Pressure Driven Micro-flow Through a Double-T Metering Junction

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Abstract

Discrete fluid volumes (plugs) are often needed for micro bioassay. Current methods of isolating discrete volumes use electrokinetic forces that require high voltages and result in ionic component separation of the sample. Pressure-driven flow through a double-T metering junction is a suggested alternative to this electrokinetic method. There has been no extensive analysis of pressure-driven plug flow. This paper outlines a method to characterize the effects of diffusive mixing of plug flow through a double-T metering junction and determine the viability of pressure driven flow as an alternative to electrokinetically driven flow for bioassay.

Introduction

"Lab on a chip" systems have undergone rigorous development in recent years. These bioassay systems are typically comprised of pumps, valves, mixing chambers, and complex channeling [1,2]. Many of these designs analyze discrete volumes of high-purity liquid. These volumes are often times defined by geometry and electrokinetic forces [3,4].

Electrokinetic forces ionic separate components of the fluid by applying a high potential (approximately 400V-1000V) across the sample. Although the use of electric fields is a powerful tool for separation of molecules, there are shortcomings in using this as a general method of fluidic transport. For example, electrophoretic de-mixing occurs when pumping heterogeneous solutions due to the separation of the different ionic components. This problem can be partially compensated by alternating plugs of low and high-conductivity buffer, but other problems can arise [5]. The use of high voltages is also problematic for developing mobile, low power, µ-assay systems. These types of systems are being pursued for military and public health applications [6].

To avoid ionic separation and exceeding the energy budget of self-contained low-power micro systems, pressure-driven flow through a double-T metering junction is suggested. This method of metering utilizes geometry and pressure differences rather than an electronic potential to isolate a discrete volume of sample between two plugs of buffer fluid. Although plug transport has been demonstrated with electrophoretic forces [3-5], extensive analysis of pressure driven plug flow has not been pursued. Mixing between sample and buffer will be analyzed by optical imaging of dyes and particle image velocimetry (PIV). PIV can be used to characterize flow velocity profiles, and possibly, buffer and sample interface diffusion.

Test structures will be fabricated using standard glass micro machining processes or hot embossing of plastic. A cover plate with through holes will be required for liquid input and output. The cover plate can then be bonded to the micro machined glass wafer or hot embossed plastic. Different structures will be fabricated in a single process allowing for flow analysis of straight channels and t-junctions.

This paper will outline a method for characterization of pressure driven plug flow including the development of test structures for comparing modeled and experimental results. The results produced will be used to determine the viability of pressure-driven plug flow as an alternative to electrokinetic methods.

Design

Pressure-driven flow through a double-T metering junction is suggested as a low power option to electrokinetic metering systems. A double-T metering junction utilizes geometry to isolate a discrete volume of sample between two plugs of buffer fluid. A schematic of the double-T metering junction is shown in *Figure 1*. The following steps define a discrete volume:

- 1. Flood system with buffer and stop flow.
- 2. Drive sample towards waste outlet past point **b** and stop flow.
- 3. Drive buffer towards assay outlet.

These steps result in a volume of sample defined by the distance between points \mathbf{a} and \mathbf{b} and the depth and width of the channel.



Figure 1: Schematic of double-T metering junction

A sample volume of approximately 20 nanoliters and a flow rate of 1 μ L/min (60 μ L/hr) are reasonable values for "lab on a chip" systems. If the channels shown in *Figure 1* are 100 μ m X 100 μ m, an average flow velocity of ~1.67 mm/s and thus a Reynolds number of ~0.167 will result. This low Reynolds number indicates laminar flow and implies mixing will be dominated by diffusion. The average velocity and Reynolds number will change with different geometries but not enough to enter a turbulent regime.

Micro-syringe pumps will be used to provide pressure sources to drive flow through the test structures. These pumps are capable of delivering flow rates as low as 0.001 μ L/hr (well below the specified 60 μ L/hr). After volume definition, mixing and velocity profiles can be determined.

Particle image velocimetry (PIV) will be used to characterize the flow velocity profile. PIV requires that the flow be seeded with particles that can scatter laser light. A CCD captures images of the scattering and software crosscorrelates the pictures to develop a vector field describing the flow velocity.

Diffusion can be characterized by capturing images of dyed fluid plugs as they travel through the channel. Image intensity changes will represent dye diffusion between plugs.

Measuring pH may be another method of measuring diffusion. Two fluids of differing pH will represent a sample and buffer. By measuring the pH of these fluid volumes after the double-t, an estimation of mixing can be determined. This would require integration of electrodes into the cover plate.

Theory

Due to the very small channel size, the Reynolds number for μ -flow is typically < 1, well below turbulent regimes. For flow analysis, we can use the Navier-Stokes equation (eq. 1).

$$\frac{D\mathbf{U}}{Dt} = -\frac{1}{\rho}\nabla P + \frac{\mu}{\rho}\nabla^2 \mathbf{U}$$
(1)

For steady flow in the x-direction, at very low Reynolds numbers, this equation simplifies to the Stokes equation (eq. 2).

$$\frac{\partial^2 \mathbf{U}}{\partial y^2} + \frac{\partial^2 \mathbf{U}}{\partial z^2} = \frac{1}{\mu} \frac{\partial P}{\partial x}$$
(2)

If we also assume that the flow is much more dependent on the y direction (i.e. the channel is much wider than it is deep) and the pressure gradient is constant, then the equation simplifies further to

$$\frac{\partial^2 \mathbf{U}}{\partial y^2} = -\frac{K}{\mu} \qquad \frac{\partial P}{\partial x} = -K \qquad (3)$$

By solving this equation we find that the velocity profile across the depth of a channel is

$$U_{x} = \frac{1}{2\mu} [y(h-y)]K$$
 (4)

where h is the height of the channel, μ is the viscosity, ρ is the density, P is pressure, and K is a constant equal to the pressure gradient [7].

Diffusion affects can be defined by the advection-diffusion equation (eq. 5),

$$\frac{\partial C}{\partial t} + \mathbf{U} \cdot \nabla C = D \nabla^2 C \tag{5}$$

where C is the concentration and D is the diffusivity. This equation describes the advection and diffusion of a chemical or particle in a fluid [8].

Simple modeling of the flow velocity was performed. *Figure 2* shows the effect of channel width on fluid element position. *Figure 3* depicts

the position of fluid elements in the x direction as time progresses.



Figure 2: Channel width effect on fluid element position



Figure 3: Fluid element position from 0-10 seconds

Test Structure

Flow channels will be fabricated using a standard glass micro-machining process or hot embossing of plastic. For glass fabrication the channels will be patterned in photoresist and this pattern will be transferred to the glass substrate using DRIE or HF etch. DRIE has the advantage of creating square channel structures. A second glass wafer will be machined with traditional methods to create through holes for liquid inlet and outlet. The two wafers will then be aligned and bonded.

For fabrication using hot embossing, a template is first created using bulk silicon micro

machining or traditional machining. The template is an inverse of the desired pattern. The template is then used to imprint an image into a plastic such as polymethylmethacrylate (PMMA) or polycarbonate (PC) at a temperature above glass transition. The master and polymer are then allowed to cool just below the glass transition and are separated [9]. Both of these plastics are optically transparent so they would work well for imaging fluid flow and diffusion optically and by PIV.

Fabricated test structures will include double-T junctions, cross-junctions, and straight sections. Double-T junctions of 100-1000 μ m channel width will have the geometry shown in *Figure 4*. Straight sections will also be 100-1000 μ m in width and be used to characterize flow fields in a straight channel, including contractions and/or expansions. These straight sections will have geometry similar to that shown in *Figure 5*. Cross-junctions will be tested to see if plug flow can be developed with this type of geometry (*Figure 6*).



Figure 4: Double-T metering junction



Figure 5: Straight channel sections



Figure 6: Cross junction

Expected Results

The degree of mixing between a buffer and sample at their interface and within the sample volume will be obtained from PIV, optical imaging and/or pH measurement. Plots of buffer and sample concentration as a function of flow velocity and geometry will be used to describe mixing. Fluid modeling using computational fluid dynamics, or another type of finite element analysis, will be completed to predict the flow pattern for comparison with experimental results. These results will help to determine the viability of pressure driven micro flow as an alternative to electrokinetically driven flow.

Conclusion

Pressure driven flow through a double-T metering section has been proposed as an alternative to electrokinetically developed fluid flow. In order to extensively characterize pressure-driven flow for bioassay related plug flow, u-flow channels will be fabricated with standard glass micro-machining processes or hot embossing of plastic. These test structures will be used to determine the effects of geometry and pressure driven flow on mixing. Flow and diffusion analysis will be performed with particle image velocimetry and optical imaging. Modeling using computational fluid dynamics software will be performed to obtain precise theoretical models of the flow. These results will be compared to experimental results obtained from the test structures outlined in this paper. The viability of pressure driven µ-flow as an

alternative to electrokinetically driven flow will result from this analysis.

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