OSCILLATORY AND ALTERNATE FLOWS IN A MICROFLUIDIC DEVICE

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Abstract: The mixing properties of systems with oscillatory or alternate flows are studied by numerical methods. Preliminary results show that, for alternate flows, the contact area between high and low concentration regions increases and mixing is achieved from the combination of transversal diffusion and axial advection. The improvement in the mixing process shows that this method is very useful for designing mixers in lab-on-a-chip devices.

Keywords: oscillatory flow, alternate flow, fluidic mixer

INTRODUCTION

The healthcare sector is nowadays one of the most dynamic and where the novelty is a strategic and operational imperative. The possibility of perform clinical analyses with instantaneous results and outside the clinical laboratories has led to the development of microfluidic devices with the fluidic, detection and readout systems integrated in a single-chip [1]. The advantages associated with shrinking clinical analysis systems include: small sample volume, high degree of system integration, automation of measurement, short response time, improved analytical performance, laboratory safety and reduced cost [2]. The patients are the direct beneficiaries of such microsystem, once it allows more and better information and new and superior relationships and attendances by the health care personnel. Moreover, their diagnostic become easier and they will have instantaneous access to critical information for their activity and decision.

The spectrophotometry based on colorimetric detection is a very convenient and often used analytical technique in clinical laboratories for routine tests analyses. It allows the selective detection of the concentration of biomolecules in biological fluids samples [3]. The measurement is based on optical absorption in a part of the visible spectrum defined by the reaction of the specific biomolecule with a specific reagent. In addition, the biomolecule concentration is measured by using a mixture of a reagent with a sample.

An essential requirement for any practical fully integrated lab-on-a-chip device in a single-chip is the ability to mix two or more fluids thoroughly and efficiently, i.e., in a reasonable amount of time. The microscale conditions have distinctive properties due to its small dimensions and typically low volume flow rate. Rapid mixing becomes a challenging task, as due to strictly laminar flow conditions (it is generally operated at Reynolds numbers of less than 1), the mixing is achieved by diffusion only, which is a rather slow process, even over short distances [4]. Thus, small molecules can diffuse significant distances during the average residence time if the device will redistribute between streams. Large molecules or particles that do not diffuse significantly during the same interval will not move appreciably from their original stream unless an external field is applied (such as gravity or and electric field). That is the problem in biological reactions, once the biomolecules are large (e.g. enzymes and proteins) and have very small diffusivity coefficients.

The critical dimension that governs the extent of interdiffusion is the dimension along which diffusion occurs between streams. The mean residence time is fixed by the channel volume and the input flow rates [5]. Mass transport limitations are a key factor in the design of microfluidic devices. Poor mixing imply large mixing channels or large mixing times. To achieve mixing at low Reynolds without decreasing the channel width, it is explored, in this paper, the mixing properties of systems with oscillatory or alternate flows.

CFD MODEL

Numerical methods are used to simulate the flow, the mixing and the reaction in a T mixer. The mixer (Figure 1) has two entries, one for the reactant (**R**) and the other for the sample (**S**). Two inflow conditions were studied, an oscillatory flow in both entries and an alternate flow.

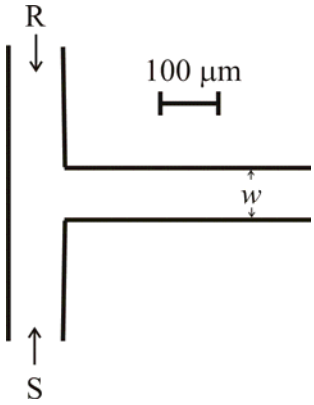

Figure 1. Schematic representation of the mixer.

Oscillatory flow is described by a sinusoidal boundary condition for the velocity:

$$\begin{cases} V_R = V_0 \sin\left(2\pi St \times t + \phi_R\right) \\ V_S = V_0 \sin\left(2\pi St \times t + \phi_S\right) \end{cases} \quad (1)$$

where V_0 is the maximum velocity, St is the Strouhal number based on the width of the channel (w), ϕ_R is the initial phase of the reactant stream and ϕ_S the initial phase of the sample stream.
Alternate flow (Figure 2) is described by the following equation:

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

The problem was solved numerically by a code developed in house based on the public available library Overture [6]. The study is being complemented by simulation using Fluent™.

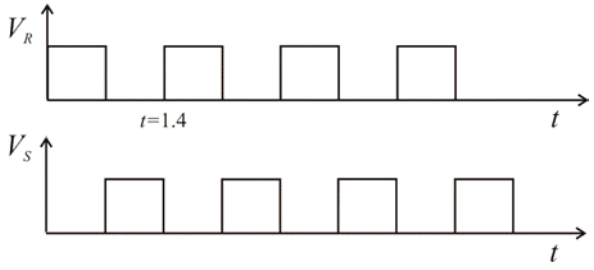

Figure 2. Inflow boundary conditions.

The developed code solves the Navier-Stokes equations and the mass transport equations for each component by a finite difference technique. The Navier-Stokes equations, in their velocity-pressure formulation, are:

$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v}\cdot\nabla\right)\vec{v} = -Eu_0\nabla p + \frac{1}{\mathrm{Re}}\nabla^2\vec{v} \quad (3)$$

$$Eu_0\Delta p = -\nabla v_x \frac{\partial \vec{v}}{\partial x} - \nabla v_y \frac{\partial \vec{v}}{\partial y} - \nabla v_z \frac{\partial \vec{v}}{\partial z} \quad (4)$$

where Eu_0 is the Euler number and Re the Reynolds number based on the channel width. The mass transport equation for each component is:

$$\frac{\partial c_i}{\partial t} + \vec{v}.\nabla c_i = \frac{1}{Pe}\Delta c_i - \alpha Da_i c_i \quad (5)$$

where Pe is the Peclet number and Da_i is the Damkohler number.

SIMULATION RESULTS

Preliminary results are presented in Figure 3 and Figure 4. Figure 3 illustrates the streamlines of the alternate flow. When $V_R = 0$ and $V_S = V_0$, the streamlines are shown in Figure 3a, while when $V_R = V_0$ and $V_S = 0$, they are shown in Figure 3b.

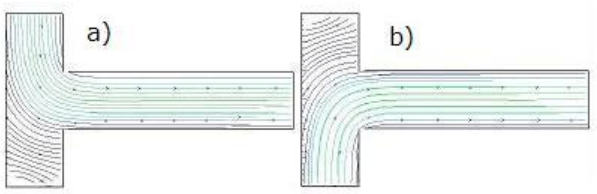

Figure 3. Alternate flow for Re = 5, St = 0.71 and ϕ_R - ϕ_S = π: a) t = 13.15, V_R = 0 and V_S = V_0; b) t = 13.71, V_R = V_0 and V_S = 0.

The results for the mixing of the reactant into the sample stream are presented in Figure 4. It shows that alternate flow generates a complex concentration pattern that changes with time. The mixing is a consequence of transport from regions of high concentration to regions of low concentration across a rippled interface. In the mixing channel, the process combines two main transport mechanisms: the molecular diffusion along the transversal direction and Taylor Dispersion along the axial direction.

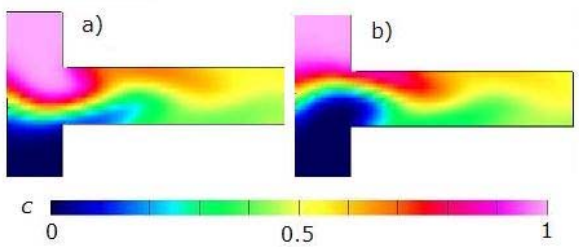

Figure 4. Reactant concentration for Pe = 250, St = 0.71 and ϕ_R - ϕ_S = π*:* a) t = 13.15, V_R = 0 and V_S = V_0; b) t = 13.71, V_R = V_0 and V_S = 0.

Further studies are on-going to understand the influence of the geometry, the reaction, the Strouhal number and the phase difference in the mixing.

CONCLUSIONS

Mixing of two streams in a microfluidic system by alternate and oscillatory flows was studied by numerical methods. Preliminary results for alternate flow show that this method can improve mixing in a T mixer. In addition, 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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REFERENCES

1. P. Connolly, *Biosensors & Bioelectronics*, 10 (1995), pp 1-6.
2. S. C. Jakeway, A. J. de Mello and E. Russell, *Fres. J. Anal. Chem*., 266 (2000), pp 525-539.
3. *Biochemistry and Organic Reagents: for bioscience investigation*. Sigma-Aldrich Diagnostics®, 2002.
4. P. C. Simpson, et.al., *Proc. Natl. Acad. Sci. USA*, 95 (1998), pp 2256-2261.
5. M. R. Holl, P. Galambos, F. K. Forster, J. P. Brody, M. A. Afromowitz, P. Yager, *Proc. of 1996 ASME Meeting*, 1996.
6. Overture, http://www.llnl.gov/casc/Overture/