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DEMONSTRATION OF THE ENHANCED MIXING AND REACTION ABILITY OF AN ALTERNATE PUMPING MICROREACTOR WITH VISUALIZATION OF THE MIXING FIELD AND THE REACTION FIELD

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ABSTRACT

In order to enhance the mixing and reaction capabilities of micromixers and microreactors, we had proposed a novel system termed alternate pumping microreactor (APMR) and had demonstrated that the APMR could generate a thin-layered structure under a particular pumping condition. This flow pattern should enhance the abovementioned capabilities. In this paper, we visualized the dilution process of methylene blue solution with water in the APMR and established a method to obtain the concentration field from the captured image according to the relation between the methylene blue concentration and the saturation of the captured color. To assess the reaction field, visualization of the reaction of ferrous sulphate and potassium thiocyanate was adopted. These visualization results suggested that the APMR enhanced the mixing and reacting capabilities and the time and channel length required for the reaction to complete were two order orders of magnitude lesser than those in the case of the ordinary reactor.

NOMENCLATURE

B Intensity of blue.
 C Concentration of methylene blue.
 C_0 Original concentration of methylene blue before mixing.

C^+ Normalized concentration ($\equiv C/C_0$).
 F Alternate pumping frequency.
 G Intensity of green.
 h Channel height.
 I Light intensity.
 l Molecular diffusion distance.
 L_{in} Inlet width.
 L_l Layer thickness.
 L_{mix} Mixing channel width.
 Q Total flow rate.
 R Intensity of red.
 Re Reynolds number.
 S Saturation.
 S' Compensated saturation ($\equiv S/\bar{S}^+$).
 S_0 Highest-frequency saturation in an image.
 S^+ Normalized saturation ($\equiv S/S_0$).
 $\bar{S}^+$ Ensemble mean value of S^+ .
 t Molecular diffusion time.
 v_{in} Infusion velocity.
 v_{mix} Velocity in the mixing channel.
 α Molecular diffusivity.
 Δt Infusion period.
 Δt^* Non-dimensional infusion period.

INTRODUCTION

In micromixers and microreactors, the mixing of substances in the working fluid is accomplished by molecular diffusion in a microchannel. For instance, by employing a T-shaped microchannel, two working fluids are infused from independent inlets into a common mixing channel and create a flat interface at the middle of the mixing channel, as shown in Fig. 1. The flow in the microchannel should be laminar and the mixing effect of turbulent vortices does not occur; this ensures that the substances are mixed only by the molecular diffusion through the interface along the channel width direction as the fluids flow downstream. The time required for mixing caused by the molecular diffusion to complete is considerably longer than that required by the turbulent mixing, and therefore, now reducing of the mixing time is one of the main issues needed to be addressed with regard to the micromixers and microreactors in order to enhance the capabilities of these devices. The diffusion time t is proportional to the square of the diffusion length l and inversely proportional to the molecular diffusivity α :

$$t \propto \frac{l^2}{\alpha}. \quad (1)$$

When the diffusion length l becomes greater than the mixing distance, the mixing is considered to be completed. Equation 1 indicates that a shorter mixing distance and/or larger diffusivity reduce the time required for mixing to complete. Because molecular diffusivity is a physical property of a substance, reducing the mixing distance is more effective than handling the diffusivity. Briefly, increasing the interface area per unit bulk volume of the fluids in the mixing channel shortens the mixing distance. To realize this practice, researchers have proposed some ideas; these ideas can be classified into two types: static method (features of channel shape) and dynamic method (features of pumping) [1–4].

We have combined a static and a dynamic method and proposed a novel system termed an alternate pumping microreactor (APMR) [5–8]; this device employs an alternate pumping system. In order to maximize the advantage of alternate pumping, the APMR has an asterisk-shaped (*) channel consisting of two inlets opposing each other and two diverging channels orthogonal with the inlets, see Fig. 2. The alternate pumping system feeds two working fluids alternately from the independent inlets into two diverging mixing channels. In order to determine the optimum pumping condition for high-efficiency mixing, we visualized the flow patterns generated under several pumping conditions using colored waters. These experiments indicated that the APMR creates a layered flow pattern under a particular pumping condition. The diverging mixing channels stretch the created layers and the interfaces expand downstream. It was predicted that an APMR operating under the optimal condition will reduce

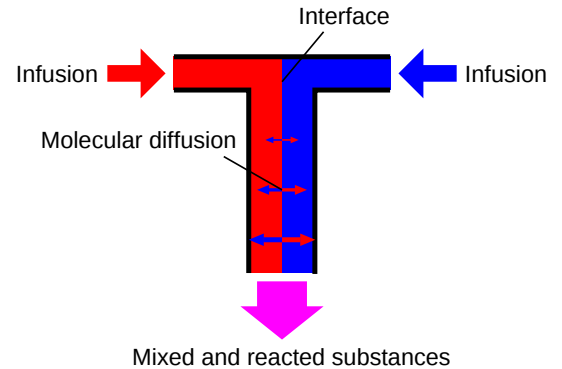


FIGURE 1. PRINCIPLE OF TYPICAL MICROREACTOR EMPLOYING T-SHAPED MICROCHANNEL.

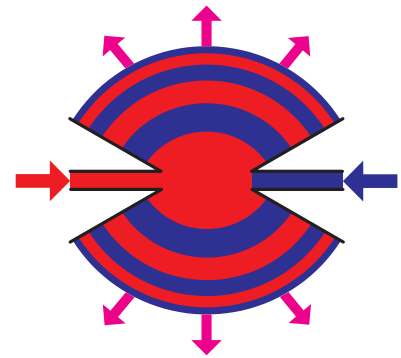


FIGURE 2. MODEL OF THIN-LAYERED FLOW PATTERN CREATED BY ALTERNATE PUMPING SYSTEM IN ASTERISK-SHAPED CHANNEL.

the mixing time by two orders of magnitude as compared to that in the case of an ordinary microreactor.

The objective of this study is to demonstrate that the thin-layered flow pattern generated by the APMR enhances the mixing and reaction ability of micromixers and microreactors. In order to obtain the concentration field from the visualized image of the dilution process of methylene blue solution with water, we investigated the relationship between the concentration and the captured image color. Using the calibration result, we assessed the mixing status. To assess the reaction, we adopted visualization of the reaction of ferrous sulphate and potassium thiocyanate, and obtained the reaction field. The obtained results of the APMR and an ordinary microreactor are compared and the superior capability of the former is demonstrated.

ALTERNATE PUMPING MICROREACTOR

Schematic of Alternate Pumping Microreactor

The alternate pumping microreactor (APMR) system has been illustrated in detail and the characteristics of the flow pattern generated in the APMR have been examined previously [5–8]. The identical equipments were used in this study and the system is briefly described below.

As shown in Fig. 3, a unit base, in which two reserve buffers are fabricated, contains an asterisk-shaped microchannel and the top is covered by a limpid polymethylmethacrylate (PMMA) plate that is drilled to match the two outlets. Pistons inserted into the buffers are connected to micrometer heads driven by stepping motors controlled by a PC. Working fluids are pumped by the displacements of the pistons pushed into the buffers and the PC controls the time sequence of the pumping, as shown in Fig. 4. From two independent inlets, working fluids are infused into the mixing channels alternately with frequency F . During each infusion period Δt , the mean infusion velocity v_{in} in the inlets is constant and the time for acceleration and deceleration is assumed to be negligible.

The asterisk-shaped microchannel is cast into a polydimethylsiloxane (PDMS) substrate. Converging channels used to consolidate the fluids at the outlets are also cast into the substrate. The inlet width L_{in} is 0.4 mm and the distance between two inlets is 2 mm. The channel height h in the entire area is 0.4 mm. The diverging angle of the mixing channels is 120 deg. The PDMS is limpid and a white PMMA plate is attached to the PDMS substrate bottom in order to reflect light.

Characteristics of Flow Pattern

In order to investigate the characteristics of the flow pattern created by the APMR associated with the alternate pumping condition, we observed the flow pattern under several pumping conditions using red- and blue-colored waters [5–8]. The results indicated that the flow pattern varied with the amplitude of the momentum of the infusion fluid. When the momentum was small, two infused fluids were divided at the middle of the mixing channels as in the case of a flow pattern generated in an ordinary microreactor as shown in Fig. 1. When the momentum was large, two infused fluids replaced each other and created an interface at the middle of the mixing channels. When the momentum was suitable, the flow pattern could be layered as shown in Fig. 2.

To quantify the flow pattern characteristics, the Reynolds number Re and the non-dimensional infusion period Δt^* can be used:

$$Re \equiv \frac{L_{in} v_{in}}{\nu}, \quad (2)$$

$$\Delta t^* \equiv \frac{\Delta t v_{in}}{L_{in}}, \quad (3)$$

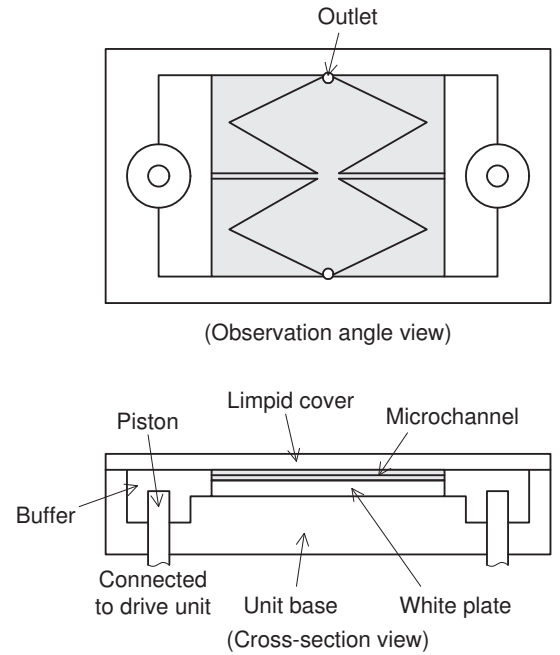


FIGURE 3. SCHEMATIC DIAGRAM OF ALTERNATE PUMPING MICROREACTOR.

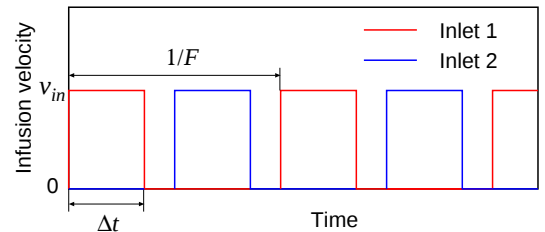


FIGURE 4. TIME SEQUENCE OF ALTERNATE PUMPING.

where ν is the kinematic viscosity of the fluid. The momentum increases with Re and/or Δt^* . When a layered flow pattern is created, Δt^* is proportional to the layer thickness. Therefore, the thinnest-layered flow pattern can be generated when Δt^* is chosen to be as small as possible and Re is a suitable value for a layered pattern.

In addition to the case of the asterisk-shaped channel, we also investigated the flow pattern in some channels having different geometries. In the case of a conventional T-shaped channel having a single mixing channel, the infused fluid immediately turns to the direction of the mixing channel and loses the infusion direction momentum, so that the creation of a layered flow pattern is difficult. In a cross-shaped (+) channel having two mixing channels that do not diverge, a layered flow pattern can be generated; however, the layer thickness does not decrease

downstream. Therefore, the asterisk-shaped channel is the most suitable channel for creating a thin-layered flow pattern.

ASSESSMENT OF MIXING FIELD

Visualization of Concentration Field

In order to assess the mixing field in the APMR, a visualization method was adopted. Figure 5 shows a schematic of the equipment setup used to capture images. Four straight fluorescent lamps were installed for lighting. To prevent UV from affecting the substances, the lamps were covered with UV protection filters. In order to equalize the net intensity of the lighting when the camera shutter opened, an inverter was used to increase the power frequency to 53 kHz. The lamps were arrayed in a sharp-shape (#) to illuminate the objective target as uniformly as possible under some physical constrains. A single-lens reflex digital camera (EOS20D, Canon, Inc.) was used to capture images of the target.

The lamps and camera were located on the same side against the observation target. The lamps emitted light that passed through the limpid channel cover, working fluid and limpid PDMS substrate; this light reflected off the white PMMA plate and passed again through the substrate, fluid and cover, and it was then detected by the camera. The fluid absorbed a particular spectrum of light and colored the detected light. The light passed through the fluid twice, and therefore, the color variance was greater than that in the case in which the light passed through the fluid only once.

To assess the mixing field, 2.35×10^{-4} mol/l solution of methylene blue and pure water were mixed in the APMR. (The reason for selecting this concentration value is described later.) In the mixed fluid, methylene blue molecules diffused and there was no chemical reaction, i.e., the APMR functioned as a mixer. The methylene blue solution looked blue and the mixed (diluted) solution was paler than the original solution. When water was filled in the channel, the white background of the channel could be seen through the water. Therefore, the captured color varied from white via pale blue to blue as the concentration of the methylene blue increased. The relationship between the concentration and the color information calibrated in advance gave the concentration (mixing) field from a captured image.

Parameters to Quantify Color

In order to establish a relationship between the concentration of the methylene blue solution and the color of the captured image, the following parameters are used.

C and C_0 denote the concentrations of the diluted methylene blue solution and the original solution before mixing, respectively. The normalized concentration C^+ is defined as C/C_0 . $C^+ = 0$ and $C^+ = 1$ indicate the pure water and the original methylene blue solution, respectively.

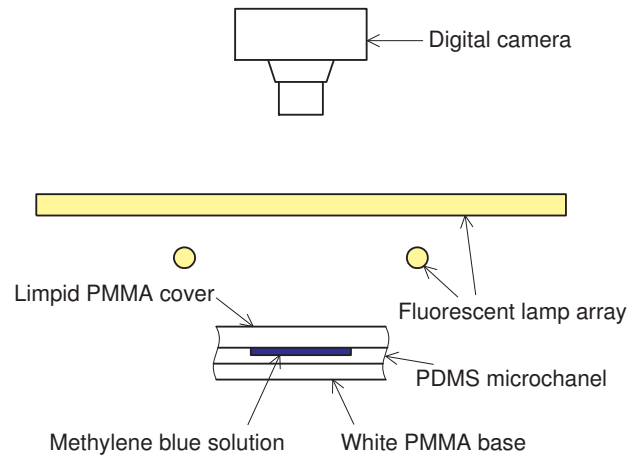


FIGURE 5. SCHEMATIC OF EXPERIMENTAL SETUP TO CAPTURE IMAGES.

TABLE 1. QUALITATIVE RELATION BETWEEN CONCENTRATION AND COLOR INFORMATION.

Low	Concentration C^+	High
White	Color	Blue
High	Intensity I	Low
Low	Saturation S	High

Digital files of captured images contain local color information that is represented by the intensities of red, green, and blue, respectively denoted by R , G , and B . We found that it was difficult to precisely associate the value of R , G , or B with the normalized concentration C^+ because of the irregularity included by R , G , and B . Therefore, as another color expression, the combination of intensity, saturation, and hue angle is adopted. In this visualization, i.e., when the color varies between blue and white, the hue angle is not suitable for quantifying the color because the hue angle of white cannot be defined. Thus, the intensity and saturation are considered. They are defined using the values of R , G , and B as follows and their characteristics are summarized in Table 1.

$$\text{Intensity : } I \equiv R + G + B. \quad (4)$$

$$\text{Saturation : } S \equiv 1 - R/B. \quad (5)$$

Here, the relation $B \geq G \geq R$ is supposed to hold.

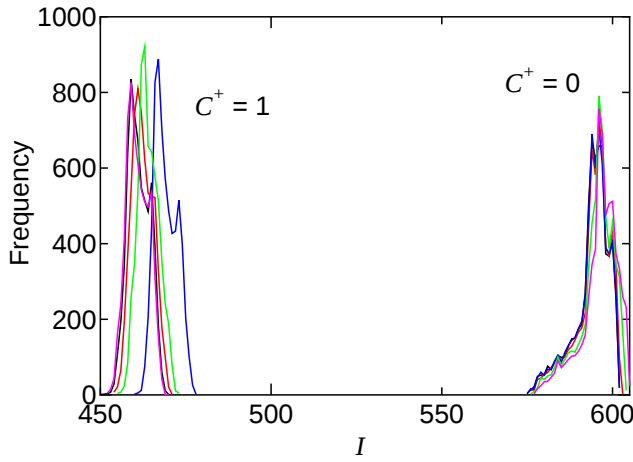


FIGURE 6. FREQUENCY OF AREA HAVING EACH VALUE OF INTENSITY I IN EACH CAPTURED IMAGE. CAPTURED IMAGES ARE DISTINGUISHED BY LINE COLOR.

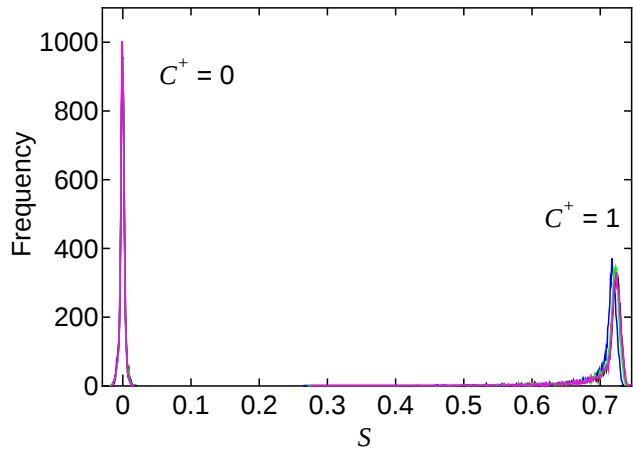


FIGURE 7. FREQUENCY OF AREA HAVING EACH VALUE OF SATURATION S IN EACH CAPTURED IMAGE. CAPTURED IMAGES ARE DISTINGUISHED BY LINE COLOR.

Calibration of Relationship between Mixed Substance Concentration and Visualized Image Information

On estimating the color information of each pixel in the captured image files, we found that the color information contained unavoidable irregularities due to the camera quality, and thus, we adopted the mean value of the color information in a 14-pixel-square area; this gave a space resolution of 0.18 mm.

To confirm the repeatability of captured images, by filling the highest concentration ($C^+ = 1$) solution of methylene blue in the channel, we captured five images continuously in a few seconds and calculated the values of the intensity I and satu-

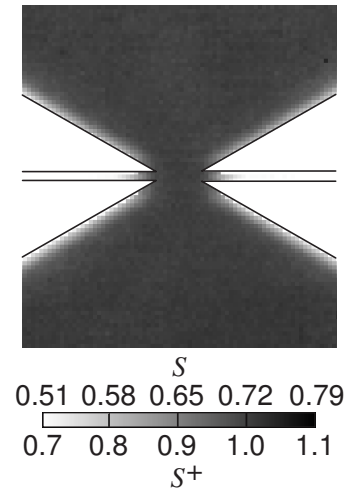


FIGURE 8. THE DISTRIBUTION MAP OF OBTAINED SATURATION S AND NORMALIZED SATURATION S^+ .

ration S of each area in the captured images. Figure 6 shows the frequency of an area having each value of I in each image. Whilst the status of the working fluid did not vary when capturing images, the value of I varied with images, especially when $C^+ = 1$. It is probable that the marginal difference between the shutter motion and/or the blinking of the illumination affected the captured images. In comparison, S indicated better repeatability because the two intensities R and B were relativized in the calculation of S and the variation of the intensity did not directly affect the value of S , see Fig. 7. Therefore, S is more suitable to associate with the normalized concentration C^+ .

When $C^+ = 1$, the frequency of S did not indicate a Gaussian distribution and there were areas having smaller S than that of the bulk. In order to investigate the distribution of S in the captured image, Fig. 8 shows the distribution map of the obtained S . Here, the normalized saturation S^+ is defined as S/S_0 ; S_0 is the highest frequency S in the image. The grey scale in Fig. 8 indicates both S and S_0 . The reflection and refraction of the light on the side walls made the captured colors in the areas near the channel side walls more whitish than that in the bulk region and S in the areas near the side walls was approximately 20 % smaller than S_0 . S^+ includes the alteration due to the channel wall effect and the unavoidable irregularity. In order to eliminate the irregularity and retrieve only the channel effect, the local values of S^+ obtained from several images were averaged. The ensemble mean value $\overline{S^+}$ in each area was given as the coefficient to compensate the local alteration. The compensated saturation S' is defined as $S/\overline{S^+}$. The frequencies of S and S' obtained from the identified image are compared in Fig. 9. It is demonstrated that this compensation does not change the value of S_0 and reduces the broadening of the value in any case of C^+ . In the following discussion, S' is

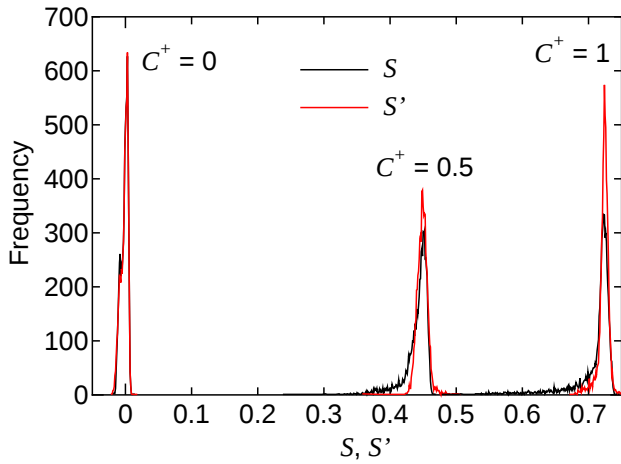


FIGURE 9. COMPARISON OF FREQUENCY OF AREA HAVING EACH VALUE OF SATURATION S AND COMPENSATED SATURATION S' .

used as the saturation value.

We captured images of several diluted solutions ($C^+ = 0 \sim 1$) and calculated the compensated saturation. The relation between the normalized concentration C^+ and the compensated saturation S' is shown in Fig. 10. The marks indicate the highest-frequency saturation S_0 . Considering the unavoidable irregularity included by the obtained S' , the error bars indicate the range of S' , in which the values have an assurance of 95 % and this range is assumed to define the measurement accuracy. By fitting these results, a function to convert the compensated saturation S' into the normalized concentration C^+ is obtained as

$$C^+ = 1.49 \times S'^3 - 6.97 \times 10^{-1} \times S'^2 + 1.11 \times S' - 7.60 \times 10^{-4}. \quad (6)$$

This equation gives the normalized concentration C^+ with the obtained S' and the measurement error of C^+ with the uncertainty included in the obtained S' . The relation between the obtained C^+ and the error included in the value is depicted in Fig. 11. The error is within ± 0.05 ; this should be the accuracy of C^+ obtained by this method. This accuracy strongly depends on the camera quality. In this experiment, an ordinary digital camera was used. A higher-quality camera is expected to further improve the accuracy of the given concentration value and the spatial resolution.

As described above, the original concentration C_0 of the solution before mixing was chosen as 2.35×10^{-4} mol/l. In order to describe its occasion, Fig. 12 shows the relationship between the concentration C and the saturation S_0 in a wide range of C . When C was larger than 3×10^{-4} mol/l, C did not vary much with C as such, and thus C could not be obtained using the relation be-

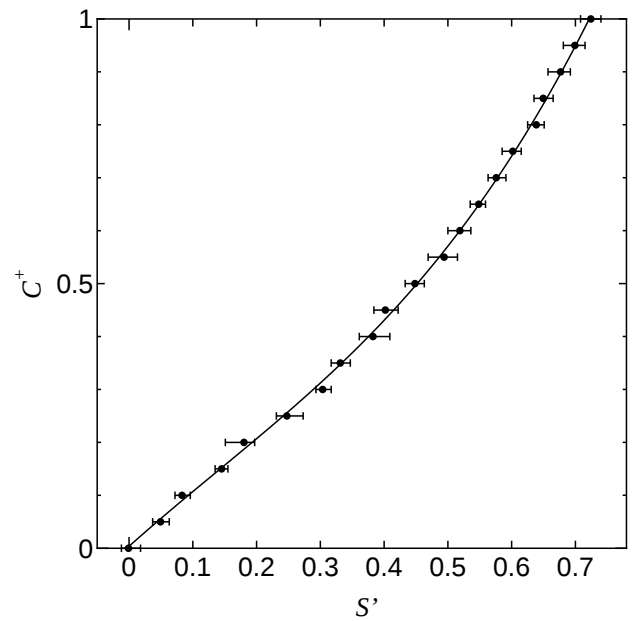


FIGURE 10. RELATIONSHIP BETWEEN NORMALIZED CONCENTRATION C^+ AND COMPENSATED SATURATION S' .

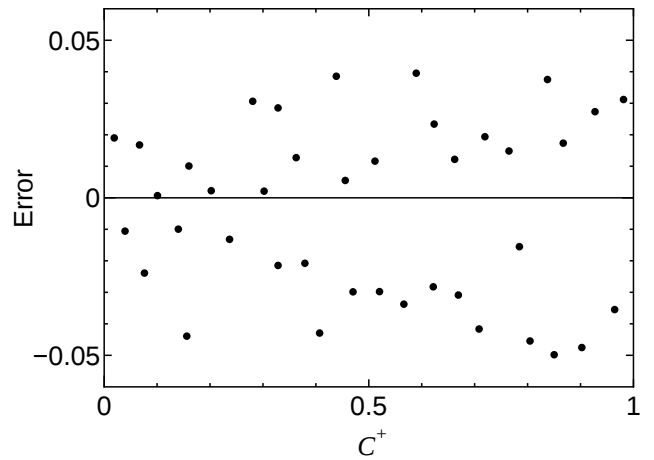


FIGURE 11. MEASUREMENT ERROR INCLUDED IN NORMALIZED CONCENTRATION C^+ GIVEN BY CONVERSION FUNCTION WITH COMPENSATED SATURATION S' .

tween C and S_0 . We chose the value of C_0 to take advantage of the relation between C and S_0 .

Mixing Fields Obtained from Visualized Images

According to the flow pattern characteristics described in the previous paper [1], we created a thin-layered structure of a methylene blue solution and water in the APMR and captured

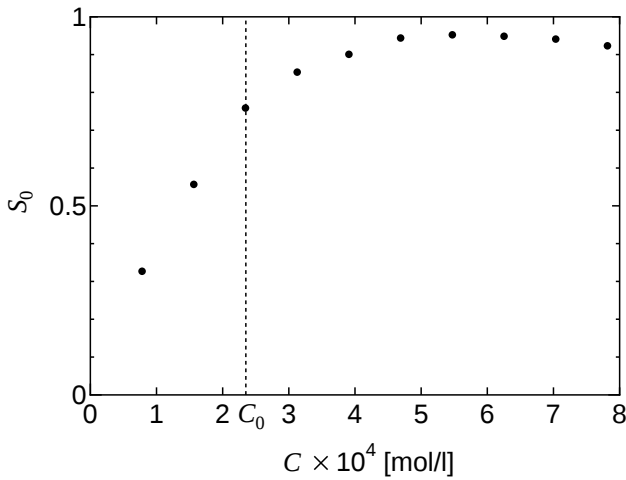


FIGURE 12. RELATIONSHIP BETWEEN CONCENTRATION C AND HIGHEST-FREQUENCY SATURATION S_0 IN WIDE RANGE.

the visualized image, which gave the concentration field according to the calibration results. To compare the mixing fields in the APMR and an ordinary microreactor, we carried out the same experiment using a T-shaped channel as two fluids are concurrently pumped at a constant rate. In terms of the application of these equipments, the results were compared under the condition that the total flow rate Q ($= 5.12 \mu\text{l/s}$) was identified. Q in the APMR was given by $2v_{in}L_{in}h\Delta tF$ and the constant pumping rate in each channel of the ordinary reactor was $Q/2$.

Figure 13 and 14 show the captured images and the distribution maps of C^+ , respectively. Considering the error of the obtained value of C^+ , the area in which mixing was completed is determined as the area in which $C^+ = 0.5 \pm 0.05$. Figure 15 shows a plot of the mixing-completed areas. In the ordinary reactor, the mixed area did not particularly spread in the observed region and the mixed area was confirmed only at the middle of the mixing channel where the interface was created. In the APMR, many mixed areas around the interfaces except the areas near the side walls were observed. A comparison of the mixing fields in the two reactors demonstrated that the APMR enhanced the mixing ability. The absence of the mixed area near the side walls in the APMR could be attributed to that the shear forces from side walls and the effect of the converging channels to consolidate the fluids at the outlets resulted in the restriction of the flow near the side wall and the fluid was not replaced regardless of the bulk flow. Modification of the channel shape to flow outward is expected to overcome this problem.

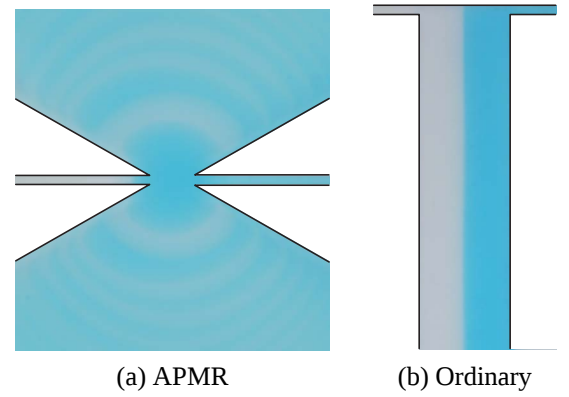


FIGURE 13. CAPTURED IMAGES IN APMR AND ORDINARY MICROREACTOR.

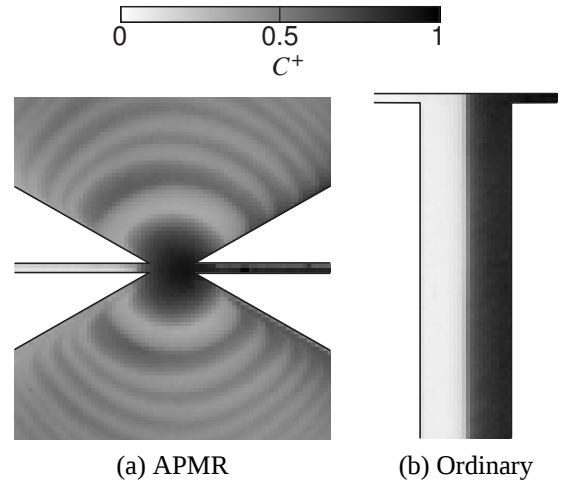


FIGURE 14. COMPARISON OF DISTRIBUTION MAPS OF OBTAINED NORMALIZED CONCENTRATION C^+ IN APMR AND ORDINARY MICROREACTOR.

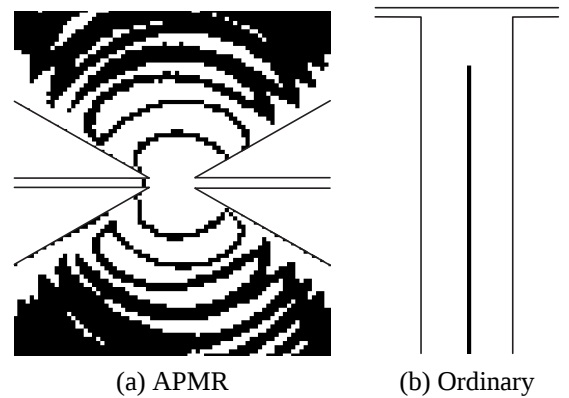


FIGURE 15. COMPARISON OF MIXING FIELDS.

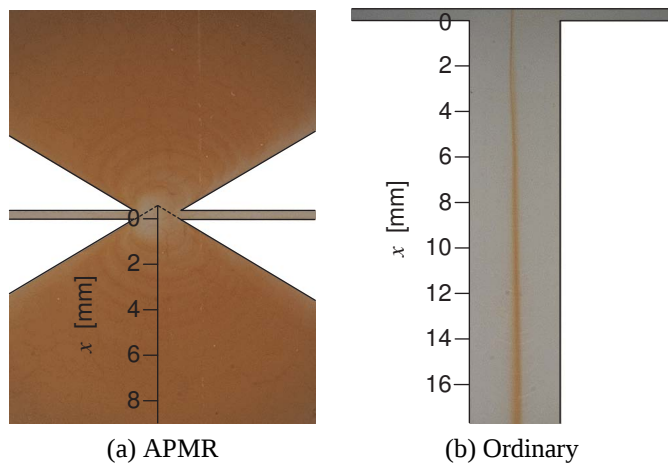
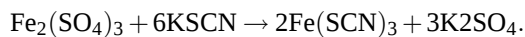


FIGURE 16. CAPTURED IMAGES OF REACTION FIELDS IN APMR AND ORDINARY MICROREACTOR.

ASSESSMENT OF REACTION FIELD Visualization of Reaction Field

For assessment of the reaction field in the APMR, we adopted visualization of the reaction between ferrous sulphate (III) and potassium thiocyanate. Solutions of these substances are almost limpid. When the solutions are mixed and the substances react, the fluid now becomes a mixture of ferrous thiocyanate and potassium sulphate solution, and is looking red in color:



As working fluids, 6.3×10^{-3} mol/l solution of ferrous sulphate and 37.8×10^{-3} mol/l solution of potassium thiocyanate were used. In the case of these concentrations, the substances reacted completely when solutions with the same volume were mixed. These concentration values were selected because the color variation decreases if the concentrations are smaller and the effect of the separated substances is not negligible if the concentrations are larger. In the reactor channel, a white background was seen through the fluid in which the substances had not reacted, and the area in which the substances had reacted looked red.

Visualized Images of Reaction Fields

Figure 16 shows the captured images of the reaction fields in the APMR and the ordinary microreactor. The pumping conditions were identical to those in the mixing field visualization experiments.

In the case of the ordinary reactor, a reacted area can be seen at the middle of the mixing channel, and this steadily spreads in the wide direction downstream. When a thin-layered flow pattern

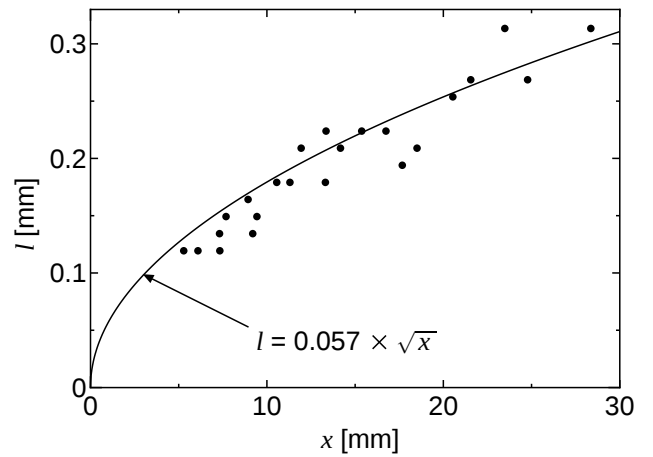


FIGURE 17. RELATIONSHIP BETWEEN DIFFUSION DISTANCE l AND DISTANCE x FROM INLETS IN ORDINARY MICROREACTOR.

was generated in the APMR, reacted areas were created around the interfaces and these hung over the entire region downstream. A comparison of these results demonstrated that the APMR enhances the reaction ability of the microreactor.

The enhancement of the reaction ability is assessed qualitatively. Equation 1 indicates that the molecular diffusion distance l is proportional to the square root of the time t and the proportional coefficient including the molecular diffusivity α , which is represented by A :

$$l = A\sqrt{t}. \quad (7)$$

In the case of the ordinary reactor, the distance x from the inlets is proportional to the flow velocity v_{mix} in the mixing channel; $v_{mix} = Q/(L_{mix}h)$, where L_{mix} is the mixing channel width. The elapsed time after the fluids are infused is equal to the molecular diffusion time t . Therefore, x is given as $x = v_{mix}t$, which is adopted to Eq. 7 and the following relationship is obtained.

$$l = \frac{A}{\sqrt{v_{mix}}} \sqrt{x}. \quad (8)$$

Assuming that the mixed substances react immediately, l is accounted for the distance between the interface at the middle of the channel and the outer edge of the reacted area that looks red, where the substances should react partially; however, this account is reasonable because the estimated values are used to compare the orders of the time and channel length required for the reaction to complete in the APMR and the ordinary reactor. Using the captured images of the ordinary reactor, the values of l

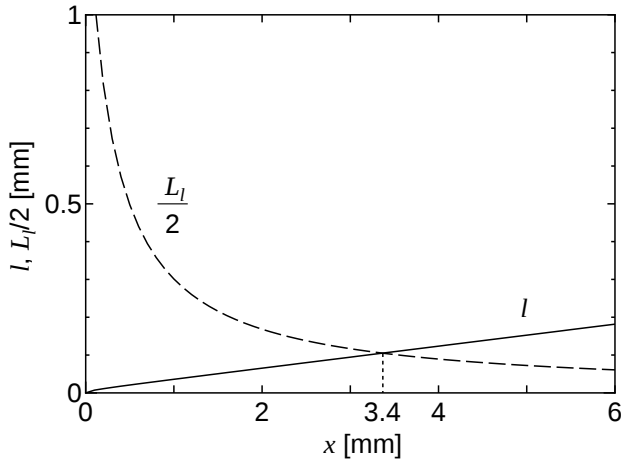


FIGURE 18. COMPARISON BETWEEN l AND $L_l/2$ AS FUNCTIONS OF x IN APMR.

and x were measured and Fig. 17 shows their relationship. Fitting these results by Eq. 8 and adopting the experimental condition, $v_{mix} = 3.2$ mm/s, the value of A is given as 0.10 mm/s^{1/2}. Presuming the time required for the reaction to complete as the time required for the red area to reach to the channel side wall, i.e., l overcomes the half value of the channel width L_{mix} , Eqs. 7 and 8 indicate that the time and channel length required under this condition are 400 s and 1200 mm, respectively.

The model of the thin-layered flow pattern created in the APMR is considered as follows. The fluid flows radially and the interfaces are on concentric circles. The distance from the inlets to the center of the circles is denoted by x_0 . Where the distance from the inlets is x , the local layer width along the arc is expressed as $\theta(x + x_0)$. Therefore, the local flow velocity is given by

$$\frac{dx}{dt} = \frac{Q}{2\theta(x + x_0)h}. \quad (9)$$

Adopting $x = 0$ when $t = 0$ to this equation, the following relation is derived.

$$\frac{\theta h}{Q} (x^2 + 2x_0x) = t. \quad (10)$$

Substituting this relation in Eq. 7, l can be expressed as a function of x :

$$l = A \sqrt{\frac{\theta h}{Q} (x^2 + 2x_0x)}. \quad (11)$$

The volume of each layer is half of the volume ($v_{in}L_{in}h\Delta t$) of the fluid infused in one step of the alternate pumping and the local layer thickness L_l is expressed as

$$L_l = \frac{v_{in}L_{in}\Delta t}{2\theta(x + x_0)}. \quad (12)$$

The condition that must be satisfied the reaction to complete is that l prevails the half value of L_l . Comparing the aspects of l and $L_l/2$ variances with x in Fig. 18, l equals $L_l/2$ when $x = 3.4$ mm; this should be the required length of the mixing channel for the reaction to complete. Substituting the value of x in Eq. 10, the required time is estimated as 1.1 s. The asterisk-shaped channel has two mixing channel, so that the total channel length should be 6.8 mm.

In summary, it is estimated that the time and channel length for the reaction to complete in the APMR are approximately 1/400th and 1/200th of those in the case of the ordinary reactor.

CONCLUSION

In order to demonstrate the enhanced ability of the alternate pumping microreactor (APMR), we conducted visualization of the mixing field and reaction field in the APMR.

To estimate the mixing field, the dilution process of methylene blue solution with water is available. The color information of the captured image can be quantified by the saturation S and the effect of the channel side wall on S can be compensated. According to the obtained relationship between the normalized methylene blue concentration C^+ and the compensated saturation S' , the value of S' in the captured image gives C^+ . A comparison of the concentration fields in the APMR and an ordinary microreactor indicated that the mixing area in the APMR was considerably larger than that in the ordinary microreactor.

For assessment of the reaction field, we adopted visualization of the reaction between ferrous sulphate (III) and potassium thiocyanate. When these substances react in a reactor, the reacted product looks red in color and the reacted region can be identified. Using the captured images, we estimated the time and channel length required for the reaction to complete and compared these values for the APMR and the ordinary microreactor. It was demonstrated that the APMR made the required time and channel length to be two orders of magnitude lesser than those in the case of the ordinary reactor.

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