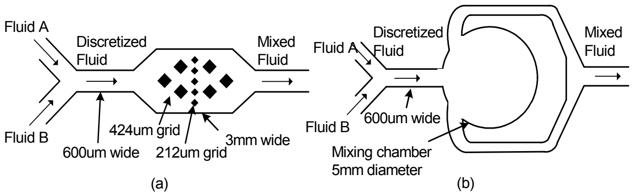

Figure 7. (a) The mixing chamber (3mm wide) with rectangular obstacles (424μm and 212μm grid). (b) The mixing chamber (5mm diameter) and special microchannels (600μm wide) linked to it.

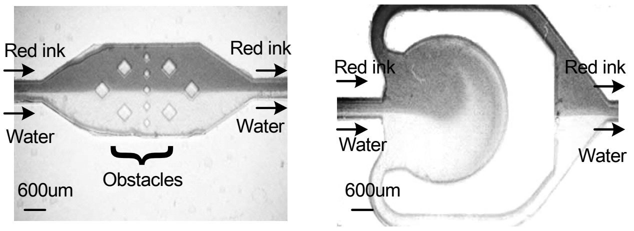

Figure 8. Fluids (DI water and red ink solution) are pumped into the expansion (mixing) chamber at approximately the same flow rate. Two fluids flow separately in the down stream of the chamber, i.e., this configuration will not initiate any mixing.

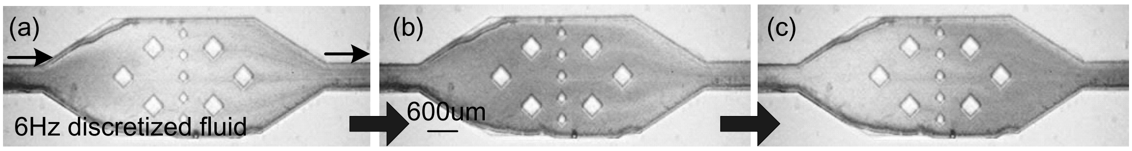

Figure 9. A sequence of microscopic images of one cycle of the discretized fluid, which is discretized by the vortex micropumps at the swapping frequency of 6Hz. The fluid was pumped into the expansion (mixing) chamber with obstacles from left to right direction. The time distance of each image is 80ms. The fluid was blocked by the rectangular obstacles such that the flow field inside the mixing chamber becomes complex to enhance the mixing performance.

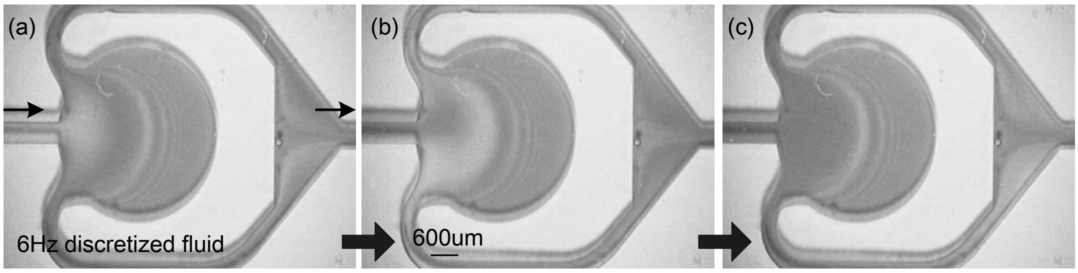

Figure 10. A sequence of microscopic images of one cycle of the discretized fluid, which is discretized by the vortex micropumps at the swapping frequency of 6Hz. The fluid was pumped into the expansion (mixing) circular chamber with special linked microchannel from left to right direction. The time distance of each image is 80ms. The fluid was mixed inside the circular chamber.

CONCLUSION

In this paper, the design, implementation and experimental results of a new concept of microfluidic discretized mixing is presented. The discretized mixing phenomenon was demonstrated on an integrated microfluidic mixing system with two vortex micropumps, a mixing chamber and connecting microchannels. Two geometries of mixing chambers were studied in this experiment. The discretized mixing had been successfully achieved without external energy in the chambers.

The vortex micropump and discretized mixing technique presented in this paper can be used for the large-scale integrated microfluidic systems for the bio-optical detection applications in the future.

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