CONVECTION-LIMITED SURFACE TRANSPORT IN NANOFLUIDIC CHANNELS

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ABSTRACT

In this presentation, we describe the conditions under which transport and surface binding of analytes in microfluidic devices becomes convection-limited, i.e. limited by the influx of analyte to the detection zone. Convection-limitations appear in channels typically of less than 10 microns thick due to a high relative number of binding sites at the surface compared to the number of analytes in the bulk. The effect is experimentally observed and quantified in micron-size channels.

Keywords: Microfluidics, Mass Transfer, Adsorption Kinetics, Surface-Based Sensors.

1. INTRODUCTION

The study of mass transfer and binding to microchannel surfaces is a crucial part of the development of sensitive on-chip protein sensors such as protein arrays, surface plasmon resonance (SPR) or evanescent wave sensors. This work provides evidence that, as channel thicknesses decrease to the micron-size or less, surface transport of biomolecules becomes limited by the influx of analytes (convection-limited) in the device instead of either by diffusion or reaction rates (Figure 1). Thus, the commonly used mass transfer models developed for SPR [1], which assume transport from the bulk through a mass transfer boundary layer at the surface, break down. New models must be used which account for sample depletion in the bulk of the channel. Analytic models are supported both by numerical simulations and experimental observation in simple nanofluidic channels.

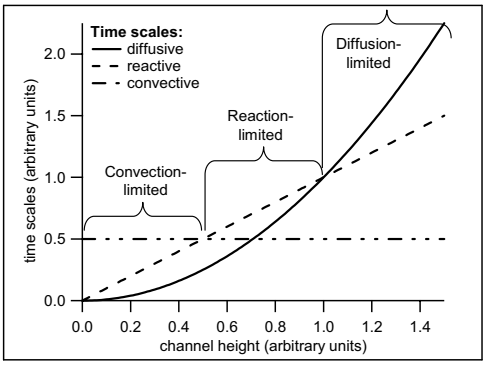

Figure 1. Transport time scales for diffusion ($h^2 \cdot D^{-1}$), surface reaction ($h/k_{on}C_{s0}$) and convection (length/U_{fluid}). When channel height h is too high, reaction kinetics is obscured by diffusion-limitations, when h is too small, kinetics can be obscured by convection-limitations.

2. THEORY

In thinner channels, the amount of available surface binding sites per analyte molecule in the bulk becomes larger and incoming sample will be depleted due to the surface binding. As more sample flows over the binding surface, binding sites will saturate, thus allowing the free analytes to propagate further down the channel. Convection-Diffusion-Reaction models have been used to characterize this behavior and show that analyte transport occurs from the inlet to the outlet in a wave-like fashion (Figure 2) with an effective velocity U_{eff}

lower than the velocity of the carrying fluid (U_{fluid}). The velocity and shape of this propagating front has been characterized and shown to depend directly on the channel thickness and the relative amount of available receptors per analyte in the bulk [2]. In a parallel plate geometry channel, the amount of delay introduced due to surface interaction can be expressed as:

$$\frac{U_{fluid}}{U_{eff}} = 1 + \frac{n_w C_{s0}}{h} \cdot \frac{1}{C_{b0} + K_d}, \qquad (1)$$

where C_{b0} (mol·mm^{-3}) and C_{s0} (mol·mm^{-2}) are the concentration of bulk analytes and surface binding sites respectively, n_w is the number of walls where the reaction occurs (1 or 2), h is the channel height (mm), and K_d the first order equilibrium dissociation constant (mol·mm^{-3}).

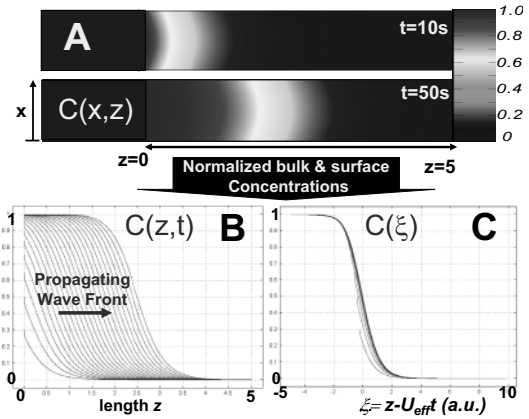

Figure 2. Convection-limited transport model behavior (FEMLAB™)
A) 2D concentration profile (channel side-view, $C(x,z=0)=1$ at the inlet). Bulk and surface concentration enter a self propagating wave moving at velocity $U_{eff} < U_{fluid}$.
B) Cross-section averaged concentration profile $C(\zeta,,t)$ for time increments of 5 s.
C) Concentration profile $C(\xi)$ in the reference of the wave front using the variable change $\xi = z - U_{eff} t$. All lines from B collapse onto a single one, indicating that the propagation velocity U_{eff} is constant.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Convection-limited transport has been observed in 1μm-thick and 2 mm-long silicon nitride channels used in suspended microresonator sensors [3]. Biotinylated bovine serum albumin (bBSA) was physisorbed onto the channel walls and fluorescently-labeled streptavidin (SA) or anti-biotin IgG flowed over the surface for detection. In the presence of bBSA adsorbed on the walls, the propagation velocity of SA was decreased by a factor typically of 10-100 (or more, depending on the bulk concentration used) compared to the free flow of SA or IgG in the absence of bBSA at the walls (Figure 3). This retardation effect has been observed to increase linearly with a decrease in the analyte concentration or channel thickness.

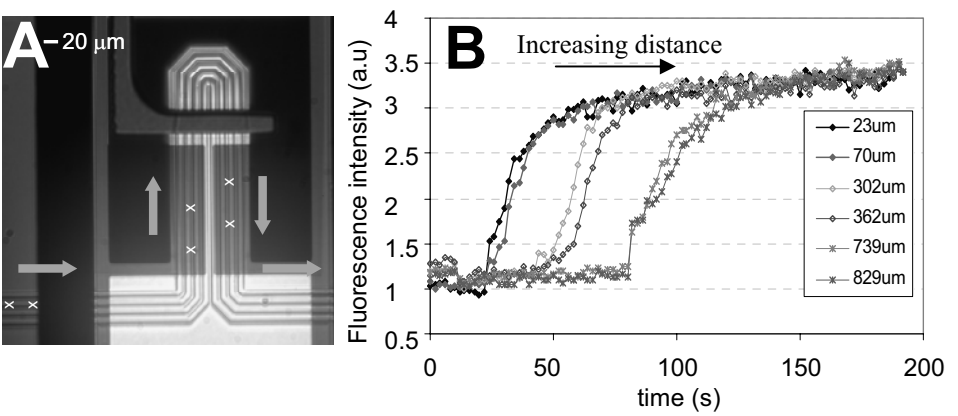

Figure 3. A) Bright field image of the suspended resonator microchannel used for the measurements. The "X's" represent the fixed points where the intensity data was collected over time. B) Fluorescence intensity data (a.u.) vs time (at fixed point) The effective retardation is calculated by determining the time taken for the front to move from one of the detection points to another and comparing with the measured fluid velocity. Retardation factor in this set of curves is found to be of 20 (with C_{s0}≈20 fmol/mm^2, C_{b0}=3.6 μM, h=1 μm).

To further characterize convection-limited transport in nanofluidics, we have fabricated T-injector devices with thicknesses ranging from one to several micrometers using either laser ablation in glass (Figure 4) or soft lithography. These simple devices allow us to measure analyte flow velocities (U_{eff}) to verify the extent of this effect on protein transport in thicker microfluidic channels.

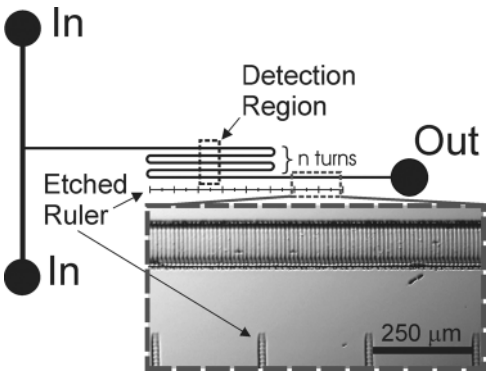

Figure 4. T-injector fabricated in glass using excimer laser ablation techniques (here, depth h=5 μm, width w=100 μm).

Finally, it is commonly expected that reducing the size of microfluidic sensors will yield shorter analysis times and allow one to resolve faster binding kinetics [4]. Convection-limited transport, just as the diffusion-limited one, imposes physical limits to this statement at the micron scale or smaller (Figure 1). Understanding this phenomenon will prove useful to provide design criteria for nanofabricated sensors, notably to characterize and control surface passivation and on-chip binding assays.

REFERENCES:

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