

Simulation of electro-osmotically driven microsynthesis systems

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ABSTRACT

Modeling, optimization, and the realization of an electro-osmotically driven chemical microsynthesis system for Wittig reactions are presented. Essential for good functioning of the chemical liquid reaction system is controllability of the supplied chemicals, independently of the reservoir heights. System analysis turned out to be crucial for designing new improved chips. In the article the main aspects of development are discussed.

Keywords: electro-osmotic flow control, micro reactor, microsynthesis, bondgraph, FVM.

1 INTRODUCTION

Miniaturized chemical analysis systems have gained a tremendous interest during the last years. The reason is the commercial and research interest in DNA separation analysis. With microtechnology it turned out to be possible to gain good separation efficiencies at short residence times [1] with relative simple chip designs.

Just as, or maybe even more interesting for the chemical society are ways to do chemical analysis and synthesis reactions on chip. Next to speed, micro reactors offer possibilities such as better control of the reactions (better uniformity and fast thermal heating / cooling) in a safe way (protection against toxicity / explosives). Miniaturized reactor systems however have not yet reached the success they deserve. The likely reason for this is the complexity of the necessary fluid handling components. Designs like proposed in the early days of microfluidics systems, comprising of downscaled "macro" principles [2,3], are difficult and expensive to make and not suitable for integration. Electro-osmosis however offers, despite its drawbacks, new opportunities for downsizing as only simple channel structures with field electrodes [4] with or without gate electrodes [5,6] are needed. With electro-osmotic flow (EOF) control, dense channel networks with mixers, reaction chambers, and separation columns, integrated on small chips, become feasible.

2 THE MICROSYNTHESIS CHIP

The chip, which is discussed, is developed by the University of Hull [7] for performing Wittig reactions by electro-osmotic flow control. The aim is to use these miniaturized reaction systems for optimization of chemical synthesis by automated parallel processing in a series of chips. This will yield a much faster process analysis and consequently saves e.g. much expensive drug development time. Essential for this application is the stability and controllability of the delivered flows in time and the reproducibility of the synthesis in different chips at different times such that data, obtained from different chips can be compared. Chip reproducibility is a matter of fabrication process control whereas controllability can be optimized with the results from simulation tools.

Initially the chip consisted of one main channel of about 200 μ m wide and 100 μ m deep with 3 inlet channels for the chemicals and one outlet for the reaction product. Glass is used as construction material. Powder blasting [8] was used for creating holes for the in- and outlets whereas powder blasting or wet / dry etching techniques can be used for the channels. Both glass wafers were bonded together using fusion bonding. Additionally a metal layer (e.g. platinum or gold) for the field electrodes can be selectively applied by sputtering through a shadow mask. An example of an improved version of the chip is shown in figure 1.

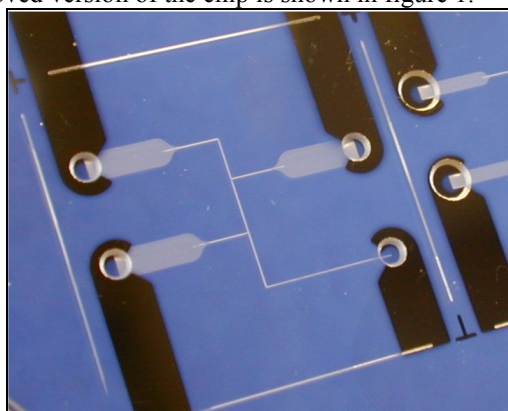


Figure 1: Picture of the improved EOF-driven chip design

Since the sputtered platinum electrodes are in direct contact with the chemicals and the driving voltages are above redox potential level ($\sim 1.25V$), electrochemical reactions will take place at the electrodes, creating bubbles. As these bubbles could block the channels, the electrodes are patterned in a half-moon shape at the walls of the hole. During measurements this design turned out to work well since no electrical resistance fluctuations due blocking of the channels by bubbles could be observed as happened with previous electrode designs that fully covered the bottom of the holes.

3 SYSTEM MODELING

The initial designs did have channels of $200 \times 100 \mu m$ cross section only. Since the hydraulic resistance of the channels is very low, net flow generation stops at low pressure drops. Furthermore, the flow is dominated by Poiseuille flow rather than EOF. Initially the inlet reservoirs are filled, inducing a forward-oriented, pressure driven flow, whereas during pumping the pressure and thus flow rate is reduced until it stops when the EOF and Poiseuille flows balance. At this moment only a flow circulation arises with forward oriented flow near the walls and backward directed flow in the channel center.

One solution is to use for instance a package of glass beads (frids) in the entrance holes [7]. By doing this, the hydraulic resistance is increased and consequently the pressure-driven backflow was reduced. In the chip, shown in figure 1, these frids were replaced by $10 \mu m$ deep powder blasted resistance structures, which improved the maximum reachable pressure significantly. However injection and mixing measurements showed that back flow still occurred such that reaction products flow back and mix with the clean feed reactants.

Consequently system models were needed to simulate the flow rates and especially the direction and size of the flow velocity in the center of the channels as a function of applied voltages, pressures and reservoir dimensions etc. The equations used to describe a mixed EOF / Poiseuille flow in a channel network between points i and $i+1$ can be expressed in terms of effort, pressure p_{hyd} or electric potential p_{con} , flow rate ϕ_{hyd} or current ϕ_{con} , related by the admittance G according to the next equations:

Hydraulic domain

$$\phi_{i\ hyd} = (p_{i\ hyd} - p_{i+1\ hyd}) \cdot G_{i\ hyd} \quad (1)$$

Where the admittance is the inverse of the hydraulic resistance.

Electric domain

$$\phi_{i\ con} = (p_{i\ con} - p_{i+1\ con}) \cdot G_{i\ con} \quad (2)$$

With the admittance now resembling the electrical conductivity. The relation between the EOF and applied potentials is defined by (3).

Electro-osmotic coupling

$$\phi_{i\ eof} = (p_{i\ con} - p_{i+1\ con}) \cdot G_{i\ eof} \quad (3)$$

With the electro-osmotic admittance defined as:

$$G_{i\ eof} = \omega_{i\ eof} \cdot A_i / l_i \quad (4)$$

where A and l are the cross section area and channel length respectively and ω_{eof} the electro-osmotic mobility [m^2/Vs]. These equations are only valid under the conditions of small double layers relatively to the channel diameter, which is the case for our channel depths of around $8 \mu m$ and more. Secondly, the electrical energy transport by EOF is neglected (no 100% energy conservation). Since both the electro-osmotic admittance and conductivity depend on the ratio A / l , a simple resistor network model based on equations (2) suffices to solve the EOF component when the dielectric constant and viscosity of the liquid is constant in all network branches. Commercially available electronic network simulation packages could be used [9] to solve the pressure-driven flows and EOF's separately after which both flow components could be summed to obtain the net flows.

Since chemicals will be mixed and reactions will take place, the materials parameters will change. Furthermore, for networks consisting of FlowFET devices [6] the Zeta potential can be actively controlled such that mobilities can vary per branch. Accordingly we decided to use the bondgraph simulation package 20-SIM [10] for solving the equations since it is a very flexible tool for solving transient, domain-specific equations. In figure 2 the implementation of the chip design of figure 1 in bondgraphs is shown.

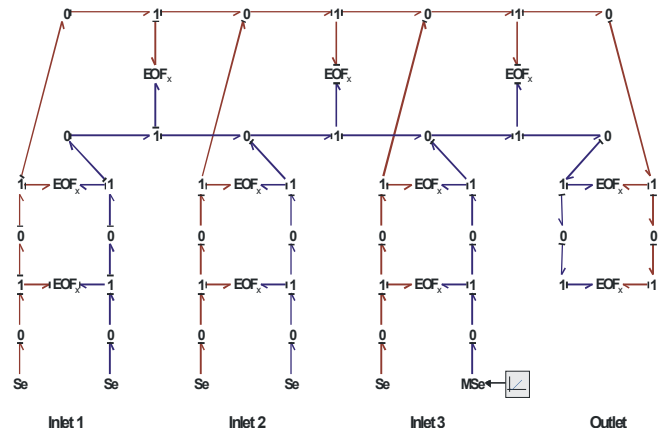


Figure 2: Bondgraph model of the chip design of figure 1. The left arrows indicate the electrical energy flows whereas the right hand side arrows indicate the hydraulic domain. The channel behavior is modeled by the EOF_x objects.

In all branches the flows, pressures and centerline velocities can be analyzed in time. In figure 4 the flow rates and centerline velocities are shown in time for a simple straight channel with a rectangular cross-section and different depths (see bondgraph of figure 3). The reservoir diameters are 1mm, initially filled at the entrance reservoir only with $1 \mu l$ water.

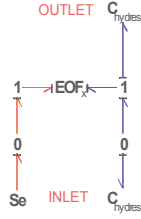


Figure 3: Bondgraph of a single channel with two reservoirs.

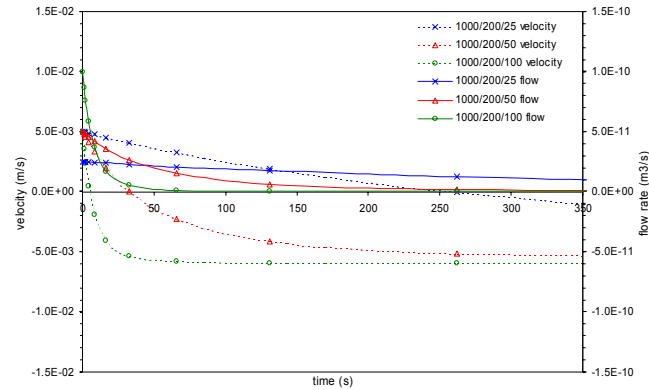


Figure 4: Centerline velocities and flow rates in time for different channel dimensions (length/width/depth).

As can be observed from the plotted results, the velocity at the channel center much faster reverses than the time it takes to balance the pressure-driven flow with the EOF. For a square channel with depth d , and width w the design constraint becomes:

$$d \leq w \sqrt{\frac{C}{C - 1/4 w^2}} \quad \text{with} \quad C = \frac{8}{5} \mu \omega_{eof} \frac{\Delta p_{con}}{\Delta p_{hyd}} \quad (5)$$

in which the delta sign indicates the potential and hydraulic pressure drop over the channel and μ the dynamic viscosity [Pa.s]. For a 2cm long channel and a reservoir level difference of 5cm H₂O, the channel width versus depth is plotted in figure 5.

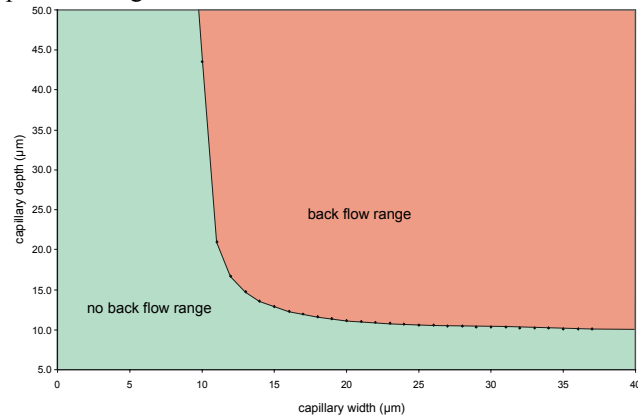


Figure 5: Design range to avoid backflow in 2cm long channels with 5cm reservoir level difference: for channels less than 10μm deep no back flow occurs.

4 INJECTION AND MIXING ANALYSIS

The injection of chemicals takes place in a continuous way through the three entrance branches. To get a uniform and fast reaction, fast mixing of the chemicals is needed only over the channel width, whereas forced mixing over the channel length must be minimized. Since wide, shallow channels are required for good flow control to avoid back flowing, the average diffusion length is strongly increased when injection from side channels, perpendicular to the reaction channel, is used. As a consequence the mixing is dramatically deteriorated as shown in the measured and simulated results of figure 6. Hence simulations were done to visualize and improve the injection and mixing.

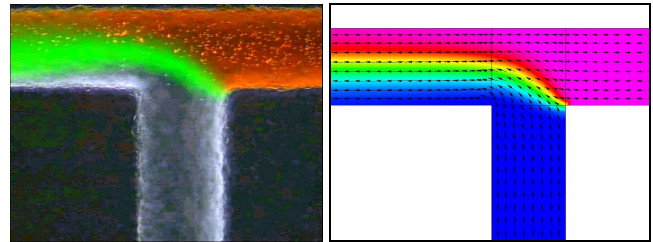


Figure 6: Measurement (left) and simulation (right) of the diffusion in a simple junction of a shallow channel. Due to the long diffusion length the diffusion of the chemicals at the walls takes a long time such that a poor uniformity of the reaction is obtained. For channels with higher width/depth ratios, diffusion is even worse.

The high width/depth ratio can be used to speed up diffusion when the flows can be injected such that a vertical lamination is obtained. In pressure-driven systems such injection is well possible when a deep, narrow injection slit [11] is used which injects the chemicals on top of the main flow. From results obtained with the finite volume simulations in CFDRC ACE+ [12], it turned out that this effect is much more difficult to obtain in electro-osmotically driven systems.

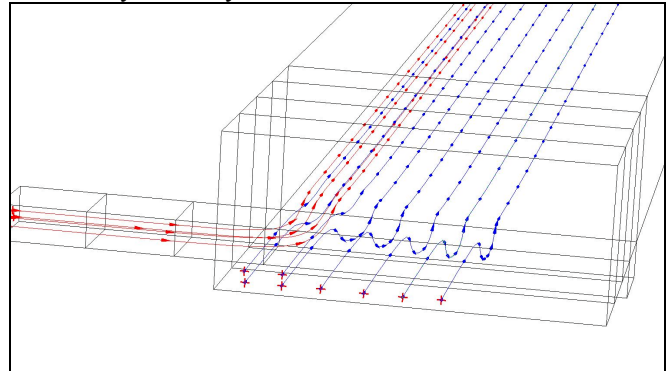


Figure 7: Streamlines of the injection of electro-osmotically driven flows from a side branch into the main channel: a poor diffusion will be obtained due to the dominant electrical field line concentration which drives the injected flow directly along the wall to the outlet (no layered flow).

Figure 7 shows that the injected flow does not follow the injection slit but immediately changes direction and flows towards the outlet such that the resulting diffusion length is increased. This effect is caused by the concentration of the electrical field lines along the shortest path length from the entrance to the outlet electrodes. The injected chemicals will follow these field lines and thus change direction immediately. To reduce this effect the electrical fields from the injection channels must be changed to be more uniformly merged with the field in the main channels. One way to achieve this is to use a thin, electrically insulating membrane at the injection point as shown in figure 8.

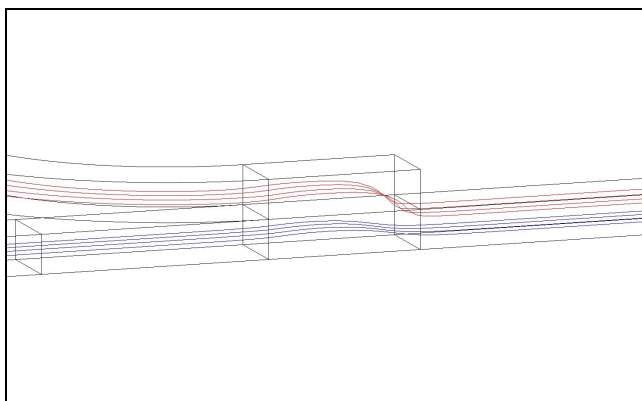


Figure 8: Simulation of a uniform layered injection obtained by placing a thin, electrically insulated membrane in between the two channels.

Although the best solution, this design could not be realized in the two-layer chip fabrication process. An alternative is injecting the flow from aside and putting obstacles in the channel to 'squeeze' the flow over a short distance such that the diffusion distance is locally strongly reduced and the mass diffusion boundary layers are destabilized, resulting in a better mixing. The effect with and without the mixing elements is shown in figure 9.

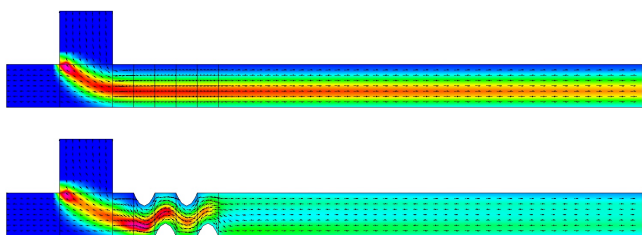


Figure 9: Enhancing effect of 'squeezing' of the flow on the diffusion by placing obstacles in the flow path. The color intensity indicates the diffusion rate.

5 CONCLUSIONS

An electro-osmotically driven system for performing automated chemical synthesis reactions was designed, tested and improved. Since electro-osmotic pumps are (poor) flow-sources with low internal flow impedance, system models were developed to eliminate back flow, induced by reservoir level differences. From the simulations it showed that the direction of centerline velocity is the criteria to design on. A formula for this design criterion for a straight channel has been derived.

For complex systems, a bondgraph simulation package (20-SIM) was used to implement the EOF-Poiseuille flow coupling. With the implemented models, the transient behavior of the system can be modeled with varying material parameters for the different channel branches which means that effects of mixing / reactions and charged channel walls can be taken into account. The model is applicable to channels with relative large dimensions compared to the double layer thickness. In the future we hope to extend the model to be able to apply it to nano channels as well and to achieve 100% energy conservation.

From the CFDRC finite volume modeling results it showed that flow injection by EOF behaves different than for pressure-driven flows which makes it difficult to obtain uniform layered flows to improve diffusion of the injected flows. 'Squeezing' the flows by bulges in the channel geometry showed to be a simple way to enhance the diffusion.

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