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# Design and evaluation of a cylindrical micromixer using ultrasonic vibration in torsional vibration mode

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***Abstract*—Micromixers which have microchannels for mixing have advantages such as efficient mixing and high temperature controllability. However, microchannels are clogged and a mixing performance is degraded in such micromixer. Therefore, we have proposed a new cylindrical micromixer for the purpose of improving mixing performance by using an ultrasonic vibration. The micromixer oscillates channel plates in a torsional direction. We have evaluated the mixing performance of the fabricated micromixer by Villermaux/Dushman reaction experiments. As a result, the mixing performance of the micromixer has been improved by the ultrasonic vibration.**

***Keywords—Micromixer, Ultrasonic vibration, Torsional vibration, Villermaux/Dushman reaction***

## I. Introduction

Microreactors that use microspaces such as microchannels have advantages such as efficient mixing and high temperature controllability. Many micromixers are already proposed for mixing solutions at high speed by utilizing the characteristics [1]. However, microchannels are easily clogged and the mixing performance decreases on mixing conditions. Therefore, micromixers are required to avoid such clogging. Some mixing devices applying ultrasonic vibration have been reported [2, 3]. We also proposed a cylindrical micromixer using ultrasonic vibration in flexural vibration mode in IUS 2018 [4].

In this study, a micromixer which can be used under a high pressure condition has been fabricated. The micromixer oscillates some channel plates in a torsional direction. The vibration direction is orthogonal with that of the fluid flow. To evaluate the mixing performance, Villermaux/Dushman reaction experiment has been conducted for the fabricated micromixer.

## II. Structure and Evaluation of a Cylindrical Micromixer

### A. Structure of a proposed micromixer

In this study, the proposed micromixer has the structure of a multi-stage split and recombine type microchannel mixer as in the reference [5]. The multi-stage split and recombine type microchannel mixer was developed for the purpose of mixing fluids under high pressure conditions. The micromixer is composed of a plurality of channel plates which have regularly arranged microchannels. Each channel has a diameter of 0.8 mm. The arrangement pattern of microchannels is different in odd stage plates and even stage, and turbulence is generated and mixes fluids. A micromixer reported in IUS 2018 referred to the multi-stage split and recombine type microchannel mixer and utilized the flexural vibration [4]. But, the micromixer was influenced by fluid viscosity and flow rate, and the flexural vibration was suppressed. Therefore in order to develop a new micromixer which isn't influenced by fluid viscosity and flow rate, we have utilized the torsional vibration for the micromixer.

Figure1 shows the schematic of the fabricated micromixer. Figure 2 shows the fabricated and assembled micromixer and the result of the FEM simulation about the vibration mode. The fabricated micromixer consists of a bolt with a channel plate and two nuts with a channel plate, two channel plates, a fixing nut, two PZT rings of 1 mm thickness, two Cu electrodes of 0.1 mm thickness. The material of the parts except PZT rings and Cu electrodes are SUS304. In order to apply the torsional vibration to the micromixer, two PZT rings are polarized in the circumferential direction. The PZT rings are formed as Bolt-clamped Langevin-type Transducer (BLT). The BLT efficiently applies the torsional vibration to the micromixer. Figure 2 shows the torsional vibration mode at the driving frequency of 121 kHz.

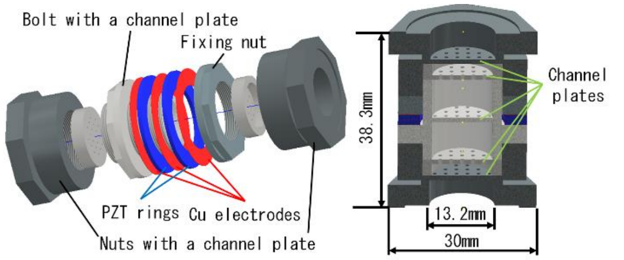


Fig. 1 Schematic of the torsional vibration mixer (left) and cross-sectional view of the torsional vibration mixer (right)

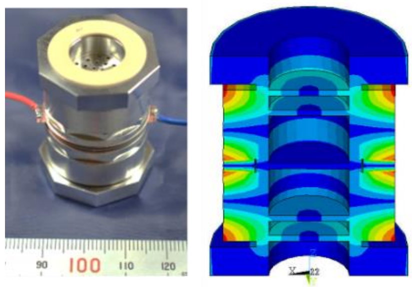


Fig. 2 Photograph of the torsional vibration mixer (left) and the result of FEM simulation (right)

## B. *Characteristics of the fabricated micromixer*

First, admittance measurement was conducted to evaluate the characteristics of the micromixer. The result is shown in Fig. 3. Figure 3 indicates that the fabricated micromixer has vibration modes at driving frequencies of 80 kHz and 130 kHz.

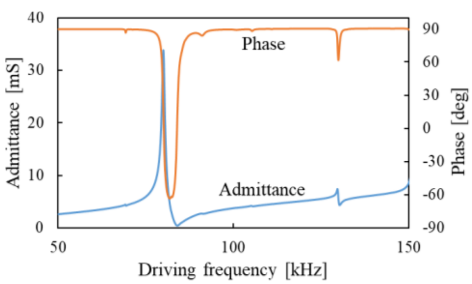


Fig. 3 Result of admittance measurement

Subsequently, the vibration speed in torsional direction of the fabricated micromixer was measured when the driving frequency was 131 kHz. Measurement point is in the first channel plate and located in 4 mm from the center axis of the micromixer as shown in Fig. 4. Figure 5 shows a relationship between the applied voltage and the vibration speed of the fabricated micromixer. As applied voltage increases, the vibration speed of micromixer also increases.

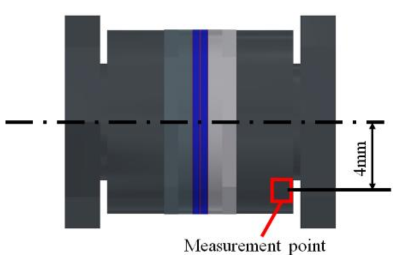


Fig. 4 Measurement point about vibration speed

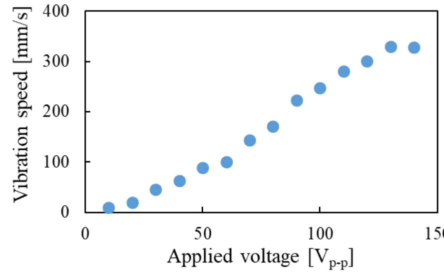


Fig. 5 Relationship between applied voltage and vibration speed

## III. Evaluation of Mixing Performance

Villemaux/Dushman reaction experiment was conducted to evaluate the mixing performance quantitatively. Table 1 shows solutions used in the experiment. This evaluation method uses the difference between two reactions [6, 7]. One reaction is neutralization reaction with acid ($H^+$) and a solution of $H_2BO_3^-$, and the other is iodide-iodate reaction. Iodide- iodate reaction generates $I_2$ by solutions of KI and $KIO_3$ reacting with acid ($H^+$), and $I_3^-$ is generated by equilibrium reaction. The neutralization reaction is infinitely faster than iodide-iodate reaction. $I_3^-$ absorbs ultraviolet light with a wavelength of 352 nm. Therefore, mixing performance can be evaluated by measuring UV absorbance.

Table 1 Solutions used in Villemaux/Dushman reaction experiment

| **Solution** | **Substance** |
|---|---|
| Solution 1 | HCl |
| Solution 2 | $H_3BO_3$ |
| | KI |
| | NaOH |
| | $KIO_3$ |

Figure 6 shows the experimental setup. The solutions are supplied from the pressurized tanks. The flow rate is controlled by adjusting the air pressure to the tank. The solution mixed by the micromixer is put into an optical cell, and UV absorbance is measured using a spectrophotometer (PMA-12, Hamamatsu Photonics) in a dark room. The micromixer was driven at a driving frequency of 131 kHz by using a function generator.

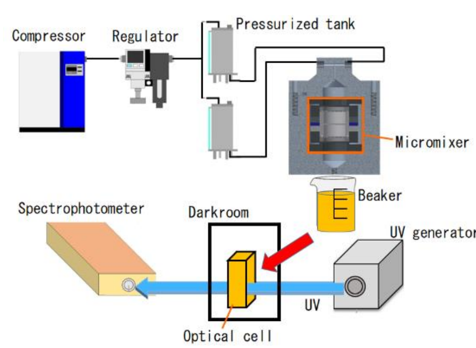


Fig. 6 Experimental setup of Villermaux/Dushman reaction

Figure 7 shows the measurement result of the UV absorbance when the flow rate of the solution was changed with and without ultrasonic vibration. The voltage applied to the fabricated micromixer is fixed at 120 $V_{p-p}$. The lower absorbance value means the higher mixing performance. Figure 7 indicates that mixing performance is improved by giving the ultrasonic vibration. Higher flow rates tend to improve mixing performance. This is probably due to a synergistic effect by the flow and the ultrasonic vibration. Therefore, the ultrasonic vibration is dominant for mixing at the lower flow rate condition. The synergistic effect of the flow and the ultrasonic vibration is both effective at the higher flow rate condition.

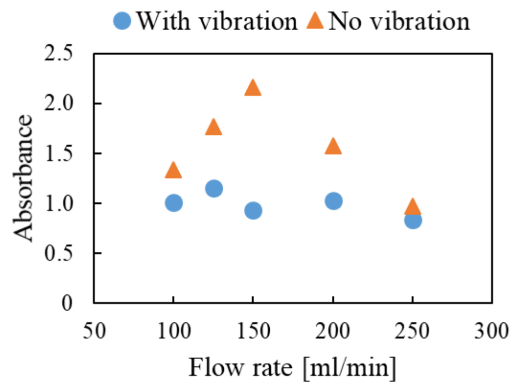


Fig. 7 Relationship between flow rate and UV absorbance when the applied voltage for the micromixer was 120 $V_{p-p}$

Figure 8 shows the measurement result of the UV absorbance when the voltage applied to the fabricated micromixer was changed. The flow rate of the solution was fixed at 200 ml/min. The UV absorbance decreases when the applied voltage increases. In other words, mixing performance of the fabricated micromixer can be improved by increasing vibration speed at the channel plates. Therefore, the mixing performance is further improved by increased vibration speed as shown in Figs. 7 and 8.

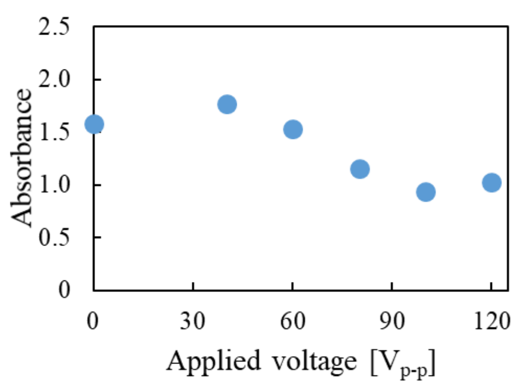


Fig. 8 Relationship between flow rate and UV absorbance when the flow rate was 200 ml/min

## IV. CONCLUSION

In this study, a new cylindrical micromixer which can be used under high pressure conditions has been proposed and fabricated. In the proposed micromixer, microchannel plates are oscillated ultrasonically in torsional direction. The fabricated micromixer was evaluated by conducting Villermux/Dushman reaction. The result shows that the ultrasonic vibration in torsional direction is effective to improve the mixing performance.

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