MICROFLUIDIC DROPLET-BASED LIQUID-LIQUID EXTRACTION FOR FLUORESCENCE-INDICATED MASS TRANSFER

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ABSTRACT

This paper demonstrated a fluorescence-indicated mass transfer liquid-liquid extraction process based on a droplet microfluidic system. Analysis of the droplet-based liquid-liquid extraction process based on the description of mass transfer into or out of droplets is conducted. The relationship between the extraction efficiency and the droplet size is measured and the mass transfer coefficient for fluorescein from octanol to PBS buffer is determined as 3.07×10^{-5} m/s. This work has wide potential applications in extraction system design and other chemical-biological areas.

KEYWORDS: Microdroplet, Liquid-liquid extraction, Mass transfer, Micro-opto-fluidic-systems (MOFS).

INTRODUCTION

Liquid-liquid extraction, also known as solvent extraction and partitioning, is a method to separate compounds based on their relative solubility in two different immiscible liquids such as water and an organic solvent. It is an extraction of a substance from one liquid phase into another liquid phase. Liquid-liquid extraction is an important technique which has wide applications in chemical engineering, analytical chemistry and biology. Since the conventional process is time-consuming and expensive, there is great interest in miniaturizing the system. An obvious effect of shrinking the system to the micrometer scale is the huge increase in surface area relative to volume, often by several orders of magnitude. For a liquid, the effect allows for more efficient mass transfer in microsystems: relatively more interface is available for transfer to occur, and less total mass or energy needs to be transferred to reach the final state. Therefore both the creation and the homogenization of solute gradient are faster as system size is reduced.

In recent years, droplet-based microfluidic systems have been shown to be compatible with a wide variety of chemical and biological operations [1]. Several groups reported various liquid-liquid extraction microfluidic chips. As one liquid phase disperse in the other, the description of mass transfer into or out of droplets in needed as a basis for the modeling and design of an extraction process. The droplet size distribution, the chemical reaction at the interface and the flow condition of the continuous phase influence mass transfer. This paper analyzes the droplet-based liquid-liquid extraction process based on the description of mass transfer into or out of droplets. The relationship between the droplet size and extraction efficiency is described and the mass transfer coefficient value is measured.

DESIGN AND THEORY

The microdroplet-based liquid-liquid extraction process is illuminated in Fig. 1. The solute molecules are rapidly dissolved into aqueous phase when a droplet is formed in the microchannel. As the droplet travel along the microchannel, the concentration of solute molecules become higher and higher. Finally the equilibrium condition is reached and the droplet becomes saturated. Since the microfluidic devices provide an opportunity for precisely manipulating generated droplets, individual dispersed droplets serve as floating containers that can work for kinetic measurements. The special position within a microchannel will correlated with reaction time. A given position in the channel will correspond to the same kinetic state. Signals can be collected from several successive droplets and integrated, making it possible to monitor even relatively fast reactions. That is why just analyze a single microphoto of a serious droplets in the microchannel can tell the whole process of the droplet-based liquid-liquid extraction.

To further study the liquid-liquid extraction process, we define a special parameter k called mass transfer coefficient, which can describe the rate of mass transfer in extraction process when the interfacial area and concentration difference inside a single droplet is known. The whole process can be expressed as

$$C_{(t)} / C_{(sat)} = 1 - \exp(-kat) \qquad (1)$$

where $C_{(t)}$ is the concentration of the droplet depending on time variation, $C_{(sat)}$ is the final saturated concentration, a is the surface area

(a)

(b)
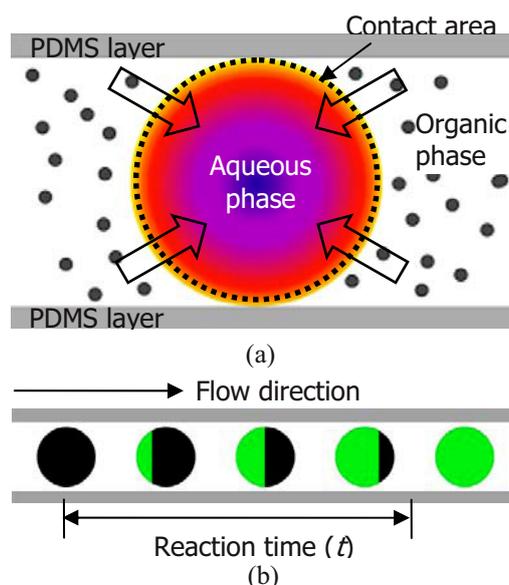
Figure 1: (a) Schematic of molecule mass transfer across the two immiscible phase boundary. (b) Schematic of the solute extracting (concentration varying) process indicated by droplets at different reaction times.

to volume ratio which is determined by the droplet size and k is the mass transfer coefficient, a critical constant of the mass transfer process [2].

On the other hand, when the extraction process is detected and the droplet size is known, the mass transfer coefficient k can be calculated as

$$k = -\frac{r}{3t}\ln(1-\frac{C_{(t)}}{C_{sat}})$$

(2)

DESIGN AND EXPERIMENTAL SETUP

Fig. 2(a) shows the design of the microchip. Phosphate buffer solution (PBS) droplets are generated in octanol using the flow-focusing structure. Fluorescein is initially added in the octanol and mass transfer into PBS when the droplets are flowing along the channel. The measurement system consists of a mercury lamp connected to a filter for different wavelength as excitation source, a collimating lens, the microfluidic chip, a collecting lens and a charge coupled device camera (DP70, Olympus). Two immiscible

(a)

(b)

Figure 2: (a) Schematic of microfluidic chip for droplet generation, and (b) the process of droplet generation using the flow-focusing structure.

liquids are injected by syringe pumps (NE-1000, New Era) into the microfluidic chip. Fig. 2(b) shows the droplet generation process. The size of the droplets can be controlled over a broad range by changing the flow rates of two immiscible phases [3].

EXPERIMENTAL RESULTS AND DISCUSSIONS

(a)

(b)
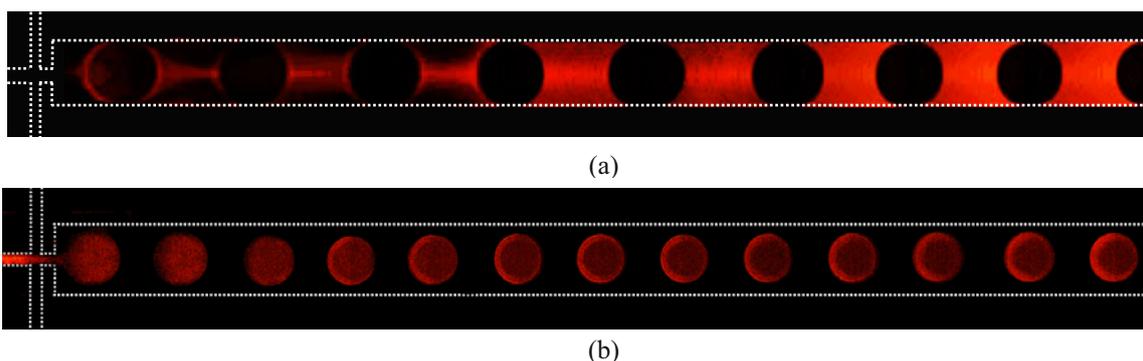
Figure 3: Fluorescence micrographs of droplet-based liquid-liquid extraction process: (a) rhodamine B, and (b) fluoresce-labeled BSA

To observe the droplet-based liquid-liquid extraction process, two experiments for conditions whether the liquid-liquid extraction happen or not happen are designed. Rhodamine B, which has a better solubility in octanol than PBS was added initially in the PBS phase. When the droplets formed at the orifice and travelled along the microchannel, rhodamine B quickly mass transfer through the phase interface into octanol. Then the continuous octanol phase becomes brighter as shown in Fig. 3(a). In the other condition, the fluoresce-labeled BSA, which has a better solubility in PBS rather than in octanol was also added initially in the PBS phase. However, when the droplets formed, the fluoresce-label BSA does not mass transfer through the phase interface. The molecules still confined inside the PBS droplets so the intensity of fluoresce keeps. Another phenomenon is the BSA molecules start to accumulate at the back part of the droplets because the droplets moving ahead inside the microchannel as shown in Fig. 3(b).

Fig. 4 shows the fluorescence micrographs of droplets in the microchannel. The solute molecule fluorescein is added into the organic phase at the beginning. The extraction happens that fluorescein mass transfer into the PBS droplets. The PBS droplets become brighter as more fluorescein molecules mass transfer across the phase boundary. Initially, a fluorescent ring is formed along the droplet boundary. Its width grows gradually and eventually fills up the entire droplet homogeneously with a steady amount. The extraction processes of three different size droplets (30 μm, 60 μm and 90 μm) show that the reaction time to reach the final saturated state depends on the size of the droplet.

Fig. 5 illustrates the experimental results of the normalized fluorescence intensity, which is related to the concentration in the droplets, as a function of reaction time. The reaction time to reach the saturated concentration is directly proportional to the droplet radius. Using these data, the fluorescein mass transfer coefficient can be calculated as 3.07×10^{-5} m/s, which agreed with the theoretical results.
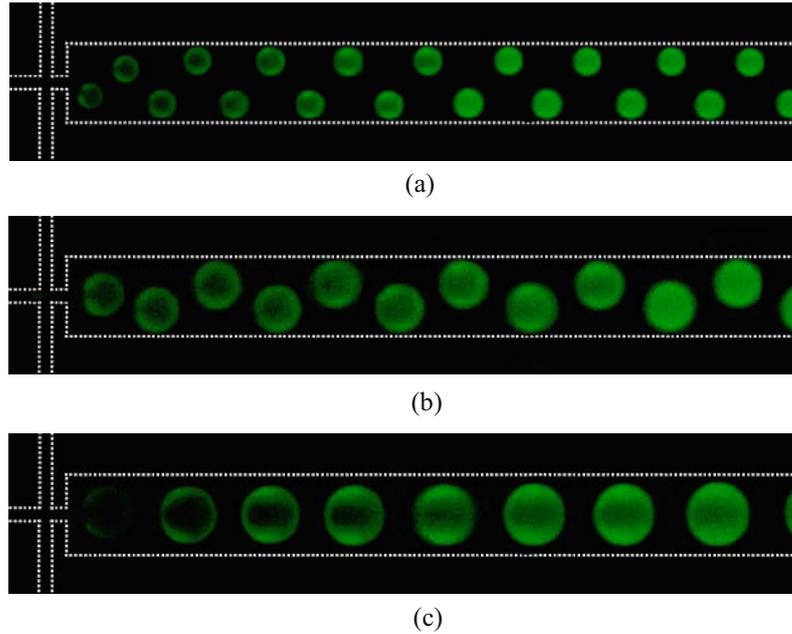
Figure 4: Fluorescence micrographs of droplets at different times in the channeldroplet radius: (a) r = 60 μm; (b) r = 90 μm; (c) r = 120 μm.
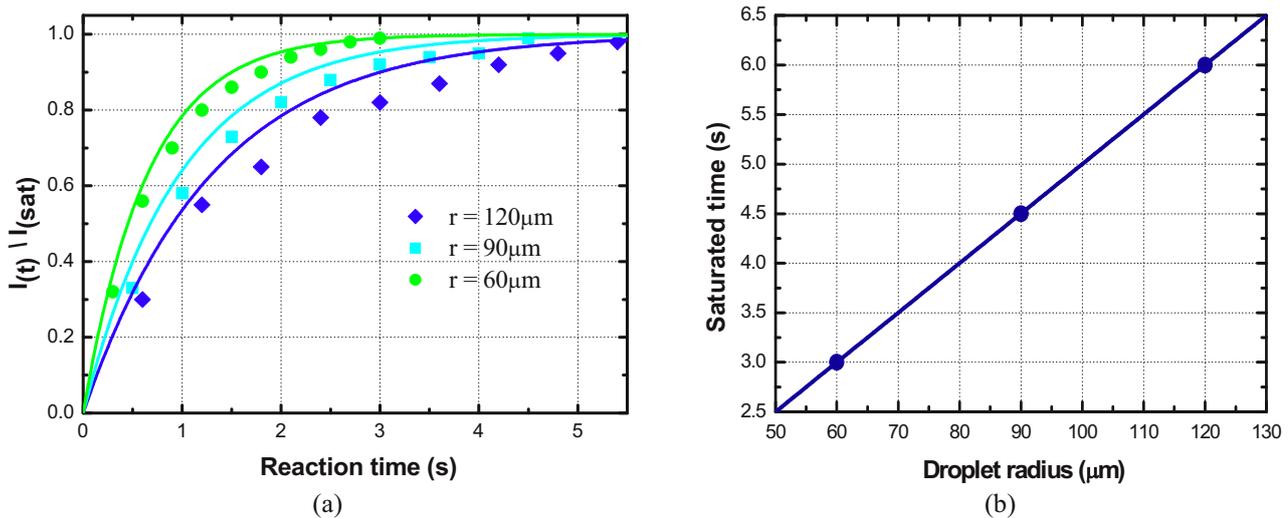
Figure 5: Experiment results compare with the calculation curve (a) normalized intensity of fluorescence as function of time within the droplets (b) relationship between saturated time and droplet size

CONCLUSIONS

In conclusion, a fluorescence-indicated mass transfer liquid-liquid extraction process based on a droplet microfluidic system is demonstrated. The relationship between the extraction efficiency and the droplet size is measured and the mass transfer coefficient for fluorescein from octanol to PBS buffer is determined as 3.07×10^{-5} m/s. This work has wide potential applications in extraction system design and other chemical-biological areas.

REFERENCES

[1]   S. Y. Teh, R. Lin, L. H. Hung and A. P. Lee, Droplet microfluidics, Lab on a Chip, **8**, 198 (2008).
[2]   E. L. Cussler, Diffusion: Mass transfer in fluid systems, Cambridge University Press (1997).
[3]   S. L. Anna, N. Bontoux and H. A. Stone, Formation of dispersions using "flow focusing" in microchannels, Applied Physics Letters, **82**, 364 (2003).

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