Au/PPy Actuators for Active Micromixing and Mass Transport Enhancement

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Abstract: This study documents our efforts towards a novel design of an active micromixing device that employs Gold/Polypyrrole (Au/PPy) actuators. The devices were manufactured by the sequential deposition of a polyimide layer, a thermal evaporation of gold, and electrodeposition of PPy layer on top of the gold electrodes. Several types of mixers ranging in size from 10 by 1 mm to 380 by 38 μm were successfully actuated at frequencies up to 3 Hz. Mass transport in the solution was studied in a series of chronoamperometric experiments with a Redox sensor placed in close proximity to the actuators. Differential mass transport effects with and without the actuation of micromixers were recorded for several system configurations. In addition, numerical simulations of a biological surface-microreaction (i.e., DNA hybridization) were carried out. Simulation results indicate that compared to passive diffusion-limited transport active micromixing is capable of increasing reaction rates by 30% for sub-mm size actuators and by 100% for mm-size actuators.

Keywords: Au/PPy actuators, active micromixing, microrarray assays.

1. INTRODUCTION

Recent advances in microfabrication techniques have significantly contributed to many different areas of research related to chemistry (chemical and biochemical sensing applications), medicine and biology (drug delivery, medical implants, genomics, etc.) [1, 2]. The possibility to fabricate sensors, fluidic systems, power and heat sources, and other devices on the micron scale has resulted in the emerging field of microdevices that are less expensive, faster, portable, and have better resolution than their macro scale predecessors. A growing field of research known as "Lab on a Chip" [3] integrates a wide variety of separate disciplines such as microfluidics, micromechanics, microelectronics and biology in order to design and fabricate miniaturized chemical and biological sensors. When handling fluids of micron and sub-micron size dimensions, certain physical phenomena become more relevant. Microfluidics emphasizes the role of surface tension, energy dissipation and electrostatic retention – effects that dominate fluid behavior in microchannels.

Within microfluidics a particularly challenging area of research is micromixing (mixing in microreservoirs and microchannels) which has numerous uses in the study of reaction kinetics of chemical and biological processes (like protein folding) [4], in improving traditionally diffusion-limited reactions (i.e. DNA hybridization or other multiplexed microspot-based assays) [5, 6] and in other applications [7-9]. Micromixing, however, is traditionally a diffusion-limited process due to the low Reynolds (**Re**) numbers that are typically encountered in such small domains. Therefore, miniaturized assays involving reactions with biological macromolecules (with large molecular weights and small diffusion coefficients) might not take full advantage of being carried out in such small environments, unless effective solutions aimed at improving mass transport are used.

At the microscale, passive diffusion-based micromixing can only be enhanced by implementing strategies aimed at the reduction of diffusion path-lengths [10, 11] and inducing chaotic advection (random motion of particles due to chaotic dynamics of the flow) in the fluid. Although steady, incompressible two-dimensional flows cannot exhibit chaotic trajectories, steady three-dimensional and unsteady two-dimensional flows can have chaotic streamlines [12-14] even at very low **Re** numbers. Thus, strategies for efficient micromixing that can be integrated in microdevices and microfluidic platforms are essential for improving kinetics of diffusion limited processes in emerging "Lab on a Chip" technologies. Considerable progress has been made in the last decade in both passive micromixing (using geometry and topology of microchannels to enhance mixing) and active micromixing (where mixing is enhanced by externally generated disturbances in the fluid flow) [15]. In this document we present a novel approach towards active micromixing by using gold/polypyrrole (Au/PPy) bilayer actuators. Polypyrrole is an electroactive conjugated polymer that changes volume when a small bias (in the range of 0.8 to 1.2 Volts) is applied. This volume change is caused by expulsion or inclusion (depending on the sign of the applied bias) of solvated cations from the surrounding aqueous solution. While PPy experiments volume changes, the underlying Au layer doesn't. Hence stresses are created on the surface of the Au layer, producing bending. The repeated switching of the applied voltage causes significant oscillations of PPy/Au bilayers. Detailed fabrication procedure and operation of electroactive polymer actuators are described elsewhere [16-19].

Inspiration for present work comes from the classic work by Purcell [20] that describes aquatic life at low **Re** numbers. Like microorganisms swim in water by moving their flagella, the reverse holds true - a system of Au/PPy microactuators can be used to move portions of a fluid. This is feasible due to the flexible nature of these structures and also because several of them can be actuated at the same time. By employing an array of microactuators it is possible to develop

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complex flow patterns in microfluids to achieve chaotic advection and thus enhance conventionally diffusion limited mass transport processes (including micromixing and the yield of surface reactions).

We believe that utilization of this technology for the development of integrated multiplexed miniaturized assays has several advantages compared to other active and passive mixing systems. Passive micromixing due to chaotic advection or bubble formation in microchannels requires channel lengths on the order of several cm per step. In order to achieve multiplexing - parallel implementation of hundreds or even thousands of assays - very long total channel lengths would be required, posing difficult challenges for miniaturizing such systems. The technology discussed in this work is capable of efficient mixing in isolated microvolumes, it is reusable, easy to fabricate and actuate, biocompatible, and minimizes the amount of power, analyte and reagents needed for analytical tests.

To quantify enhancement of mass transport in the presence of functioning Au/PPy actuators we performed a series of Chronoamperometric (CA) experiments. Results of these experiments are compared to results of diffusion-limited mass transport experiments. Furthermore, numerical simulations of a DNA hybridization reaction (localized on the bottom surface of a microchamber) under the effect of several configurations of the Au/PPy microactuators were performed and the results are reported below.

2. EXPERIMENTAL

Materials

Pyrrole (reagent grade, 98%), NaDBS, $K_4Fe(CN)_6$, NaCl, KCl, Na_2HPO_4 , KH_2PO_4 (all reagent grade) were purchased from Sigma-Aldrich. PBS was prepared by dissolving 80 g NaCl, 2 g KCl, 14.4 g Na_2HPO_4 and 2.4 g KH_2PO_4 in 10 L of distilled water. 99.999 % gold pellets and chromium granules were purchased from American Elements. Shipley 1827 was used as positive photoresist (PR) and PIRL III as Polyimide containing solution. The potentiostat used in all experiments was a Gamry FAS2 Femtostat. The Function Generator used to activate the actuators (*via* sinusoidal-wave mode) was a HP/Agilent 8116A. All fabrication steps were carried out at the Integrated Nano Research Facility (INRF) at University of California, Irvine.

Actuators Fabrication Process

The fabrication process for the actuators is depicted in Fig. (1).

Glass slides (Step A) were initially cleaned with DI water, acetone, and isopropanol. After that, using a thermal e-beam evaporator metal deposition system, first a thin layer of Chromium (Cr), between 30 to 80 nm, and then a Gold (Au) layer, ranging from 25 to 100 nm, were deposited on the glass slides. Positive photoresist (PR) was then spin coated on the Cr/Au deposited surface. After a 2 min soft-bake at 90 °C the samples were exposed under the appropriate FeO mask and PR was developed in MF-319. Au and Cr etchants were used to remove excess metal to produce electrical contact pads and lines (Step B). In the next step, a thin layer

(ranging from 100 nm to 500 nm) of polyimide was spin-coated, soft-baked (at 200 °C for 10 min) and patterned (Step C). This polyimide layer was used to allow a faster detachment of the actuator from the substrate (due to polyimide's lower adhesion to Au as compared to glass). A PR layer was deposited on the Polyimide layer, soft-baked, exposed, developed (in this step the Polyimide also became patterned) and stripped off. Then, a thermal e-beam deposition and patterning of the final Au layer of the flap (with thicknesses ranging from 50 to 300 nm) was performed (Step D). For the concluding process step, a PPy deposition (Step E), a solution of 0.1M Pyrrole and 0.1M NaDBS was prepared. The devices were introduced in the solution and connected (*via* the initially patterned contact pads) to the working electrode (WE) of the potentiostat, using a 3-electrode-cell mode (with a calomel reference electrode (RE) and a Au counter electrode (CE)). Then a CA experiment (with step potentials between 0.4 V to 0.6 V on the WE) was run to deposit a PPy layer of thicknesses ranging from 0.5 to 3 μm - maintaining a PPy:Au thickness ratio of 10:1, as suggested for maximum actuator bending [17].

Fig. (1). Fabrication process for Au/PPy actuators.

CA Experiments for Evaluation of Mass Transport Effects

To evaluate how the flow promoted by these actuators could convectively increase mass transport over diffusion limits, a Redox sensor was combined with Au/PPy actuators in two different systems (presented in the next section). The Redox sensor was a Au electrode submerged in a solution of $Fe(CN)_6^{4-}$ species (at concentrations between 0.1 to 10^{-5} M) in the presence of Phosphate Buffered Saline (PBS) supporting electrolyte. This electrolyte was chosen because its saline composition is similar to blood plasma (and so it simulates a substrate from a biological sample) and its ionic species and concentration are suitable for effective actuator activation. Using a potentiostat in a 3-electrode-cell mode with the WE connected to the Redox sensor and the same RE and CE used for PPy deposition, when a sufficiently high positive step-voltage function is applied on the WE the recorded current over time (CA experiment) is a direct function of convective and diffusive mass transport [21]. Thus, the higher the rate at

Fig. (2). Sensor Near Flap system and dimensions.

which Fe(CN)_6^{4-} species reach the surface of the sensor and are oxidized to Fe(CN)_6^{3-} , the higher is the recorded current. When comparing an experiment under strict diffusion-limited conditions (stagnant, unstirred solution) with an identical experiment in the presence of a system of moving actuators, a measurement of mass transport enhancement due to convection can be obtained from the difference between the recorded currents that correspond to presence and absence of advection in the system.

The movement of the actuators was also recorded on videotape while the CA experiments were being carried, so that a real time comparison could be made between any increase in CA response and the actuators motion characteristics. All systems were actuated in open beakers with large amounts of Redox species (semi-infinite approach).

Sensor/Actuator Systems

Two sensor/actuator systems, presented below, were explored: Sensor Near Flap (Fig. 2) and Microsensor Near Flaps (Fig. 3). The goal of Sensor Near Flap systems was to test the ability of these actuators, several mm in size, to en-

hance mass transport and convectively increase the response of a CA sensor placed right in front of the actuator.

The goal of the Microsensor Near Flap systems was to test the feasibility of enhancing the response of a Redox microsensor by actuating several micron-size actuators around it, so that diffusion boundary layer disruption and chaotic advection would increase mass transport rate over diffusion limits. Four different configurations were designed for these systems (shown in Fig. 3) with variables such as number of flaps (either 2 or 6 flaps) and the mode of actuation – flaps could either be actuated “in-phase” or 180° out of phase (“off-phase”).

Noise and Noise Treatment

When sensing circuits are placed in close proximity to power circuits, electromagnetic interference (EMI), in the form of capacitive and inductive coupling, usually results. EMI noise was evidenced during CA experiments due to the presence of the electronically driven actuators near the CA sensor. In addition, due to their electronic conductive nature, the actuators could also behave as electrodes in the solution,

Fig. (3) Microsensor Near Flaps configurations and dimensions.

with capacity to reduce and oxidize $\text{Fe}(\text{CN})_6^{4-}/\text{Fe}(\text{CN})_6^{3-}$ species, altering their local concentration around the CA sensor and hindering the real convective effects promoted by the actuators.

For these reasons “noise experiments” were run to study the effect of EMI and Redox interferences in each system, so that a noise filtering method could be implemented to obtain mass transport data. These noise experiments consisted of applying a range of sinusoidal electrical functions (from 0 to 2 V and from 1 to 5 Hz) to the actuators before PPy was deposited on them, while running CA experiments on the sensor. By doing so the interfering electrodes were held motionless at the initial position (closest to the sensor), which was likely to create the highest EMI disturbance. The resulting signal was then compared to a diffusive-limited blank experiment so the interferences could be isolated and filtered out.

3. NUMERICAL METHODS

A two-dimensional numerical model of two oscillating actuators in a microchannel was designed to forecast the effectiveness of the moving actuator in a scaled-down domain and the impact on the removal rates using second order reaction kinetics representative of biological processes. The objective of the numerical study was to test the effectiveness of the moving actuators at the micro-scale using flaps of 150 μm in length, representative of a realistic size for use in a functioning microdevice. The initial experiments using the

Au/PPy actuators were conducted in relatively large open containers. The objective of the numerical model was to forecast the effectiveness of the flaps for scaled down processes in a bounded domain.

In the actual experiments, while easily detectable using a Redox sensor, $\text{Fe}(\text{CN})_6^{4-}$ in solution has a mass diffusivity that is roughly 1 order of magnitude higher than biological materials such as DNA [22, 23]. The numerical model, therefore, is also useful in illustrating the effectiveness of the flap on the removal rate of biological macromolecules from the fluid and the accumulation in concentration at the reaction sites. Biological processes such as DNA hybridization have been shown to follow a second order rate model with rate coefficients that have been derived and matched with experimental data [22-24]. The second order rate equation in dimensionless form is,

$$\frac{\partial c_s}{\partial t} = \frac{Da}{\varepsilon Pe \kappa_A} (\kappa_A c_w (1 - c_s) - c_s) \quad (1)$$

where c_s is the normalized surface concentration (attached to the reaction sites), c_w is the normalized bulk concentration at the wall, ε is the surface to bulk concentration ratio $C_{s,\max}/L_f C_0$, Da is the dimensionless reaction rate $C_{s,\max} L_f k^1/D$, Pe is the Peclet number $U_f L_f/D$, and κ_A is the equilibrium constant $k^1 C_0/k^{-1}$. The solution properties and variables are the maximum end flap velocity U_f , the bulk concentration C_0 , the maximum surface concentration $C_{s,\max}$, the length of the flap L_f , the forward reaction rate k^1 , the

Fig. (4). Microchannel arrangement and flap motion diagram. **A:** 2 aligned flaps moving 180° out of phase; **B:** 2 aligned flaps moving in phase; **C:** 2 opposing flaps moving 180° out of phase.

Table 1. Typical Values of the Flow Variables Encountered in Bimolecular Processes

Variable	Value ^a	Units	Variable	Value	Units
C _s	2 x 10 ⁻⁹	mol m ⁻²	Re	0.045	
C _o	1 x 10 ⁻⁶	M	Pe	400	
k ¹	1 x 10 ⁴	(M s) ⁻¹	Da	30	
k ⁻¹	0.01	s ⁻¹	ε	13.3	
D	1 x 10 ⁻¹⁰	m ² s ⁻¹	κ _A	1	
v	9 x 10 ⁻⁷	m ² s ⁻¹			
L _f	150	μm	t _d	225	s
f	0.13	Hz	t _{sr}	7.5	s
U _f	0.27	mm s ⁻¹	t _f	7.5	s

^aGervais and Jensen 2006, Pappaert and Desmet 2006.

reverse reaction rate k^{-1} , and the molecular Diffusivity D . Using typical values of the concentrations and rate constants for the mass transport and reaction kinetics describing general biological processes, the numerical model was used to quantify the enhancement, due to the flap motion, of the removal rates for these types of reactions along the bottom channel surface. The values for typical biological processes are shown in Table 1 [22, 23]. The frequency of the flaps modeled was chosen such that the period of oscillation, t_f , is equal to the reaction time, t_{sr} . The diffusion time, t_d , is roughly 2 orders of magnitude greater than both the reaction time and the period of oscillation of the moving flaps. In the numerical model, the entire channel's bottom surface was treated as a reaction site since the optimal probe locations in the flow field had yet to be identified. A diagram of the microchannel arrangement used in the numerical model with multiple flaps and the motions considered is shown in Fig. (4).

Governing Equations

The details and numerical validation of the numerical model of multiple flap motion in a microchannel can be found in a previous numerical study examining the effects of single flap motion in a microchannel [25]. The momentum equations are solved in two-dimensional form using the pressure correction method. The continuity and momentum equations in dimensionless form are,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \frac{1}{\text{Re}} \nabla^2 \mathbf{u} \quad (3)$$

where $\mathbf{u}$ is the velocity vector, p is the pressure, Re is the Reynolds number $U_f L_f / \nu$, and ν is the kinematic viscosity. The mass transport equation in the bulk fluid in dimensionless form is expressed as,

$$\frac{\partial c}{\partial t} + \nabla \cdot (\mathbf{u} c) = \frac{1}{\text{Pe}} \nabla^2 c \quad (4)$$

The boundary conditions for the velocity field are the no slip boundary conditions on all the solid surfaces. For the mass transport equation the boundary condition on the non-reacting solid surfaces is the zero mass flux boundary condition,

$$\frac{\partial c}{\partial x} = 0 \quad (5)$$

Along the bottom channel surface, the mass flux toward the wall is equal to the reaction rate in eq. (1) and the boundary condition for the surface reaction is,

$$\left. \frac{\partial c}{\partial y} \right|_{y=0} = \varepsilon \text{Pe} \frac{\partial c_s}{\partial t} \quad (6)$$

The position of the moving flaps is identified using a distance function, ϕ , a passive scalar commonly used in the level set method [26]. The motion of the beam is forced oscillatory motion with a prescribed angular velocity of $\omega = A \sin \beta t$ where the amplitude of the oscillation is expressed as $A = \pi S / 2r \Delta t$ where S is the arc length, r is the flap radius, and Δt is 1/2 the period of oscillation. The frequency of the flap motion is $\beta = \pi / \Delta t$. The rotational velocity of the flaps is $\mathbf{u} = \omega \times \mathbf{r}$.

4. RESULTS AND DISCUSSION

Noise Characterization and Treatment

The noise experiments run for Sensor Near Flap showed that the interferences behaved as periodic functions that overlapped with the diffusion-limited CA response of the Redox sensor. This response consisted of a current vs. time data series that, depending on the time-scale of the experiment and the frequency of data acquisition (usually 0.01s), typically had 30,000 points. To remove periodic components from the underlying signal, a set of new series was iteratively created. Each point of the new series was created by averaging 11 points of the previous series: the central point (at the same time) with its five immediately preceding and following points. By iteratively repeating this process (typically 200 iterations) a final series was obtained, where the periodic

Fig. (5). Typical results of noise experiments for Sensor Near Flap, before and after numerical treatment. Comparison with a diffusion-limited experiment under identical conditions. The results of the experiments where EMI signal is filtered out match well with the data obtained from the diffusion-limited experiments.

components of the initial series had been smoothened out. When this numerical method was used on the data of the noise experiments, the resulting filtered data matched well (within 2%) with the data of diffusion-limited experiments (without actuators and consequently without EMI), as shown in Fig. (5). Thus, the same numerical approach was used as a noise filtering method for the experiments involving moving

actuators, and the filtered data is assumed to relate directly to mass transport phenomena around the sensor.

A similar noise filtering technique was not applicable for Microsensor Near Flap systems because when the microactuators were in motion the disturbances observed were more pronounced and variable than when only motionless elec-

Fig. (6). Effect of flap motion on the CA response of a Sensor Near Flap system of size 1 x 10 mm, 300 nm Au thickness and 3 μ m PPy thickness. The initial concentration of $\text{Fe}(\text{CN})_6^{4-}$ was 1.0 M in PBS. The step Voltage for the CA experiment on the sensor was 0.4V. The figure reports the CA results of two different tests: a diffusion-limited experiment (thick dashed line) and a mixing experiment with the real, “noisy” signal (solid thin line) and the numerically treated, “noise-free” signal (solid thick line). The sinusoidal electrical functions applied to the actuator during the mixing experiment are also reported (bottom box). The pictures show the actuator position at several stages during the mixing experiment.

Fig. (7). Motion amplitude of flaps for two Microsensor Near Flap systems, consisting of flaps moving 180° out of phase. The flaps dimensions were 380 x 38 μm, 200 nm Au thickness and 2 μm PPy thickness.

trodes were used. Given that it was impossible to precisely measure the electrodes position in time, the contribution of their motion to the EMI could not be accurately evaluated. Hence, it was concluded that the CA sensing method was unsuitable for these microsystems.

CA Experimental Results

Fig. (6) contains the result of one CA experiment with Sensor near Flap systems. The data indicates that the response of the sensor could be increased up to a 100% over diffusion limits due to advection created by these actuators. Similar results were obtained for CA experiments with other Sensor Near Flap configurations.

During these experiments the following observations were made. Applied functions with frequencies higher than 3 Hz would produce fast movement of the flap but at low amplitudes (pictures 1-2 in Fig. 6). Under these circumstances no relevant increase in the sensor response was observed, even when the flaps were in close proximity to the sensor.

When flaps were actuated at frequencies between 1 and 2 Hz, higher movement amplitudes were achieved and a substantial increase of the sensor signal (relative to the diffusion-limited signal) was observed (pictures 3-4 and 5-6 in Fig. 6). When the amplitude of motion was considerable but the initial flat position was not recovered (pictures 7-8 and 9-10 in Fig. 6), a steady decay of the sensor signal was observed until the diffusion-limited current level was reached. Thus, significant advection in the vicinity of the sensor (which was evidenced by an enhanced rate of the oxidation reaction) was observed for two characteristics of the actuator motion: substantial amplitude of movement and full range of motion of the flaps (i.e. repeated return to the flat position of the actuator during each cycle).

For Microsensor Near Flap systems quantitative analysis of the enhanced mass transport was not performed due to impossibility to clean the sensor data from EMI noise. Pictures of these experiments are presented in Fig. (7) as a demonstration of the actuation capabilities of these devices.

Fig. (8). Motion model for actuators of length to width ratio of 10. Geometrical estimation of the bending shape of the flap and the spatial position of its tip, build on experimental observations. D stands for the diameter of the represented circumferences and L is the length of the flap.

Fig. (9). Concentration contours and streamlines for a) Case A b) Case B and c) Case C at $t = 51.8$ s after 7 oscillations.

The flaps shown in Fig. (7) were electrically actuated with sinusoidal functions at frequencies up to 3 Hz (with bias not exceeding 1V) reaching substantial movement amplitudes. At higher actuation frequencies, as seen in the previous systems, the movement amplitude decreased substantially.

Flap Movement: Model and Characteristics

Fig. (8) presents a geometrical model of the flap motion. Length to width ratio for all flap actuators is equal to 10. While the experimental observations of the actuators behavior are consistent with the presented model we did not incorporate this geometrical model into these numerical simulations (where actuators modeled as rigid beams) for the sake of simplicity. This is being approached in ongoing work.

Numerical Simulation Results

The effects of multiple flap motion on the total adsorbed concentration at the reaction site was determined for 3 different flap motions as illustrated in Fig. (4). Both flaps are positioned on the bottom channel surface in the enclosed microchannel, with no inlet flow. The only source of fluid motion is due to the motion of the moving flaps. The initial normalized concentration of the solution is $C_0 = 1$ and the initial wall concentration is zero, $C_s = 1$. In case A, the flaps are moving in the same direction but 180° out of phase. In case B, the flaps are moving in the same direction and are in phase. In the last scenario, case C, the flaps are moving opposite to each other and 180° out of phase.

The contour plots illustrating the concentration contours in the bulk fluid and the streamlines surrounding the moving flaps for cases A, B, and C are shown in Fig. (9). The concentration contours are shown at $t = 51.8$ s after 7 flap oscillations. The effect of the moving flap on the surface concentration along the bottom channel surface at three different times is shown in Fig. (10a-c) for all three cases. For two flaps moving out of phase (Case A), the largest surface con-

centrations can be found at $x = 450 \mu\text{m}$ and $x = 625 \mu\text{m}$. The percent increase in the surface concentration at these two locations in comparison to the purely diffusive case without flap motion is 28.1% and 15.3% respectively after $t = 11.2$ s. The spike in the surface concentrations that are located at the flap positions are not considered since a steep drop off in concentration occurs and would not be an ideal location to place a probe or reaction site. For two flaps moving in phase (Case B), the largest surface concentrations can be found at the same locations as in Case A but at slightly lower concentration levels at the three given time periods. For Case B, the increase in surface concentration in comparison to the case without flap motion at $x = 450 \mu\text{m}$ is 19.2 % and at $x = 625 \mu\text{m}$ is 15.3% for $t = 11.2$ s. For two flaps moving opposite to each other and out of phase (Case C), the maximum surface concentrations are located at $x = 400 \mu\text{m}$ and $x = 550 \mu\text{m}$. At these locations the increase in surface concentration in comparison to the purely diffusive case without the moving flaps is 13.3% and 12.3% respectively at $t = 11.2$ s.

The results in Fig. (10a-c) show that the largest increase in surface concentration occurs in Case A when both flaps are moving in the same direction and 180° out of phase with one another. The time progression of the surface wall concentration at the two locations where peak concentrations are observed, $x = 450 \mu\text{m}$ and $x = 625 \mu\text{m}$, are plotted versus time in Fig. (10d). The results show that the location with the greatest increase in the surface concentration lies between the two flaps at $x = 450 \mu\text{m}$.

It is also necessary to mention that higher actuation frequencies implemented in the simulations didn't deliver larger reaction yields. In the model, which incorporates reaction kinetics parameters typical of DNA hybridization reactions, one limiting case for the overall reaction yield calculation is reached when mass transport from the bulk toward the surface of the reactive spot is faster than the kinetics of the reaction. In this case, no matter how fast the molecules reach the reactive spot, the reaction kinetics will govern the resulting yield. The results presented above, then, fall in the con-

Fig. (10). Surface concentration profiles along the bottom channel surface for **a)** Case A, **b)** Case B and **c)** Case C; **d)** time progression of the surface wall concentration at maximum concentration locations for Case A in comparison to the case with no moving flaps.

text of this case, where mass transport is no longer a limiting factor, and only reaction kinetics are.

5. CONCLUSIONS

As it has been demonstrated, Au/PPy actuators of several mm in length can enhance diffusion-limited processes by promoting flows that increase convective mass transport. When fabricated at the micron scale, these actuators are still capable of similar effects as demonstrated with the numerical simulations. The results of the simulations also show that the effect of the moving actuators can be improved when combinations of several microactuators are used, thereby indicating that certain spatial and actuation configurations are more efficient than others. It should also be noted that a 28% increase in the reaction yield predicted by this early model is a promising result. Higher actuation frequencies didn't improve the reaction rate, thus, it represents the limiting case where the reaction is kinetics-limited (not mass transport-limited), and so for other reactions with faster kinetics the yield would be larger. Also, real 3D configurations with flexible actuators would further improve mass transport capabilities.

The fabricated microactuators achieved substantial movement amplitudes at frequencies up to 3 Hz with low required input voltage bias (less than 1 V), providing motion amplitudes of comparable magnitude to the ones implemented in the simulations. Thus, we conclude that these actuators are capable of both, surface reaction rate enhancement and mixing in the microdomain, and further experiments toward precise quantification of these processes will

be performed. Future work will consist of a new set of experiments using alternative analytical methods (such as confocal laser scanning microscopy) to quantify and examine with greater depth the micromixing potential of these microactuators in practical applications (e.g., biochemical reactions in microchannels). The experimental results will be used to test and validate a more accurate simulation method taking into account a more realistic flap motion model with flexible, bending actuators.

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