HEAT TRANSFER IN JET MIXING VESSEL WITH ROTATING NOZZLE AROUND THE VESSEL AXIS

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Measurement of the heat transfer coefficient at the vessel wall was made in a jet mixing vessel with rotating nozzle around the vessel axis. The observed heat transfer coefficient was correlated with power input per unit volume, and the resultant correlation equation at low nozzle rotation speed roughly agreed with that for an agitated vessel with anchor. The heat transfer coefficient at higher nozzle rotation speed decreased with increase of the nozzle rotation speed (i.e., the inner shaft rotation speed) and approached that for coaxial rotating cylinders. Baffle plates in the jet mixing vessel did not improve the heat transfer coefficient.

Introduction

Jet mixing has frequently been used as a mixing process for making a mixture homogeneous in temperature and concentration by intensifying heat transfer and dispersion. Jet mixing time in the conventional jet mixing vessel was measured by many investigators.[2,9-11,17,18,21,24,27] Koh *et al.*[15,16] measured the jet mixing time in both a rotating vessel and a vessel with rotating nozzle, and elucidated the effect of jet flow rate, number of jet nozzles, nozzle angle, baffle plate and rotation speed of the vessel or nozzle shaft on the mixing time. The heat transfer coefficient in a jet mixing vessel, however, has not yet been described.

Heat transfer in a mixing vessel usually occurs through heating or cooling across the vessel wall with jacket or through a submerged coil using suitable heating or cooling media. For agitated vessels many investigators[1,4-8,19,23,26] have correlated the heat transfer coefficient in terms of Nusselt, Reynolds and Prandtl numbers in the turbulent region as

$$Nu = C Re^{2/3} Pr^{1/3} (\mu/\mu_w)^{0.14} \tag{1}$$

However, Eq. (1) cannot be applied directly to the jet mixing vessel. Moo-Young and Cross[19] and Bourne *et al.*[4] correlated the heat transfer coefficient by using the following expression:

$$h(\rho c_p) = K(P_V \mu/\rho^2)^{1/4} Pr^{-2/3} \tag{2}$$

Hiraoka[12] showed that the coefficient K in Eq. (2) was almost independent of the ratio of impeller to vessel diameter in the range of $d/D < 0.9$. Equation (2) can be easily applied to the correlation of heat transfer coefficient in a jet mixing vessel because the jet mixing energy can be easily calculated from the liquid velocity at the jet nozzle.

This paper deals with the measurement of the heat transfer coefficient in a jet mixing vessel with rotating jet nozzle around the vessel axis under various conditions of jet flow rate, nozzle angle, rotation speed of nozzle (i.e. of inner shaft), baffle plates and viscosity, and with the comparison of the heat transfer coefficient with that in an agitated vessel with anchor via Eq. (2).

1. Experimental

A schematic diagram of the experimental apparatus and details of the mixing vessel are shown in **Figs. 1** and **2**, respectively. The vessel is an aluminum cylinder of 29 cm inner diameter (I.D.) and 20 cm height. The vessel height is supplemented 4 cm with an acrylic resin and Teflon cylinder to prevent heat conduction to the top plate. The outer surface of the aluminum vessel is spiralled with grooves of 3.4 mm width, 5 mm depth and 7 mm pitch, for insertion of four heaters, each 3.2 mm in diameter and 6.8 m in length, as heat source. The outside of the vessel is insulated with glass wool, 30 cm in thickness. To measure the temperature of the inner surface of the vessel, four thermocouples are placed in grooves, 0.5 mm deep by 1.4 mm wide, which are at 3, 7, 12 and 17 cm vertically from the vessel top and at 90° intervals to tangential direction.

The acrylic resin inner rotating shaft, 8 cm in outer diameter, has an injection nozzle hole and a suction nozzle hole, 0.7 cm I.D. and 1.4 cm I.D., respectively, set horizontally at 10 cm height above the bottom of

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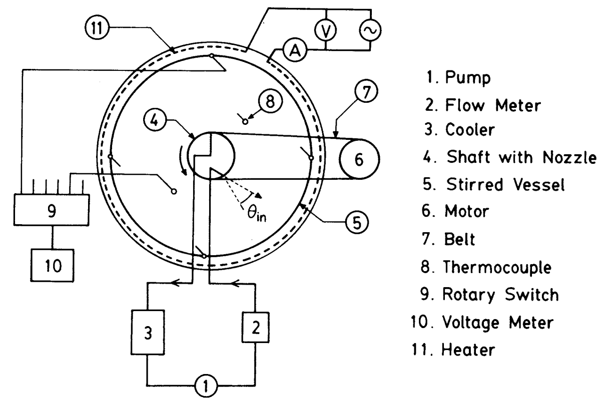

Fig. 1. Schematic diagram of experimental apparatus

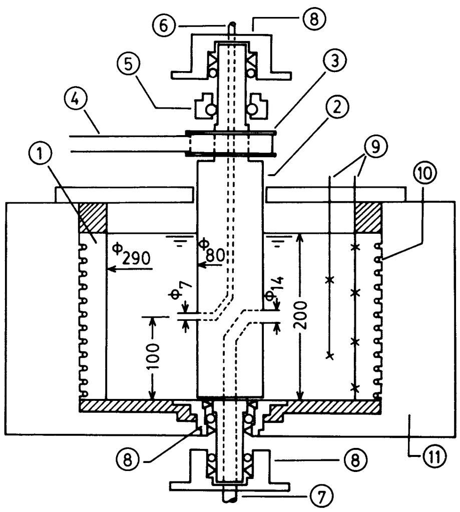

Fig. 2. Details of jet mixing vessel with heater

the vessel. The injection nozzle hole is directed to 0- or 30-degree from the radial direction. These holes are connected to each other with a polyvinyl chloride tube via a liquid cooler, a centrifugal pump and a rotameter. The inner shaft is rotated by a variable-speed motor via gear belt.

The liquids used are deionized water and 40 wt% glycerine aqueous solution, which are poured into the vessel up to a liquid height of 20 cm. To measure bulk liquid temperature, two thermocouples are set at depths of 7 and 14 cm and a radius of 10 cm. For the baffled vessel, four 2.9 cm-wide baffles of acrylic resin were mounted vertically on the inner wall of the vessel in 90° intervals.

The stainless steel anchor used is 26 cm in diameter, 2.9 cm in width and 18 cm in height.

The heat transfer coefficient at the vessel wall, h, is calculated from the heat transfer rate Q_H and the temperature difference between vessel wall and bulk liquid, $T_w - T_b$, as

$$h = Q_H / [A(T_w - T_b)] \tag{3}$$

where A is the heat transfer surface area and Q_H is calculated from measured voltage V and current I as $Q_H = IV$. The values of I and V were read to the first decimal place with an analog ampere meter and a voltage meter, respectively. The observed error in Q_H was about 0.4%. Heat loss was negligible because the heat loss through the insulator was only about 0.5% of input heat.

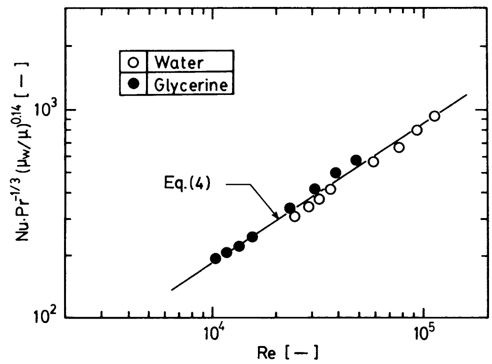

Fig. 3. Heat transfer coefficient for anchor

2. Results and Discussion

Figure 3 shows the heat transfer coefficient for the anchor over the range of impeller Reynolds number, Re, from 10,000 to 113,000. Applying Eq. (1), the experimental data were correlated with

$$Nu = 0.39 Re^{2/3} Pr^{1/3} (\mu/\mu_w)^{0.14} \tag{4}$$

For 40 wt% glycerine viscosity and density were measured with an Ostwald viscometer and a pycnometer, and heat capacity and thermal conductivity were from reference 25. The physical properties of water were from reference 20 and 22. The data for water and 40 wt% glycerine deviated slightly from Eq. (4) to the opposite side. This deviation may be due to the exponent value of Pr. For the correlations stated below, the exponent value of 0.4 for Pr for a narrow range of Pr from 4 to 11 will be used.[3] The constant of 0.39 in Eq. (4) is almost the same value as the 0.38 and 0.35 reported by Uhl[26] and Bourne *et al.*,[4] respectively. This result confirms that the experimental apparatus has no defect in design or setting for executing experiments in heat transfer in a jet mixing vessel.

The heat transfer coefficients for both anchor and jet are correlated with the power input per unit volume P_V in **Fig. 4**, based on the correlation expression of Eq. (2), where the exponent of Pr is corrected from $-2/3$ to -0.6, as mentioned before.

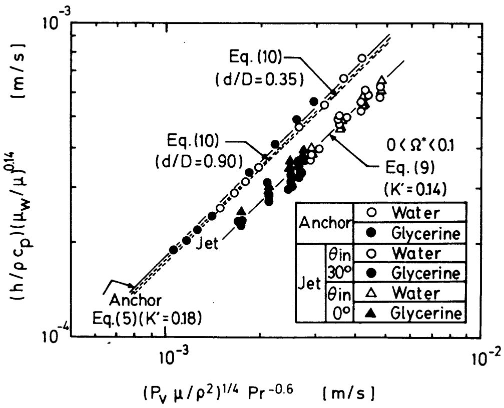

Fig. 4. Heat transfer coefficients for anchor and jet with respect to power input per unit volume

$$\frac{h}{\rho c_p}=K'\left(\frac{P_V\mu}{\rho^2}\right)^{1/4}Pr^{-0.6}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{5}$$

The data used for the jet in this figure are only in the range of low rotation speed $0<\Omega^*<0.1$, where Ω^* is defined by Eq. (11) below. In the present experiments the power input per unit volume, P_V, is defined as

$$P_V=P/\{(\pi/4)(D^2-d_s^2)H\} \tag{6}$$

where D and d_s are the vessel and shaft diameters, respectively. The power input P for the anchor was estimated from the correlation of the friction factor proposed by Hiraoka *et al.*[13] (see **Appendix**). The power input in jet mixing with a rotating nozzle around the vessel axis was defined as

$$P=\frac{1}{2}\rho u^2 Q+P_R \tag{7}$$

neglecting the kinetic energy flowing out from the suction nozzle. P_R was the power input by rotation of the inner shaft and was estimated from the friction factor of Eq. (13) described later, in a similar manner to that for an agitated vessel (refer to Appendix) as follows.

$$P_R=\omega\left\{\frac{f}{2}\rho\left(\omega\frac{d_s}{2}\right)^2\cdot(\pi d_s H)\cdot\left(\frac{d_s}{2}\right)\right\} \tag{8}$$

The influence of P_R on the power input P at low nozzle rotation was very small, i.e., 2% for water and 5% for 40 wt% glycerine at $\Omega^*=0.1$. These percentages had little effect on K': 0.6% for water and 1.3% for 40 wt% glycerine, respectively. The ratio of P_R to P, however, increased to 0.25 for water and 0.39 for 40 wt% glycerine at $\Omega^*=0.27$. For the anchor with setting slope = 1 the least squares method gives 0.18 for the coefficient K', which is similar to values in the literature, where Calderbank and Moo-Young[5] and Bourne *et al.*[4] reported 0.13 and 0.16, respectively. For the jet mixing vessel the data for both 40 wt% glycerine and water lie on a single line regardless of nozzle angle, and the coefficient K' is about 0.14. Then Eq. (9) can be obtained for the jet mixing vessel at low nozzle rotation speed.

$$\frac{h}{\rho c_p}=0.14\left(\frac{P_V\mu}{\rho^2}\right)^{1/4}Pr^{-0.6}\left(\frac{\mu}{\mu_w}\right)^{0.14} \qquad (0<\Omega^*<0.1) \tag{9}$$

The heat transfer coefficient for the jet mixing vessel was slightly smaller than that for the anchor.

For an agitated vessel with impeller, Hiraoka[12] proposed the following expression for the cofficient K in Eq. (2).

$$K=\frac{0.106\sqrt{\beta}}{(1+\alpha)^{1/4}}\left\{\frac{(\beta(D/d))^3}{\eta\ln(D/d)}\right\}^{1/4} \tag{10}$$

Setting $K'\fallingdotseq K$, Eq. (10) is shown with the dotted line in Fig. 4. Equation (10) agreed well with the data for the anchor ($d/D=0.90$). For the jet mixing vessel the apparent impeller diameter d was set at $d\fallingdotseq d_s/0.8$, assuming that the shaft diameter d_s was equivalent to that of the cylindrically rotating zone in an agitated vessel. Then $d/D=0.35$. Equation (10) gave a higher value than the experimental data for the jet mixing vessel.

Figure 5 shows the dependence of the coefficient K' on the angular velocity of the rotating nozzle, where the dimensionless angular velocity Ω^* is defined as

$$\Omega^*=(\omega d_s/2)/u \tag{11}$$

The experimental data for the mixing vessel are shown by open and closed circles with solid and broken line, respectively. When $\theta_{in}=0°$, the lines for $\Omega^*<0$ are the mirror image to those for $\Omega^*>0$ because the flow pattern on the negative side of Ω^* is symmetrical to that on the positive side of Ω^*. For rotation in the jet nozzle direction (the positive side of Ω^*) for $\theta_{in}=30°$ and for the rotation for $\theta_{in}=0°$ the data for both 40 wt% glycerine and water give 0.14 for K' in the range of $0<\Omega^*<0.1$, and then the value of K' decreases as Ω^* increases, regardless of jet nozzle angle or liquid viscosity. For rotation against the jet nozzle direction (the negative side of Ω^*) for $\theta_{in}=30°$ the value of K' decreases monotonously as $|\Omega^*|$ increases.

The heat transfer coefficient and friction factor for coaxial rotating cylinders were reviewed by Kataoka,[14] i.e., for the heat transfer coefficient h at the fixed outer cylinder in the turbulent region of $Ta>10^2$

$$Nu=0.78\,Ta^{1/2}Pr^{1/3} \tag{12}$$

and for the friction factor f on the inner rotating cylinder in the turbulent region of $Ta>10^3$

$$f\cdot Ta=0.19\,Ta^{0.522}(f\cdot Ta)_{lam} \tag{13}$$

In both equations the dimensionless numbers are defined as

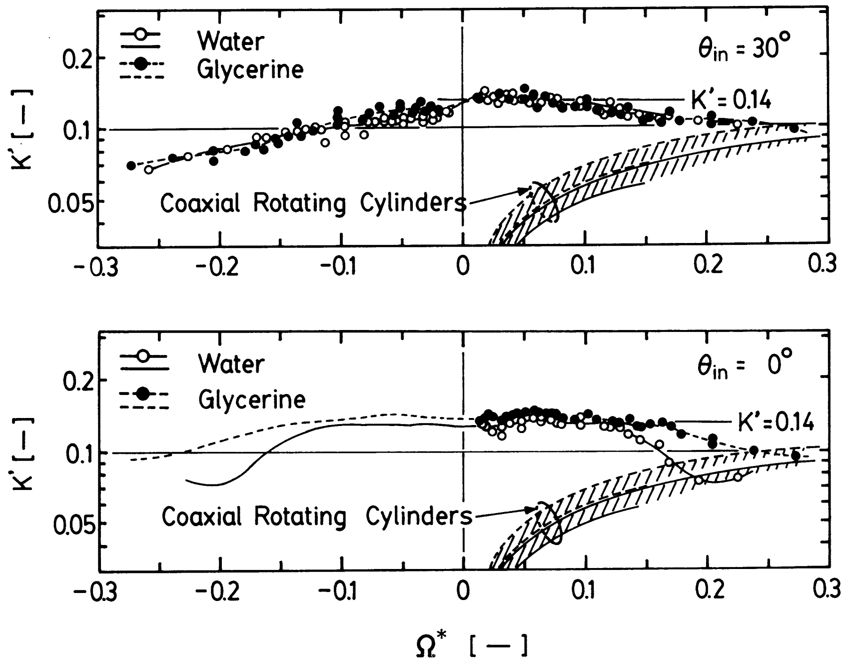

Fig. 5. Coefficient K' in Eq. (5) with respect to dimensionless angular velocity of rotating nozzle

$$Nu = 2hl/k$$

$$Ta = \{(d_s/2)\omega l/\nu\}\sqrt{l/(d_s/2)}$$

$$f/2 = \tau_{wi}/\rho(\omega d_s/2)^2 \qquad (14)$$

$$(f \cdot Ta)_{lam} = \frac{4\{l/(d_s/2)\}^{3/2}}{1 - \{1 + l/(d_s/2)\}^{-2}}$$

$$l = (D - d_s)/2$$

where τ_{wi} is the shear stress on the inner rotating cylinder and l is the clearance between the inner and outer cylinders. For the present experimental conditions the heat transfer coefficient h and the friction factor f were calculated from Eqs. (12) and (13), respectively. The calculated values of K' in Eq. (5) were shown by the hatched area in Fig. 5, where the observed coefficient K' for jet mixing seems to approach the calculated value for the coaxial rotating cylinders as Ω^* increases over 0.25, except for the case of water at $\theta_{in} = 30°$. This result means that the heat transfer on the mixing vessel wall at higher rotation speed of the rotating nozzle (i.e. of the inner shaft) is mainly affected by the tangential flow. From the result of Fig. 5 it may be supposed that the heat transfer for small Ω^* mainly depends on the surface renewal mechanism by turbulent eddy, whereas that for large Ω^* mainly depends on the mean flow pattern in the vicinity of the vessel wall.

Figure 6 shows the effect of baffle plates on the coefficient K', where the origin of the abscissa for the baffled vessel with $\theta_{in} = 30°$ was shifted to 0.06 in the positive direction of Ω^*, because the observed mixing time profile in the non-baffled vessel was almost symmetrical with respect to the axis of $\Omega^* = 0.06$, though that in the baffled vessel was nearly symmetrical with respect to $\Omega^* = 0$.[16] Figure 6 shows that the behaviour of the coefficient K' in the baffled vessel was almost the same as that in the non-baffled vessel within experimental accuracy, though the coefficient in the baffled vessel with $\theta_{in} = 0°$ seems to be slightly smaller than that in the non-baffled vessel. These results mean that the plates in a jet mixing vessel do not improve the heat transfer, as for the case of the mixing time in the jet mixing vessel with baffles.

Conclusion

The heat transfer coefficient at the vessel wall was measured in a jet mixing vessel with a rotating nozzle around the vessel axis. The observed heat transfer coefficient was well correlated with the power input per unit volume in the same manner as for an agitated vessel, though the correlation coefficient K' is slightly smaller than that for an agitated vessel. The heat transfer coefficient at higher nozzle rotation speed decreased with increase of the nozzle rotation speed (i.e. the inner-shaft rotation speed) and approached that for coaxial rotating cylinders. Baffle plates in the jet mixing vessel did not improve the heat transfer coefficient.

Appendix Estimation of power input for anchor agitator

The friction factor in a non-baffled agitated vessel, f, was correlated by Hiraoka *et al.*[13] as

$$f/2 = 0.121(Lv_\theta \rho/\mu)^{-1/3} \qquad \text{(A-1)}$$

where v_θ and L are the characteristic velocity and length, respectively, and they are defined as

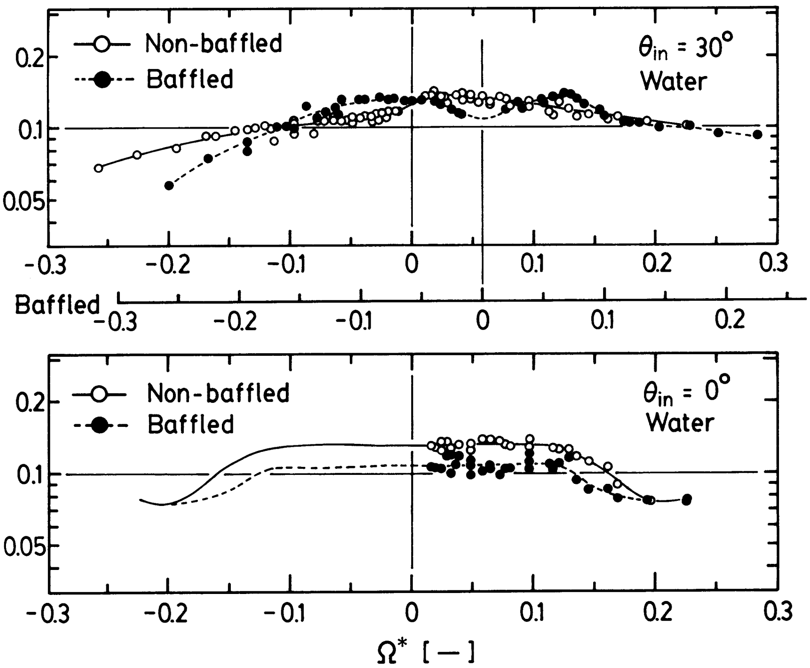

Fig. 6. Effect of baffle plates on heat transfer

$$\left.\begin{aligned} \tau_w &= (f/2)\rho v_\theta^2 \\ v_\theta &= (\pi/2)\mathrm{N}d\beta \\ \beta &= 2\ln(D/d)/\{(D/d)-(d/D)\} \\ L &= \{(D/2)\ln(D/d)\}\cdot\eta \\ \eta &= 1+\exp[-10\{(D/d)-1\}] \end{aligned}\right\} \qquad \text{(A-2)}$$

τ_w is the mean shear stress at the vessel wall, and D and d are the vessel and impeller diameters, respectively. From the angular momentum balance in the vessel the power input, P, can be expressed as

$$P = (2\pi N)\{(\tau_w \cdot \pi DH)(1+\alpha)(D/2)\} \qquad \text{(A-3)}$$

where α is the correction factor for the shear stress on the bottom wall and is determined experimentally to be 0.2. For the given values of N, D, d, ρ and μ, the power input P can be calculated from Eq. (A-3) with the help of Eqs. (A-1) and (A-2).

Nomenclature

A	= heat transfer surface area	[m^2]
C	= coefficient in Eq. (1)	[—]
c_p	= heat capacity at constant pressure	[J·kg^{-1}·K^{-1}]
D	= vessel diameter	[m]
d	= impeller diameter	[m]
d_s	= shaft diameter	[m]
f	= friction factor	[—]
H	= liquid height	[m]
h	= heat transfer coefficient	[W·m^{-2}·K^{-1}]
I	= current	[A]
K	= coefficient in Eq. (2)	[—]
K'	= coefficient in Eq. (5)	[—]
k	= thermal conductivity	[W·m^{-1}·K^{-1}]
L	= characteristic length	[m]
l	= clearance between inner and outer cylinders	[m]
N	= rotation speed	[s^{-1}]
Nu	= Nusselt number, hD/k	[—]
P	= power input	[W]
Pr	= Prandtl number, $c_p\mu/k$	[—]
P_V	= power input per unit volume	[W·m^{-3}]
Q	= jet flow rate	[m^3·s^{-1}]
Q_H	= heat transfer rate	[W]
Re	= Reynolds number, $Nd^2\rho/\mu$	[—]
Ta	= Taylor number, $(d_s\omega l/2\nu)\sqrt{(2l/d_s)}$	[—]
T_b	= bulk liquid temperature	[K]
T_w	= vessel wall temperature	[K]
u	= mean velocity of liquid at jet nozzle	[m·s^{-1}]
V	= voltage	[V]
v_θ	= characteristic velocity	[m·s^{-1}]
α	= ratio of torque at bottom wall to that at side	[—]
β	= correction factor defined by Eq. (A-2)	[—]
η	= correction factor defined by Eq. (A-2)	[—]
θ_{in}	= jet nozzle angle to the radial direction	[deg]
μ	= liquid viscosity	[Pa·s]
ν	= kinematic viscosity	[m^2·s^{-1}]
ρ	= liquid density	[kg·m^{-3}]
τ_w	= mean shear stress at wall	[N·m^{-2}]
τ_{wi}	= shear stress on inner rotating cylinder	[N·m^{-2}]
Ω^*	= dimensionless angular velocity defined by Eq. (10)	[—]
ω	= angular velocity	[rad·s^{-1}]

Literature Cited

1) Askew, W. S. and R. B. Beckmann: *Ind. Eng. Chem. Process Des. Dev.*, **4**, 311 (1965).
2) Bathija, P. R.: *Chem. Eng.*, **89**, (25), 89 (1982).
3) Bird, R. B., W. E. Stewart and E. N. Lightfoot: "Transport Pheonomena", p. 402, John Wiley & Sons, Inc., New York (1960).
4) Bourne, J. R., M. Buerli and W. Regenass: *Chem. Eng. Sci.*, **36**, 347 (1981).
5) Calderbank, P. H. and M. B. Moo-Young: *Chem. Eng. Sci.*, **16**, 39 (1961).
6) Chapman, F. S., H. Dallenbach and F. A. Holland: *Trans. Instn. Chem. Engrs.*, **42**, T398 (1964).
7) Chilton, T. H., T. B. Drew and R. H. Jebens: *Ind. Eng. Chem.*,

36, 510 (1944).
8) Desplanches, H., M. Bruxelmane, J. L. Chevalier and J. Ducla: *Chem. Eng. Des.*, **61**, 3 (1983).
9) Fossett, H. and L. E. Prosser: *J. Inst. Mech. Engrs.*, **160**, 224 (1949).
10) Fox, E. A. and V. E. Gex: *AIChE J.*, **2**, 539 (1956).
11) Hiby, J. W., M. Modigell and H. Tsue: *Proceedings of World Congress III of Chem. Eng.* (part III), p. 358, Tokyo (1986).
12) Hiraoka, S.: "Kagaku Kogaku no Shinpo No. 9, Netsu Process Kogaku," p. 147, Maki Shoten, Tokyo (1986).
13) Hiraoka, S., I. Yamada, N. Doi, H. Takeda, A. Kawai, Y. Usui and R. Ito: *Bull. Nagoya Inst. Tech.*, **26**, 239 (1974).
14) Kataoka, K.: Ph. D. Thesis, Kyoto Univ., Japan (1970).
15) Koh, S. T., S. Hiraoka, I. Yamada, Y. Tada, T. Aragaki and T. Takahashi: *J. Chem. Eng. Japan*, **22**, 611 (1989).
16) Koh, S. T., S. Hiraoka, Y. Tada, T. Takahashi, T. Aragaki and I. Yamada: *J. Chem. Eng. Japan*, **23**, 462 (1990).
17) Lane, A. G. C. and P. Rice: *Ind. Eng. Chem. Process Des. Dev.*, **21**, 650 (1982).
18) Maruyama, T., Y. Ban and T. Mizushina: *J. Chem. Eng. Japan*, **17**, 120 (1984).
19) Moo-Young, M. and J. V. Cross: *Can. J. Chem. Eng.*, **47**, 369 (1969).
20) Nihon Kagakukai: "Kagaku Binran," p. II-42, II-73, Maruzen Co., Tokyo (1983).
21) Okita, N. and Y. Oyama: *Kagaku Kogaku*, **27**, 252 (1963).
22) Perry, R. H. and C. H. Chilton: "Chemical Engineers' Handbook," p. 3–71, 3–126, Fifth Edition, McGraw-Hill Book Co., New York (1973).
23) Pollard, J. and T. A. Kantyka: *Trans. Instn. Chem. Engrs.*, **47**, T21 (1969).
24) Racz, I. G. and J. G. Wassink: *Chem. Ing. Techn.*, **46**, 261 (1974).
25) The Japan Society of Mechanical Engineers: "Thermophysical Properties of Fluids," p. 477, 478, JSME, Tokyo (1983).
26) Uhl, V. W.: *Chem. Eng. Progr. Symp. Series*, No. 17, **51**, 93 (1955).
27) Van de Vusse, J. G.: *Chem. Ing. Techn.*, **31**, 261 (1959).