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Effects of channel geometry on mixing performance of micromixers using collision of fluid segments

Nobuaki Aoki, Kazuhiro Mae *

Department of Chemical Engineering, Graduate School of Engineering, Kyoto University, Kyoto-Daigaku Katsura, Nishikyo-ku, Kyoto 615-8510, Japan

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Abstract

This paper shows effects of design factors for micromixers using the collision of fluid segments on mixing performance. Design factors are collision zone diameter, outlet channel diameter, collision angle of reactant fluids, and number of fluid segments for collision. We evaluate mixing performances of T- and Y-shape micromixers and the K–M mixer using the Villermaux/Dushman reaction. When the Reynolds number in the outlet channel, Re, is less than 200, the fluid segment size determined by only channel geometries, W_c, and Re are significant on mixing performance. From the results in this Re range, we correlate the by-product UV absorbance with the effective fluid segment size after collision, $W_e = W_c/Re^n$. The absorbance is linearly fitted with W_e. Thus, W_e expresses effects of total flow rate, outlet channel diameter, and number of fluid segments for collision on mixing performance. We can improve mixing performance by increasing flow rates as well as reducing channel sizes, leading to avoid extremely small channels to improve mixing performance and a high pressure drop in mixer channels. When $Re > 200$, high share rates applied to fluid segments also enhance the mixing performance. This indicates that high mixing performance and high throughput can be achieved simultaneously.

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Keywords: Micromixer; Channel geometry; Collision of fluid segments; Share rate; Reynolds number

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1. Introduction

Microreactors are miniaturized reactors including microchannels of characteristic dimensions in the sub-millimeter range [1]. The reactor miniaturization provides improved mass- and heat-transfer rate and thus enables us to proceed reactions under more precisely controlled conditions than conventional macro-scale reactors, leading to a possibility of improved yield and selectivity of desired products [2]. Enhancing mixing performance in microreactors is also an essential issue to produce desired products in high yield and selectivity by precisely controlled reactor operation. Selectivities of desired products for very fast multiple reactions have been improved using micromixers, that is, miniaturized mixing devices [3]. Micromixers are, thus, important components of microreactors for controlled reactor operations.

Many mixing principles for enhancing mixing performance in micromixers have been developed [4]. Many principles have been derived by focusing on reducing the diffusion length between reactants. This is because mixing in microreactors is mainly driven by molecular diffusion, since reactor miniaturization leads to low Reynolds numbers in reactor channels. In micromixers, splitting reactant fluids into small fluid segments is a method to reduce diffusion length and thus to enhance their mixing performance. Two principles are mainly used to split reactant fluids into small fluid segments. The first principle is to divide reactant fluids into many fluid segments using channel geometry of micromixers. A mixing method using this mixing principle is that reactant fluids are split into many laminated fluid segments by the geometry of inlet channels into the mixing chamber. Examples of micromixers using this mixing method are the interdigital mixer [5], and the multi-stream mixer with focusing after confluence [6,7]. When we use only this mixing principle, to shorten the diffusion length by channel reduction is essential for fast mixing. However, the channel reduction also leads to a high-pressure drop in the channel and thus to a limited flow rate, resulting in a low productivity and operability. Another principle to enhance mixing performance is, therefore, needed for industrial production where high throughput is needed.

The second principle to split reactant fluids into small fluid segments is the collision of reactant fluid streams for applying shear to the streams. In laminar flow mixing, applying high

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* Corresponding author. Tel.: +81 75 383 2668; fax: +81 75 383 2658.
E-mail address: kaz@cheme.kyoto-u.ac.jp (K. Mae).

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shear rates to reactant fluids is important to shorten mixing time [8]. Collision of two fluid streams is the simplest method for this mixing principle. T- and Y-shape microchannels are examples of micromixers using this mixing principle and have been employed in the investigation on the relation between design factors such as channel sizes and flow rates in the mixers, flow pattern, and mixing performance in the micromixers [9–12]. The previous investigations show that the mixing performance depends on Reynolds number. In the high Reynolds number region, vortices are generated at the collision zone of reactant fluids. The vortices split reactant fluids and thus reduce diffusion length, resulting in an enhanced mixing performance. In contrast, a low flow rate leads to a low Reynolds number in mixing channels and thus to a low mixing performance.

Combining the two principles mentioned above is an effective method to split reactant fluids into small fluid segments. This method enables us to avoid extremely small channels to produce small fluid segments and high pressure drops in the channels. The micromixer based on the combined mixing method has been developed [4,13]. We have also developed the K–M mixer to which this mixing method is applied [14]. K–M is the abbreviation of Kyoto University-MCPT (The Micro-Chemical Process Technology Union). In this mixer, reactant fluids are divided into fluid segments by relatively small channels to reduce diffusion length, and the fluid segments then collide at a single point to be applied shear. After collision of the fluid segments, reactant fluids enters the channel of the outlet plate and thus confluence. In micromixers based on multi-laminating flow such as the SuperFocus mixer and cyclone mixer [4], several fluid segments confluent in a single outlet channel. However, the K–M mixer effectively leverages effect of share by collision of fluid segments as well as the confluence to enhance mixing performance. The results of the previous paper [14] show that combining these two mixing principle is effective to greatly improve mixing performance for miscible and immiscible fluids. Moreover, since the K–M mixer can be operated under the conditions that flow rate is more than 18 mL/min without clogging and high-pressure drop [14,15], the mixer enables high throughput mixing. Since we can flexibly select the number of microchannels for dividing each reactant fluid by changing the mixing plate having various patterns of inlet holes, the wide range of flow rate ratio of two fluids is available and a flow rate ratio of 14 has been realized [15]. Thus, the K–M mixer can be operated under a wide rage of total flow rate and flow rate ratio of reactant fluids and flexibly designed to meet demands of products. Besides the high mixing performance, throughput, and operability, the K–M mixer provides the ease of maintenance. The mixer is composed of the three plates, and it can be easily disassembled and cleaned.

To use micromixiers combining the two mixing principles in an industrial production, we need a precisely controlled mixing according to conditions for the production such as the mixing performance for ideal mixing determined by reaction kinetics of the reaction system and the throughput satisfying the demand for the product. For achieving controlled mixing, we need a method to determine design factors of micromixers, such as channel geometry, according to these conditions. Relations between design factors of micromixers and mixing performance are necessary to establish a method to determine design factors of micromixers. To identify effects of design factors on mixing performance, we experimentally examined mixing performance of micromixers such as the T- and Y-shape micromixers and the K–M mixer with varying design factors of the mixers. The design factors were total flow rate of reactant fluids, collision zone diameter, diameter of the outlet channel connecting to micromixers, collision angle of reactant fluids, and number of fluid segments colliding at the mixing zone. The mixing performance for a micromixer of a set of design factors was evaluated by a parallel-competitive reaction system called the Villermaux/Dushman reaction. The UV absorption of the by-product gives mixing performance of the micromixers. From relations between the design factors and mixing performance, we then discuss the dependence of mixing performance on share rate applied to reactant fluids at the collision zone and Reynolds number in the outlet channel of micromixers. In the discussion, we use shear rate and Reynolds number, since these quantities have been considered as the important indices for performances of mixers [16] and can be determined from the design factors of each micromixer. We also discuss effects of the collision of reactant fluids on mixing performance from the viewpoint of the reduction of fluid segments. In this discussion, we correlate the mixing performance with the effective fluid segment size after collision of them. The correlation gives the relation between the fluid segment size after collision and the design factors of micromixers using the collision of fluid segments. Once the size is established, we can determine the value of the dimensionless group representing the ratio of reaction rate to diffusive mixing rate as addressed in our previous study [17,18]. From the relation between desired product yield and value of the dimensionless group, we can determine the threshold value for ideal mixing. When the reaction rate is given, the fluid segment size for ideal mixing can be determined from the threshold value of the dimensionless group. Thus, the correlation between a mixing performance and an effective fluid segment size is useful to establish the design method of micromixers using collision of fluid segments.

2. Experimental

2.1. Micromixers and design factors

Collision of two fluid streams is the simplest method for mixing by collision of fluid segments. T- and Y-shape mixers are examples of micromixers using this mixing principle. We used the 1/16-in. union tees (Swagelok®) as T-shape micromixers to study effects of the collision zone diameter on mixing performance. The diameters of the collision zone of the union tees are 1.3 and 0.3 mm and are referred as T-1.3 and T-0.3, respectively. We also applied T- and Y-shape microchannel mixers made of glass (Eikoh Co. Inc.) to the study on effects of the collision angle of reactant fluids on mixing performance. Fig. 1 shows the photographs of the micromixers. In the Y-shape channel, two fluid streams collide at the angle of 90°. In the whole of the channels of both mixers, the channel width and depth are 0.5 mm, and the channel length after collision of two fluid streams is 5 cm. We

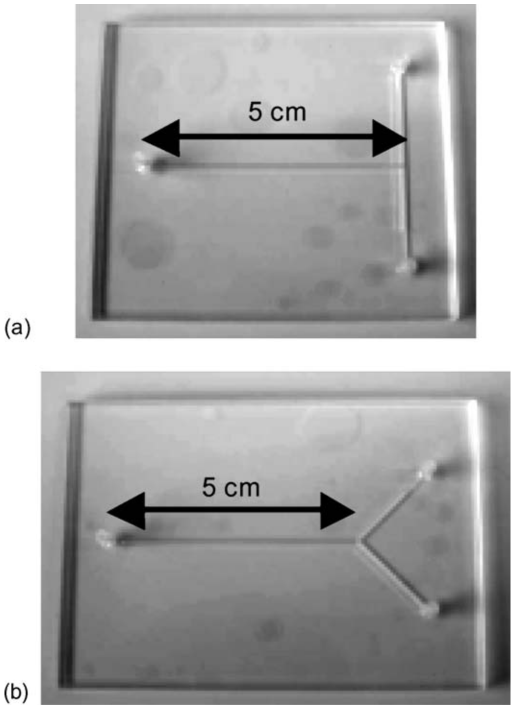

Fig. 1. T- and Y-shape microchannels made of glass: (a) T-0.5 and (b) Y-0.5.

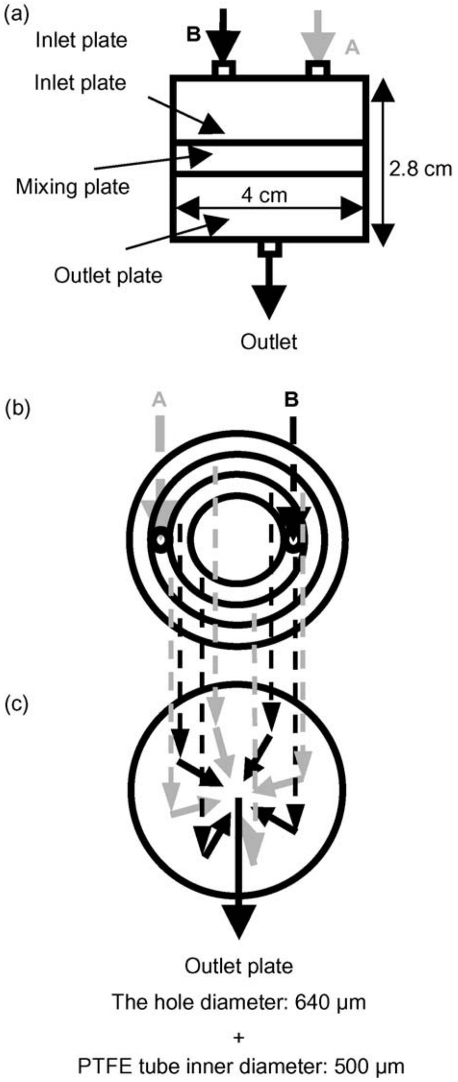

Fig. 2. Schematics of the K–M mixer: (a) overview, (b) inlet plate and (c) mixing plate.

refer the T-shape channel as T-0.5 and the Y-shape channel as Y-0.5.

Fig. 2a illustrates the schematics of the K–M mixer. This micromixer consists of three stainless steel plates, that is, the inlet plate, the mixing plate, and the outlet plate. The details of the K–M mixer such as the fabrication method are explained in the previous paper [14]. Fig. 2b and c illustrate the internal flow in the micromixer of a mixing plate. Two reactant fluids, first, flow into the K–M mixer from the inlet plate. In the inlet plate, the annular channels are connected to the two inlets for two reactant fluids, respectively. The two fluids spread uniformly in the annular channels and then enter the mixing plate. After entering the mixing plate, each fluid stream is divided into fluid segments. The fluid segments for the two fluids encounter at the center of the mixing plate. The encountered fluids then flow into the outlet plate. This plate has a hole for the exit of the mixed fluid at the center of the plate. The diameter of the hole in the outlet plate was 640 μm. Finally, the mixed fluid enters the PTFE tube, which is considered as the outlet channel. In this study, we examined effects of the number of fluid segments to collide on mixing performance by exchanging the mixing plate. We used the three mixing plates having different radial channel geometries as illustrated in Fig. 3. In the experiment, this figure shows the channel geometry, the channel diameter to the collision zone, D_t (μm), the number of channels to divide each reactant fluid, n (–), and the collision zone diameter, D_c (μm), of each mixing plate. We refer each K–M mixer using the value of D_t, n, and D_c.

We connected a PTFE tube at the outlet of each micromixer mentioned above. We refer the inner diameter of the PTFE tube as the outlet channel diameter. We set the total channel length from the collision zone of two reactant fluids to the outlet of the PTFE tube at 30 cm. For example, since the channel length after collision of two fluid streams is 5 cm in the glass device as shown in Fig. 1, a 25 cm-PTFE tube was connected at the outlet. Unless otherwise noted, the outlet channel diameter was 0.5 mm. We examined effects of the outlet channel diameter, and the outlet channel diameters were changed to 0.8, 0.5, and 0.25 mm. In this study, we used T-1.3 and T-0.3. We also confirmed effects of the collision zone diameter on mixing performance for each outlet channel diameter.

2.2. Evaluation method of mixing performance

We evaluated mixing performances of the micromixers mentioned in the previous section using a parallel-competitive reaction system called the Villermaux/Dushman reaction [19]. This reaction system is often used to quantify micromixing phenomena in mixers and applied to evaluate mixing performances of mixcromixers [5,20,21]. The reactions occur by mixing two

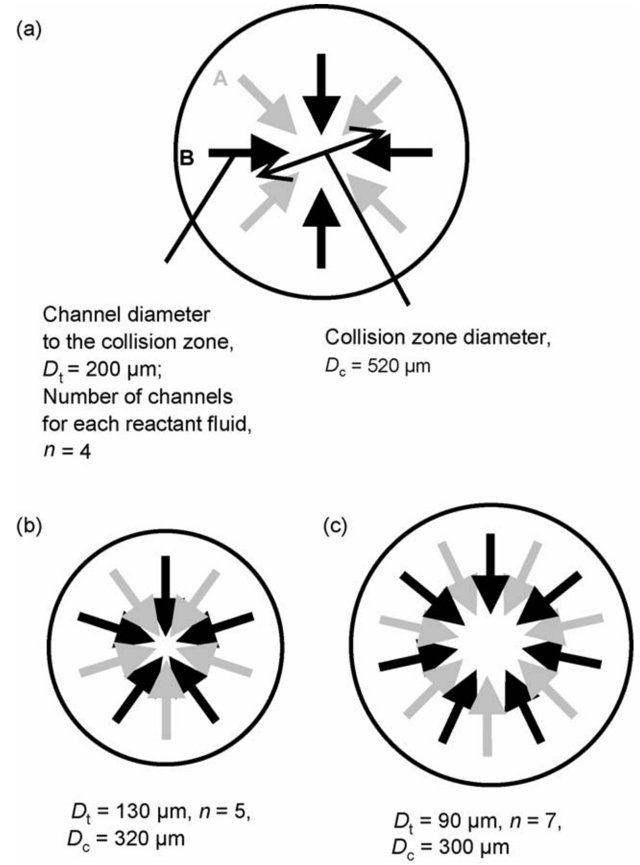

Fig. 3. Mixing plates of the K–M mixer for: (a) KM200-4-520, (b) KM130-5-320, and (c) KM90-7-300.

reactant fluids of water solutions: One is a solution of diluted strong acid such as HCl and H_2SO_4; the other is a buffer solution (weak acid (e.g., H_3BO_3, CH_3COOH) and strong base (e.g., NaOH)) containing KI and KIO_3. In the experiments, the solution of 0.016 mol/L of KI (Wako Pure Chemical Industries Ltd.), 0.0032 mol/L of KIO_3 (Wako Pure Chemical Industries Ltd.), 0.09 mol/L of NaOH (Nacalai Tesque Inc.), and 0.09 mol/L of H_3BO_3 (Kanto Chemical Co. Inc.) was mixed with the solution of 0.03 mol/L of HCl (Wako Pure Chemical Industries Ltd.) in the micromixers at room temperature [5,20]. When boric acid is used as a weak acid for the buffer solution, the reaction formulas are as follows:

$$H_2BO_3^- + H^+ \rightleftarrows H_3BO_3 \tag{1}$$

$$5I^- + IO^{3-} + 6H^+ \rightleftarrows 3I_2 + 3H_2O \tag{2}$$

$$I_2 + I^- \rightleftarrows I^{3-} \tag{3}$$

where reaction (2) is fast, but reaction (1) is instantaneous and is much faster than reaction (2). When mixing is slow, the protons of acid are consumed by reaction (2), and I_2 is produced. The iodine then reacts with iodide ions quickly by reaction (3). The product of reaction (3), that is, triiodide ion has the strong UV light absorbance around 352 nm. Thus, the UV light absorbance at 352 nm depends on mixing performance of the two reactant fluids. Thus, we can use the UV light absorbance at 352 nm as a measure of mixing performance.

2.3. Experimental procedure

We then explain the experimental procedure using the micromixers and the evaluation method of mixing performance shown in the previous sections. The two reactant fluids were fed into the micromixers using a syringe pump (IC3210, Kd Scientific Inc.). The flow rates of the two fluids were the same for all the experiments. The flow rate of each fluid was thus half of the total flow rate. The mixed fluid from the outlet of the PTFE tube was sampled in a UV cell. The optical length of the cell was 4 mm. The absorbance of UV light at 352 nm, ABS (352 nm), was measured with a UV–vis spectrometer (Multispec-1500, Shimadzu Corp.) within a minute after the sampling. We measured the mixing performance of each micromixer with varying total flow rate of the two reactant fluids. The range of total flow rate is 0.25–22 mL/min. We increased the total flow rate of a micromixer until ABS (352 nm) reaches less than 0.05. The measurement for each mixer and total flow rate was repeated at least three times, and the mean value of the measured absorbances was employed as the results shown in the following sections.

3. Results and discussion

3.1. Collision zone diameter and outlet channel diameter

Fig. 4 shows effects of the collision zone diameter on the relation between the absorbance at 352 nm and the total flow rate of the reactant fluids for each outlet channel diameter. The absorbance decreases with improving mixing performance. This figure also shows the Reynolds number in the outlet channel, *Re*, corresponding to the total flow rate. The Reynolds number is expressed by:

$$Re = \rho \bar{u}_{\text{out}} D_{\text{out}} / \mu \tag{4}$$

where ρ is the density of the reactant fluids (998 kg/m^3), $\bar{u}_{\text{out}}$ the mean velocity of each reactant fluid in the outlet channel (m/s), D_{out} the outlet channel diameter (m); μ is the viscosity of the reactant fluids (1.05 mPa s).

We first discuss effects of collision zone diameter on mixing performance. For all the outlet channel diameters, the difference in mixing performance between the two mixers is small in the low total flow rate range, that is, the low *Re* range. In this *Re* range, collision zone diameter is insignificant on mixing. Mixing performance of the two micromixers improves with increasing total flow rate and thus *Re*. At the same total flow rate and the Reynolds number, T-0.3, however, gives higher mixing performance than T-1.3 especially when the Reynolds number is larger than 200. The difference in mixing performance can be explained using share rate at the collision zone. The share rate $\dot{\gamma}$ (s^{-1}) is defined as:

$$\dot{\gamma} = \bar{u}_c / D_c \tag{5}$$

where $\bar{u}_c$ is the mean velocity of each reactant fluid at the collision zone (m/s) and D_c is the collision zone diameter (m). At the same total flow rate, share rate applied to fluid segments at the collision zone is inversely proportional to the cubic of collision

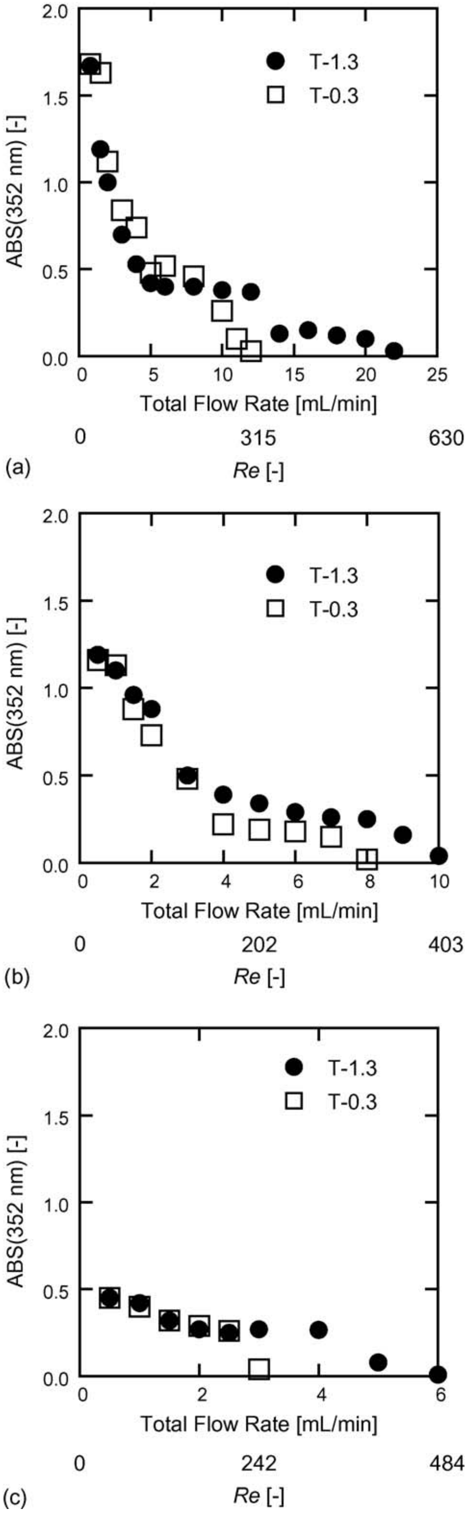

Fig. 4. Effects of collision zone diameter on mixing performance with varying outlet channel diameter. The outlet channel diameter is: (a) 0.8 mm, (b) 0.5 mm, or (c) 0.25 mm.

Table 1
Shear rate applied to fluid segments at the collision zone for the T-shape mixers

Total flow rate (mL/min)	Shear rate (s^{-1})	
	T-1.3	T-0.3
0.5	2	196
4	19	1572
8	39	3144
12	58	4716
16	77	6288

zone diameter. Table 1 shows the share rates applied to fluid segments at the collision zone for the micromixers as a function of total flow rate. From the viewpoint of share rate, T-0.3 is, thus, more favorable than T-1.3 for fast mixing, since the share rate applied in the collision zone of T-0.3 is larger than that of T-1.3 at a total flow rate. This result also indicates that *Re* determines the threshold whether the share rate affects mixing performance and is a parameter determining mixing performance.

Around $Re = 200$, the mixing performance is almost unchanged with increasing total flow rate. In this *Re* range, the improvement of mixing rate by increasing *Re* is compensated by short residence times due to high fluid velocities. Engler et al. calls this range vortex flow regime [9]. In the further increased *Re*, flow regime moves into the engulfment flow regime. The mixing performance is enhanced again with increasing total flow rate and *Re*.

We then discuss effects of outlet channel diameter on mixing performance. In both mixers, the mixing performance improves with decreasing outlet channel diameter. This is because the diffusion length is reduced by decreasing the outlet channel diameter. As mentioned earlier, at a fixed *Re* in the low *Re* range, the collision zone diameter and the share rate are insignificant. The outlet channel diameter, thus, has a decisive influence on mixing performance. These results also indicate that mixing proceeds in the outlet channel as well as at the collision zone.

The total flow rate for reaching a value of ABS (352 nm) less than 0.05 decreases with reducing outlet channel diameter. The reduction in diffusion length by channel reduction is the first reason. This tendency is also attributed to the Reynolds number in the outlet channel. At the same total flow rate, the Reynolds number is inversely proportional to the outlet channel diameter. In other words, the total flow rate to reach a Reynolds number decreases with reducing outlet channel diameter. In this way, total flow rate for ideal mixing depends on outlet channel diameter.

From the viewpoint of the size of fluid segment after collision, we then discuss the effect of outlet channel diameter and *Re* on the mixing for the range $Re < 200$. Once the relation between the fluid segment size after collision and design factors of micromixers is established, we can also evaluate mixing performance using the dimensionless group ϕ representing the ratio of reaction rate to diffusive mixing rate as addressed in our previous papers [17,18]. For example, in the reaction $A + B \rightarrow R$ whose reaction rate r is expressed by $r = kC_A C_B$, ϕ is given by $kC_{B0}W^2/D$, where k is the rate constant, C_j the concentration of component j, the subscript 0 represents the initial condition, W the size of fluid segment; D is the diffusion coefficient. From the relation between desired product yield and value of the dimensionless group, we can determine the threshold value of ϕ for ideal mixing. When the reaction rate is given, W for ideal mixing can be determined from the threshold value of ϕ. Thus, an effective fluid segment after collision of fluid segments, W_e (m), which means W for fluid segments after collision is needed in the design of the micromixers using collision of them.

First, we define the fluid segment size in the outlet channel determined by only channel geometry, W_c (m). The cross-sectional area of each fluid segment in the outlet channel is inversely proportional to the number of fluid segments in the outlet channel, N, and the effective dimension of each fluid segment is inversely proportional to $\sqrt{N}$. The dimension is also proportional to the outlet channel diameter, D_{out} (m). Thus, the fluid segment size after collision is given by:

$$W_c = D_{out}/\sqrt{N} \tag{6}$$

For instance, W_c of the T-shape mixers with the PTFE tube of 0.8 mm diameter is determined to be $800/\sqrt{2} = 566\ \mu m$.

In the range of $Re < 200$, the mixing performance depends on fluid segment size by outlet diameter and Re. Mixing performance can be correlated using $W_e = W_c/Re^n$. We hypothesized that the correlation is expressed by:

$$\text{ABS}\ (352\ \text{nm}) = \text{A}(W_c/Re^n) + \text{B} \tag{7}$$

Fig. 5 shows the absorbances for the T-shape mixers in the range of $Re < 200$ as a function of W_e and a fitted line by the least square method. The multiplier n is determined by the least square method so that R^2 value is maximized. The determined value of n is 0.7. The T-shape mixers discussed here have large W_c and should be operated in the range of $Re > 200$ where high share rates improve mixing performance for achieving ideal mixing. Thus, only reducing W_c and increasing Re ($W_c/Re^{0.7} \rightarrow 0$) are insufficient to reach to ABS (352 nm) = 0, and the intercept of the fitted line has a positive value.

The effective fluid segment size simultaneously expresses the effects of increasing total flow rate and reducing outlet channel diameter on mixing performance. By using the expression of W_e, we can improve mixing performance by increasing the total flow rate as well as reducing the channel size. This mixing operation, thus, enables us to avoid extremely small channels to improve mixing performance and a high-pressure drop in the mixer channels. Therefore, the mixing operation of colliding fluid segments is effective to improve operability of micromixers as well as their mixing performances.

4. Collision angle

Fig. 6 shows the mixing performances of the micromixers having different collision angles. For comparison, the same relation of T-1.3 with the PTFE tube of 0.5 mm diameter is shown in the same figure. This figure also shows the Reynolds number in the outlet channel corresponding to the total flow rate. The difference in ABS (352 nm) for the two micromixers due to collision angle is smaller than those due to collision zone diameter and outlet channel diameter. We increased the total flow rate to reduce the absorbance at 352 nm less than 0.05. The mixer Y-0.5, however, needs much higher total flow rate to reach this criterion than T-0.5. We discuss this difference using share rate applied to fluid segments at the collision zone. Though the Reynolds numbers of the two mixers are the same at the same total flow rate, the share rate at the collision zone in the width direction of T-0.5 is $\sqrt{2}$ times larger than that of Y-0.5. The difference in mixing performance between the two micromixers is large in the high Re range, where a high share rate is applied to fluid segments. The results also confirm that share rate affects mixing performance in the high Re range.

We then compare the mixing performance of the glass microchannels with that of the union tee mixer. The share rate $\dot{\gamma}$ of T-1.3 is higher than that of Y-0.5. For instance, when the total flow rate is 8 mL/min, $\dot{\gamma}$ of T-1.3 is 39 s^{-1}, and that of Y-0.5 is 377 s^{-1} (in the width direction). The mixing performance of T-1.3 is, however, comparable to that of T-0.5. At the point

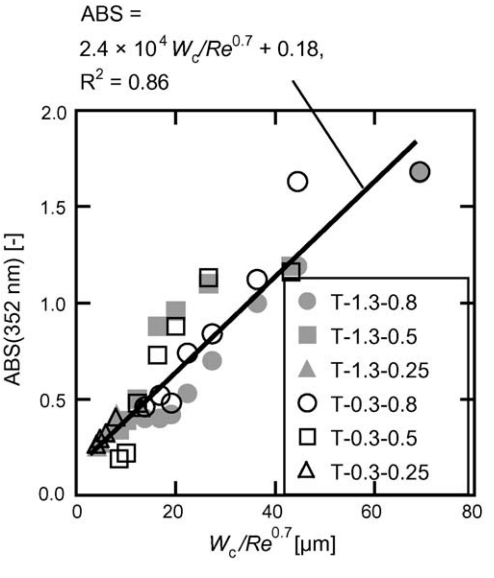

Fig. 5. Correlation between the mixing performance and the effective fluid segment size $W_e = W_c/Re^{0.7}$ for the T-shape mixers. $Re < 200$. The legends represent the collision zone diameter–outlet channel diameter.

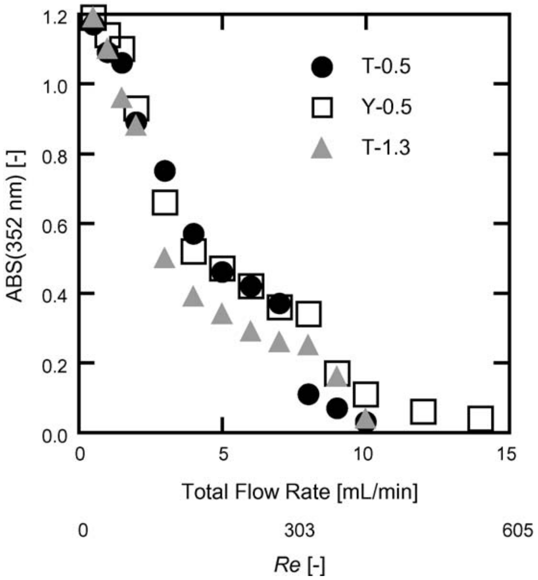

Fig. 6. Mixing performance of the micromixers having different collision angles and T-1.3. The outlet channel diameter is 0.5 mm.

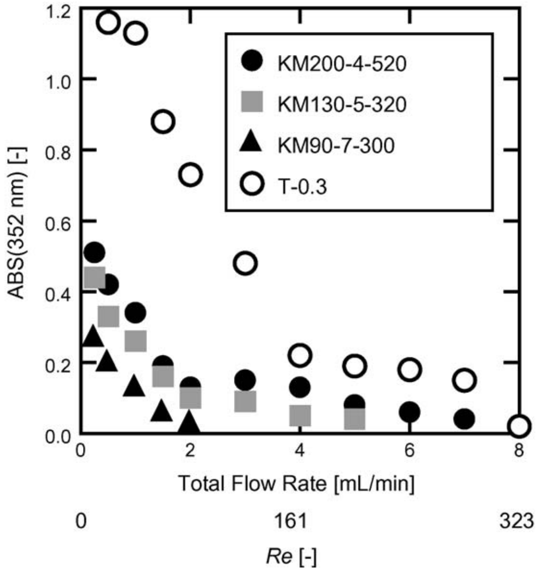

Fig. 7. Mixing performance of the K–M mixer with various numbers of fluid segments for collision and T-0.3. The outlet channel diameter is 0.5 mm.

where the glass device joints the PTFE tube, the channel size is enlarged, and the flow bents. These flow phenomena would affect mixing performance.

4.1. Number of fluid segments

Fig. 7 shows the mixing performances of the K–M mixers with various numbers of fluid segments. For comparison, the results of T-0.3, which gives the highest mixing performance among the T- and Y-shape micromixers discussed earlier, is also plotted in the same figure. The highest ABS (352 nm) of the K–M mixer is lower than 0.6. The mixing performance of the K–M mixer is, thus, much higher than those of the T- and Y-shape micromixers, especially in the low total flow rate range. Mixing performance improves with increasing number of the fluid segments. The increase in the number of channels for dividing reactant fluids decreases the size of divided fluid segments and thus leads to reduce the diffusion length between the reactants. In addition, after collision of the fluid segments, reactant fluids enters the outlet channel and thus confluence. The number of fluid streams for confluence of the K–M mixer is larger than those of the T- and Y-shape micromixers. Therefore, the K–M mixer effectively leverages the effect confluence to enhance mixing performance. The mixing performance of each K–M mixer improves with increasing total flow rate and is higher than those of the other micromixers at the same *Re* owing to the small divided fluid segment and the confluence of multiple fluid segments. Therefore, the K–M mixer gives a high mixing performance even at low flow rates.

Besides the small fluid segments and effective confluence by the channel geometry, high share rates are applied to fluid segments at the small collision zone in the K–M mixer. Table 2 lists the share rate calculated by Eq. (5) for the K–M mixer of each Mixing plate. In the reaction system mentioned in Section 2.2, ABS (352 nm) for KM-90-7-300 and KM-130-5-320 reach to 0.0 before entering the range of $Re > 200$, where high share rates are expected to enhance mixing performance. As demonstrated in our previous papers [14,15], the K–M mixers, however, can be operated under higher total flow rates than those shown in this section. Thus, further increase in total flow rate, leading to a high share rate and a high *Re* more than 200, can realize higher mixing performance in the K–M mixer than that can be measured using this reaction system. This also means that the size of fluid segment after collision can be smaller than the size measurable using the reaction system. Moreover, since the flow rate is high when *Re* is higher than 200, and a high share rate is applied to fluid segments, the effect of high share rate also indicates that this mixing method offers an opportunity for a high throughput production with an efficient mixing. We conclude that the combination of dividing reactant fluids into small fluid segments and then applying high shear rates to the fluid segments by the collision of them is an effective method to enhance mixing performance, operability, and throughput in micromixers.

Table 2
Shear rate applied to fluid segments at the collision zone for the K–M mixer of each mixing plate

Total flow rate (mL/min)	Shear rate (s^{-1})		
	KM90-7-300	KM130-5-320	KM200-4-520
0.5	245	154	50
4	1960	1233	401
8	3919	2465	801
12	5879	3698	1202
16	7839	4931	1603

For the K–M mixer in the range of $Re < 200$, we also derive a expression of W_e and relation between ABS (352 nm) and W_e. The number of fluid segment, *N*, is varied with the Mixing plates and twice the number of channels for dividing each reactant fluids. For instance, W_c for the KM130-5-320 ($n = 10$) with the outlet channel of 0.5 mm diameter is $500/\sqrt{10} = 158\ \mu\text{m}$. To obtain the relation, we used the same method for the T-shaped mixers. Fig. 8 shows the absorbances for the K–M mixers in the range of $Re < 200$ as a function of W_e and a fitted line by the least square method. The value of *n* is determined to be 0.2. The experimental data fit well on the line. This result also indicates that for the K–M mixer, the effect of the number of fluid segments for collision on mixing performance can be also included in W_e. The value of *n* is smaller than that of the T-shape mixers. This means that the effect of W_c on mixing performance is greater than that of the T-shape mixers. In the K–M mixer, W_c is small by the channel geometry of dividing reactant fluids into fluid segments, and mixing condition studied here is focused on low flow rate range. As a result, W_c for the K–M mixer has greater importance on mixing performance than that for the T-shape mixers. The intercept of the fitted line is below 0. In other words, W_e for the ideal mixing (ABS (352 nm) = 0.0) is a positive finite value, and the mixing can be ideal before entering the range of $Re > 200$. In the K–M mixers, especially KM130-5-320 and KM90-7-300, W_c are small, and *Re* are also small for reaching a value of W_e. Consequently, these two mixers reach to the ideal mixing before

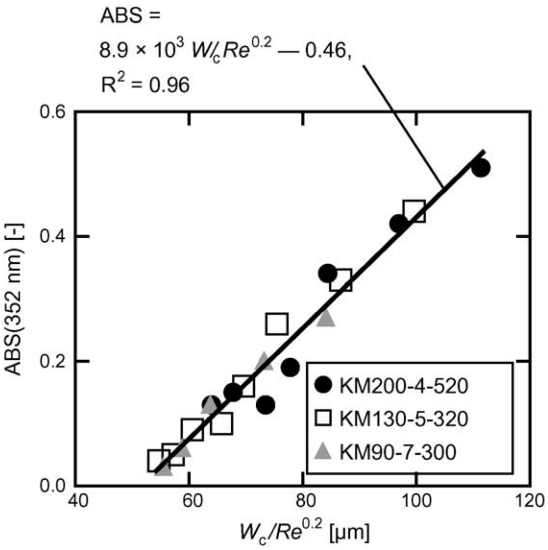

Fig. 8. Correlation between the mixing performance and the effective fluid segment size $W_e = W_c/Re^{0.2}$ for the K–M mixer. $Re < 200$.

entering the high *Re* range. The intercept value also confirms that the K–M mixer provides a high mixing performance even at low flow rates and *Re*.

5. Conclusions

We have studied effects of design factors of micromixers using the collision of fluid segments, such as T- and Y-shape micromixers and the K–M mixer. The design factors are total flow rate, collision zone diameter, outlet channel diameter, collision angle of reactant fluids, and number of fluid segments colliding at the mixing zone. The mixing performance for a micromixer of a set of design factors was evaluated by the UV absorbance of the product of the slower reaction in a parallel-competitive reaction system called the Villermaux/Dushman reaction.

We have considered the results by dividing two ranges of the Reynolds number in the outlet channel, *Re*. First, the outlet channel diameter, the number of channels dividing reactant fluids, and the total flow rate are significant on mixing performance, when the Reynolds number in the outlet channel, *Re*, is lower than 200. Mixing performance improves with increasing *Re* and reducing fluid segment size determined by only channel geometry, W_c. We have, thus, correlated the mixing performance with an effective fluid segment size after collision, $W_e = W_c/Re^n$. The mixing performance can be correlated well and fitted linearly by W_e for the T-shape mixers and the K–M mixer. The multiplier *n* for the K–M mixer is smaller than that for the T-shape mixer. In the K–M mixer, W_c is small by the channel geometry of dividing reactant fluids into fluid segments, and mixing condition studied here is focused on a low flow rate range. As a result, W_c for the K–M mixer has greater importance on mixing performance than that for the T-shape mixers. The intercept of the fitted line for the K–M mixer is below 0. In other words, W_e for the ideal mixing (ABS (352 nm) = 0.0) is a positive finite value, and the mixing can be ideal entering the range of $Re > 200$. In the K–M mixers, especially KM130-5-320 and KM90-7-300, W_c are small, and *Re* are also small for reaching a value of W_e. Consequently, these two mixers reach to the ideal mixing before entering the high *Re* range. The intercept value also indicates that the K–M mixer provides a high mixing performance even at low flow rates.

In the second range, $Re > 200$, mixing performance depends on not only Reynolds number but also share rate at the collision zone. At the same *Re* in this *Re* range, higher share rate gives higher mixing performance. Using this tendency, we can explain the effects of the improvement of mixing performance with reducing collision zone diameter and the collision angle of the two reactant fluids on mixing performance.

From the expression of W_e, we can improve mixing performance by increasing the total flow rate as well as reducing the channel size. This mixing operation, thus, enables us to avoid extremely small channels to improve mixing performance and thus a high pressure drop in the mixer channels. Moreover, mixing performance is highly improved by applying a high share rate to fluid segments in the range of $Re > 200$. The effect of high share rate under high flow rate conditions indicates that this mixing method offers an opportunity for a high throughput production with an efficient mixing. Therefore, the mixing operation of colliding fluid segments is effective to improve the operability and throughput of micromixers as well as their mixing performances.

The correlation between the absorbance and the effective fluid segment size would allow us to evaluate mixing performance of the operation of collision of fluid segments using the dimensionless group that represents the ratio of reaction rate to diffusive mixing rate. From the relation between desired product yield and value of the dimensionless group, we can determine the threshold value for ideal mixing. When the reaction rate is given, the fluid segment size for ideal mixing can be determined from the threshold value of dimensionless group. Thus, relations between the design factors, the absorbance, and the fluid segment size after collision from this correlation are useful in the design of micromixers using collision of fluid segments. When share rate affects mixing performance, the absorbance for some experimental runs, however, reaches 0 in the reaction system. Further study in the range where share rate greatly affects mixing performance would contribute to establish the design method for the micromixers. The measurement method for this range is also the issue for this study.

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