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Laser-Assisted Active Microfluidic Mixer

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Abstract - Many analytical microsystems use molecular diffusion to mix small quantities of different liquids. However, this passive mixing process requires a relatively long microchannel which may impose design restrictions on the physical dimensions of the fluidic network. To shorten the length of the mixing channels, an active micromixer driven by a focused laser beam is described in this paper. The proposed solution improves the mixing rate by using low power laser radiation to heat the disparate fluids being transported through the channels. The operating principle is based on the observation that the rate of molecular diffusion for non-reactive fluids increases with elevated temperatures. Preliminary experiments on a Y-channel micromixer were conducted using a 1mW, 670nm laser. The laser beam was focused on the microchannel using a 100mm focal length objective lens. The laser-assisted mixing of the test fluids showed a 36.4% increase in the average diffusion coefficient value with 1 to 10 μ L/min flow rates. The maximum percentage difference of diffusion distances had increased by approximately 7.85% over the non-laser-assisted conditions.

Keywords - microfluidics; micromixing; laser assisted; active micromixers.

I. INTRODUCTION

The miniaturization and integration of various analytical laboratory processes on a single, often disposable, platform is a key design requirement for many Lab-on-a-chip (LOC) and microfluidic devices used for medicine and environmental monitoring. Building blocks of these integrated microsystems include micromixers, micropumps, separators, filters, reaction chambers, and waste disposal chambers. The reduction in physical size of these functional components have increased the speed of analysis, lowered operating costs due to the consumption of small quantities of reagents, and enabled the design of miniaturized portable devices. These integrated microfluidic systems must also be disposable and used only once to avoid the potential biological sample cross-contamination.

One of the most important components on the microsystem platform is the microfluidic mixer. Efficient mixing of chemicals or biological substances, in order to create the desired reactions, is an essential step in preparing the sample for analysis. At a macroscale, the typical mechanism for mixing fluids creates turbulent flows at a high Reynolds number. In the micro-domain, however, mixing liquids becomes more difficult because laminar flow dominates the process and molecular diffusion as the primary mixing mechanism [1,2]. To improve the mixing rate over shorter length microchannels, researchers have developed various

micromixer designs [1-21]. These microfluidic mixers can be categorized into passive or active mixing, depending on whether an external source of energy is being used to assist mixing operation [3].

Passive mixers do not require external power sources and, typically, use specially designed microfluidic channel microstructures to improve the overall mixing rate [4-15]. The simplest passive micromixers designs are T- and Y-micromixers for combining the liquids in two adjacent streams [4-6]. Unfortunately, a lengthy microchannel is required because the mixing mechanism is completely depended on the molecular diffusion rate. To improve the mixing rate, Kamholz et al. [4] use a parallel lamination micromixer to split the streams into a number of substreams. These substreams are then recombined to improve mixing over shorter channel lengths. The higher mixing rate of the split-join approach is due to the increased contact surfaces between fluids. Several works employed the similar approaches to improve mixing are also reported such as split-join [7], split-split-join [8], and multiple intersecting [9].

Instead of splitting both streams to increase contact surface between fluids, injection mixers that using a nozzle array to inject one stream into another are also reported to increase mixing rate [10]. Chaotic advection micromixers are also used to improve mixing via employing specially design geometries to generate splitting, stretching, folding, and breaking the flows [11-15]. Wang et al. [11] reported the simulation of micromixing where obstacles were placed in the channels to create the chaotic advection in turn to assist mixing. Three-dimensional (3D) complex microstructure micromixers were also introduced to generate a chaotic advection type of micromixing [12-15], such as the connected out-of-plane L-shape microchannels [12] and twisted microchannels [13].

The advantages of passive mixers have been their relative operating simplicity, reliability, and robustness over the designed microflow range. However, to be efficient these mechanisms require lengthy microchannels or complex 3D microchannel structures. The additional material and fabrication steps for 3D structures can significantly increase the cost of any disposable LOC device that must be produced in large quantities.

In contrast, active micromixers use an external energy source to create disturbances in liquid streams to improve mixing rates [16-21]. Fujii et al. [16] reported using an external micropump to generate pressure disturbance to improve mixing. Electrohydrodynamic and electrokinetic disturbance are also reported to improve mixing rates [17-18].

Suzuki and Ho [19] describe a micromixer integrated with electrical conductors that generate magnetic fields, which then move 1 to 10 μm diameter magnetic beads to create a disturbance in the flow stream. Liu et al. [20] reported using the acoustic streaming technique to induce air bubbles in streams where the bubbles disturb the flows to improve mixing. Tsai and Lin [21] reported utilizing a microheater embedded in microchannels to thermally generate air bubbles that disturb the streams.

Active micromixers require peripheral hardware to introduce additional energy into the flow stream or to activate a moving mechanism. This approach results in higher mixing rates but may become unreliable because of increased opportunities for mechanism failure. Furthermore, the higher unit cost of fabricating disposable LOC devices with embedded active components has discouraged industry from commercializing microfluidic devices.

This paper describes an active micromixer driven by a focused laser beam. The motivation of this study is that the diffusion coefficient for non-reactive fluids can be altered by raising localized temperature of the adjacent fluid streams. Section II describes the basic laser-assisted micromixing mechanism. This approach increases the molecular diffusion rate and, thereby, the mixing rate without introducing complex 3D microchannel structures. An experimental investigation of a laser-assisted Y-channel micromixer is presented in Section III. Results are discussed in Section IV, and conclusions are summarized in Section V.

II. MICROMIXING MECHANISM

Laminar flow predominates over turbulence in microscale liquid flow streams where the Reynolds number is small, $\text{Re} < 100$. When Re is small, molecular diffusion becomes the primary mixing mechanism. Under this condition, the mixing action can be represented by Fick's law of molecular diffusion [3],

$$\tau = \frac{d^2}{2 \cdot D} \quad (1)$$

where τ is the time required to complete the diffusion in seconds, d is the channel width in μm , and D is the diffusion coefficient in $\mu\text{m}^2/\text{sec}$. The channel length required for mixing to be completed can be approximately described as:

$$L = U \cdot \tau \quad (2)$$

where L is the microchannel length in μm , τ is the diffusion time in seconds, and U is the average flow velocity in $\mu\text{m}/\text{sec}$.

The higher average flow rate U implies that a longer channel is required to complete the mixing. The diffusion coefficient D is defined as:

$$D = \frac{k_B \cdot T}{6 \cdot \pi \cdot \mu \cdot R_A} \quad (3)$$

where k_B is the Boltzman constant ($1.38 \times 10^{-23} \text{ J/K}$), T is the system temperature in K, μ is the dynamic viscosity of the pure solvent, and R_A is the radius of the solute particle [22].

The diffusion coefficient D in (3) shows a direct proportional relationship with the temperature T . As the temperature increases, the amount of energy available to the particles in the flow stream also increases causing them to move faster and, thereby, increasing the diffusion rate. A higher diffusion rate implies the mixing of the streams can be completed in a shorter period of time τ or over a shorter microchannel length.

The objective of the following experimental study is to validate the laser-assisted micromixing concept. Since the diffusion coefficient depends on the temperature, an appropriate temperature rise of the mixing streams should increase the diffusion rate. Fig. 1 illustrates the basic concept.

Figure 1. An illustration of laser-assisted micromixing where a focused laser beam delivers a small amount of optical energy that is absorbed by a microfluidic stream and alters the localized diffusion coefficient.

III. EXPERIMENTAL STUDY

Figure 2 shows a Y-channel micromixer designed with a larger chamber about 450 μm wide for the experiments. LCWM (Laser Cutting, Welding, and Molding) method was used to fabricate the micromixer [23]. The LCWM method is a non-lithography-based method that fabricates metallic mold masters for replication of PDMS-based microfluidic devices. The method involves laser cutting of microchannel features from a thin metallic sheet and the microchannel features were then laser welded onto a metal substrate to form the final mold masters.

A 50 μm thick stainless steel sheet was used to machine the Y-channel feature using AVIA UV laser from Coherent Inc., USA. This cutout was then laser welded using StarWelder from Rofin, Germany. The mold master was completed in about 30mins in this case study. PDMS was subsequently poured onto this master. Once the PDMS was cured, the PDMS part is demolded from the master and bonded reversibly with an acrylic plate that was predrilled with three connecting holes for fluidic connections.

Two colored water streams, dark (blue) and light (yellow), were introduced to the chamber using 5mL syringes that connect to the Y-channel inlets of the micromixer. The outlet reservoir was connected with a tube that collects the mixed colored solution. The experimental flow rates were adjusted from 1 to 10 $\mu\text{L}/\text{min}$.

For the experiments, a 1mW, 670nm diode laser was used as the radiation source. The laser beam was focused on the microchannel using a 100mm focal length objective lens. The selection of this focal length is to provide a greater depth-of-focus to reduce focusing error as well as to provide a relative even heat input across the microflow stream. The laser was mounted at 45° degree from vertical to avoid damaging the CCD camera sensor by the reflected laser beam.

To minimize the random error of the measurements, four measurements were taken at each setting: flow rate - 1, 3, 5, 8 and 10 $\mu\text{L}/\text{min}$, laser on, and laser off conditions. Again, to reduce the random error, the laser assisted and non-laser assisted mixing condition measurements were taken one after another at each flow rate setting. The measurements were then averaged and the standard deviations were calculated.

IV. RESULTS AND DISCUSSION

The optical microscopic views of the two parallel streams in the microchannel, Fig. 2, show strong laminar flow characteristics and the molecular diffusion is the key mixing mechanism. The diffusion region was measured using a CCD camera mounted on the microscope and captured images were then processed with Scion Image analysis software, Scion Corporation, USA. The captured colored images were converted to gray scale images in order to use the intensity-analyzing function tool in the software to determine the diffusion distance.

Figure 3 shows the 3D intensity graph and Fig. 4 shows the typical intensity graph at the measured cross-section. The distinctive regions of molecular diffusion between the two streams of the dark and light colored water are clearly shown. The percentage of diffusion distance (d/W) captured in the experiments are given in Fig. 5. The graph shows a clear difference in the diffusion distance between the laser-assisted and non-laser-assisted conditions. The non-laser-assisted condition exhibits a linear negative correlation with the flow rate, as expected based on (1) and (2). As the given flow rate is increased, a shorter period is given to particles to travel laterally. In other words, a longer channel is needed at higher flow rates.

In general, the overall mixing rate was consistently increased with the laser-assisted condition over the non-laser condition. The measured percentage increase of diffusion distance was 5.12% in average, laser-assisted conditions over the non-laser assisted mixing conditions, maximum was 7.85% at 1 $\mu\text{L}/\text{min}$ and the minimum was 2.76% at 5 $\mu\text{L}/\text{min}$. The average standard deviations calculated for the laser-assisted and non-laser-assisted condition were 2.19% and 3.13%, respectively.

At 1 $\mu\text{L}/\text{min}$ flow rate, an approximately 7.85% increase of the percentage diffusion distance under the laser-assisted over non-laser-assisted condition was observed. As the flow rate further increased, this percentage difference in diffusion distance narrowed to the minimum, about 2.76% at 5 $\mu\text{L}/\text{min}$. However, the percentage difference of diffusion distance was widen again and reached about 6.02% at the flow rate 10 $\mu\text{L}/\text{min}$.

The calculated overall average diffusion coefficients under both the laser-assisted and non-laser-assisted conditions are 2.21×10^6 and $1.62 \times 10^6 \mu\text{cm}^2/\text{sec}$, respectively, – about 36.4% increase in average of the diffusion coefficient value.

Figure 2. Microscopic views of the microchannel used in this experiment: a) non-laser assisted mixing, b) laser-assisted mixing condition, and c) illustration of the diffusion distance.

Figure 3. A 3D intensity graph generated from the captured microscopic image of the microchannel. Note that the dark and light colored water exhibit different intensity values.

By fitting the data in Fig. 5, a linear curve (4) can be used to represent the non-laser-assisted condition and a polynomial

curve (5) can be used to approximate the relationship between flow rate and % diffusion distance for the laser-assisted condition. The relationship can be mathematically represented as:

$$d_{\text{laser off}}(\%) = -1.63 \cdot U + 40.13 \quad (4)$$

$$d_{\text{laser on}}(\%) = -0.012 \cdot U^3 + 0.44U^2 - 5.31 \cdot U + 51.68 \quad (5)$$

where U is the flow rate in $\mu\text{L}/\text{min}$ and $d(\%)$ is the percentage of diffusion distance in %.

Figure 4. Typical cross section of the intensity graph used in measuring the diffusion distance.

Figure 5. Measurements of the percentage diffusion distance under the conditions of the laser-assisted and non-laser-assisted mixing of two microfluidic streams.

The laser wavelength used in these experiments does not have the highest absorption wavelength for water but this wavelength also prevents over heating the water that may destroy biological samples at an elevated temperature. In fact, for some application, MEMS engineers can select a laser wavelength that is invisible to the targeted biological samples

to avoid laser radiation damages yet the selected wavelength is able to increase the buffer solution temperature appropriately to increase the mixing rate in order to shorten the analysis time.

Another issue of the wavelength absorption is that the particles of the darker colored water tend to absorb more heat energy than the light colored water; an unsymmetrical diffusion rate is resulted due to an unsymmetrical temperature distribution. However, for the concept validation purpose, these experimental results demonstrated the validity of the concept adequately.

The advantage of using a laser-assisted micromixing mechanism is that only simple microchannel structures are required and the active mixing components embedded on the LOC device are completely avoided which reduce design complexity and fabrication cost. In addition, because of this off-the-chip active mixing mechanism, the sample contamination is completely avoided by this "contactless active mixing mechanism." Small lasers are commercially available at low cost and it is compact and easy to be integrated into handheld devices.

V. CONCLUSIONS

In this paper, an active microfluidic mixing mechanism assisted via a focused laser beam was presented. Preliminary experimental results show enhancement of mixing rate was found by using a low power diode laser focused at the microstreams to raise the flow temperature in order to improve the diffusion rate - mixing rate. The results show the percentage of diffusion distance increased by 5.12% in average from various flow rates, under the laser assisted mixing condition over the non-laser assisted mixing. The maximum percentage difference of the diffusion distance was 7.85% and the minimum was 2.76%. This off-the-chip active mixing mechanism approach reduces the waste of an active mixing component to be discarded in each analysis which to avoid the cross-contamination issue.

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