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Improving Alternate Flow mixing by Obstacles Located along a Micro-Channel

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Abstract— **An essential requirement for any practical fully integrated lab-on-a-chip device is the ability to mix two or more fluids thoroughly and efficiently, i.e., in a reasonable amount of time. This paper presents a way to improve mixing in microfluidic systems combining alternate flows with obstacles using passive mixers. Numerical simulations show that the layers of high and low solute concentration, created by the alternate flow, are split into smaller chunks of fluid, due to the obstacles inserted in the mixing channel, increasing the contact area between high and low concentration regions and decreasing the critical mixing length. This improvement can lead to shorter mixing channels and to low-cost mixers fabricated by planar lithographic technology.**

I. INTRODUCTION

LAB-ON-A-CHIP devices require a method to mix two or more fluids thoroughly and efficiently, i.e., in a reasonable amount of time. Rapid mixing becomes a challenging task, due to strictly laminar flow conditions (it is generally operated at Reynolds numbers of less than 1). Turbulent diffusion is absent and the mixing must be achieved by molecular diffusion (which is a rather slow process, even over short distances [1]) or by chaotic advection [2, 3].

It is possible to improve mixing by using periodic flows [4, 5], which will create a flow with layers of low and high solute concentration along the mixing channel. However, the thickness of these layers should be smaller than the half channel width.

Pressure driving flows have parabolic velocity profiles. The parabolic profile contributes to mixing since different layers will interpenetrate each other allowing mixing by diffusion in the transversal direction. However, the fluid in the center of the channel has a smaller residence time and a high local Peclet Number.

Periodic flow mixing can be improved if combined with passive mixing. In this work, the combination is made by using alternate flow in a mixer with obstacles. The function of the alternate flow is to create alternate layers of low and high concentrations. The function of the obstacles is to delay the fluid in the center of the mixing channel and to split the layers into smaller chunks that are easily mixable.

II. MIXER DESIGN

Preliminary work was done to optimize the mixer. The mixer was designed so that the layers created by the alternate flow must be symmetrical and thinner than half the width of the mixing channel. A conventional *T* mixer is not adequate because the smaller layers of flow are not symmetrical and the larger layers which are symmetrical are too large. For this reason, the conventional *T* mixer was modified. It was introduced an ejector, which has width smaller than the width of the mixing channel (Fig. 1).

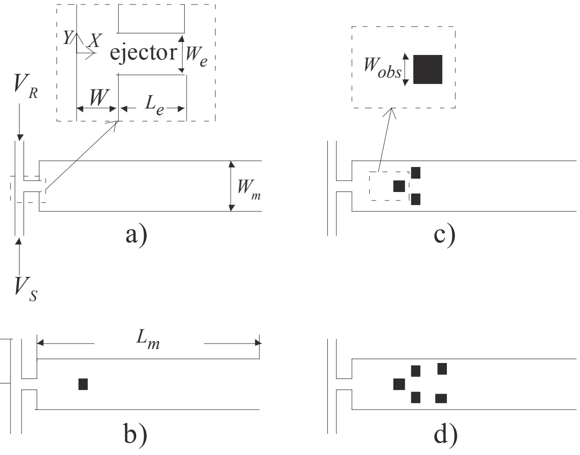

Fig. 1. Schematic representation of the studied mixers.

The mixer has two entries, one for the reactant (*R*) and the other for the sample (*S*). The purpose is to mix a stream *R* with a stream *S*. The stream *R* is rich in a reactant *R* and the stream *S* is rich in a sample *S*. Four versions of the mixer were studied: a version without obstacles (Fig. 1a), a version with a central obstacle (Fig. 1b), a version with three obstacles (Fig. 1c) and a version with 5 obstacles (Fig. 1d). All versions have two feed channels (of width *W* and length L_f) and an ejector (of width W_e and length L_e), which

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connects to the mixing channel (of width W_m and length L_m). The width of the squared obstacle is W_{obs}. The width of the feed channel was taken as the characteristic dimension.

Alternate flow (Fig. 2) is described by the following equation:

$$\begin{cases} V_R = 0.5V_0\left\{1+\beta\,\mathrm{sgn}\left[\sin\left(2\pi St\times t+\phi_R\right)\right]\right\} \\ V_S = 0.5V_0\left\{1+\beta\,\mathrm{sgn}\left[\sin\left(2\pi St\times t+\phi_S\right)\right]\right\} \end{cases} \quad (1)$$

where sgn() is the sign function:

$$\mathrm{sgn}(x) = \begin{cases} -1 & \text{for } x<0 \\ 0 & \text{for } x=0 \\ 1 & \text{for } x>0 \end{cases} \quad (2)$$

V_0 is the mean feed velocity, *St* is the Strouhal number based on the width of the feed channel (*W*), ϕ_R is the initial phase of the reactant stream, ϕ_S the initial phase of the sample stream and β is a constant. If this constant is higher than 1, the velocities are negative during half of the cycle and above V_0 in the other half of the cycle. The non-dimensional time, *t*, is given by:

$$t = V_0 T / W \quad (3)$$

where *T* is the dimensional time. The Strouhal number is given by:

$$St = fW/V_0 \quad (4)$$

where *f* is the frequency of the alternate flow.

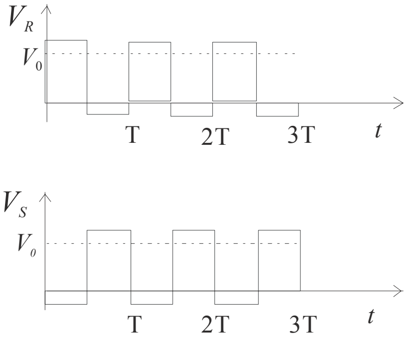

Fig. 2. Inflow boundary condition $\phi_R - \phi_S = \pi$.

The mixing of a passive tracer was simulated using commercial computational fluid dynamics software, Fluent^{TM}. Mixing was measured in vertical lines along the mixing channel. Mixing was quantified by (see [5, 6]):

$$M = 1-\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{C_i}{\overline{C}}-1\right)^2}{N}\left|\frac{Vx_i}{\overline{V}}\right|} \quad (5)$$

where C_i is the concentration of each point in the vertical line sampled several times during a complete cycle, Vx_i is the tangential component of the local velocity, $\overline{C}$ is the concentration of a perfectly mixed solution and $\overline{V}$ is the average velocity.

III. RESULTS

Numerical results (Fig. 3) show that the flow is independent of the Reynolds number (*Re*), for *Re* less than 1. For higher *Re*, the inertial effects start to become important. However, Re is very low in microfluidic devices, often bellow 1.

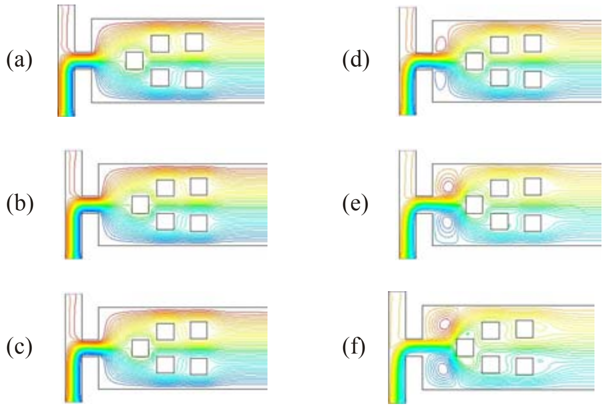

Fig. 3. Stream lines for V_R = -0.001 m/s and V_S = 0 m/s and different Reynolds numbers: (a) *Re* = 0.01; (b) *Re* = 0.1; (c) *Re* = 10; (d) *Re* = 100; (e) *Re* = 500; (f) *Re* = 1000.

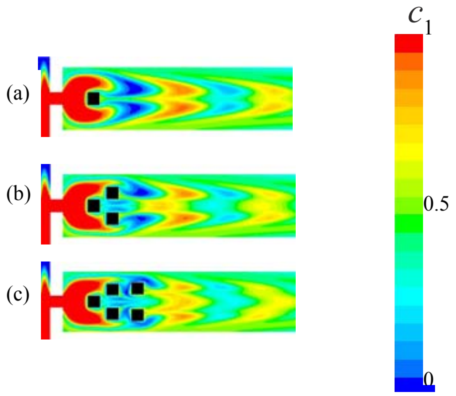

Fig. 4. Concentration field for steady state (*Re* = 0.01, *Pe* = 1450, *St* = 3.33×10^{-2}, $\phi_R - \phi_S = \pi$, W_{obs} = 1, W_e = 1, β = 1.1 and W_m = 5): (a) alternate flow with an obstacle; (b) alternate flow with three obstacles; (c) alternate flow with five obstacles.

The introduction of an obstacle in the axis of the channel (Fig. 4a) contributes to delay the fluid, to break the layers into smaller chunks and to increase de interfacial area between fluids with different composition. This effect is further increased by the introduction of more obstacles which break the smaller chunks into smaller ones (Fig. 4b and Fig. 4c).

Mixing in the device depends on the Strouhal number. Figure 5 shows the results obtained for Strouhal numbers from 3.33×10^{-3} to 0.133. For $W = 10^{-4}$ and $V_R = V_S = 10^{-3}$ ms^{-1}, the Strouhal number of 3.33×10^{-3} corresponds to a period of 30 s and the Strouhal number of 0.133 corresponds to a period of 0.75 s. As the Strouhal number increases, the mixing improves. Increasing the frequency contributes to the decrease of homogeneous chunks of fluid.

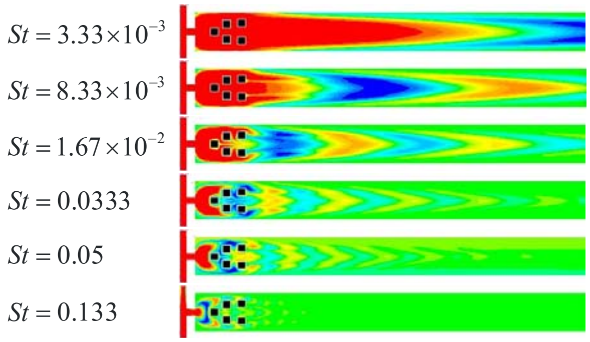

Fig. 5. Concentration fields for steady state ($Re = 0.01$, $Pe = 1450$, $\phi_R - \phi_S = \pi$, $W_{obs}/W = 1$, $W_e/W=1$, $\beta = 4.0$ and $W_m/W = 5$).

The effects of the combination between Strouhal number and obstacles were studied by measuring the ratio between the mixing index with and without obstacles (M_5/M_0). M_5 represents the mixing index with 5 obstacles and M_0 represents the mixing index with no obstacle. Figure 6 represents the ratio M_5/M_0 along the mixing channel. The results show that the introduction of obstacles increases mixing. The effect of the obstacles is higher for intermediate Strouhal numbers. In general, the effect of the obstacles decreases along the mixing channel, but results for intermediate Strouhal numbers have a local maximum.

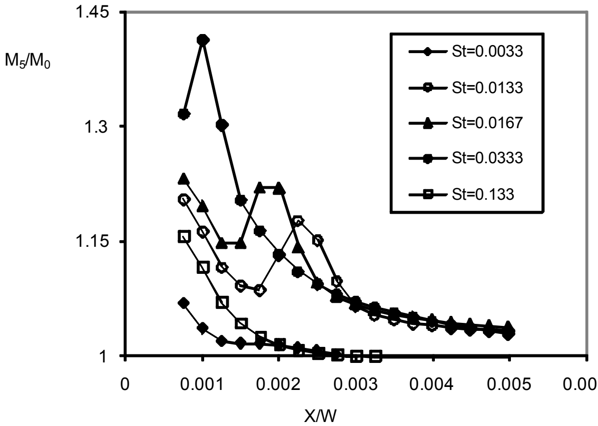

Fig. 6. Ratio between the mixing index with and without obstacles, M_5/M_0 along the mixing channel ($Re = 0.01$, $Pe = 1450$, $W_{obs}/W = 1$, $W_e/W = 1$, $\phi_R - \phi_S = \pi$. $\beta = 4.0$, and $W_m/W = 5$).

IV. CONCLUSION

Alternate flow mixing enhanced by obstacles located in the mixing channel was studied by numerical methods. The results show that the introduction of obstacles in the mixing channel improves mixing for intermediate Strouhal numbers. For biological fluids analysis using lab-on-a-chip devices, this improvement can lead to faster results and to low cost mixers fabricated by planar lithographic technology.

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