Mixing Characteristics of High Viscous Fluid by a Multi-Holed Static Mixer

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Abstract

The mixing characteristics of a multi-holed static mixer have been studied for high viscous fluid. A multi-holed static mixer composed of five pairs of 4- and 5-hole elements. Each hole has the diameter of 6mm at its inlet and outlet, d[m], and the size of straight part of the hole, a[m], was changed in two steps of 2mm and 5mm. The fluid viscosity and fluid velocity are also changed as parameters. Flow visualization experiments in a test pipe with 18mm diameter was performed in order to observe the occupation ratio of dyed fluid, which is injected from the nozzle with 4mm diameter mounted in the upstream of the static mixer and flows through the static mixer, and to reveal the mixing mechanism of the present system. From the results, it is found that the Reynolds number based on the mean velocity in the 4 hole element and the hole size, Re_a[-], divided by a contraction ratio of the hole, a/d, well correlates the mixing and pressure loss characteristics. From the flow visualization in the hole, it is observed that the twin vortices are formed and that they have a spiral structure. This flow structure is intensified by the increase of the velocity. Then, this is concluded to be the mixing mechanism of the present system.

Introduction

In order to save energy and space in mixing process and to realize high mixing efficiency, static mixers have been often applied in chemical industrial processes. Static mixers commonly used realize division and twist processes in a pipe flow without additional power. Then, industrial process becomes very simple. Until now, some types of static mixers have been suggested such as Kinetics(Berkman & Calabrese, 1988; Szalai & Muzzio, 2003; Wageningen, Mudde, van den Akker, 2004) Sulzer(Zalc, Szalai, Muzzio & Jaffer, 2002; Das, Legrand, Morancais & Carnelle, 2005) and Lightnin(Heyouni, Roustan & Do-Quand, 2002). They have been applied in many situation of mixing and many reports have been published on their efficiencies and mixing characteristics(Hobbs & Muzzio, 1997). However, the efficiency of such a static mixer seriously depends on fluid properties, pipe size and streamwise space. Additionally, it is very difficult for such static mixers to respond various situations because they have very complex structures inside in order to realize effective mixing. There is no new trend mixer suggested until now due to this difficulty.

In this paper, a multi-holed static mixer with a simple structure is treated. This new type of a static mixer consists of some simple elements only with several holes tapered at the inlet and outlet in a simple disk-shaped plate mounted normal to a flow. The effective mixing is realized by a combination of these elements. This has a large advantage on scale-up problems because of its simplicity of the structure. Especially, the effective mixing in the core region of a pipe can be expected. The previous static mixers such as Kinetics mainly use large-scale twist flows, and then, such mixers is effective for outer region in a pipe. On the other hand, it is very difficult for such twist-type mixers to mix the core region. The present type mixers can effectively deriver fluid from inner region to outer and reversely.

This paper reveals its efficiency for high viscous fluid mixing by flow visualization experiments and image processing methods. Especially, the effects of fluid viscosity, the velocity through the hole and the hole-size of the elements on the occupation ratio of dyed tracer in the test cross-section are investigated carefully. From the results, the mixing characteristics and the mixing mechanism of the multi-holed static mixer is discussed.

Experimental Methods

Material

As working fluid, starch syrup aqueous solution was adopted. The Newtonian viscosity of the fluid, μ[Pa・s], was changed in three steps of 0.0978, 0.209 and 0.367 Pa・s by adjusting the concentration of starch syrup in solution. The fluid temperature ranged from 24 to 26^{o}C by room temperature control in the present experiments. The viscosity of the fluid was checked before and after each flow visualization experiment.

Static mixer elements

Figure 1 shows the configuration of the static mixer elements used in this study. A static mixer treated in this paper consists of a pair of elements with 4 and 5 holes. Each element has 5mm thickness and 18mm diameter as fitted to the test pipe diameter, D[m]. The holes of these elements were positioned in a coaxial manner, but with different distance from the center axis of the element as each outlet hole contacts with each other. Each hole has 45 degree taper at the inlet and the outlet as the inlet and outlet diameters of the respective holes, d[m], were set at 6mm. The axis angle of each outer hole was fixed at 45 degree in each pair set. In this pair, 3 or 4 times of 18.2% area per one hole of inlet and outlet holes is overlapped. Each element is made of transparent acrylic resin for flow visualization experiments.

Five pairs of elements, which were totally 10 elements, were applied in a line. The hole-size of each element was set uniform in a respective combination. The hole-size, a[mm], of each combination was changed in two steps of 2 and 5 mm in diameter. These combinations of mixing systems are called 2/6 and 5/6 systems in this paper, respectively. The hole open ratio to the cross-sectional area in flow path is 6.18 % in 4 hole section and 4.96% in 5 hole section for 2/6 system, and 38.7% and 30.9% in 5/6 system.

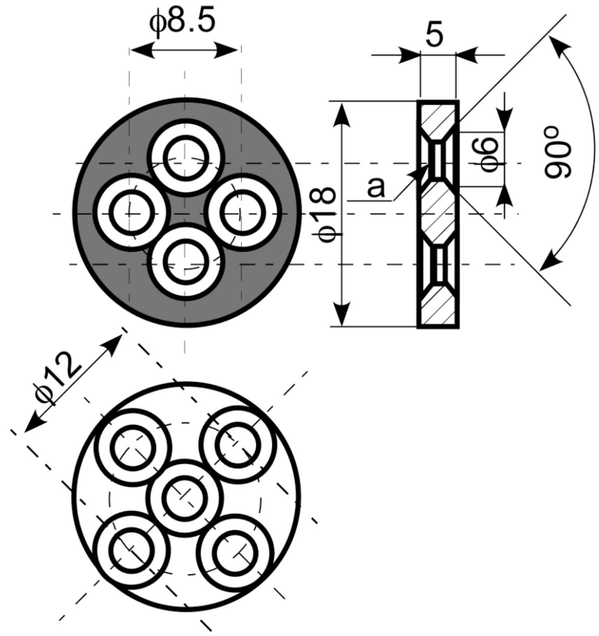


Fig.1 Configuration of static mixer elements

Flow System

In this study, flow visualization experiments were performed in order to investigate the mixing characteristics and the mixing mechanism. Figure 2 shows the schematic view of flow system applied for this study.

The combined static mixer mentioned above was mounted in experimental flow apparatus, which consists of a reservoir tank, a pump, a tracer injection part, a test section and an observation window. The size of the test straight pipe, D[m], was set at 18mm diameter.

Flow visualization experiments for investigating mixing characteristics were performed at a cross-section downstream of the static mixer. The test cross-section was located at 0.07m downstream of the end of the static mixer and a slit light with 5mm width was inserted there from the outside of the test pipe. The dyed tracer fluid whose viscosity was set at the same as the bulk flow viscosity was inserted from a nozzle installed at a center axis of the test pipe. The dyed fluid is injected from the tank pressurized by nitrogen gas as the velocity of tracer fluid takes the same value as the bulk fluid velocity. The tracer injection nozzle with 4mm diameter was mounted at

0.07m upstream of the inlet of the static mixer in the present experiments. As the dyed tracer, uranine was used for the experiments to measure the tracer occupation ratio mentioned in the next section.

Digital photos of the test cross-section were taken from an observation window at the downstream end of the test pipe. By using of an image processing method as mentioned in the next section, the occupation area of tracer dye was calculated by a computer.

For the experiments studying mixing mechanism, micro-size air bubbles were used as tracer. The bubbles were inserted from the reservoir tank to the main pipe flow. The slit light was inserted to a 5-hole element of 4th pair. Digital photo was also taken from the observation window at the downstream end of the test pipe. The side view of the static mixer was also observed. In this experiment, micro-size bubbles were also used as tracer.

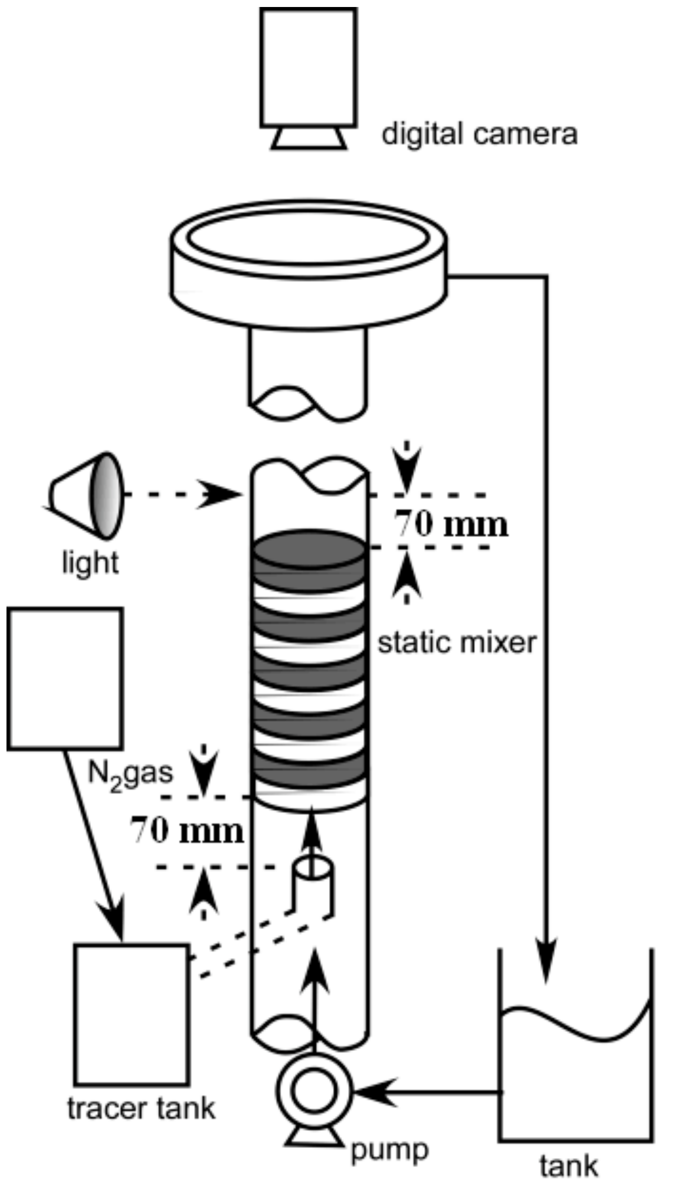


Fig.2 Experimental apparatus

The bulk velocity was controlled by an inverter of pump and ranged from 0.0305 to 0.45m/s. In these conditions, bulk Reynolds number, Re_D[-], defined by the following equation ranged from 4 to 73.

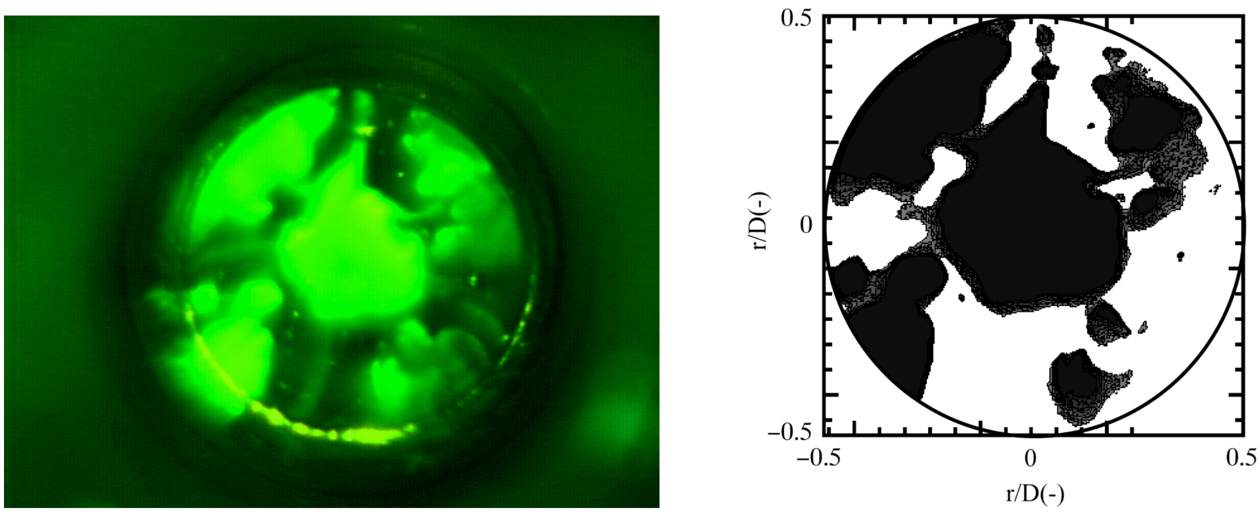
$$\mathrm{Re}_D = \frac{\rho U_m D}{\mu} \tag{1}$$

Here, U_m[m/s] and ρ[kg/m^3] are bulk mean velocity in the test pipe and fluid density, respectively. In this paper, hole Reynolds number, Re_a[-], defined by the following equation are also used as a parameter.

$$\mathrm{Re}_a = \frac{\rho U_a a}{\mu} \tag{2}$$

Here, U_a[m/s] is the mean velocity in 4-hole element.

Image processing method



(a) Original Photo (b) Processed Image

Fig.3 An example of image processing

The photo image taken by the method mentioned above was processed with an image processing method. An example of the photo images of dye expanding in a pipe after the mixing is shown in Figure 3(a). As shown in this photo, the original photo image includes contamination of light reflection from pipe walls. Then, the boundary of dyed area is not clear as shown in the figure. In this paper, the area that has 50% intensity of the maximum brightness of dye image in each photo is defined as the tracer occupation area. Figure 3(b) shows the brightness contour corresponding to the photo shown in Fig. 3(a). In this figure, r [m] is radial coordinate, and the area having the brightness more than 50% intensity of the maximum value is divided to 20 regions. This processed image will be mainly discussed in the followings.

Through this process, the tracer occupation ratio, R_A[-], defined in the following.

$$R_A = \frac{4A_T}{\pi D^2} \tag{3}$$

Here, A_T[m^2] is the dyed area defined as mentioned above in the test cross-section. This occupation ratio of dyed area in the test cross-section for each case was investigated as an evaluation index of mixing characteristics in this paper.

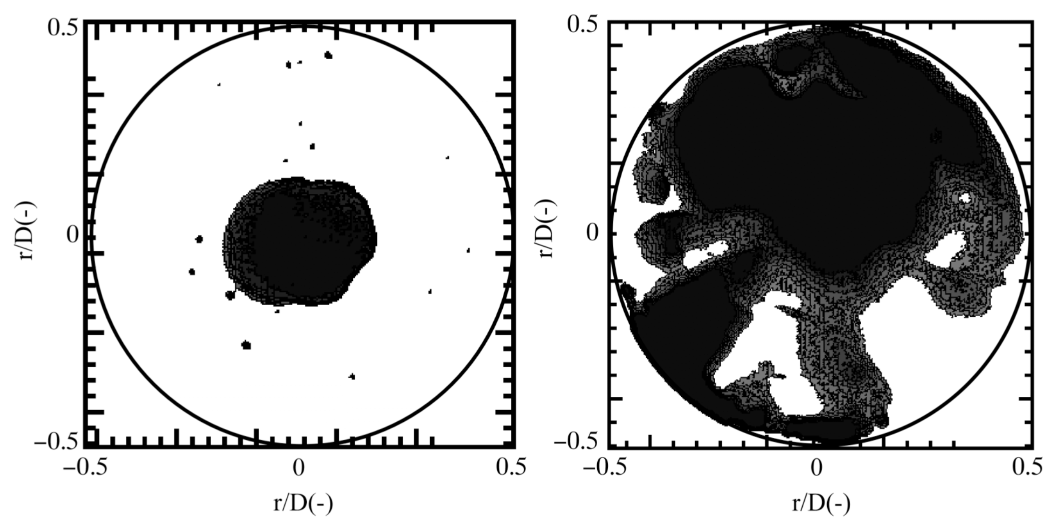
The gyration radius of dyed area was also calculated as a standard deviation around the centroid of dyed area, r_g[m], in this study. The gyration radius, σ[-], normalized by the pipe radius, r_D[m], is defined by the following equation.

$$\sigma = \frac{1}{r_D}\sqrt{\frac{1}{N}\sum\left(r - r_g\right)^2} \tag{4}$$

Here, N[-] and r[m] are the number of dyed pixels and radial position of dyed pixels, respectively. This indicates the expansion manner of dye.

Results and discussion

Effect of flow rate and viscosity



(a) without a Mixer (b) with a Mixer

Figure 4 Tracer distributions without and with the mixer

In the first of all, the effects of the existence of the static mixer and of flow rate will be discussed.

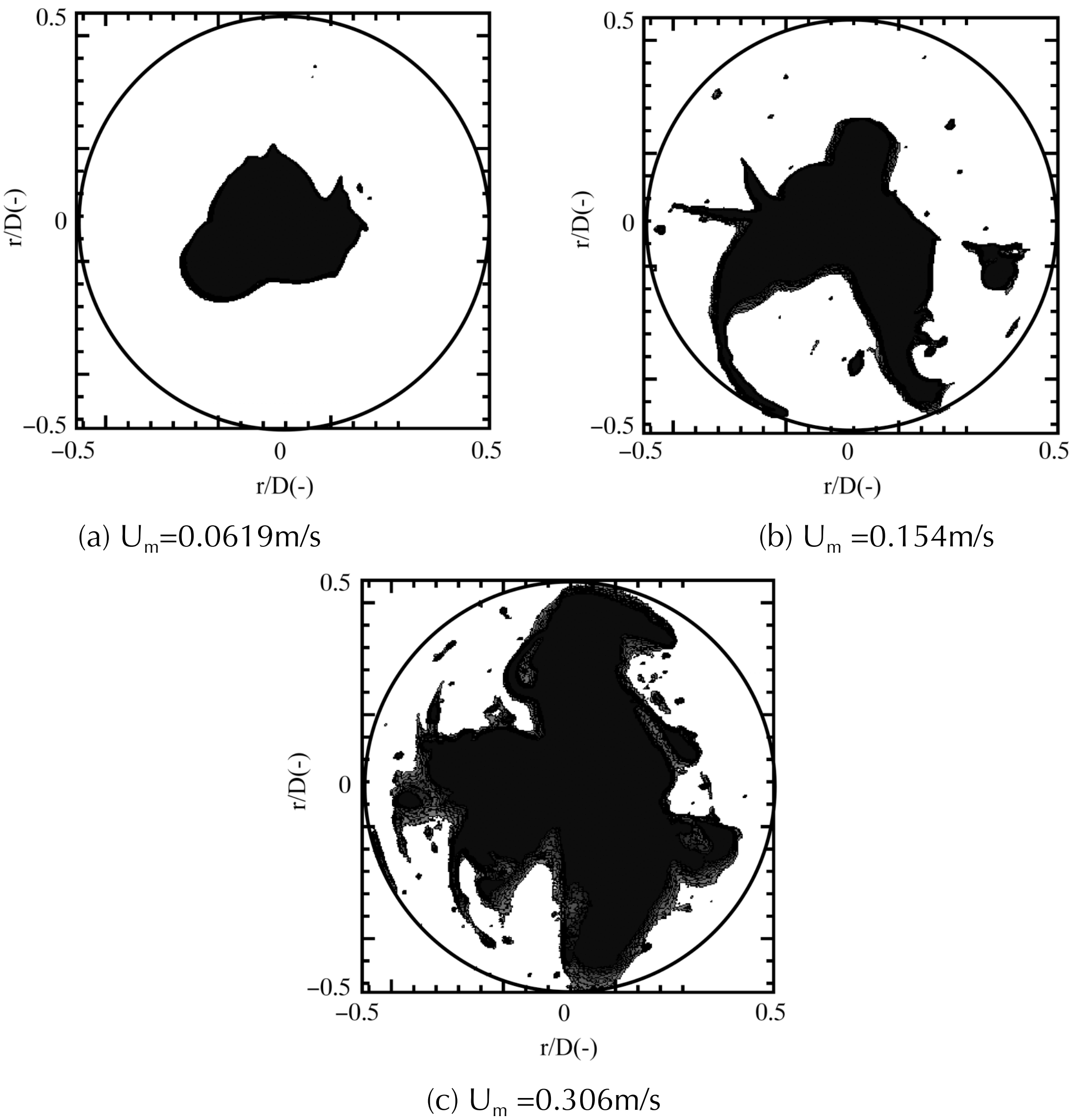
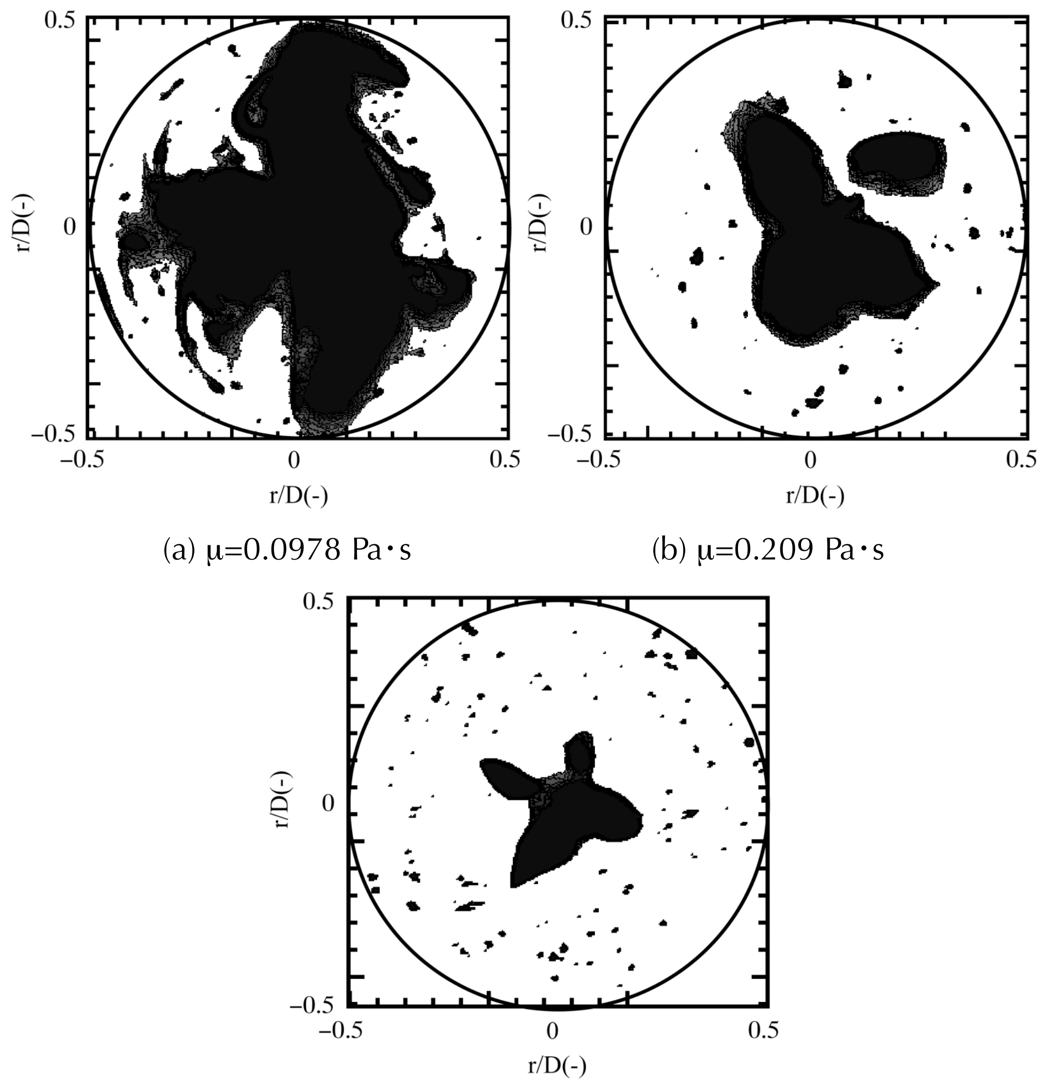


Figure 5 Effect of bulk velocity on tracer distributions at μ=0.0978 Pa·s

Figure 4(a) and (b) shows the processed images in the cases without and with the static mixer of 5/6 system. From this figure, the dyed area in the case without a static mixer shows a round shape but is slightly expanded by diffusion from 4.93% of the original tracer occupation ratio up to 11.2% in this case. This diffusion effect depends on the bulk velocity and the fluid viscosity, but the tracer occupation ratio at the test cross-section remains within 10% to 13% in the present study. On the other hand, the existence of a static mixer causes marked expansion of dyed area in a pipe. The occupation ratio of dyed area in the test cross-section becomes 78.4% by the existence of the static mixer. This value is found to be meaningful compared with the result without the mixer.

Figure 5(a), (b) and (c) show the results with the static mixer of 5/6 system in the cases when the bulk velocities, U_m, are 0.0617, 0.154 and 0.306 m/s, respectively, when the viscosity is fixed at 0.0978 Pa･s. From this figure, the dye area increases with bulk velocity. The respective tracer occupation ratios are 13.8, 40% and 55.3%. As, in this paper, the measuring cross-section was fixed at 0.07m from the static mixer, this result indicates that the mixing enhancement by inertia becomes larger in spite of decrease of the diffusion thickness in the present condition.



(a) μ=0.0978 Pa･s (b) μ=0.209 Pa･s

(c) μ=0.367 Pa･s

Figure 6 Effect of viscosity on tracer distribution at U_m=0.306m/s

From this figure, it is also found that the dyed area expands in the radial direction along the axis of outer holes when the effective mixing can be observed such as in the case of U_m=0.306m/s. This indicates the delivery of fluid from the center to the outer is one of mechanism of the present static mixer.

Figure 6 shows the effect of viscosity in the cases with 5/6 systems, when the bulk velocity is kept constant at 0.306m/s. In this figure, (a), (b) and (c) are the results in the cases of 0.0978, 0.209 and 0.367 Pa・s, respectively.

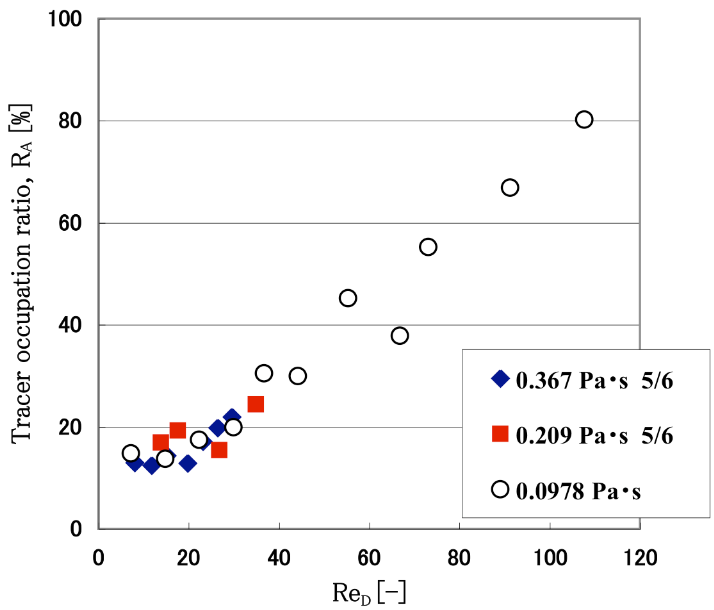


Figure 7 Occupation ratio on bulk Reynolds number

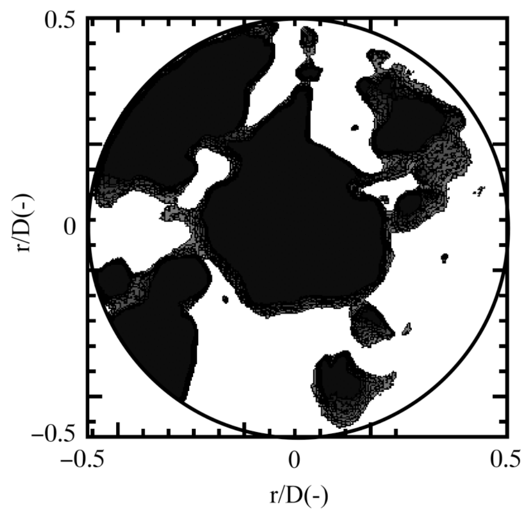
From the figure, the dye area becomes smaller as the viscosity increases. This indicates that the viscous dissipation disturbs the mixing process by the present systems and that the mixing efficiency becomes a function of a kind of Reynolds number.

Figure 7 shows the tracer occupation ratios, R_A[-], against the bulk Reynolds number, Re_D[-], defined with pipe diameter and the bulk mean velocity in a cross-section of the pipe as shown in Equ. (1). From this figure, it is found that the bulk Reynolds number well correlates the occupation ratios in the cases when the hole-size is set uniform.

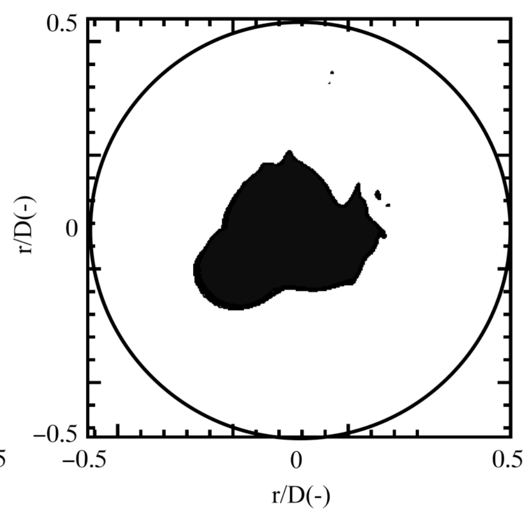
Effect of hole-size

In this section, the effect of hole-size of the static mixer will be discussed. Figure 8(a) and (b) show the results of 2/6 and 5/6 systems, respectively, in the case at the same bulk Reynolds number of 15.

From the figure, it is found that the dyed area becomes larger with the decrease of hole-size in the case when the bulk Reynolds number is kept constant. Figure 9 shows the occupation ratio on the bulk Reynolds number. In this figure, the results in the cases of 5/6 systems are also re-plotted. This figure indicates that the mixing efficiency in each hole-size system is well correlated with bulk Reynolds number, but that the bulk Reynolds number cannot correlate the effect of hole-size. The mixing process in the present static mixer is enhanced in each hole. Then, the mixing efficiency is considered to relate not to the bulk Reynolds number but deeply to relate the hole Reynolds number based on the mean velocity in each hole and hole-size, a, as defined in Equ. (2).



(a) 2/6 system



(b) 5/6 system

Figure 8 Effect of hole-size at Re_D=15 on tracer distribution

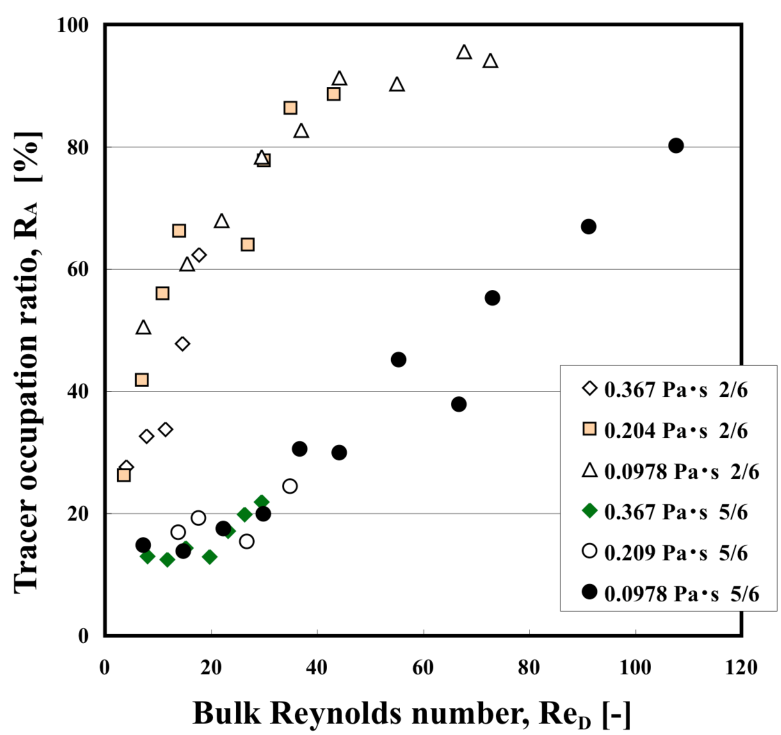
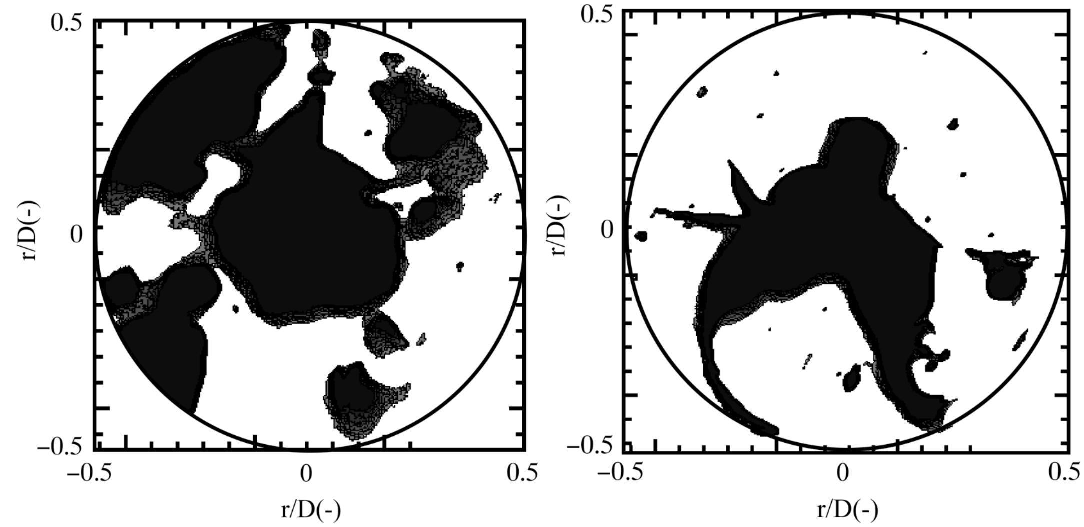


Figure 9 Effect of hole-size on occupation ratio



(a) 2/6 system (b) 5/6 system

Figure 10 Effect of hole-size at Re_a=34 on tracer distribution

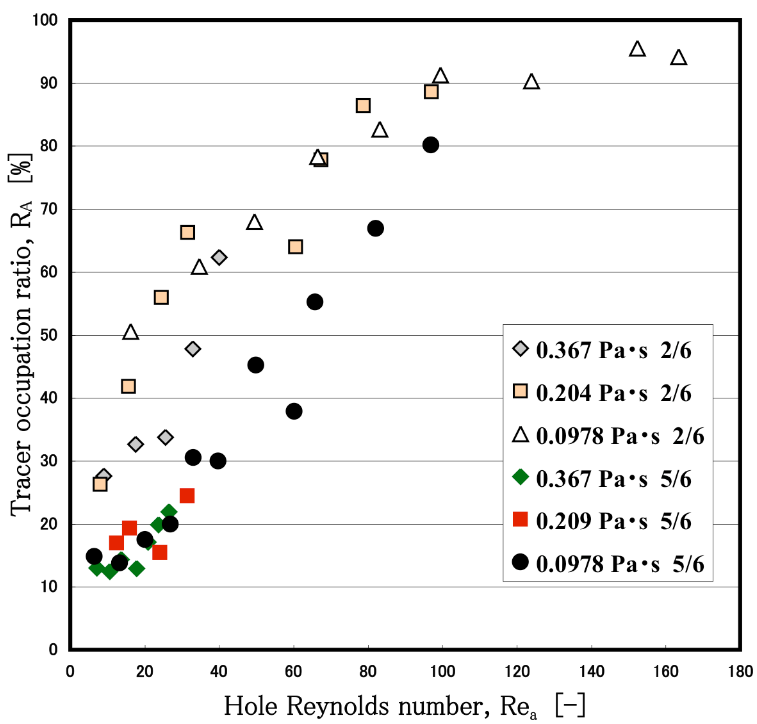


Figure 11 Tracer disribution on hole Reynolds number

Figure 10 shows the comparison of the results between 2/6 and 5/6 systems when the hole Reynolds number, Re_a[-], based on the mean velocity in 4 hole element and hole-size, a, takes the same value of 34 with each other. From this figure, it is that the dye occupation area becomes rather close to each other in the case of the same hole Reynolds number.

Figure 11 shows the occupation ratio on the hole Reynolds number. It is found from this figure that the hole Reynolds number is rather more effective parameter on the mixing by the present system. However, it does not enough correlate the size effect. This is because the hole Reynolds number does not include the effect of the distance between holes. In the present mixing system, it is considered that there exist two mechanisms. One of them is the mixing process in the hole and the other is the delivery process through flow path between holes. The hole Reynolds number is related only to the mixing process in the hole. Then, the correlation with the hole Reynolds number does not sufficiently express the occupation ratio.

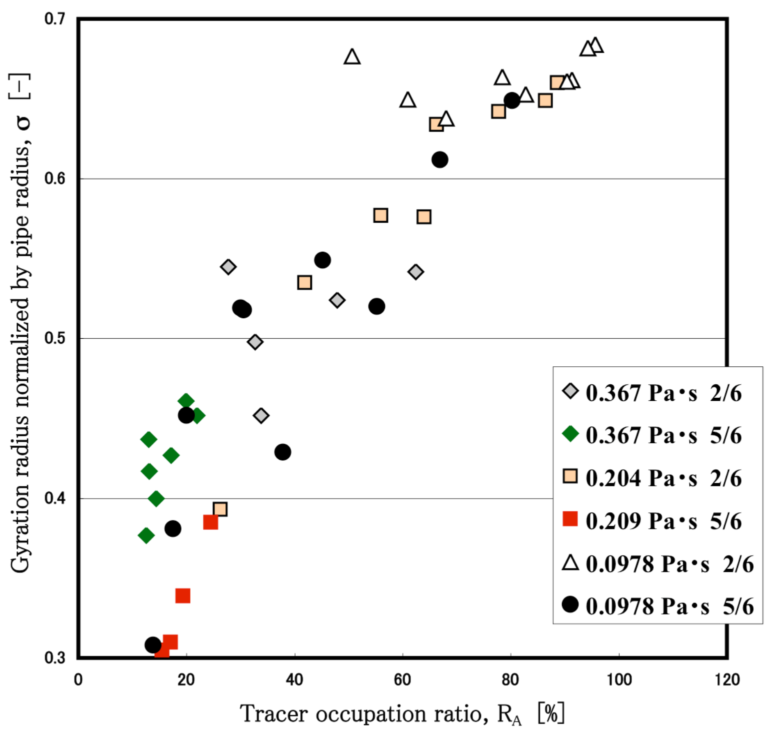


Figure 12 Gyration radius on occupation ratio

Mixing mechanism in the present system

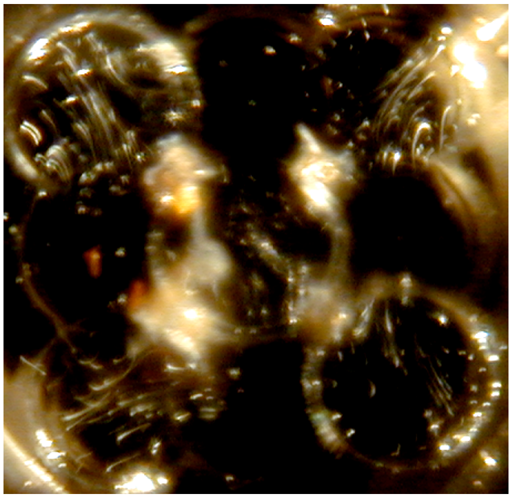
In this section, the mixing process will be discussed.

Figure 12 shows the gyration radius defined by Equ. (4) on the occupation ratio. From this figure, the gyration radius is found to be on one curve, independently of viscosity, velocity and hole size. This indicates that the primary mechanism of the mixing by the present systems is not affected by such parameters, especially by the hole-size of system. This might be because the flow regime is laminar in the present study.

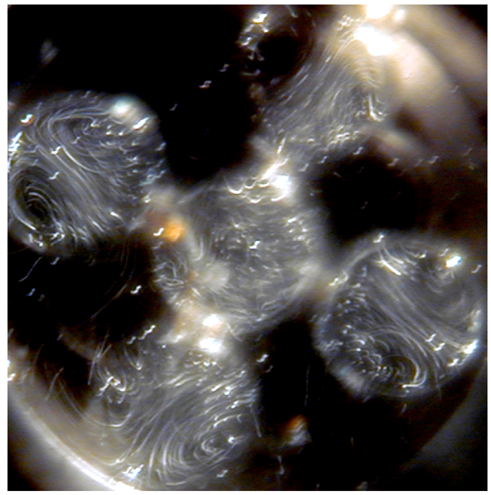
Figure 13 shows the flows in the hole of 4th 5-hole element of 5/6 system, when the viscosity is set at 0.0978 Pa･s. In the figure, (a), (b) and (c) correspond the cases when the bulk velocities are 0.0619, 0.154 and 0.306m/s, respectively.

From this figure, it is observed that the twin vortices are formed in the outer holes of

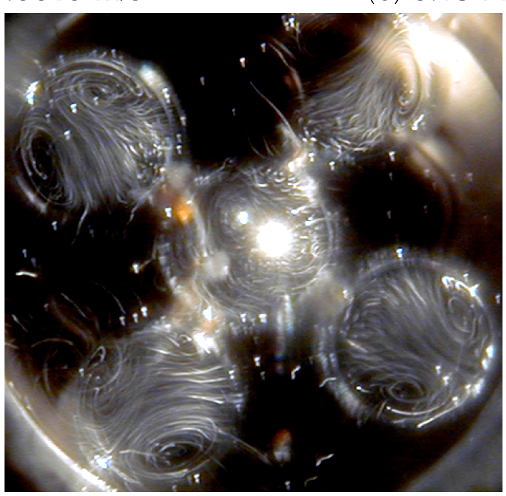
5-hole element when the velocity becomes larger, while there exists no vortices in the case of low bulk velocity when no effective mixing occurs. It is also found that the twin vortices become smaller as the bulk velocity increases, but that its vorticity is intensified by intensification of the jet-like flow from both side holes of 4-hole element to the outer hole of 5-element, which is observed between twin vortices.



(a) 0.0619 m/s



(b) 0.154 m/s



(c) 0.306m/s

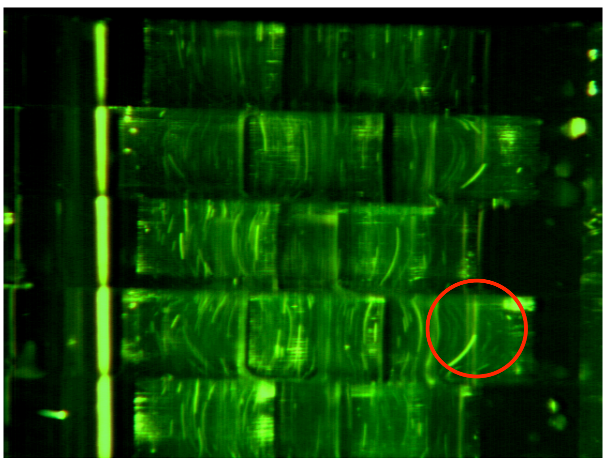
Figure 13 Flow in a hole of 5-hole element

Figure 14 shows the side view in the corresponding cases. These photos show the view of the last 5 elements from the 3rd 4-hole element to the 5th 4-hole element. In this figure, the fluid flows upward. As paying attention to the bubble tracer motion of the outer holes of the 4th 5-hole element (2nd element from the bottom of this figure as marked by a red circle), it is found the tracer follows a spiral curve in the hole when the velocity is large. This spiral period becomes small when the bulk velocity becomes high because the jet-like flow is intensified.

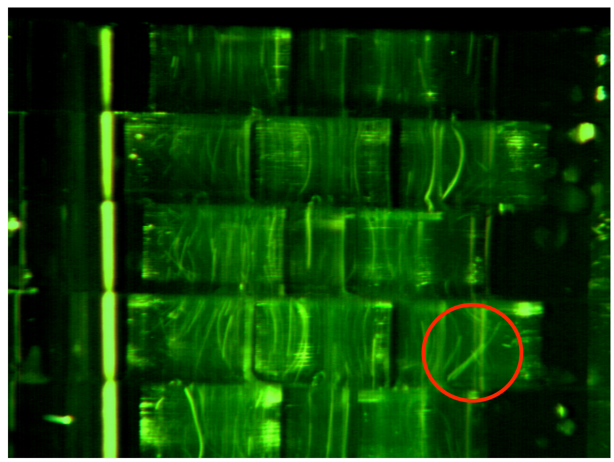
Then, it is concluded that this is one of the main mixing mechanisms of the present system.

The twin vortices observed in the hole are intensified by the hole velocity and the hole inlet diameter but their sizes becomes small with the hole-size. On the other hand, the delivery distance of fluid becomes larger with the hole inlet diameter in the present system. Then, the present mixing process can be assumed to depend on the contraction ratio, a/d.

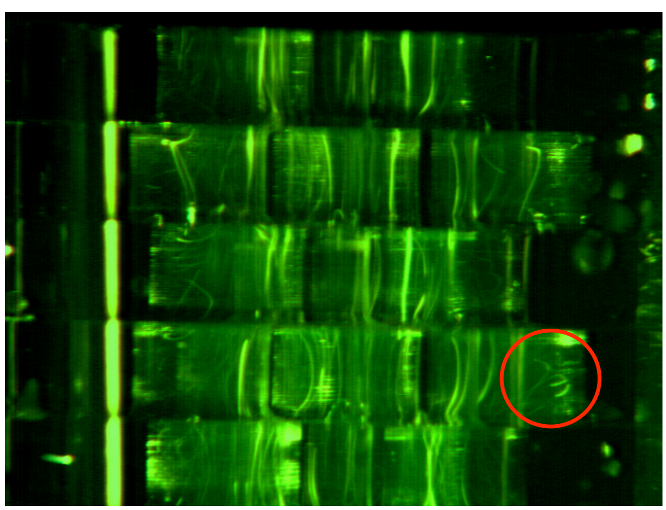
Figure 15 shows the occupation ratio on the hole Reynolds number divided by the contraction ratio. From this figure, it is found that the hole Reynolds number divided the contraction ratio, $Re_a(d/a)$, well correlates the effect of hole-size. In the present system, the hole inlet diameter dominate the overlap area between 4-hole and 5-hole elements. Then, it can be changed only in a very small range. Then, it is unknown that this correlation can be applied for a wider range of hole inlet diameter. However, this correlation at least is concluded to be enough useful in the practical use.



(a) 0.0619m/s



(b) 0.154m/s



(c) 0.306m/s

Figure 14 Side view in static mixer elements

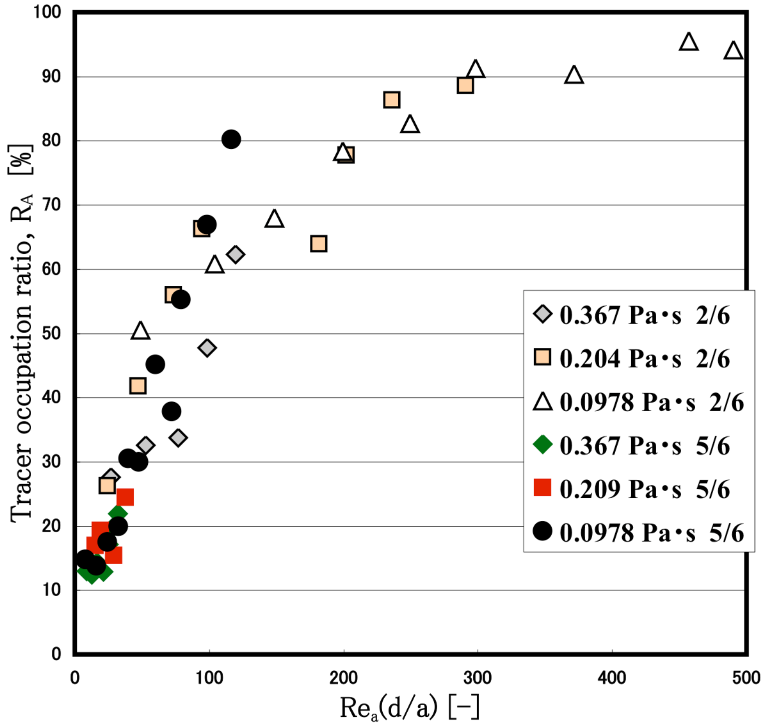


Figure 15 Occupation ratio on $Re_a(d/a)$

Pressure loss coefficient

Finally, the pressure loss penalty will be discussed.

Figure 16 shows the pressure loss coefficient, ζ[-]. The pressure loss coefficient is defined in this study as follows.

$$\varsigma = \frac{\Delta P}{\frac{1}{2}\rho U_a{}^2} \tag{5}$$

Here, ΔP[Pa], U_a[m/s] and ρ[kg/m^3] are pressure loss in the static mixer, the mean velocity in the hole of 4 hole element and fluid density, respectively. The abscissa in the figure is the hole Reynolds number divided by contraction ratio of the hole, $Re_a(d/a)$.

From this figure, it is found that the pressure loss coefficient based on the hole velocity is also well correlated by the hole Reynolds number divided by contraction ratio of the hole. From this, it is concluded that $Re_a(d/a)$ is the primary parameter in this static mixer.

4. Conclusions

The mixing characteristics of a multi-holed static mixer system applied for high viscous fluid have been studied by flow visualization experiments in this study. From the results, the following conclusions have been obtained.

(1) The mixing process is dominated by a parameter of the Reynolds number based on the mean

velocity in a hole and the hole size, divided by the contraction ratio of the hole.

(2) The pressure loss defined with the hole velocity is also well correlated by the same parameter.

(3) The vortices are formed in each hole when the velocity becomes higher. This is the mechanism of the mixing process with the present multi-holed static mixer.

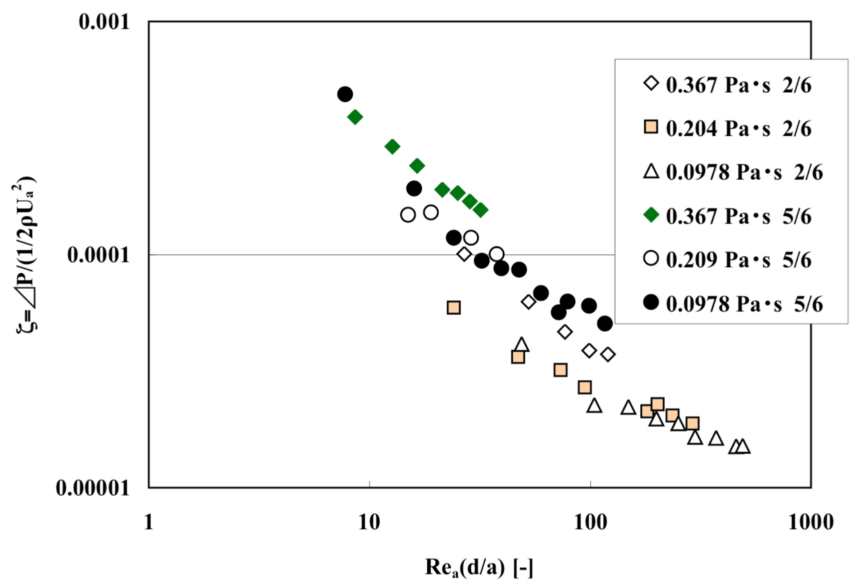


Figure 16 Pressure loss coefficients

Notation

A_T=	tracer occupation area	m^2
a =	hole size	m
D =	pipe diameter	m
d =	hole diameter	m
N =	number of dyed pixels	
R_A =	tracer occupation ratio	
Re_a =	hole Reynolds number	
Re_D =	bulk Reynolds number	
r =	radial coordinate	m
r_D =	radius of a test pipe	m
r_g=	centroid of dyed area	m
U_a =	mean velocity in 4-hole element	m･s-1
U_m=	bulk mean velocity	m･s-1
ΔP=	pressure drop	Pa

ζ= pressure loss coefficient

μ= viscosity Pa・s

ρ= density kg・m^{-3}

σ= gyration radius normalized by pipe radius

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