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Microdroplets for the Study of Mass Transfer

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1. Introduction

As the development in the microfabrication technology in the last two decades has allowed the easy fabrication of microchannels with low cost, many studies have been conducted on the transport of fluid and the realization of various functions using fluids (Whitesides, 2006; Dittrich et al., 2006). The realization of the microchannel-based fluidic system and the relevant study are called microfluidics. In the scale in which microfluidics is concerned, the surface force is dominant over the body force, since the surface-to-volume ratio is large. The dominant influence of the surface force allows the production as well as the movement and control of micro-sized droplets in a microchannel. This study area is called droplet-based microfluidics (Beebe et al., 2002; Kim, 2004; Stone et al., 2004). Droplet-based microfluidics is expected to enable chemical and biological applications such as particle synthesis (Frenz et al., 2008), microextraction (Mary et al., 2008), and protein crystallization (Zheng et al., 2003). In a general microfluidics system, the Reynolds number (Re) is very small as 0.1-10, and thus the fluid forms a laminar flow. Such a laminar flow makes it difficult for two different fluids to be mixed with each other. However, if droplets are used, different fluids can be mixed with each other, because an internal circulation flow takes place in the droplets (Tice et al., 2003).

This chapter describes the microextraction based on the droplet-based microfluidics. Firstly, we will explain the electrohydrodynamic droplet generation and control technology in the aqueous two-phase system (ATPS) that we employed for the study, and the application of the generated droplets to microextraction. In particular, we were able to control the rate of extraction, which was impossible in the previous extraction methods, and analyzed the microextraction behaviour by simulating the phenomena based on a simple dissolving model.

1.1 Droplet-based microfluidics

The technology that is firstly required in droplet-based microfluidics is the method to generate droplets in a microchannel. Droplet generation is related with capillary number (Ca), which is the ratio of viscous force to interfacial tension (Squires & Quake, 2005). In a macroscopic system, droplets can be easily generated by vigorously shaking immiscible fluids, but the size distribution is very wide. In a microfluidics system, on the contrary, droplets are generated by various controllable methods so that the size distribution can be limited. Microfluidic methods for forming droplets can be either passive or active. Most methods are passive, relying on the flow field to deform the interface and promote the

natural growth of interfacial instability (Christopher & Anna, 2007). Specially designed geometries that affect the streams or externally applied forces are used to generate droplets in the microfluidic systems depending on the characteristics of the immiscible fluids such as viscosity, interfacial tension, wettability to the material surface and other electric properties. Flow rates of the dispersed phase (Q_d), continuous phase flows (Q_c) and their ratio (Q_d/Q_c) are the parameters that can be controlled during the droplet formation operation. Three common techniques that are often used for generation of droplet in microfluidic system are dispersing fluid in a continuous phase with the configuration of co-flowing stream, cross-flowing in T-junction and flow-focusing as shown in Figure 1 (Anna et al., 2003). These techniques are feasible particularly for fast generation of droplets of oil/water two-phase system with uniform size distribution.

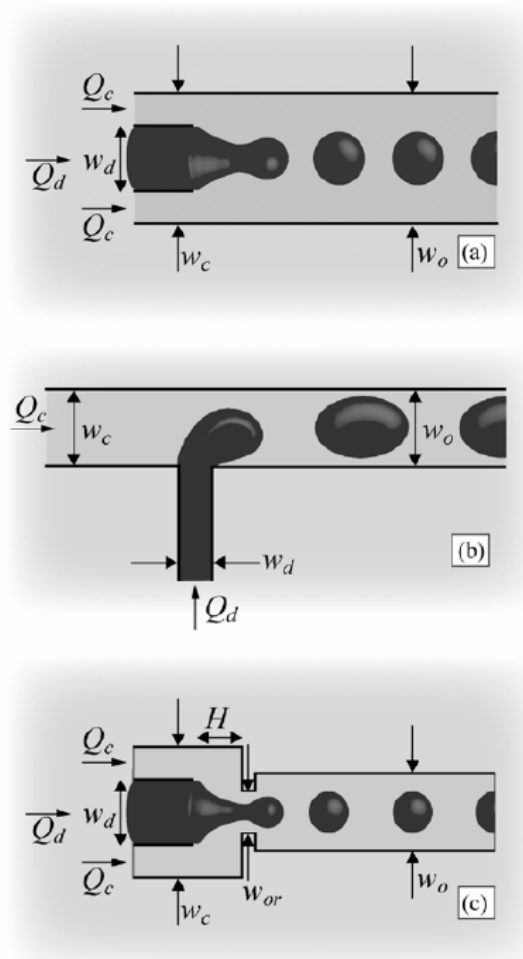


Fig. 1. Illustrations of the three main microfluidic geometries of methods used for droplet formation. (a) Co-flowing streams, (b) crossflowing streams in a T-shaped junction, and (c) elongational flow in a flow focusing geometry. In each case the widths of the inlet and outlet streams are indicated. It is assumed that the device is planar with a uniform depth h . (Anna et al., 2003)

Different from the passive methods, the active methods generate droplets by applying various external forces. Electrohydrodynamic methods are the most frequently used for the active generation. Although electrohydrodynamic methods require electrodes to apply an

electric field, they have the advantages that the electric signals can be easily controlled and there is not a concern for fatigue fracture since there is not a moving part. Electrohydrodynamic methods can be used not only for the generation of droplets but also for their control, and thus there can be many applications of the methods. Several applications of EHD method have been reported in droplet-based microfluidic system. Ozen et al. (Ozen et al., 2006a, 2006b) formed monodisperse droplets using the EHD instability of the interface between two liquids and analyzed the stability in the case where the fluids are assumed to be leaky dielectric. EHD generation of a single droplet in an aqueous two-phase system (ATPS) which has high salt concentrations in both phases was also reported (Song et al., 2007; Choi et al., 2008). The results are considered in Section 2.1.

Generated droplets should be manipulated properly for further utilization in the same microfluidic system. This includes manipulation of droplets by breakup, sorting and coalescence, etc. Various techniques have been published for the effective manipulations of droplet in the microfluidic systems. For breakup of generated droplets, geometry of the microchannels has been specially designed (Link et al., 2004; Ménétrier-Deremble & Tabeling, 2006) and electrical field has been applied for the control (Choi et al., 2006). Tan et al. reported sorting of droplets through controlling the bifurcating junction geometry and the flow rates of the daughter channels (Tan et al., 2008). Ahn et al. developed dielectrophoretic manipulation of droplets for high-speed microfluidic sorting devices (Ahn et al., 2006). Prakash et al. demonstrated synchronization of bubble movements via planar fluidic resistance ladder network (Prakash & Gershenfeld, 2007). An active method of controlling charged droplets electrically was reported by Link et al. (Link et al., 2006). Coalescence of droplets is essential for the reaction of molecules confined in different droplets and thus it has been extensively studied including the mechanism and methodology for microfluidic systems (Bremond et al., 2008; Zagnoni & Cooper, 2009; Tan et al., 2007; Ahn et al., 2006).

1.2 Microextraction in microfluidic systems

Microextraction has been developed and widely applied as an efficient tool for molecular transport in microfluidic devices, taking the advantages of small dimension such as stable and continuous operation without the need of shaking and settling as in conventional extraction system and enhanced separation caused by large interfacial distance and short diffusion time. Several research results on microfluidic extraction of metal ion complexes within organic-aqueous two-phase system have been published by Kitamori's group (Tokeshi et al., 2000a, 2000b; Surmeian et al., 2002; Hisamoto et al., 2003). Kitamori's group realized microextraction in the microfluidic system by forming a laminar flow with two or more fluids in a microchannel and using the interfaces between different fluids. When the microextraction is realized in a droplet-based microfluidic system, a more rapid mass transfer can be expected than in a laminar flow-based system because the ratio of the interfacial area between the different fluids per the unit volume is larger. As an example of the droplet-based microextraction, Xu et al. (Xu et al., 2008) demonstrated extraction of succinic acid from *n*-butanol to aqueous droplets containing sodium hydroxide. Mary et al. studied the extraction of a solute from the continuous phase and purification where the solute transport was in the opposite direction (Mary et al., 2008). Castel et al. (Castell et al., 2008, 2009) reported continuous molecular enrichment in a microfluidic system aided by the vortex within segmented droplets and developed liquid-liquid phase separator which turns segmented flow to continuous flow. These examples of droplet-based microfluidics indicate

that droplets not only help mass transfer through the droplet surface but also mix the fluids by means of the circulation flow inside them and serve as carriers of fluids by themselves. These properties show that droplets can be used for microextraction as well as microreaction.

1.3 Aqueous two-phase system

In this study, we employed aqueous two-phase system (ATPS) to realize the microextraction in the microfluidic system. The liquid-liquid system, called ATPS or aqueous biphasic system was first studied by a Swedish biochemist P. Å. Albertsson (Albertsson, 1986). ATPS has become a powerful tool for separation of a range of biomaterials, including plant and animal cells, microorganisms, fungi, virus, chloroplasts, mitochondria, membrane vesicles, proteins, and nucleic acids. It can also be an appealing system for microfluidic droplet application, since the two phases are all aqueous (Walter et al., 1985; Hatti-Kaul, 2000). An ATPS consists of two immiscible phases formed by dissolving two incompatible polymers, such as poly(ethylene glycol) and dextran, or one polymer and an appropriate inorganic salt, or a cationic surfactant and a salt. The phase separation, which finally leads to equilibrium, is thought to be due to the incompatible physicochemical properties of components. Thus one phase is predominantly rich with one component and the second phase is enriched by the other component. ATPS is highly advantageous because the high water content (usually 70-90%) provides biocompatibility and selectivity for the stable pre-concentration of hydrophilic molecules with relatively low interfacial tension compared to that of organic/water two-phase system. It can be a versatile partitioning system for the separation of many kinds of dyes, metal ions, silica particles, proteins and cells (Walter & Johansson, 1986; Walter et al., 1991). Various factors such as concentration and type of phase-forming polymer or salts and the choice and addition of affinity ligands can affect the distribution of a solute over the two phases, thus giving more flexibility for the customized systems.

Several applications of ATPS into microfluidic systems have been reported for continuous partitioning of cells (Yamada et al., 2004; Nam et al., 2005), taking the advantage of PDMS (polydimethylsiloxane)-compatibility avoiding swelling problem that is commonly caused when organic/water two-phase system is applied to PDMS microfluidic device. The ATPS-based partitioning systems developed in these research works have almost same protocol because the direction and configuration of mass transfer where the material being extracted is transported from one phase to the other are almost identical with those of the two-phase system based on oil and water. Although laminar nature of liquid-liquid flow in microfluidic channel makes continuous separation possible, control of the interface has been known as a difficult task because the immiscible nature of the two liquid phases causes competition between interfacial tension and the viscous force. As Dreyfus et al. reported (Dreyfus et al., 2003), only in a certain regime of flow rates of liquid phases, stratified structure of flows, that is necessary for continuous microextraction, can be maintained.

2. Droplet generation and manipulation

In this chapter, electrohydrodynamic droplet generation in aqueous two-phase microflow and manipulation of ATPS droplets are discussed. ATPS droplets usually have electrophoretic mobility due to the presence of anions. If the interfacial tension is sufficiently high, the interface can respond to the applied d. c. electric field based on the same reason. Though much lower than that of organic/aqueous two-phase system, interfacial tension in tetrabutylammonium bromide (TBAB)/ammonium sulfate(AS) ATPS is relatively high

(about 4-5 dyne/cm) compared to that of common ATPS formed with poly(ethylene glycol) and dextran (10^{-4} to 0.1 dyne/cm). Thus the interface readily responds to the external electric field in microchannels. The fabricated microfluidic device has a T-junction at which the two-phase flow may have the configuration that can generate dispersed droplets by the electric potential difference applied. The threshold voltage necessary for the electrohydrodynamic droplet generation depends on pH due to the degree of dissociation and charge accumulation. Electrokinetic control of droplet break-up and switching of droplet movement direction were also demonstrated based on the same electrophoretic mobility of ATPS droplets. Volume of broken droplets and the direction of droplet movement were effectively controlled by the applied DC electric field. In addition, simple manipulation of ATPS droplets was demonstrated in the microchannels that are branched at the end.

2.1 Electrohydrodynamic generation of droplets

The ATPS for the droplet generation was prepared by dissolving TBAB and AS in water by 15 and 30%, respectively, by stirring the solution well. The prepared solution is left still for more than 12 hours so that it can be divided into two phases by the difference in the specific gravity. After separating the stable phases, TBAB-rich phase and AS-rich phase were individually introduced at the inlets of the microfluidic system by syringe pump, which controlled the flow rates of each phase independently. The microfluidic system in Figure 2 was fabricated by using the general PDMS replica. The ratios of flow rate of TBAB-rich phase to AS-rich phase were fixed at 0.133 and 0.156 in which the two streams were laminar as shown in figure. In these ratios, the more viscous TBAB-rich phase occupied about half of the channel width, but from T-junction one branched channel was totally occupied by TBAB-rich phase and the other branched channel by TBAB-rich phase and AS-rich phase together. Application of an electric field in this state through the electrodes shown in Figure 2 causes the change in the interface as in Figure 3, as the AS-rich phase is drawn in the direction toward the positive electrode. The interface at the center of T-junction was deformed to the positive electrode, which is located at the outlet where only TBAB-rich phase was flowing out. At the same time, the interface in the part of the channel connected to the negative electrode was also deformed due to the temporary change in volumetric flow

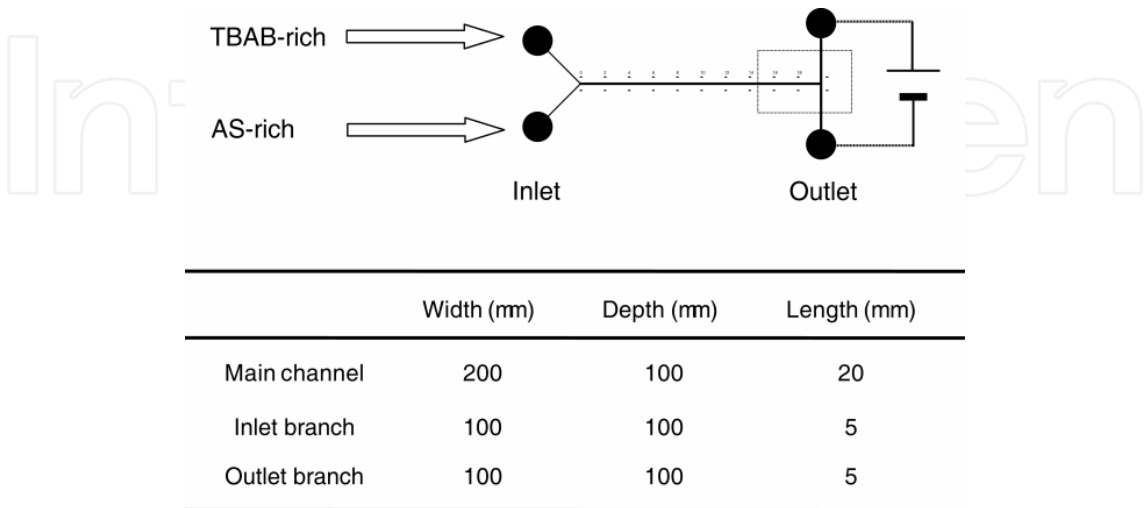


Fig. 2. Schematic illustration of the device for electrohydrodynamic generation of droplets and the dimensions of the channels

rate of AS-rich phase. When the electric pulse signal was switched off, the interface returned to its original shape. When the applied voltage was increased, the deformation of AS-rich phase became larger and small volume of AS-rich phase was detached from main AS-rich phase stream forming a droplet dispersed in TBAB-rich phase Figure 4.

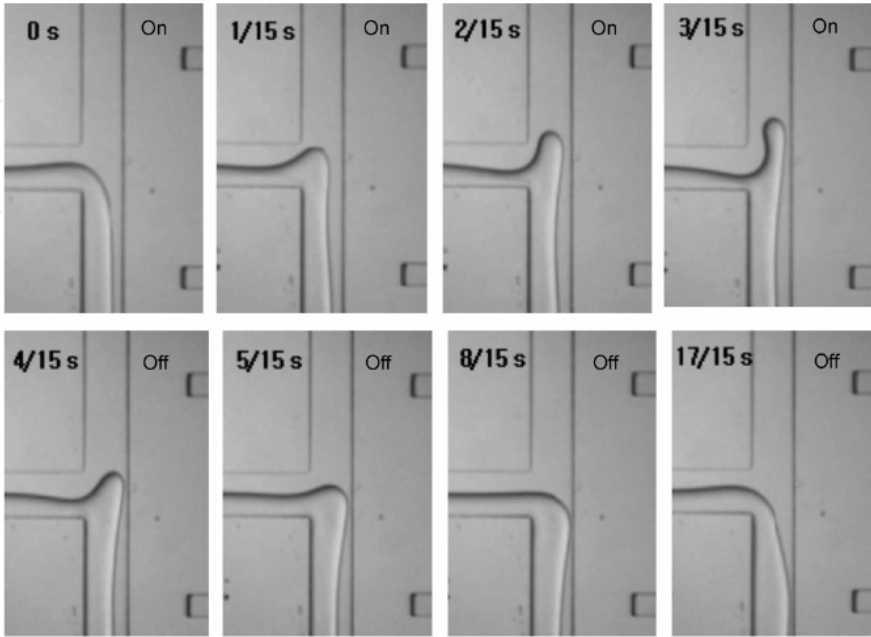


Fig. 3. Change of interface configuration by d.c. 12 V electric pulse application. The electric pulse was applied from 0 second to 4/15 second (200 ms) as shown in the first four pictures. The positive electrode is located at the end of the channel on the upward side

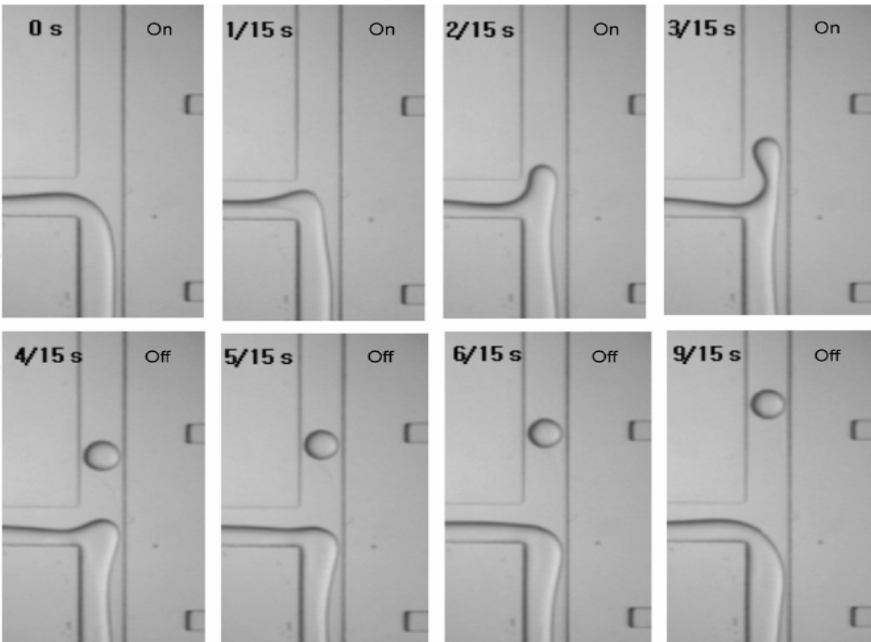


Fig. 4. Generation of a single droplet 20 V electric pulse application. The electric pulse was applied from 0 second to 4/15 second (200 ms) as shown in the first four pictures. The positive electrode is located at the end of the channel on the upward side

The higher potential difference of electric pulse results in generation of multiple droplets with different volume in each droplet, usually the first droplet being the largest in diameter as shown in Figure 5. During switching-on of the electric pulse, the droplets have bell-shapes and are attracted to the positive electrode in a way similar to electrophoretic motion, while the spherical droplets flow freely with continuous phase after switching off. The number of droplets generated is controlled by the change in the magnitude and duration of a d.c. electric pulse as shown in Figure 6. Longer pulse at higher voltage usually generated more droplets.

Capillary number of this particular droplet-generation can be calculated. The capillary number for the ATPS microfluidic system is $Ca = \eta_{TBAB} \cdot U_{AS} / \sigma$ where U_{AS} is the speed of the AS-rich phase η_{TBAB} is the continuous TBAB-rich phase viscosity, σ is two-phase interfacial tension. For example, when the ratio of TBAB-rich phase flow rate to that of AS-rich phase is 0.133, their actual flow rates were 0.133 $\mu\text{l}/\text{min}$ and 1 $\mu\text{l}/\text{min}$, respectively. With 40cP ($4 \times 10^{-3} \text{ kg}/\text{m}\cdot\text{sec}$) of η_{TBAB} , $1.7 \times 10^{-3} \text{ m}/\text{s}$ of U_{AS} and the 5dyne/cm ($5 \times 10^{-3} \text{ N}/\text{m}$), the calculated Ca is 1.36×10^{-3} . This number falls between the range of Ca studied by Jullien et al., (4×10^{-4} and 2×10^{-1}) (Jullien et al., 2009) where droplet breakup may occur in microfluidic T-junctions. This method of droplet generation has the advantage that the time and frequency of droplet generation can be controlled using the electric signals without a moving part, different from the piezoelectric method (Ziemecak et al., 2011). Moreover, the droplet generation using ATPS can be achieved at a very low electric potential when compared with that of the other electrichydrodynamic methods using different two-phase systems.

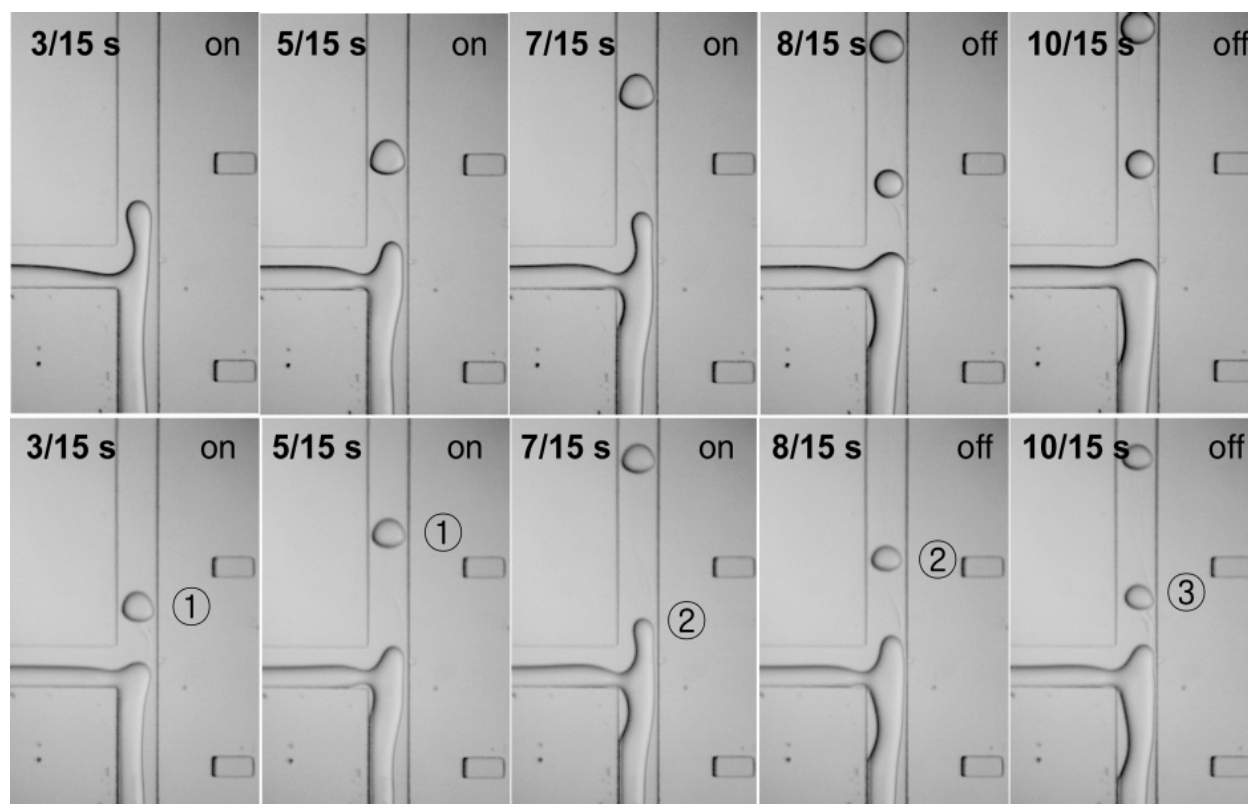


Fig. 5. Multiple-droplet generation by electric pulse application. Two (first row) and three (second row)-droplet generation by electric field application. Two drops are generated by a 20 V, 500 ms pulse (above). Three drops are generated by a 20 V, 800 ms pulse

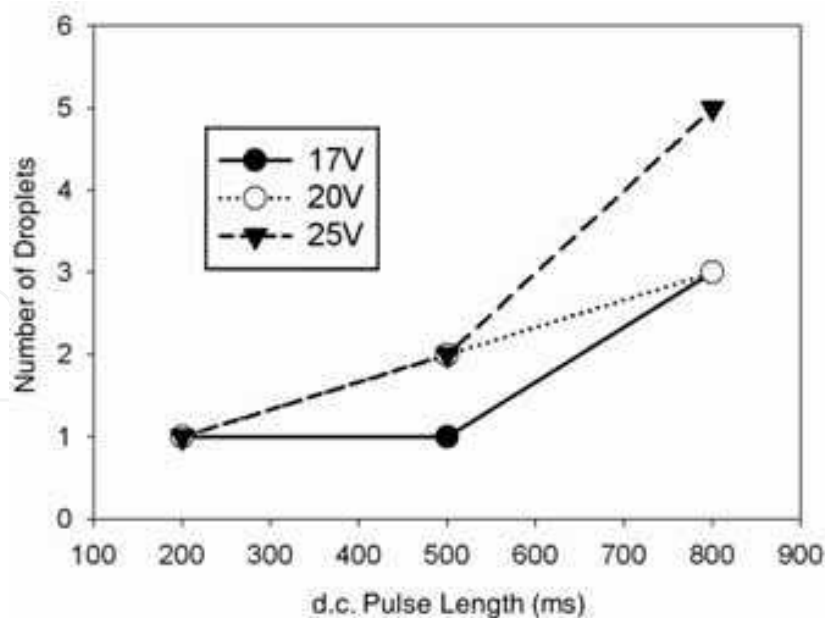


Fig. 6. Number of generated droplets controlled by the mode of electric pulse application. The number of droplets generated is controlled by the change in the magnitude and duration of a d.c. electric pulse. Longer pulse at higher voltage usually generated more droplets

2.2 Electrohydrodynamic manipulation of droplets

Manipulation of droplet movement is an essential technique for the availability of a microfluidic system to transport a certain droplet to the desired part of the system. Since passive manners for droplet transportation have limitation of complex channel design and flow rate control, active manners are usually preferred. For instance, Ahn et al. developed dielectrophoretic manipulation of droplets for high-speed microfluidic sorting devices (Ahn et al., 2006). Active method of controlling charged droplets electrically was reported by Link et al (Link et al. 2006). In line with these previous studies, the method to manipulate the movement of droplets of TBAB/AS ATPS in the microfluidic channels was developed, separating and directing the droplets of specific number into desired part of the device from the sequential flow of droplets, by applying the programmed d. c. electric field which was synchronized with the droplet frequency.

In this study, droplets were produced passively by shear force at the Y-junction where the two streams first contact with each other in the microfluidic device of the design shown in Figure 7. For the period without electric field, droplets flow toward outlet 1 because the branched channel that leads to outlet 1 is shorter than that toward outlet 2 as shown in Figure 7, thus it has higher pressure gradient. For the period with electric field on, droplets are attracted toward outlet 2 due to the electric attraction. In this way, a specific droplet can be selectively separated from the line of droplets that flows through the channel. Figure 8 shows the result of the experiment where the generated droplets were sent to the outlet 1 and outlet 2 alternatively by applying electric signals in a certain interval. As shown in these results, the electrohydrodynamic transport is a convenient method for handling droplets inside microfluidic devices without any moving part. The control of direction is possible only by changing the pulse signals with a simple switching on and off program. This simplicity will allow the realization of complicated and multi-functional microfluidic system based on aqueous two-phase droplets.

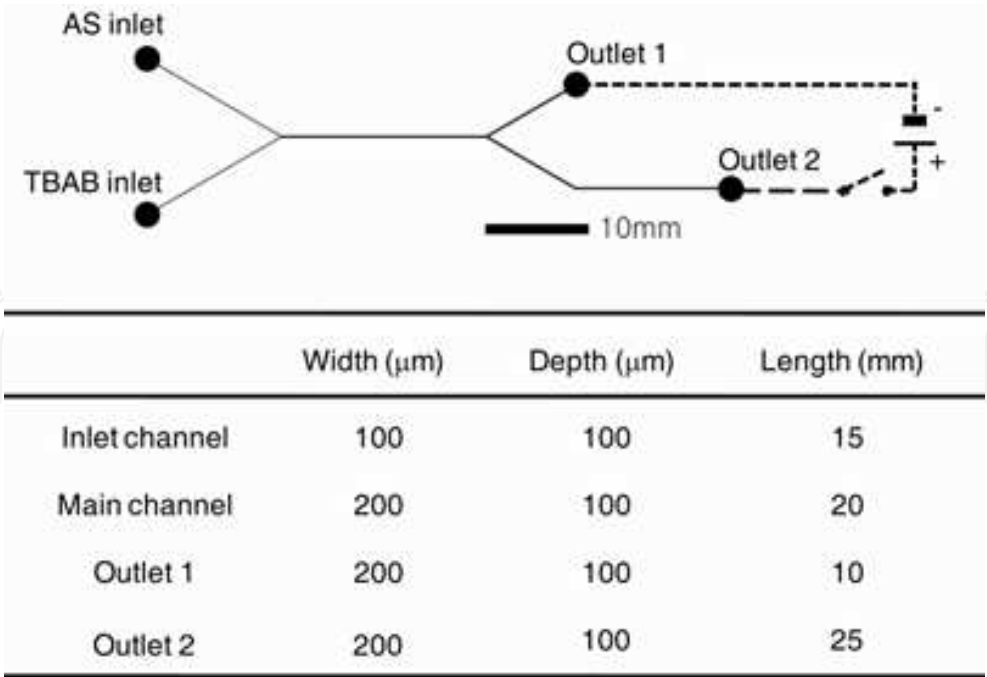


Fig. 7. Y-branched microfluidic device design for the droplet transport experiment

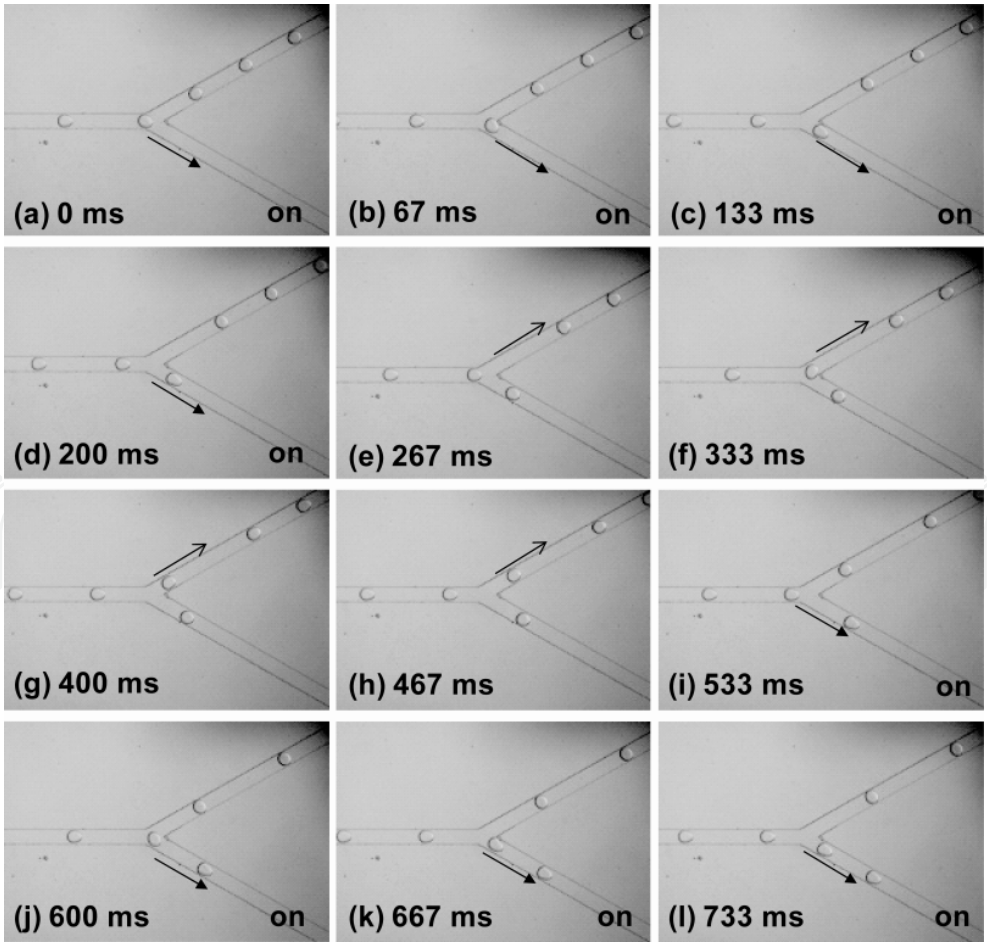


Fig. 8. Transport of a droplet into the desired channel by the application of electric pulses

3. Aqueous two-phase droplet-based microextraction

This chapter is about microfluidic extraction systems based on droplet of aqueous two-phase system (ATPS). Fast mass transfer between continuous phase and dispersed droplet is demonstrated by microextraction of ruthenium red within a microfluidic device which can also generate droplets with electrohydrodynamic method. By comparing brightness data of known concentrations of ruthenium red droplets with those of droplet of interest, change of ruthenium red concentration was traced along the microextraction channel, resulting in good agreement with Fick's diffusion model, and more details are found at Choi et al., 2010. It is also suggested the method for cessation of microextraction which is essential for controlling solute concentration inside a droplet by means of the electrohydrodynamic manipulation of droplet movement direction demonstrated in Section 2.1. Droplets of different ruthenium red concentration were moved to branched channels designed for each of the droplet to move to desired place of microfluidic system for further reaction. The microextraction system based on ATPS droplets has extensive potential to be used in effective and convenient mass transfer of solutes which have different solubility with advantage of handling discrete volume of liquid of desired concentration.

3.1 Microextraction kinetics

This section is devoted to the ATPS droplet-based microfluidics system for ruthenium red extraction. The microextraction kinetics in the microfluidic system was analyzed. As shown in Figure 9, we fabricated the microfluidic system that consisted of the droplet-generation part and the extraction part to which a microchannel of 70 mm belonged. The length of the microchannel, 70 mm, was determined by considering the convergence of the ruthenium red concentration in the droplet after the sufficient extraction. The feed flow rates of ammonium sulfate (AS)-rich phase and tetrabutylammonium bromide (TBAB)-rich phase into droplet-generation part are kept at $5.04 \mu\text{l}/\text{min}$ and $0.14 \mu\text{l}/\text{min}$, respectively. In the microextraction part, ruthenium red-containing TBAB-rich phase is introduced to the main microextraction channel, as shown in Figure 4.1a and b schematically, at the flow rate of $0.24 \mu\text{l}/\text{min}$.

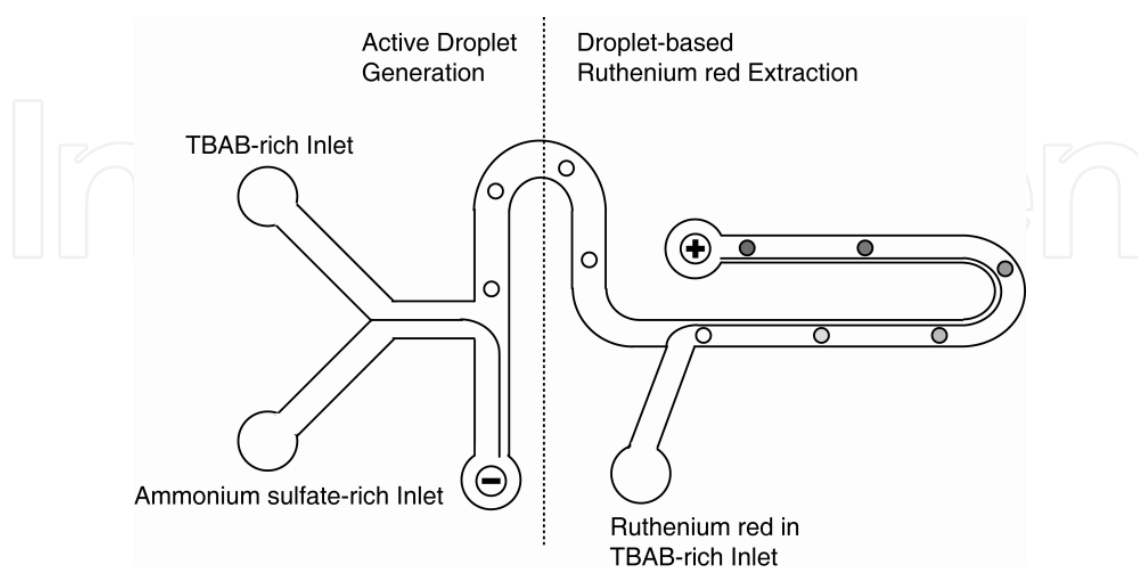


Fig. 9. The schematic diagram of the microfluidic system for the analysis of kinetics of microextraction of ruthenium red

The flow rate combination is selected carefully to have appropriate pressure drop and width of each stream, especially at the T-junction in droplet-generation part and at the junction where ruthenium red stream is introduced in microextraction part. Six kinds of ruthenium red-containing TBAB-rich phases were prepared by dissolving ruthenium red in the TBAB-rich phase with the concentration of 0.05, 0.07, 0.09, 0.11, 0.13 and 0.15% (w/w). Ruthenium red of which molecular weight is 786.36, has the structural formula of $[(\text{NH}_3)_5\text{Ru}-\text{O}-\text{Ru}(\text{NH}_3)_4-\text{O}-\text{Ru}(\text{NH}_3)_5]\text{Cl}_6$. It is dispersed in the TBAB-rich phase as solid particles, but is highly soluble in AS-rich phase as identified by its color.

In this study, the extraction of ruthenium red from the TBAB-rich phase to the AS-rich phase droplet was assumed as the combination of two different processes for the analysis. The first process was the dissolution of the ruthenium red in the TBAB-rich phase at the AS-rich phase surface up to the saturated concentration. This process was required because ruthenium red existed in the TBAB-rich phase as solid particles dispersed due to its low solubility in that phase. The general equation for the process involving dissolution of dispersed solid particles can be written as (Mary et al., 2008; Xu et al., 2008)

$$\frac{\partial C_s}{\partial t} = k_{\text{diss}} (C_{\text{sat}} - C_s) \quad (1)$$

where C_s denotes the concentration at the surface of the droplet, C_{sat} the concentration when saturated, and k_{diss} the dissolution rate coefficient. Integrating above equation gives C_s as a function of time as follows:

$$C_s = C_{\text{sat}} (1 - \exp(-k_{\text{diss}} t)) \quad (2)$$

The next process required was the spread of the dissolved ruthenium red over the AS-rich droplet in the direction of the droplet center. This second process can be described with the one-dimensional model of simple diffusion with spherical coordinate system:

$$\frac{\partial C_{\text{in}}}{\partial t} = D \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \frac{\partial C_{\text{in}}}{\partial r}), \quad (3)$$

where C_{in} and D denote the concentration of solute inside the droplet and the effective diffusion coefficient, respectively. This model assumes no internal motion of the fluid in the droplet. The concentration in the continuous phase is assumed to be constant because TBAB-rich phase with fixed concentration of ruthenium red is continuously fed to the microextraction device.

The boundary conditions at $r=0$ and $r=R$ for this equation are specified as

$$\frac{\partial C_{\text{in}}}{\partial r} = 0 \quad \text{at } r = 0, \quad (4)$$

$$C_{\text{in}} = C_s = C_{\text{sat}} (1 - \exp(-k_{\text{diss}} t)) \quad \text{at } r = R. \quad (5)$$

The initial condition is

$$C_{\text{in}} = 0 \quad \text{at } t = 0 \text{ for all } r. \quad (6)$$

The first boundary condition (Eq. 4) assumes symmetry at the center of the droplet. In the second boundary condition (Eq. 5), C_{sat} is the concentration on the surface of the droplet at saturation, which corresponds to the product of concentration of ruthenium red in TBAB-rich phase and distribution coefficient between two phases. Although concentration in the TBAB-rich phase is known and assumed to be constant, the distribution coefficient is not available. After sufficiently long extraction time, the droplet will be saturated with solute and the concentration will correspond to C_{sat} . In this work, it is assumed that the extraction time is long enough and the final concentration at the end of extraction is considered to be C_{sat} . Solving Eq. 3 using the previously described boundary conditions gives the radial distribution of concentration in the droplet at each time of concentration measurement. The C_{avg} inside the droplet at each time interval can be calculated. The model validity was verified by comparing the C_{avg} with the experimental result.

Because the information about C_{sat} , k_{diss} and D is required to solve the equation numerically, here we briefly introduce the method to calculate these parameters. The measured concentration of ruthenium red at 70 mm position which is the end of the microchannel was chosen as C_{sat} in each experiment. The k_{diss} value was determined as 0.09 (sec^{-1}) by fitting experimental results from the entire microextraction process and applied to solve the equation with five different C_{sat} (We have used the same C_{sat} for experiments of 0.13 and 0.15% (w/w) assuming that the C_{sat} has reached its solubility limit). Diffusion coefficient of ruthenium red in AS-rich phase, D , was measured by using 'T-sensor' developed by Kamholtz et al. (Kamholtz et al., 1999). Solutions of simple diffusion model with experimental results are shown in Figure 10. Here, C_{out} is the concentration of ruthenium red in the continuous TBAB-rich phase. Time-dependent simulation results are in good agreement with the experimental results except the lowest concentration results ($C_{\text{out}}=0.05\%$ (w/w)) in their initial time stage where simulation overestimates the concentrations. One explanation for this error may be that in the early stages of microextraction, the ruthenium red is mainly in the region near the surface of the droplet which is excluded in the brightness measurement especially when the concentration of ruthenium red is very low. As the extraction process continues, more ruthenium red is diffused to the region belonging to the brightness measurement, and simulation shows better agreement with experimental result.

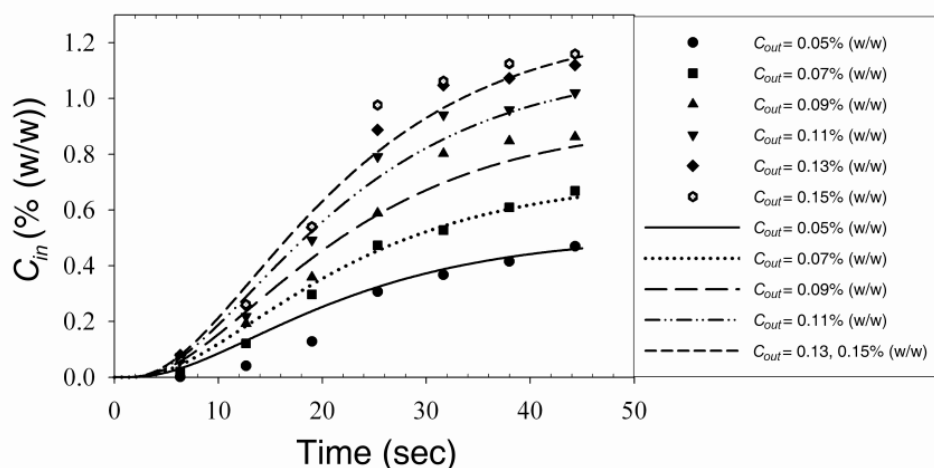


Fig. 10. Comparison of the experimental (e0.05, e0.07, e0.09, e0.11, e0.13 and e0.15) and theoretical data (s0.05, s0.07, s0.09, s0.11, s0.13 and s0.15) of the droplet-based microextraction kinetics

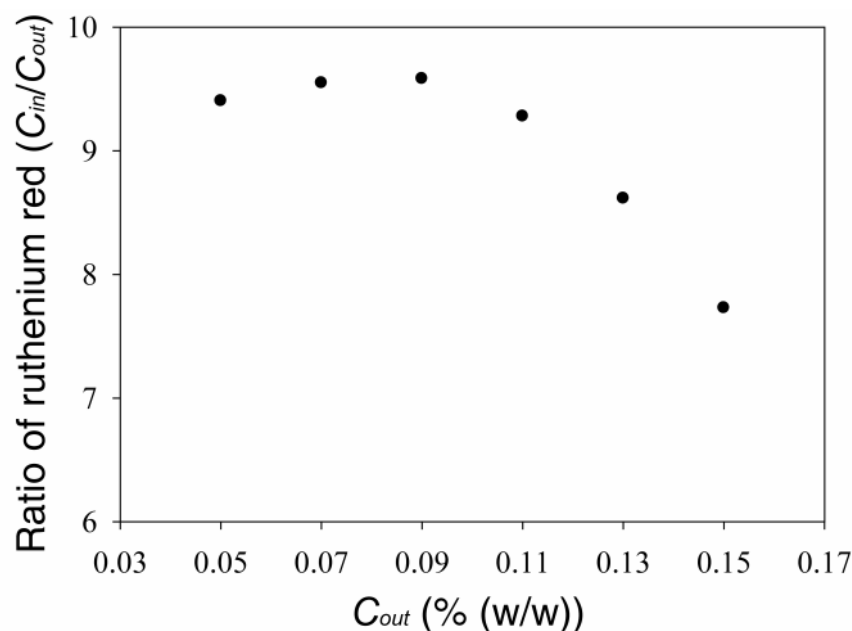


Fig. 11. Ratio of the ruthenium red concentration in the droplet at the 45 seconds of microextraction to that of continuous TBAB-rich phase initially introduced to the microextraction device

Figure 11 shows the ratio of the concentration of ruthenium red in the droplet after 45 seconds of microextraction to that of the continuous TBAB-rich phase fed initially. In the first three cases of low ruthenium red concentrations (0.05, 0.07 and 0.09% (w/w)) in TBAB-rich phase, the ratio is almost constant. However, the ratio decreases, as the concentration of ruthenium red of the TBAB-rich phase increases for high range of concentration of ruthenium red. This suggests that there exists the solubility limit of ruthenium red in the AS-rich droplet above which the concentration cannot increase independent of the concentration in the TBAB-rich phase. The solubility limit of ruthenium red in the AS-rich phase droplet, corresponding to C_{out} of 0.13 and 0.15% (w/w), is about 1.15% (w/w) in this experiment.

3.2 Microextraction control

In the previous section, the microextraction was performed using the droplet-based microfluidic system. When a macroscopic system is realized in a microfluidics system, various functions that are impossible in a macroscopic system can be realized. This section describes the method to stop the microextraction before reaching the equilibrium by moving the droplet from the ruthenium red-containing TBAB-rich phase stream to the pure TBAB-rich phase stream using the EHD force. This function enables to obtain a droplet of a specific concentration of a substance without any other additional treatments in a microfluidics system in which the process for chemical reaction or analysis is integrated following microextraction. In the previous Section 3.1, the time-dependent profile of microextraction process was derived from the experimental and simulation results, and thus stopping of microextraction was possible using the carefully designed microextraction device and the droplet-motion guiding techniques. The microextraction device that was designed by considering this function consisted of two branched channels at the position of 10 and 20 mm from the junction of the ruthenium red injection where microextraction begins, as

shown in Figure 12. The branched channels were arranged to have an angle of 45° so that droplets can readily move toward the branched channels. AS-rich phase that forms laminar flow with TBAB-rich phase in the droplet-generation part of the device is fed at the flow rate $5.4 \mu\text{l}/\text{min}$. The droplet produced in the droplet-generation part of the device moves to microextraction part, and then extraction starts at the junction where TBAB-rich phase with ruthenium red concentration of 0.29 (\%, w/w) is injected. Only when the droplet crosses the streamlines and is fully surrounded by the ruthenium red containing TBAB-rich phase, isotropy of microextraction is guaranteed. To force droplet to enter the ruthenium red stream, the microchannel that has a narrow cross section was fabricated as shown in Figure 13 a. Because the flow rate of the main TBAB-rich phase, which initially carries the AS-rich droplet, is kept at $0.24 \mu\text{l}/\text{min}$, smaller than that of ruthenium red solution ($0.51 \mu\text{l}/\text{min}$), the droplet moves toward the ruthenium red solution due to the pressure difference. Microextraction continues until the d. c. electric pulse with the duration of 200 ms is applied at the end of the branched channel. At that moment the droplet departs ruthenium red-containing TBAB-rich phase by approaching the electrode located at each end of the branched microchannel and microextraction is terminated.

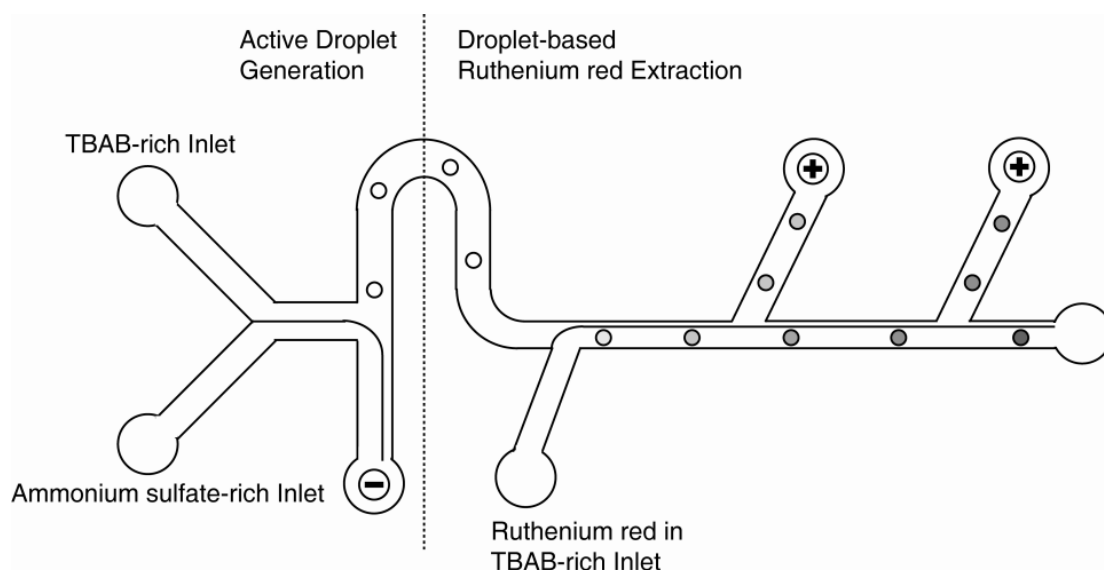


Fig. 12. The schematic diagram of the microfluidic system for microextraction control. Droplets can moved to one of the two branched channels by applied electric pulse after cessation of microextraction

As shown in Figure 13 b and c, the thresholds located at 10 and 20 mm positions serve as leaping boards for the droplet. When d. c. electric potential is not applied, the droplet moves freely, following its streamline over the threshold as shown in Figure 13 b. When electric potential is applied on the electrode at the end of the branched channel, the droplet changes its direction at the junction so that it leaves the flow stream of ruthenium red-containing TBAB-rich phase and jumps into the branched channel with increased speed due to the electrophoretic effect as shown in Figure 13 c. The concentrations of droplets at the first and second branched microchannel when microextraction is terminated are 0.12 and 0.24 (\%, w/w) and corresponding concentrations which have been predicted by simulation are 0.11 and 0.28 (\%, w/w), which shows that the droplet-based microextraction can be terminated depending on the needs in a process, even before reaching the equilibrium state.

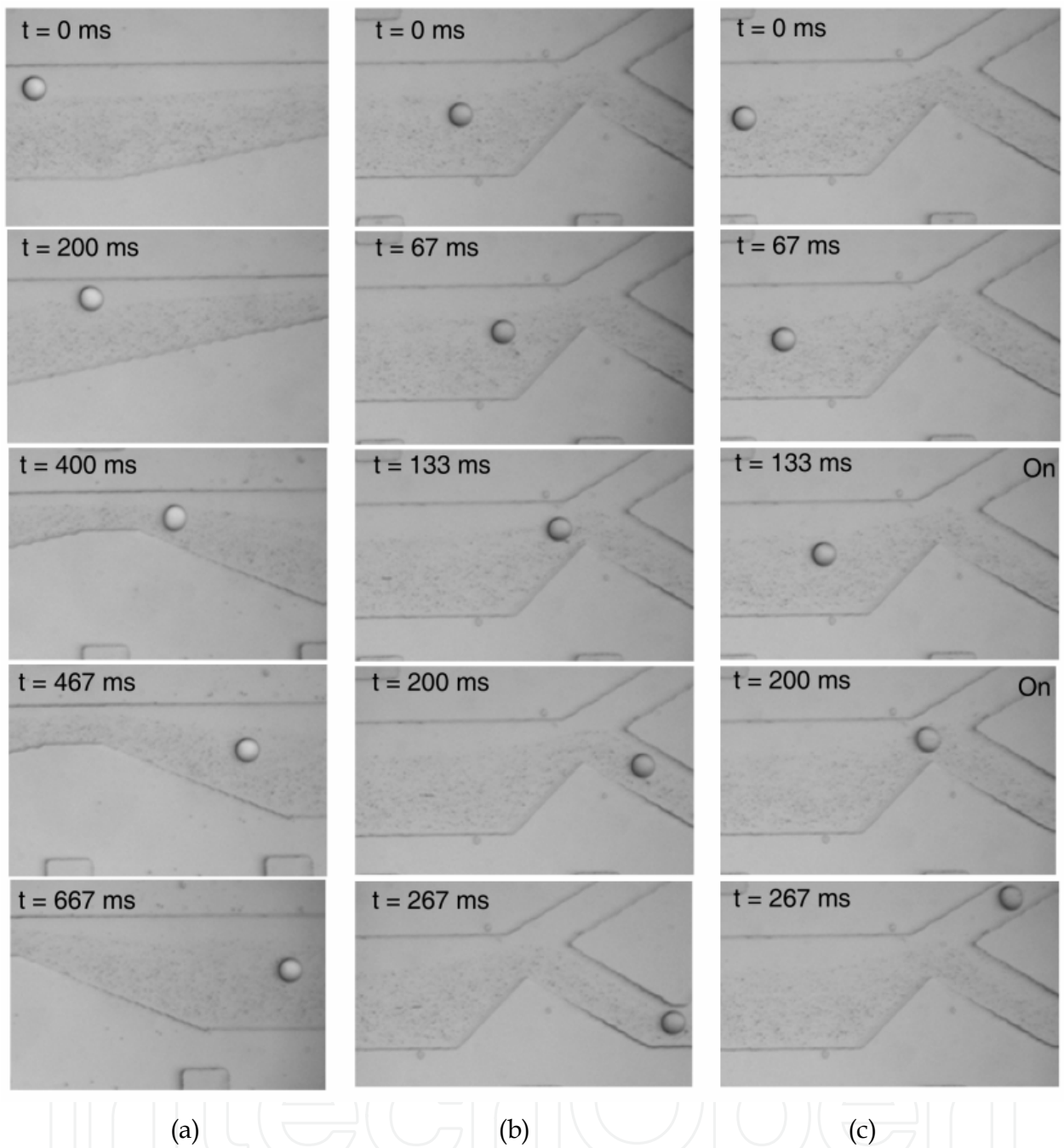


Fig. 13. Microextraction control and manipulation of droplet within the microextraction system shown in Figure 4.1b. (a) Beginning of microextraction: The AS-rich phase droplet is dipped into the ruthenium red-containing TBAB-rich phase at the narrowed part of the microchannel and starts microextraction. (b) The first branched channel at the position of 10 mm from the starting point of microextraction. In this case shown in the picture, the electric pulse is not applied so that the droplet can move continually through the microextraction channel. (c) The second branched channel at the position of 20 mm from the starting point of microextraction. The applied electric pulse changes the movement direction of the droplet toward the branched channel so that the microextraction is stopped and the droplet can move to other part of the microfluidic system

4. Conclusion

In this study, the microfluidic system based on the aqueous two-phase system (ATPS) droplets was developed. Taking advantage of the benefits that microfluidics can provide, this study was focused on the mass transfer between two liquid-liquid phases. Droplets generated and manipulated in microfluidic system can provide unique opportunities to handle fluids in a segmented flow, offering novel platform of miniaturized system for chemical and biological processes. The two-phase that has been employed in this experimental work is the ATPS formed by tetrabutylammonium bromide (TBAB)/ammonium sulfate (AS). Among the numerous possible liquid-liquid two-phase systems available, only a few of them can be operated in microfluidic system both in the stratified laminar flow and in segmented droplet-based flow. This unique feature comes from the moderate interfacial tension between the TBAB-rich phase and AS-rich phase.

Generation of TBAB/AS ATPS droplets by electrohydrodynamic method was studied. Initially fed as laminar flow, the AS-rich phase was destabilized and eventually dispersed as droplets in the continuous TBAB-rich phase at the T-junction in the microfluidic system when the d. c. electric potential difference was applied as pulses. Based on the pH dependency of the threshold electric voltage required to generate a single droplet, the electrophoretic mobility of the AS-rich phase in TBAB-rich phase was discussed and a model for the mechanism was suggested. Applying the same electrohydrodynamic principle, manipulation of droplet movement direction was demonstrated in a different microfluidic device. This technique can be a fundamental method for the operation of the ATPS-based microfluidic system.

TBAB/AS ATPS droplet-based microextraction was also investigated. Ruthenium red was successfully extracted from the TBAB-rich phase to the AS-rich phase droplet in the microfluidic extraction device. The mass transportation between the two liquid phases was discussed assuming two different steps, from the continuous phase to the droplet surface and from the droplet surface to the center of the droplet, applying diffusion equation for each step. Further, the method for stopping microextraction which is essential for controlling solute concentration inside a droplet was suggested by means of the electrohydrodynamic manipulation of droplet movement direction. Here showed is just one example of TBAB/AS ATPS droplet-based microextraction. The compatibility of TBAB/AS ATPS with stable biological materials and other water-soluble inorganic molecules can provide potentials for further application in chemistry and biology. It is expected that the next applications of this ATPS in microfluidic should be in the analysis of charged biomolecules, separation of surface-treated nanoparticles and reaction of inorganic molecules in coordinate chemistry.

In addition, future development of ATPS droplet handling technique will add the merits of this microfluidic system. For example, precisely controlled coalescence of ATPS droplets can lead to reaction of the reactants confined inside the droplets. Appropriate surface treatment of the microfluidic device and proper fabrication which takes the phase properties into account can enable one to alternate the flow pattern from segmented flow to continuous flow depending on the need of the process. Application of additives that can give affinity for efficient separation and aqueous three-phase system which allows more variety can be considered as the topics for future research. Alternative aqueous two-phase-forming materials which can be used for multi-phase system in low concentrations

can widen the application in which relatively susceptible biological molecules are involved.

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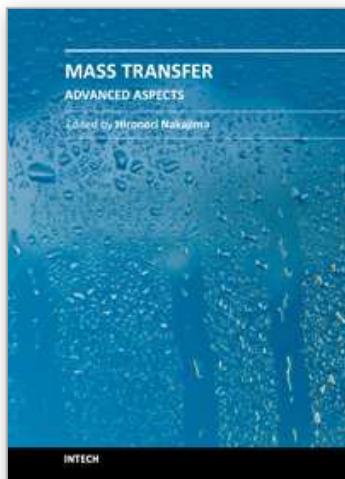
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