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Characterization of a Vertical Lamination Micromixer for IR Spectroscopy

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Abstract

A multi-lamination micromixer for time resolved infrared spectroscopy, optimized by fluid simulations is characterized for different flow rates. Using four instead of two lamination layers yields a reduction of the diffusion length and decreases mixing time significantly. Measurement results prove the ultrafast mixing performance of this micromixer (< 1 ms for aqueous solutions). This device operates in a wide range of flow rates without performance drop illustrated by the linear relation between the mixing time and the flow rate. A new custom chip holder provides easy chip handling and higher pressure durability.

Keywords: Fast, Passive Mixing, Lamination, Micromixer, IR Spectroscopy

1. Introduction

The use of micromixers in time resolved infrared (IR) spectroscopy is an effective possibility to investigate biomolecular kinetics of chemical processes [1]. In contrary to other detection techniques like optical or fluorescence-based methods the reaction under investigation does not have to be labeled before the measurement. This broadens the applicability of this technique because of the limited availability and selectivity of suitable labels. To study such reaction kinetics the mixing of reagents has to be completed before a reaction evolves. Therefore mixing time is crucial for investigating fast chemical reactions. To prevent excessive IR absorption by the medium [2], a maximum channel height of 8 μm was applied in this mixer. Furthermore, to limit the amount of - in biochemical systems rare and hence costly - reagents, low flow rates are used. The resulting small dimension of the channel and the low flow rates introduce a strictly laminar flow regime (Reynolds Number < 1). Schleeger et al have presented time resolved Fourier transform IR measurements with a lamination micromixer with two inlets, using two horizontal fluid layers in a 10 μm deep channel [3]. This contribution describes the characterization of an improved design generates four laminated fluid layers out of two fluid feeds by a distribution network shown in Fig. 1. Straight, rectangular inlet channels would generate a non uniform flow distribution across the channel; liquids fed from the left would preferably stay on this side of the mixing channel and vice versa. Therefore, wedge shaped inlet channels are used to compensate this interaction and achieve a uniform pressure and concentration profile of both liquids across the channel width. The
Figure 1: a) Schematic design of the Micromixer with a detailed section of the entrance region where the four horizontal fluid layers are formed. b) Customized chip holder system with fluid connectors.

fluid layers have different thicknesses, taking into account that diffusion occurs on both sides on the inner layers, to reduce the mixing time by a factor of 9 ($t_{mix} \sim d^2 \cdot \Delta t$) compared to a two layer system [4]. The fluid support for the chip is provided by a custom holder which allows the use of standard 1/4 inch fluid connectors (Fig. 1). Flow rates ranging from 2 μl/min up to 30 μl/min were investigated experimentally.

2. Simulation

To optimize the channel geometry and form a fluid distribution network CFD (computational fluid dynamic) simulations were used. Simulation results were applied to form an optimized inlet wedge shape for a homogeneous sample distribution over the channel width. The fluid distribution network forms four horizontal fluid layers from two fluid feeds to the macro world. These two exterior fluid feeds are driven by syringe pumps. Three different diffusion constants were assumed in the simulations, where a concentration of 50 μM is mixed with 0 μM. For each reaction 90 % mixing is marked as a reference (Fig. 2). $D = 1 \cdot 10^{-9} \text{ m}^2/\text{s}$ for slow diffusing reagents, $D = 2 \cdot 10^{-9} \text{ m}^2/\text{s}$ for aqueous reagents and $D = 5 \cdot 10^{-9} \text{ m}^2/\text{s}$ for very fast diffusion. A mixing time was calculated at a distance of 90 % mixing and plotted over the flow rates, (Fig. 2 bottom, right). The graph shows an almost constant mixing time for increasing flow rates of the same diffusion constant which means that there is no performance loss in a wide range of flow rates. A small distortion at very low flow rates is recognizable but can be explained by premixing of the reagents. A mixing time of $t_{mix} = 0.7 \text{ ms}$ for aqueous solutions and $t_{mix} = 0.29 \text{ ms}$ for quickly diffusing molecules, like proteins in solution, was calculated.
Figure 2: Simulation of the concentration along the mixing channel when mixing a 50 \( \mu \text{molar} \) solution with a 0 \( \mu \text{molar} \) solution, 90 \% mixture is marked. The graph shows the mixing behaviour of liquids with three different diffusion constants and the calculated mixing times at the bottom right.

Figure 3: Mixing experiments of \( \text{Fe}^{3+} \) and \( \text{SCN}^- \) (\( D = 2 \cdot 10^{-9} \text{m}^2/\text{s} \)) with the optimized wedge geometry. The result of 90 \% mixture of the simulations (\( t_{\text{mix}} = 0.7 \text{ ms} \)) is marked and the distance from the inlet is given. Measurements results correlate to the simulation.
3. Experimental

For the experiment two transparent liquids forming a strongly colored reaction product when mixed were used. This is necessary since, as the mixer is observed from top and the liquids are mixed vertically, it is not possible to use a simple dye to distinguish between the established fluid layers and a mixed solution. In this instance, the reaction of iron (III) ions (Fe$^{3+}$), which solution is slightly yellowish, with a colorless rhodanide ($SCN^{-}$) solution was used. When mixed, these two reagents form a bright red complex that could be measured with a standard light microscope. A common syringe pump with 1 ml syringes provided the solutions at different flow rates and was driven by a standard double-syringe pump.

The simulation results were validated for one diffusion coefficient $D = 2 \cdot 10^{-9} \text{m}^2/\text{s}$ by the coloration experiment of 0.1 M iron solution $Fe^{3+}$ and 1.1 M thiocyanate $SCN^{-}$. For the experiment the same flow rates as in the simulation were used. The results are depicted in Fig. 3. A marker indicates the calculated 90 % coloration mixture from the simulations which matches the results of the experiment very well. Flow rates higher than 30 $\mu\text{l}/\text{min}$ require such high pressures that leakage in the sealings can occur. The experiments confirm the simulation results over a decade of flow rate.

4. Conclusions

In this contribution the performance and the working range of a four-layer lamination micromixer is validated. This micromixer can be applied for both time resolved optical measurements and IR measurements. Due to the optimized inlet wedge shape this design yields fast mixing times of around 1 ms for aqueous solutions at very low flow rates down to 1 $\mu\text{l}/\text{min}$. Hence, costly reagent consumption is reduced to a minimum. Further, this device is applicable for time resolved Fourier transform IR spectroscopy to analyze the so far unclear kinetics of chemical reactions. The fabrication procedure of this device is simple and time efficient as the channel structures are generated in silicon by standard micromachining processes. The measured mixing times of a coloration experiment are in agreement with the simulations. The easy setup and handling with the custom chip holder and standard fluid connectors make this device an attractive tool for studying chemical reaction kinetics. In further experiments this micromixer could also be used for determining diffusion coefficients between different fluids (2-30 $\mu\text{l}/\text{min}$).

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