JET MIXING OF LIQUIDS IN A ROTATING CYLINDRICAL VESSEL

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Jet mixing time of liquids t_M in a rotating vessel was observed from the pulse response curve of electric conductivity. The ratio of mixing time to mean residence time, t_M/t_R, was well correlated with the dimensionless angular velocity Ω^*, which was equal to the ratio of tangential velocity at the vessel wall to jet velocity at the nozzle hole. For the present experimental conditions, t_M/t_R showed a minimum value of about 0.2 regardless of jet nozzle angle, and the minimum value appeared at $\Omega^*=0.2$–0.3. The observed response curves were classified into five types by shape. The transition of shape to shape depended only on Ω^* regardless of jet flow rate, and the transition point agreed well with the Ω^* value giving the minimum value of t_M/t_R. The ratio of mixing time to apparent circulation time, t_M/t_{AC}, was 5 to 9 for the non-rotating condition ($\Omega^*=0$), and these values were almost the same, 5 to 6, for the ratio of mixing time to circulation time in an agitated vessel with impeller. t_M/t_{AC} increases stepwise with increase of Ω^*, where the position of th step agrees with that of the transition of the shape of response curve.

Introduction

The secondary circulation flow induced with the primary tangential flow in an agitated vessel with impeller plays an important role in mixing processes, though the circulation flow is very weak compared with the tangential one. Thus the effective transformation of primary tangential flow into secondary circulation flow is very important in mixing equipment. On the other hand, circulation flow can be provided directly by using a jet, and several types of jet mixing vessels have been developed for use in chemical process plants. Studies of liquid jet mixing have been conducted by many investigators[1-3,7-12]. The characteristics of jet mixing, however, could not be compared directly with those of impeller mixing because of the difference of flow patterns in the vessels.

A jet mixing vessel can create a flow pattern similar to that in an agitated vessel with paddle impeller. Tangential flow and circulation flow can be provided by using a jet nozzle fixed at the center of a cylindrical vessel, where the circulation flow can be controlled by varying the angle of the jet nozzle and the jet flow rate, and the tangential flow can be controlled by rotating the cylindrical vessel or the jet nozzle.

This paper deals with the measurement of jet mixing time in a rotating vessel, and elucidates the effects of jet flow rate, number of jet nozzles, angle of nozzle

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and rotation speed of the vessel on the mixing time.

1. Experimental

A schematic diagram of the experimental apparatus and details of the rotating vessel are shown in **Figs. 1** and **2**, respectively. The vessel, an acrylic resin cylinder, is 30 cm in inner diameter (I.D.) and 30 cm in height. The inner cylinder, 8 cm in outer diameter, is made of acrylic resin and has two pairs of injection and suction nozzle holes, 0.7 cm I.D. and 1.4 cm I.D., respectively, which are set horizontally 10 cm above the bottom. The injection nozzle holes are directed to 0, 15, 30 or 45 degrees from the radial direction, whereas the suction nozzle hole is directed to the radial direction. Each pair of injection and suction nozzle holes is connected to a polyvinyl chloride tube via a centrifugal pump and a rotameter. The liquid used is city water, which is poured into the vessel up to a liquid height of 20 cm. The liquid volume in the jet circulation system is about 380 cm^3 and is very small compared with the vessel liquid volume of 13,000 cm^3. An electric conductivity cell is set in the polyvinyl chloride tube of the circulation system.

For the measurement of mixing time t_M, sodium chloride aqueous solution is injected through a tracer feed line into the vessel at very short intervals by using three-way valves. From this moment, the fluctuation of electric conductivity of recirculating liquid is observed with a conductivity meter and a mV recorder. The mixing time is obtained as the time at which the fluctuation of electric conductivity decays less than 1% of converged electric conductivity. Liquid temperature was room temperature and was constant within $\pm 0.5°C$ through the experiment, so the variation of electric conductivity with temperature can be neglected.

The rotation speed was 0 to 60 min^{-1} and the jet flow rate was 2.0 to 6.2 l/min. For the two-jet recirculation system, the jet flow rates of the two nozzles were the same.

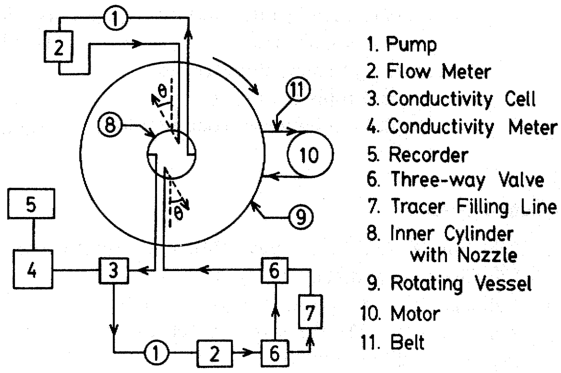

Fig. 1. Schematic diagram of experimental apparatus

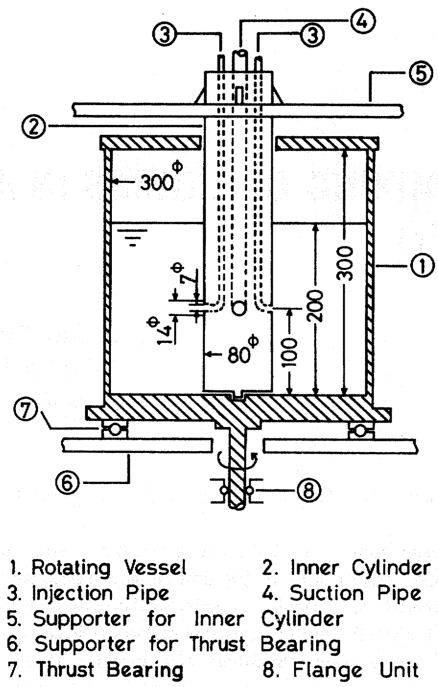

Fig. 2. Details of rotating vessel

2. Results and Discussion

2.1 Determination of mixing time

The amplitude of fluctuations of the electric conductivity of recirculating liquid with respect to time seemed to decay exponentially with time. Therefore, the variation of the amplitude at peak or valley with time could be expressed by the following equation.

$$\ln A = B - Kt \qquad (1)$$

where the amplitude, A, was normalized with the converged electric conductivity after almost complete mixing. The constants B and K were obtained by using the least squares method. Khang and Levenspiel[6] proposed the following model equation.

$$\ln A = \ln 2 - K't \qquad (K' = 2\pi^2\sigma^2/t_R) \qquad (2)$$

The observed variation of amplitude seemed to satisfy both Eqs. (1) and (2). Thereafter, Eq. (1) was adopted for the determination of the mixing time.

The mixing time t_M was decided mathematically as the time at which the amplitude in Eq. (1) becomes 0.01. The appearent circulation time t_{AC} was observed as the average time of intervals from peak to peak, or valley to valley. The mean residence time t_R is defined as

$$t_R = V/nQ \qquad (3)$$

where V is the volume of the liquid in the vessel, n the number of nozzles, and Q the jet flow rate per nozzle.

2.2 Correlation of mixing time

The observed mixing time in the non-rotating condition was correlated with nozzle Reynolds number in the same manner as that of Maruyama *et* *al.*[8] The observed mixing time showed the same Reynolds number dependency of the mixing time as that reported by Maruyama *et al.* and was almost independent of the nozzle Reynolds number in the range of $Re>8000$. Thereafter, the observed data of the mixing time at $Re>8000$ were only used in studying the mixing characteristics. The observed mixing time was also compared with the mixing time measured by another tracer injection method[4], in which tracer was injected from the free surface of vessel liquid. The difference between the two methods seemed to have little effect on the mixing time.

In **Fig. 3** the ratio of the mixing time to the mean residence time, t_M/t_R, in a rotating vessel, which is modified to $t_M/t_R n^{0.76}$ for the n-jet nozzle system, is correlated with dimensionless angular velocity, Ω^*. The correction factor $n^{0.76}$ for the ordinate was determined empirically in order that the observed dimensionless mixing times for both one- and two-jet nozzle systems would coincide well with each other. The Ω^* is defined as

$$\Omega^* = (\omega D/2)/\sqrt{n}\, u \qquad (4)$$

where ω is the angular velocity of the rotating vessel, n is the number of nozzle holes and u is the mean velocity of liquid at the jet nozzle hole and is equal to $4Q/\pi d_n^2$. The Ω^* is identical with the square root of the ratio of the kinetic energy at the rotating vessel wall to that at the jet nozzle holes, i.e.,

$$\Omega^* = \left\{\frac{1}{2}\rho\left(\frac{\omega D}{2}\right)^2 \Big/ n\left(\frac{1}{2}\rho u^2\right)\right\}^{1/2} \qquad (5)$$

The resulting correlation curve gives one or two local minimums. In the cases of 0- and 15-degree jet nozzle angle, the local minimum dimensionless mixing time appears only at one point, whereas in the cases of 30- and 45- degrees it appears at two points. Here the point giving the local minimum at the larger Ω^* is referred to as "primary" and that at the smaller value as "secondary". This figure shows that the circulation flow induced with a jet and the tangential flow with rotation of a vessel overlap each other well, leading to a positive cooperative effect on shortening the mixing time at these points.

2.3 Local minimum mixing time

Based on the results in Fig. 3, the local minimum dimensionless mixing times are plotted against the jet nozzle angle in **Fig. 4**. For the present experimental conditions it is shown that the local minimum dimensionless mixing time, especially that of the primary minimum, is about 0.2 and its value is almost independent of the jet nozzle angle. This value was also obtained in the non-rotating condition with the jet nozzle angle of 0°.

The dimensionless angular velocities giving the local minimum mixing time, Ω^*_{min}, are correlated with the

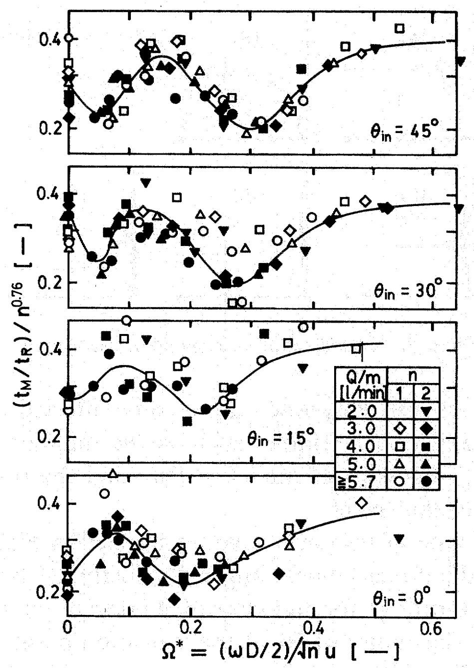

Fig. 3. Mixing time in a rotating vessel

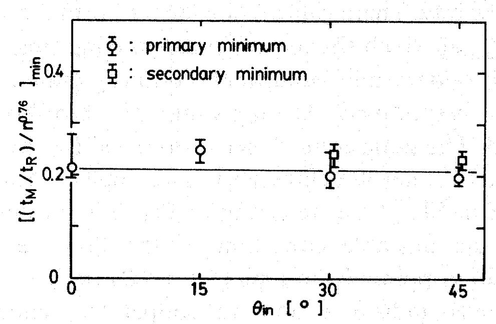

Fig. 4. Local minimum mixing time in a rotating vessel

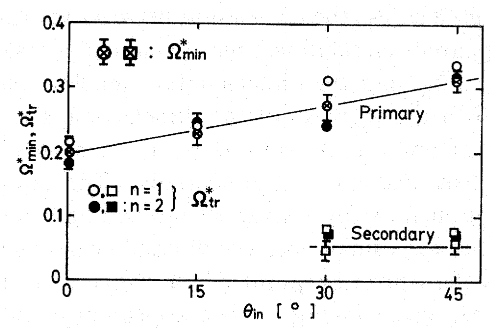

Fig. 5. Dimensionless angular velocity giving local minimum mixing time and that at transition of response curve shape

jet nozzle angle in **Fig. 5**. With the increase of the angle, the primary dimensionless angular velocity increases slightly from 0.2 to 0.3, whereas the secondary one is almost constant at 0.05.

2.4 Classification of response curve

Figure 6 shows the classification of the typical response curve shapes in electric conductivity measurements. They are classified into five types. The

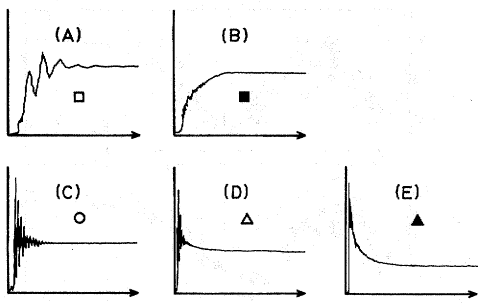

Fig. 6. Classification of response curve shapes

shape of the response curve was affected by a combination of variables such as the number of jet nozzles, the angle of the jet nozzles and the rotation speed of the vessel.

The type of response curve is mapped in **Fig. 7** by using the dimensionless angular velocity Ω^* and the jet flow rate Q for the case of 45-degree jet nozzle angle. The values of Ω^* at the transition points from type (B) to (C) and from type (C) to (D), Ω^*_{tr}, are roughly 0.08 and 0.33, respectively, regardless of the jet flow rate. These values coincide well with the values of Ω^*_{min} at which the dimensionless mixing time takes the secondary minimum or the primary minimum in Fig. 3, respectively. The Ω^*_{tr} values are also shown in Fig. 5. The same coincidence is obtained for the cases of 0-, 15- and 30-degree jet nozzle angles. From the result in Fig. 3 and referring to Fig. 6 it is estimated that the unstable condition of the flow near the transition points from type (C) to (D) or type (B) to (C) may induce a positive cooperative effect on shortening the mixing time.

2.5 Mixing time and appearent circulation time

Figure 8 shows the correlation between the ratio of the apparent circulation time to the mean residence time, t_{AC}/t_R, and the dimensionless angular velocity, Ω^*. With the increase of the dimensionless angular velocity from zero, the value of t_{AC}/t_R increases slightly and then decreases exponentially. The apparent circulation time for a large jet nozzle angle is larger than that for a small one. The dotted line in this figure shows the transition point of the shape of response curve Ω^*_{tr} given in Fig. 5. The appearent circulation time is considered to agree with the real circulation time t_C at the smaller value of Ω^*. At the larger value of Ω^* it may show the residence time for the short-pass induced with tangential flow, in which case it is referred to as "short-pass time".

The ratio of the mixing time to the apparent circulation time, t_M/t_{AC}, is correlated with the dimensionless angular velocity in **Fig. 9**. The ratio for the non-rotating condition ($\Omega^*=0$) is roughly in the range of 5 to 9 for 30° and 45° jet nozzle angles, and almost agrees with the value of 5 to 6 for the ratio of mixing time to circulation time in an agitated vessel

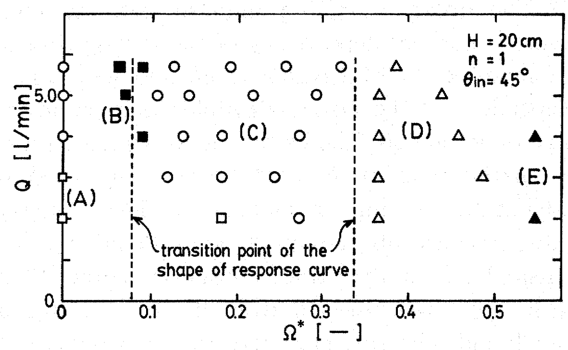

Fig. 7. Classification map of the shape of response curve

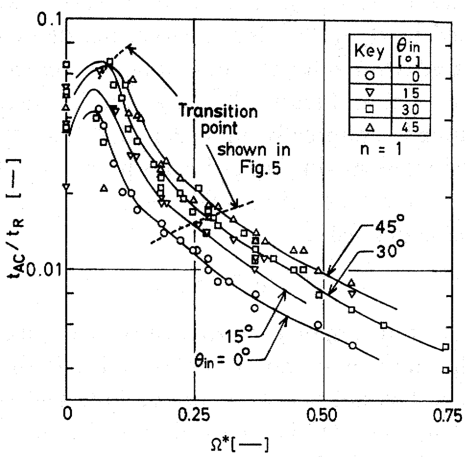

Fig. 8. Apparent circulation time

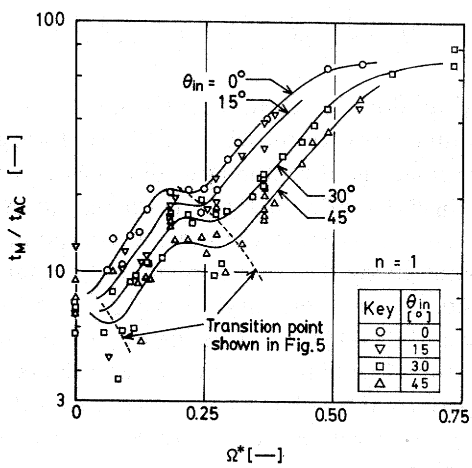

Fig. 9. Ratio of mixing time to apparent circulation time

with impeller[5]. The ratio t_M/t_{AC} increases stepwise with the increase of the dimensionless angular velocity, where the position of the step is roughly equal to the transition point of the shape of response curve shown in Fig. 5. The increase of t_M/t_{AC} with the increase of Ω^* is considered to be due to the gradual transition of t_{AC} from the real circulation time to short-pass time and/or due to the decrease of the jet mixing zone with the growth of the solid-like rotating zone near the wall of the rotating vessel at higher rotating speed.

Conclusion

Jet mixing time of liquids in a rotating vessel was measured by using the pulse response method of electric conductivity, and it correlated well with jet flow rate, angle of nozzle, number of nozzles and rotation speed of the vessel. For the present experimental conditions the dimensionless mixing time, i.e., the ratio of mixing time to mean residence time, showed a minimum value of about 0.2 regardless of jet nozzle angle, and the minimum value appeared at 0.2–0.3 of the dimensionless angular velocity, which is the ratio of the tangential velocity at the rotating vessel wall to the jet velocity at the nozzle holes.

The observed response curves of electric conductivity were classified into five types by shape. The shape depended only on the dimensionless angular velocity, regardless of the jet flow rate. The transition point of the shape agrees well with the dimensionless angular velocity that gives the minimum mixing time.

The ratio of mixing time to apparent circulation time was 5 to 9 for the non-rotating condition, where these values almost agreed with the values of 5 to 6 for the ratio of mixing time to circulation time in an agitated vessel with impeller. The ratio increased stepwise with the increase of the dimensionless angular velocity, the positions of which were almost the same as those of the transition of shape of the response curve.

Acknowledgment

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Nomenclature

A	= amplitude of oscillation curve at peak or valley point	[—]
B	= constant in Eq. (1)	[—]
D	= vessel diameter	[m]
d_n	= diameter of jet nozzle hole	[m]
H	= liquid height	[m]
K	= coefficient in Eq. (1)	[—]
K'	= coefficient in Eq. (2)	[—]
N	= rotating speed of vessel	[s^{-1}]
n	= number of jet nozzles	[—]
Q	= jet flow rate	[l/s]
Re	= nozzle Reynolds number ($\equiv ud_n/\nu$)	[—]
t	= time	[s]
t_{AC}	= apparent circulation time	[s]
t_C	= circulation time	[s]
t_M	= mixing time	[s]
t_R	= residence time ($\equiv V/nQ$)	[s]
u	= mean velocity of liquid at jet nozzle	[m/s]
V	= liquid volume in vessel	[l]
ν	= kinematic viscosity	[m^2/s]
σ	= dimensionless variance of amplitude of response curve	[—]
θ_{in}	= jet nozzle angle to the radial direction	[°]
Ω^*	= dimensionless angular velocity defined by Eq. (4)	[—]
Ω^*_{min}	= dimensionless angular velocity giving local minimum	[—]
Ω^*_{tr}	= dimensionless angular velocity at ransition point of the shape of response curve	[—]
ω	= angular velocity	[rad/s]

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