NOVEL DESIGNS FOR ELECTROKINETIC INJECTION IN μTAS

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Abstract

Novel designs for electrokinetic injection are presented in this paper. The designs emerge using CAD analysis of the injection process. The designs are aimed at improving the separation efficiency of electrokinetic injectors by providing a narrower and more symmetric band in the separation column in comparison to the classic injector case. Two designs, the first using a three-step switching sequence and the second using a six-port injector are presented. In both cases, the injected band shape is greatly improved. The corresponding separation efficiency is also expected to improve and has been confirmed subsequently by experiment.

Keywords: Electrokinetic Injection, CAD, Simulation, Switching.

I. Introduction

There is a wide interest in micron-scale integrated chemical/biochemical analysis or synthesis systems, also referred to as lab-on-a-chip or μTAS [1-2]. The basic operations in a typical system are sample injection, mixing, chemical reaction, separation, and detection. Systems employing electrokinetic, pressure driven and pneumatic mechanisms have been successfully demonstrated. Complicated relationships exist between the microchannel geometries, the device operating conditions, and the behavior of the multi-component fluids transported. Researchers have hitherto been forced to use costly trial and error methods to understand and design such microfluidic systems.

Computer-aided Design (CAD) tools have emerged in the past few years to assist in the design of these systems. CAD tools provide greater insight into the fundamental physics governing the behavior of these systems, and allow the exploration of a much larger parameter space in an efficient manner, in comparison to experiment. Several researchers have reported CAD-based analyses of microfluidic components [3-6]. These include components used in injection [3,4], transport [5,6], as well as mixing and reactions. These analyses were generally aimed at demonstrating numerical capability and fundamental understanding of the phenomena. In most cases, qualitative agreement with experiment or analytical results was provided to demonstrate the capabilities of the CAD analyses in adequately simulating the observed physics.

The real advantage of CAD tools, however, lies in their ability to design – that is, to create new designs or extend and optimize existing designs to make the components better. This may happen through better understanding of the component physics, or, simply, through thorough examination of the parameter space. In either case, CAD has the advantage over experimental techniques. Insertion of CAD into the design cycle can therefore reduce both the number of expensive experimental iterations and the time required for the design.

In this paper we demonstrate the capability of CAD tools to enable better design of μTAS components, by specifically focusing on one component – the electrokinetic injector. We will begin by presenting experimental and numerical results for the conventional pinched injector – to show that electrokinetic injection is well understood and predictable using CAD tools. We will then explore two mechanisms of improving the performance of the injector in delivering a sample into the separation column that is more ideally suited for separation than the conventional injector.

II. Numerical Methodology

The basic equations describing the fluid motion are the Navier-Stokes equations with appropriate electromigratory flux terms to represent the effect of the applied electric field on the carrier (electroosmosis) and/or the charged species (electrophoresis). The modeling of electrokinetic effects is incorporated into the FlumeCAD system. FlumeCAD is an integrated design environment consisting of 3D design, modeling and simulation software tools, which enable the creation and analysis of complex microfluidic devices. Inherent in the design flow implemented in FlumeCAD is the ability to characterize the behaviour of a device as a function of the various physical phenomena in the device.

The switching analyses presented here assume that the electrical field sets up instantaneously, relative to the species transport. The species is also assumed to be dilute in the buffer – i.e., it does not affect the material properties of the buffer during transport. This allows the field calculation to be decoupled from the species transport – the switching simulation is thus reduced to a sequence of electrophoretic transport simulations.

III. Classic Electrokinetic Injection

The simplest switching component is an intersection of two channels. Such intersections are surprisingly powerful tools that enable the definition of sample plugs at the picoliter level [2]; this in turn allows microfabricated electrokinetic systems to outperform their conventional counterparts by orders of magnitude [7]. The switching components are employed in separation and dispensing systems to inject the sample from the load channel to the separation channel. A typical system employing such switching components is presented in Figure 1, showing a microfluidic system fabricated by etching and bonding in glass.

The switch is operated as follows: the drive potential transporting the species into the intersection is supplemented by a field in the transverse channel that shapes a plug of a specified volume by generating a "pinch" in the field. Following the pinch, the flow is swept from the intersection into the separation channel by a field, while, simultaneously, current towards both top and bottom helps separate the sample plug and prevents leakage into the separation channel. A time period and a voltage and/or a current setting at each port in the design define each phase of the cycle.

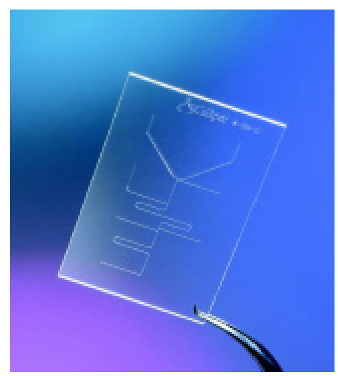

Figure 1 : Lab-On-Chip analysis system showing network of etched interconnected channels. The intersections of the channels form the injection locations.

Simulation results for the typical switch are shown in Figure 2 and compared with experimental observations in Figure 3. The results show good qualitative agreement. Greater details for both the simulation and experiment are reported in [8]. The agreement with experiment gives us confidence in the ability of the CAD tools to predict the behaviour of electrokinetic injectors. Consequently, we then focus our attention to the design of injectors that have better injection characteristics.

One of the parameters defining optimal injection is the band shape and width in the separation column. In the classic injection the band is the size of the channels, broadened by diffusion and field, and partly restrained by the "pinch" current. As shown in Figure 2 the plug is trapezoidal in shape. This broadening limits the possible resolution of the following separation column, causing the separation column to be longer than necessary. Designing injection to achieve a plug that is symmetric and narrower than the channel geometries is therefore highly desirable.

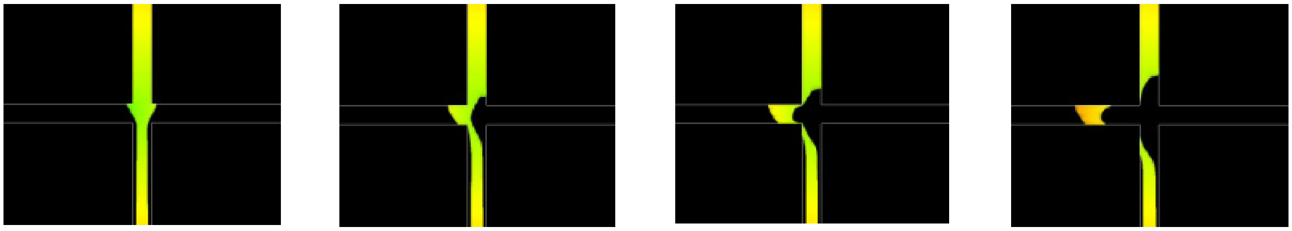

Figure 2: Simulations of electrokinetically Switched injection (the classic injector). The switching sequence has two phases (load and switch).

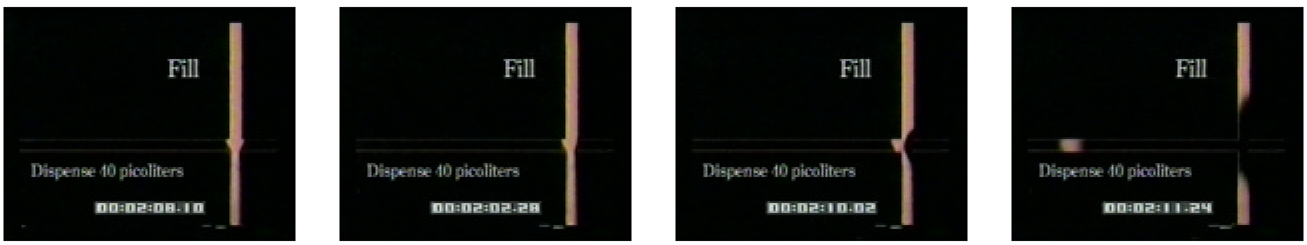

Figure 3: Experimental images of switched injection (the classic injector). Again there are two phases similar to Figure 2 above.

The shape of the injection plug in the intersection, and the subsequent separation, is governed by several parameters. Prominent among these is the geometry of the intersection and the switching fields applied. We have explored both these options in our attempt to design better injectors. Several designs were attempted – we will present two specific examples here – first, an alteration of the switching field sequence, and second, a geometry variation.

IV. Alternative Injector Designs

The first approach to generate a better injection plug is to insert a flow reversal between the load and the switch cycle. This allows the sample plug downstream of the intersection to be pulled back into the intersection prior to switching. The switched plug is now actually narrower than the intersection itself. The pull-back also removes the asymmetry arising due to the pinched field – the resulting plug in the separation column is both narrower and straighter than the conventional injector. The sequence of operations is shown in the simulations in Figure 4. This injection plug will yield shorter separation lengths in comparison to the conventional injector. Experiments were conducted to verify the injection sequence *after* the simulations and have verified the behaviour observed [8] in the simulations and have demonstrated significantly higher separation efficiency compared to the classic injector. The smaller separation lengths result in higher throughputs in the assays. An additional advantage is in the reduction of the field strengths required for the separation, which may have added benefits in the manufacturability of the device.

The drawback of this approach, however, is that it requires an additional electric field switching step, which needs to be controlled carefully. An alternative approach that has similar behaviour can be constructed by modification of the geometry and retaining the two-step switching pattern of the electrokinetic injectors. An example of this is the six-port injector, shown in Figure 5. This injector is made up of two intersections, one downstream of the other in the load cycle. The pinching is accomplished in a manner similar to the classic injector. As the sequence shown the pinch results in a narrow band at the second intersection. Switching at this intersection then results in the narrower band being injected into the separation column. The separation efficiency for this injector should also be significantly better than the classic injector.

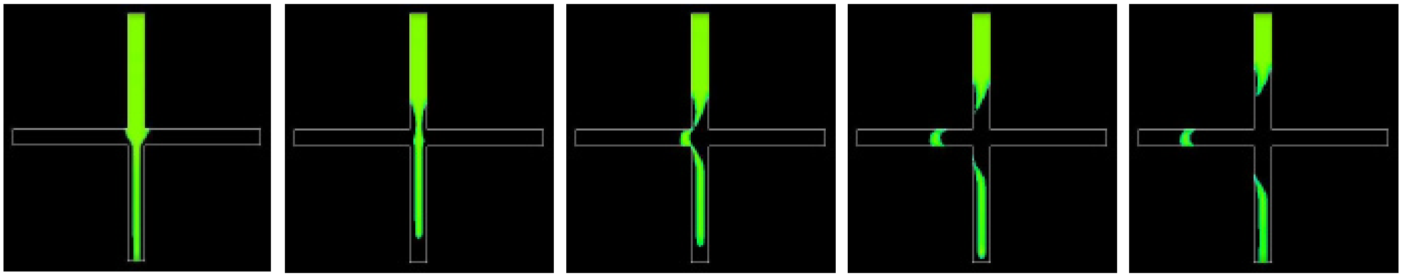

Figure 4: Reverse Injection Process showing Pullback prior to switching. The cycle is accomplished by a three-phase switch in the field – the load, pull-back and switch phases.

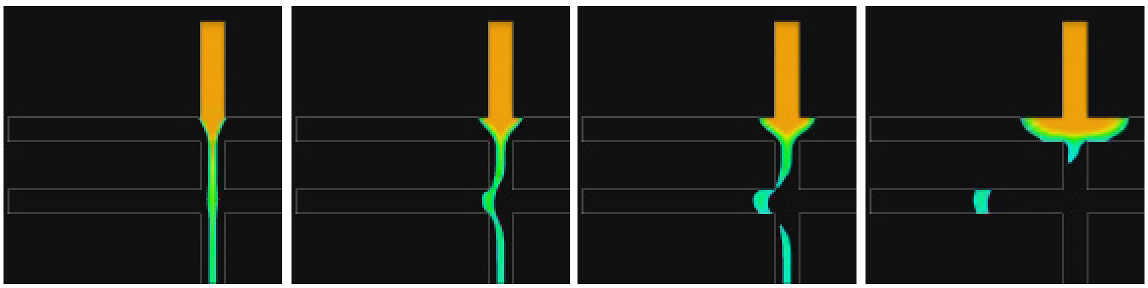

Figure 5: Six-Port injector. The cycle is two-phase – a load cycle and a switch in the downstream switch cycle.

V. Conclusions

Novel designs for electrokinetic injectors have been presented in this paper. The designs use a CAD tool that has been validated by comparing against experimental results for the conventional cross injectors. The new designs are aimed at creating a narrower and more symmetric band in the separation column. Effects due to electrical field sequences as well as geometry were considered in the designs. Specific examples demonstrating better injection band characteristics for both cases are presented here. The first case is a modification in the field using a pull-back step between the load and the switch cycle. The second case is a modification in the geometry using a six-port injector, where the switching step is actuated in the intersection downstream of the pinched intersection. In both cases the band in the separation column is narrower and straighter. The resulting separation efficiency is expected to be significantly better and has been verified by experiment discussed elsewhere.

The numerical experiments presented here demonstrate the usefulness of CAD in the design of more efficient devices and in the optimization of existing devices in μTAS.

Acknowledgments

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