

# CHEMISTRY AT LIQUID-LIQUID INTERFACES

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## ABSTRACT

Most chemical transformations, separations and purifications often involve non aqueous systems and liquid-liquid contacts between immiscible fluids. Unfortunately controlling the location of the liquid-liquid contact of these immiscible fluids and clean separation after they are in contact is not trivial in microfluidic systems. By patterning surface free energies within the microchannel, stable liquid-liquid interfaces can be achieved between immiscible liquids. The ability to pattern stable liquid-liquid interfaces opens investigation into several chemical processes involving these interfaces. These include liquid-liquid extraction, interfacial polymerization and phase transfer reaction.

**KEY WORDS: Microfluidics, Lab-on-a-Chip, Detection, Membranes**

## 1. INTRODUCTION

Conducting chemical transformations within the microfluidic platform offers several advantages. Small amounts of reagents are used and consumed; leading to lower reagent costs and waste disposal. It is thus ideal to incorporate chemical synthesis into microfluidic systems. Unfortunately, most chemical transformations, separations and purifications often involve non aqueous systems. Unlike liquids of similar natures, aqueous-aqueous or hexadecane-hexadecane solutions, immiscible liquids do not exhibit stable laminar interfaces. Differences in viscosity, interfacial free energies and densities lead to unstable interfaces making it difficult to control the location of these interfaces and separate the two liquids once in contact [1-3].

By patterning surface free energies within the microchannel, interesting phenomena have been observed and can be exploited to manipulate fluid flow[4,5]. We have previously shown that by using self-assembled monolayers (SAMs), patterning surfaces within the microchannel can be conducted in-situ by either multistream laminar flow or through photolithography [6]. These patterned surfaces show very stable liquid-air interfaces. It was later determined that these photopatterned surfaces also stabilizes liquid-liquid interfaces of immiscible liquids [7].

The ability to pattern stable liquid-liquid interfaces opens investigation into several chemical processes involving these interfaces. These include liquid-liquid extraction, interfacial polymerization and phase transfer reaction. Examples of which are described in detail below.

## 2. EXPERIMENTAL

### *Reversed Micelle Extraction of Co(II)*

An aqueous solution of  $\text{Co}(\text{Ac})_2$  (0.03 M) is prepared and the pH adjusted to 5.8 with acetic acid. A 0.1 M solution of Bis-(2-ethylhexyl) phosphoric acid (BEHPA) is prepared in hexadecane (HD). In a pre-patterned microchannel, the hydrophilic portion of the microchannel is filled with the aqueous  $\text{Co}(\text{Ac})_2$  solution. Pure HD is then used to fill the hydrophobic half of the microchannel. The HD is then displaced with the BEHPA in HD utilizing a syringe pump (flow rate = 0.03 mL/min). The cobalt solution is also placed under flow via syringe pump (flow rate = 0.11 mL/min). Visualization of the extraction is observed through a microscope.

### *Interfacial Polymerization of Nylon 6-6*

An aqueous solution of 1,6-hexamethylenediamine (62.5 mM) and a solution of diisocyanate in toluene (46.9 M) is prepared. In a pre-patterned microchannel, the hydrophilic portion of the microchannel is filled with the aqueous solution. The hydrophobic portion of the microchannel is then filled with the toluene solution. The two fluids are allowed to remain in contact for 5 min. The microchannel is then rinsed in methanol and carefully dried under nitrogen.

### *Phase Transfer Reaction of 5-(tetradecanoylamino) fluorescein*

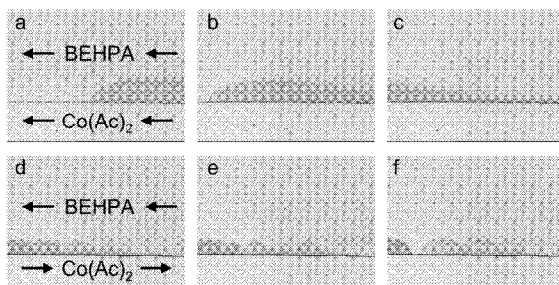
A saturated solution of 5-(tetradecanoylamino) fluorescein in toluene is prepared. Methyltrioctylammonium chloride (0.1% wt.) is added to the solution. The solution is then filtered through a 0.45  $\mu\text{m}$  syringe filter. An aqueous solution of NaOH (0.1% wt.) is also prepared. A nylon 6-6 membrane is produced in a pre-patterned microchannel. The hydrophilic portion of the microchannel is filled with the aqueous NaOH solution. The hydrophobic half of the microchannel is filled with the toluene solution of 5-(tetradecanoylamino) fluorescein. Visualization is achieved through a fluorescent microscope.

## 3. RESULTS AND DISCUSSION

### *Detection of Co(II) by Reversed Micelle Extraction*

The detection of cobalt (II) ions is possible through reverse micelle extraction with Bis-(2-ethylhexyl) phosphoric acid (BEHPA). As the cobalt ions are extracted from the aqueous phase to the organic phase a blue color is observed indicating the extraction of cobalt. An interesting phenomenon is also observed when liquids are under flow. The stability of the interface achieved through patterning, allows for the flow of liquid in either a con or counter-current fashion. The extraction of cobalt differs visually under both flow conditions.

Under con-current flow, the blue color appears at the interface of the two liquids. The extraction does not obey typical diffusional profiles of chemical extraction. A non continuous extraction is observed at the interface. Surprisingly, laminar extraction profile is not observed. A turbulent swirling extraction is at the interface. The leading edge of the extraction rotates counterclockwise as the entire mass progresses forward in the direction of flow (Figure 1a-c).



**Figure 1:** a-c) Con-current extraction of Co(II) into the organic phase. Co(II) is observed as the dark color. Direction of flow indicated by arrows. d-f) Counter-current extraction of Co(II).

The stability achieved between the immiscible fluids through surface patterning also allows for stable counter-current flow. Achieving stable counter-current flow in microchannels is not trivial and typically involves special lithography or the introduction of membranes, physically separating the two liquids. The liquid-liquid contact achieved by surface patterning produces a large

liquid-liquid contact allowing for more efficient mass transfer. The extraction of cobalt (II) ions under counter-current flow also produces turbulent extraction profiles. However unlike the rolling leading edge extraction observed under con-current flow, vortices are formed producing a more turbulent extraction of cobalt into the organic phase (Figure 1d-f). These vortices are not static and traverse down the liquid-liquid interface in the direction of the organic fluid flow.

It is believed that the BEHPA partitions at the liquid-liquid interface. The shear stress produced by the flowing liquids disrupts the BEHPA layers at the interface forming the reversed micelles to extract cobalt into the organic phase. This results in the turbulent extraction profiles.

#### *Phase Transfer Reactions*

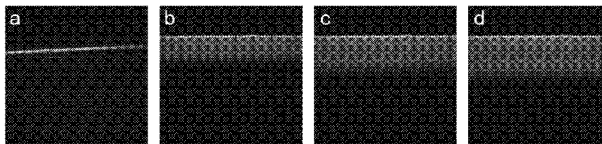
The ability to form very stable liquid-liquid interfaces within microchannels makes it possible to explore chemical transformations at these interfaces. Phase transfer reactions involve the assisted transfer of an aqueous soluble compound into the organic phase. Once this transfer occurs, chemical reactions within the organic phase can proceed. Typically the compound transferred from the aqueous phase is a hydroxide ion. This hydroxide ion can then conduct a nucleic displacement or an acid-base reaction to initiate the desired reaction. The phase transfer catalyst typically used is normally an amine that contains very long aliphatic groups which will shield the ion and make it more soluble in the organic phase. The phase transfer catalyst, however acts as a surfactant. This changes the surface wetting properties of the liquids and makes the liquid-liquid interface unstable. However inclusion of a nylon membrane stabilizes the liquid-liquid contact dramatically allowing for the successful model phase transfer reaction within the microchannel.

The model reaction involves the phase transfer of a hydroxide ion from the aqueous phase into the organic phase. The water insoluble fluorophore, 5-(tetradecanoylamino) fluorescein, is dissolved in the organic phase. In the organic phase the fluorescein moiety is in its non-fluorescent acid form. If the sodium hydroxide is successfully transferred

from the aqueous phase to the organic phase, it will deprotonate the fluorescein and results in a fluorescent molecule.

A control reaction in which the phase transfer catalyst was removed results in the observation of fluorescence only at the nylon

membrane where liquid-liquid contact is possible, but no fluorescence in the organic phase (Figure 2a). When the phase transfer catalyst is added to the organic phase, fluorescence is observed in the organic phase and diffuses further into the organic phase over time (figure 2b-d). A linear relationship is observed between the square of the distance traveled into the organic phase and time. This is typical of normal diffusional behavior. The detection of fluorescence indicates that successful phase transfer reaction has been achieved.



**Figure 2:** a) Control phase transfer reaction. Organic phase does not contain phase transfer catalyst. Only fluorescence observed is at the membrane where the aqueous phase (top) is in contact with the organic phase (bottom). b-d) Phase transfer reaction containing the catalyst (at times 43, 63, and 83 s). Fluorescence is observed diffusing into the organic phase.

#### 4. CONCLUSIONS

With the ability to pattern and form stable liquid-liquid interfaces, chemical processes involving interfaces have been achieved. Chemical extraction from one liquid system to another allows for purification as well as detection of agents. Phase transfer reactions at the liquid-liquid interface, opens the door to more complex synthesis within these microchannels. Finally interfacial polymerization has been achieved producing stable membranes as well as chemically active membranes.

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#### References:

- [1] Hisamoto H.; Horiuchi, T.; Uchiyama, K.; Tokeshi, M.; Hibara, A.; Kitamori, T. *Anal. Chem.* **2001**, *73*, 5551.
- [2] Hibara, A.; Tokeshi, M.; Uchiyama, K.; Hisamoto, H.; Kitamori, T. *Anal. Chem.* **2001**, *17*, 89.
- [3] Zhao, B.; Moore, J.S.; Beebe, D.J. Unpublished results.
- [4] Gau, H.; Herminghaus, S.; Lenz, P.; Lipowski, R. *Science*, **1999**, *283*, 46.
- [5] Darhuber, A.A.; Troian, S.M.; Miller, S.M. *J. Appl. Phys.* **2000**, *87*, 7768.
- [6] Zhao, B.; Moore, J.S.; Beebe, D.J. *Science*, **2001**, *291*, 1023.
- [7] Zhao, B.; Viernes, N.O.L.; Moore, J.S.; Beebe, D.J. *J. Am. Chem. Soc.* **2002**, *124*, 5284.