

EFFECTS OF PADDLE DIMENSIONS AND BAFFLE CONDITIONS ON THE INTERRELATIONS AMONG DISCHARGE FLOW RATE, MIXING POWER AND MIXING TIME IN MIXING VESSELS

YUJI SANO AND HIROMOTO USUI

Department of Chemical Engineering, Yamaguchi University, Ube 755

Key Words: Mixing, Discharge Flow Rate, Power Number, Mixing Time, Baffle Condition, Paddle

The interrelations among the discharge flow rate, the mixing power and the mixing time in the fully turbulent range in mixing vessels are investigated experimentally with paddles and baffle plates of various dimensions covering from non-baffled to fully baffled conditions. The discharge flow rate number is correlated as a function of the paddle dimensions and the baffle plate dimensions. The relations between the discharge flow rate number and the power number under incomplete baffle conditions are obtained in two cases. If the baffle condition level is fixed, the power number is proportional to the discharge flow rate number for the various paddles. If the paddle is fixed, the power number is proportional to the square of the discharge flow rate number for various baffle conditions. The mixing time is proportional to the time required to circulate the discharged liquid once, and the number of times of circulation to reach mixing is correlated with paddle dimensions, regardless of baffle conditions.

Introduction

In the performance of mixing vessels there are three important characteristic values: discharge flow rate of an impeller, mixing power and mixing time. Many investigators have reported on the power number and the mixing time^{6,12)} for the effects of impeller dimensions and operating conditions. However, as for the discharge flow rate of impellers, which is an important value for the flow characteristics of the mixing vessel, investigations are rather few and the experimental data are fragmental.

In the previous paper,¹¹⁾ the authors reported the interrelations of discharge flow rate number N_{qd} , power number N_p and non-dimensional mixing time $n\theta_M$ in the fully developed turbulent range under fully baffled conditions.

In incomplete baffle conditions, however, the effects of baffle plates of various level on the discharge flow rate in connection with the mixing power and the mixing time have not been investigated.

In this work, the interrelations among N_{qd} , N_p and $n\theta_M$ were investigated experimentally with paddles and baffle plates of various dimensions.

1. Experimental Apparatus and Procedures

Measurements were carried out with mixing vessels of diameters $D=0.2$ m and 0.4 m, which were almost the same as used in the previous study.¹¹⁾ The baffle conditions were changed from non-baffled to fully baffled condition by changing baffle width ($w_B/D=0$,

0.025 , 0.05 and 0.1) and number ($n_B=0, 2, 4, 6, 8$ and 12). The impellers used were paddles of various sizes ($d/D=0.3-0.75$, $b/D=0.1-0.3$, $n_p=2-6$). The paddle was installed in the axis of the vessel at half the height of liquid depth. Most measurements of the three characteristic parameters N_{qd} , N_p and $n\theta_M$ were performed in the fully developed turbulent range ($Re > 10^4$), using water at room temperature. The Reynolds number range for the measurements of N_{qd} and N_p was extended on the lower side to $Re = 10^2$, using glycerol water solution at room temperature. The liquid height was equal to the diameter of the vessel.

The measurement procedures were also the same as described in the previous paper.¹¹⁾ The discharge flow rate was measured by the flow follower method, which was first developed by Marr Jr.⁴⁾ A piece of coloured absorbent cotton of a few mm in size was used as the flow follower particle. The impeller power was measured by a torque transducer strain gauge, mounted in the shaft of the impeller. Mixing time was measured by the conductivity method, using two electrode cells made of platinum wire installed at the vessel wall. Changes in difference of resistances of the two electrodes, were recorded by a rapid response recorder. The mixing time was determined by the time at which the signal reached a final value.

2. Experimental Results and Discussion

2.1 Variations of N_{qd} and N_p with Re

Illustrations of measurement results of N_{qd} and N_p in a wide range of Re are shown in Fig. 1. N_{qd} and N_p decrease with increasing Re for the non-baffled con-

Received December 22, 1986. Correspondence concerning this article should be addressed to Y. Sano.

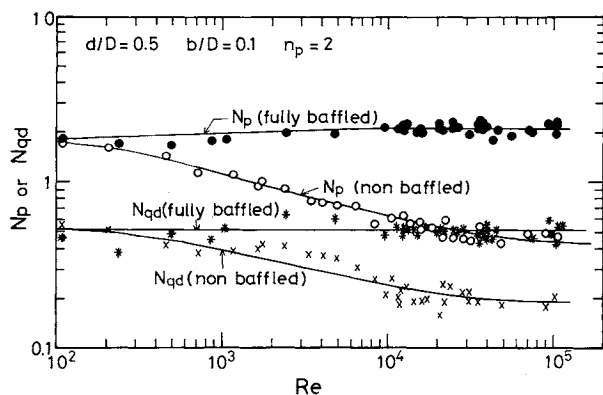


Fig. 1. Variations of N_p and N_{qd} with Re .

dition, while they remain almost constant for the fully baffled condition. In the fully turbulent range ($Re > 10^4$), however, both N_{qd} and N_p reach constant values even in the non-baffled condition.

2.2 Fully baffled condition

Power consumption of the impeller in a mixing vessel is increased by insertion of baffle plates and reaches a maximum value at a certain level of baffle conditions where the tangential flow is suppressed and the cylindrically rotating zone disappears. The fully baffled condition is defined as that at which the power consumption of an impeller reaches a maximum value by insertion of baffle plates on the mixing vessel wall. Nagata⁶⁾ has shown the fully baffled condition by the following equations.

$$n_B w_B / D = 0.5 \quad (1)$$

or

$$n_B (w_B / D)^{1.2} = 0.35 \quad (2)$$

In this report, the effects of baffle plates are assumed to be evaluated by the term $\alpha = n_B w_B / D$, which is proportional to the total area of baffle plates.

The effects of baffle plates on N_p , N_{qd} and $n\theta_M$ for a paddle of $d/D = 0.5$, $b/D = 0.1$ and $n_p = 2$ in the fully turbulent range are shown in Fig. 2, in which the value of α is changed by various combinations of n_B and w_B/D . The values of N_p and N_{qd} are increased and $n\theta_M$ is decreased by an increase of α . At the value of $\alpha = 0.4$, N_p and N_{qd} almost reach the maximum values and $n\theta_M$ reaches the minimum value. Then, in this report, the fully baffled condition is defined as follows.

$$n_B w_B / D \geq 0.4 \quad (3)$$

Nishikawa *et al.*⁹⁾ reported also that the fully baffled condition is attained by $\alpha = 0.4$ from the point of view of heat transfer and power consumption in a mixing vessel.

2.3 Correlation of N_{qd} with impeller dimensions and baffle dimensions

In the previous paper,¹¹⁾ we reported the correlation

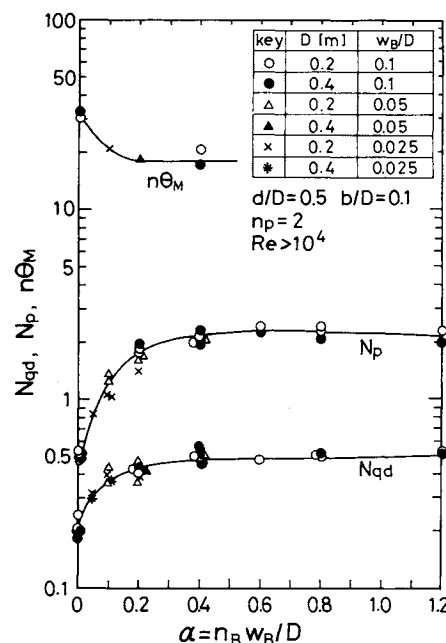


Fig. 2. Determination of fully baffled conditions.

of the discharge flow rate number of paddles in the fully turbulent range ($Re > 10^4$) for the fully baffled condition.

$$N_{qdFBC} = 1.3 \beta_{N_{qd}} \quad (4)$$

where

$$\beta_{N_{qd}} = (d/D)^{-0.86} (b/D)^{0.82} n_p^{0.60} \quad (5)$$

It is assumed that the effects of paddle dimensions on N_{qd} in the incomplete baffle condition including non-baffled condition are the same as in the fully baffled condition, expressed by the term $\beta_{N_{qd}}$. The effects of baffle plates on N_{qd} are considered by the term $\alpha = n_B w_B / D$.

Figure 3 shows the plot of N_{qd} vs. $\beta_{N_{qd}}$ for both the fully baffled condition and the non-baffled condition. It is noted that both sets of data are fairly well correlated by the term $\beta_{N_{qd}}$, even for the non-baffled condition. The data of incomplete condition of $\alpha = 0.05, 0.1$ and 0.2 , which include various combinations of n_B and w_B/D , are also well correlated by the term $\beta_{N_{qd}}$, as shown by the lines, where the data were not plotted in order to avoid confusion.

From these plots, the following correlation equation is derived.

$$N_{qd} = 1.3 [1 - 0.62 \exp(-6.8\alpha)] \beta_{N_{qd}} \quad (6)$$

in which α is taken as 0.4 if $\alpha \geq 0.4$. The plots of the correlation of Eq. (6) are shown for all the data in Fig. 4. The average deviation of the correlation is 9.9%. From Eq. (6), the discharge flow rate can be calculated by specifying the dimensions of the paddle and the baffle plate condition. The equation covers the experimental ranges of ($d/D = 0.3-0.75$, $b/D = 0.1-0.3$

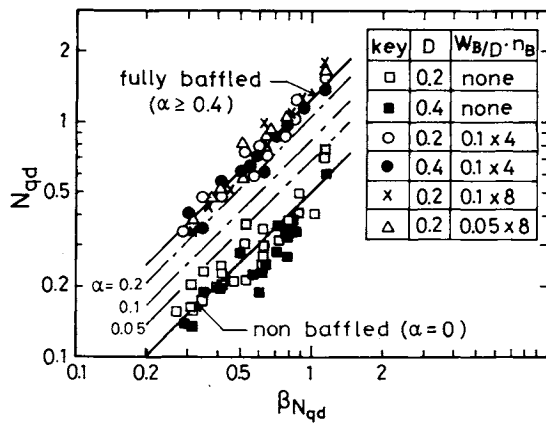


Fig. 3. N_{qd} vs. β_{Nqd} for fully baffled and non-baffled conditions.

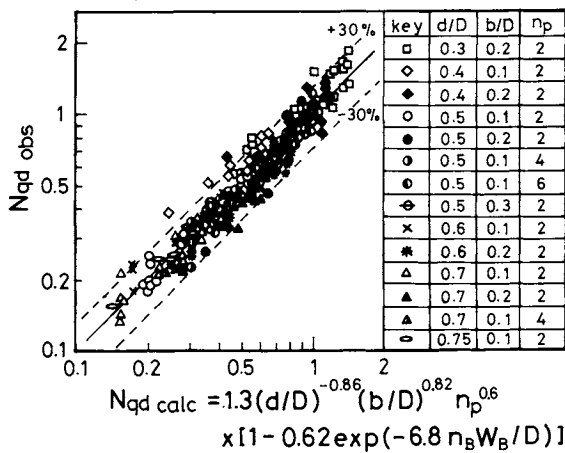


Fig. 4. Correlation of N_{qd} by dimensions of paddles and baffle plates.

and $n_p = 2-6$ for paddles and ($w_B/D = 0-0.1$ and $n_B = 1-12$) for baffle plates in the fully turbulent range ($Re > 10^4$).

2.4 Relation between N_{qd} and N_p

In the previous paper,¹¹⁾ the relation between N_{qd} and N_p in the fully baffled condition is expressed in the fully developed turbulent range by the following equation, regardless of paddle dimensions.

$$N_p = 4.3 N_{qd}^{1.34} \quad (7)$$

The relation between N_{qd} and N_p of the non-baffled condition in the fully turbulent range in which both N_p and N_{qd} are almost constant is shown in Fig. 5. From Fig. 5, N_p is proportional to N_{qd} regardless of paddle dimensions in the fully turbulent range. The correlation equation for this case is

$$N_p = 1.8 N_{qd} \quad (8)$$

The effects of baffle conditions on the relations between N_{qd} and N_p are also evaluated by the term $\alpha = n_B w_B/D$. In Fig. 6, the relation is shown for $\alpha = 0.1$ of various combinations of n_B and w_B/D , for various dimensions of paddles. The relation between N_{qd} and

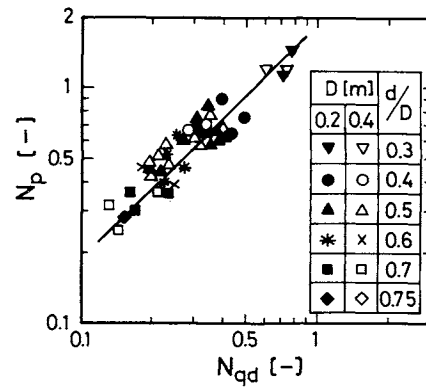


Fig. 5. N_p vs. N_{qd} for non-baffled condition.

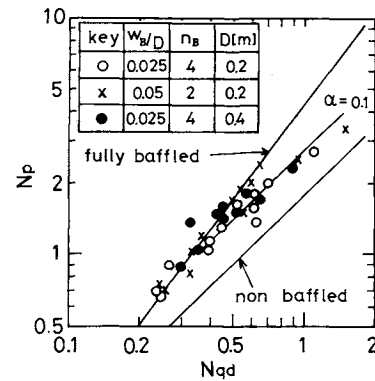


Fig. 6. N_p vs. N_{qd} for incomplete baffle conditions of $\alpha = 0.1$.

N_p is linear with a slope of 1.0 on the right-hand side from the relation for the fully baffled condition, Eq. (7), and fits with Eq. (7) on the left-hand side around the point $N_{qd} = 0.3$ which corresponds to the value of $\beta_{Nqd} = 0.2$. Namely, if $\alpha = 0.1$, the relation of N_p vs. N_{qd} obeys Eq. (7) for $\beta_{Nqd} < 0.2$. The same sort of linear relations are obtained for various values of α by various combinations of n_B and w_B/D as shown in Fig. 7. The correlation for all the data is expressed by the following equation:

$$N_p = 4.3[1 - 0.58 \exp(-6.0\alpha)]N_{qd} \quad (9)$$

which is cut off by Eq. (7) for the fully baffled condition as shown in Fig. 7. Then, for $\beta_{Nqd} < \beta_{Nqdc}$, Eq. (7) is used for the relation of N_p vs. N_{qd} , where

$$\beta_{Nqdc} = (1/1.3)[1 - 0.58 \exp(-6.0\alpha)]^{2.94} \quad (10)$$

For a given impeller, the relations of N_{qd} and N_p for various levels of the baffled condition are different from the relations of N_{qd} and N_p obtained by changing the dimensions of impellers for a fixed level of baffled condition as described above. Typical plots of N_{qd} and N_p of the paddles for various levels of baffled conditions are shown in Fig. 8. The relation between N_{qd} and N_p in this Figure is supposed to be linear, with a slope of 2.0. Then, N_p is proportional to the square of N_{qd} for the case of a fixed impeller with

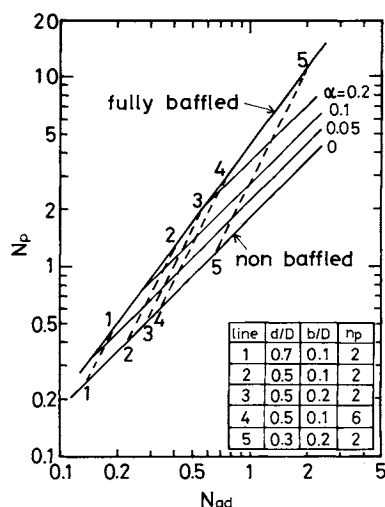


Fig. 7. Summary of relation between N_p and N_{qd} .

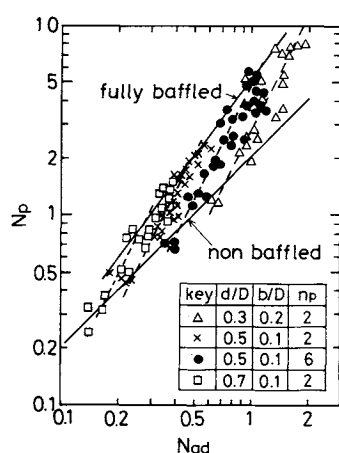


Fig. 8. N_p vs. N_{qd} for fixed paddles in various baffle conditions.

various levels of baffled condition. These relations can be expressed from Eqs. (6) and (9), as follows.

$$N_p = 3.3 N_{qd}^2 / \beta_{N_{qd}} \quad (11)$$

because $[1 - 0.58 \exp(-6.0\alpha)] \approx [1 - 0.62 \exp(-6.8\alpha)]$ for $0 \leq \alpha \leq 0.4$. Equation (11) is limited between Eqs. (7) and (8).

Both Nagase *et al.*⁵⁾ and Hiraoka²⁾ have shown the theoretical relationship in which N_p is proportional with the square of the discharge flow rate number in a mixing vessel. The linear relation between N_p and N_{qd} for the non-baffled condition has also been derived, regardless of impeller dimensions, based on an analogous consideration of the centrifugal pump.¹²⁾

A summary of the relations between N_{qd} and N_p in the present experimental results in the fully turbulent range of $Re > 10^4$ is shown in Fig. 7. N_p is proportional to N_{qd} at a fixed level of baffled condition for various impellers and for a fixed impeller N_p is proportional to the square of N_{qd} for various levels of baffled condition. Further investigations will be needed to clarify the behaviour of the relations be-

tween N_p and N_{qd} found in the present study, in view of the flow pattern in the incomplete baffle condition.

The mechanical efficiency of the mixing system is sometimes defined by the term N_{qd}/N_p .¹⁾ This value is calculated by Eq. (9). The maximum efficiency is obtained for the non-baffled condition as 0.55. In the baffled condition, the efficiency is always lower than that in the non-baffled condition. As seen in Fig. 7, the efficiency increases when a paddle of larger (d/D), (b/D) and n_p is used. In the previous paper, we recommended an impeller of larger d/D , b/D and n_p in the fully baffled condition. Here we again recommend a paddle of, say, $d/D=0.75$, $b/D=0.2$ and $n_p=6$, without baffle plates, as a more efficient mixing system.

In the lower range of Re , the relations between N_p and N_{qd} for the baffle condition level of $\alpha=0.4$ and $\alpha=0$ are shown in Fig. 9. In the lower range of $10^2 < Re < 10^3$, the difference between fully baffled and non-baffled conditions becomes smaller and closer relations for $\alpha=0.4$ and $\alpha=0.0$ are obtained, as shown in Fig. 9. However, the proportionality between N_p and N_{qd} for $\alpha=0$ seems to hold in this lower Re range.

Figure 10 shows a comparison of relations between N_p and N_{qd} in this work with data from the literature,^{1,7,8,14)} in which the discharge flow rates were obtained by direct measurements of radial velocity from impellers. The relationship in the literature for the non-baffled condition ($\alpha=0$)^{7,14)} deviates upwards from the present results and N_p is proportional to N_{qd} with a power of about 0.6. For the fully baffled condition, the data in the literature scatter. This is due to the difficulty of measurement of radial velocity in three-dimensional flow with high turbulence level in the fully baffled condition.

2.5 Relation between $n\theta_M$ and N_{qd}

In the previous paper,¹¹⁾ we showed that the observed mixing time θ_M can be related to the discharge flow rate by the following equation, assuming that mixing is mainly governed by macro-mixing due to the convection of the discharge flow.

$$\theta_M = m V / q_d \quad (12)$$

For the incomplete baffle condition ($\alpha < 0.4$), the same relation was examined. Typical data of θ_M vs. V/q_d are shown in Fig. 11 for an impeller of $d/D=0.5$, $b/D=0.2$ and $n_p=2$. In this figure, the mixing time is proportional to the time required to circulate the discharged liquid, regardless of baffle condition level, from fully baffled to non-baffled, for the given impeller.

The concept that the mixing time is proportional to the average circulation time of discharged liquid in a vessel has been proposed by several investigators. Nagata⁶⁾ showed that mixing time in the laminar

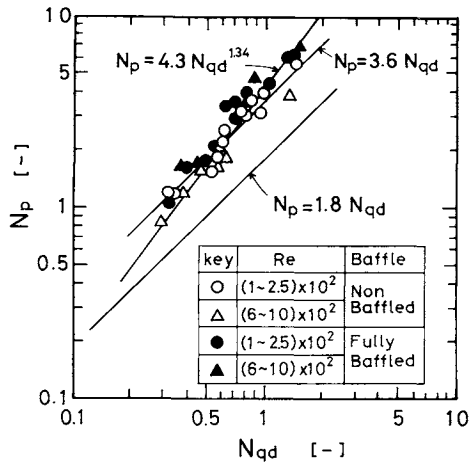


Fig. 9. N_p vs. N_{qd} for low Reynolds number.

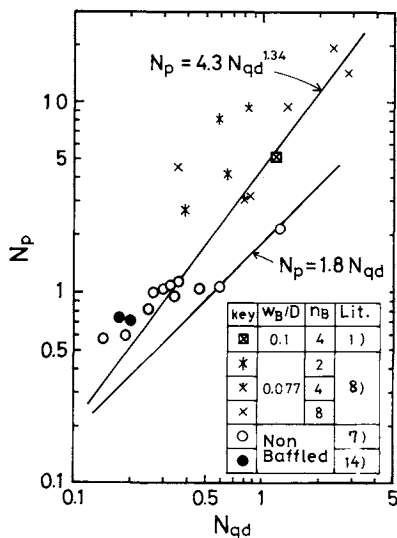


Fig. 10. Comparison of relation between N_p and N_{qd} in literature.

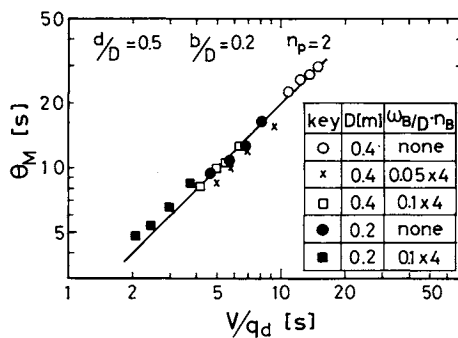


Fig. 11. θ_M vs. V/q_d in various baffle conditions.

region is expressed by Eq. (12) and that the value of m is roughly 3.0 irrespective of mixer type, if the mixer is of a circulation type. Van de Vusse¹³⁾ also reported the effects of impeller dimensions on mixing time based on the concept of Eq. (12) in the turbulent region, demonstrating that the diffusional effect in the turbulent region is so large that mixing time is governed mainly by the pumping action of the impel-

ler. Okita and Oyama¹⁰⁾ also showed a mixing time correlation based on the concept of Eq. (12) for the mixing of jet flow in a tank. Kamiwano, Yamamoto and Nagata³⁾ derived a correlation equation of mixing time in the fully turbulent range, considering the additive contribution of the effects of both convection and turbulent diffusion to the mixing time. But the additive contribution seems to be questionable, because the mixing time in a vessel is governed by the convection flow even in the laminar flow range as stated by Nagata.⁶⁾ The present data support the conclusion that mixing time in the fully developed range is mainly governed by the convection effect of the discharge flow from an impeller, given by Eq. (12). Moreover, it is interesting that the ratio $m = \theta_M / (V/q_d)$ for a fixed impeller, which means the number of times of circulation of the discharge flow in the vessel to reach the mixing time, is quite independent of baffle conditions. The average value of m for the case of Fig. 11 is 2.0. The average values of m for impellers of various dimensions are obtained from the same plots as in Fig. 11. The average values of m thus obtained are correlated in Fig. 12. The correlation equation is

$$m = 3.8(d/D)^{0.5}(n_p b/D)^{0.1} \quad (13)$$

which depends only on the dimensions of the paddles and is independent of baffle condition. Equation (13) is the same as the equation derived in the previous paper¹¹⁾ for the fully baffled condition.

From Eqs. (4), (5), (6), (12) and (13), the dimensionless mixing time $n\theta_M$ can be expressed as

$$n\theta_M = (n\theta_M)_{FBC} / [1 - 0.62 \exp(-6.8\alpha)] \quad (14)$$

where

$$(n\theta_M)_{FBC} = 2.3(d/D)^{-1.67}(b/D)^{-0.74}n_p^{-0.47} \quad (15)$$

Equation (15) is consistent with the previous results.¹¹⁾

Conclusions

The discharge flow rate, the mixing power and the mixing time are measured for paddles ($d/D = 0.3-0.75$, $b/D = 0.1-0.3$, $n_p = 2-6$), installed at half the height of liquid depth in vessels of $D = 0.2$ m and 0.4 m. The baffle conditions are changed in the range $n_B = 0-12$, $w_B/D = 0.025-0.1$. The interrelations among the discharge flow rate, the mixing power and the mixing time are obtained in the fully turbulent range. Among these three variables, two are related to one another.

1) The fully baffled condition is defined by Eq. (3).

2) The discharge flow rate is correlated by Eq. (6) for paddles of various dimensions and baffle plates of various dimensions.

3) The relations between N_{qd} and N_p are expressed by Eqs. (7), (8) and (9). When the baffle condition is

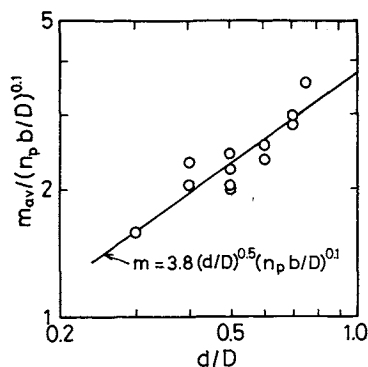


Fig. 12. Correlation of number of times of circulation of discharged liquid to reach mixing time.

fixed, the relations between N_{qd} and N_p are linear for the condition of $\beta_{N_{qd}} > \beta_{N_{qdc}}$ where $\beta_{N_{qdc}}$ is given by Eq. (10). When the impeller dimensions are fixed, the relation is $N_p \propto N_{qd}^2$, as shown by Eq. (11).

4) The mixing time is governed by the convection of the discharge flow as expressed by Eq. (12). The number of times of circulation of the discharged liquid to reach the mixing time is correlated by Eq. (13). The mixing time is correlated with the dimensions of the paddle and the baffle plate, as shown by Eqs. (14) and (15).

5) In the low Reynolds number range, the effects of baffle plates on the relation between N_{qd} and N_p become small, as shown in Fig. 9.

Acknowledgment

The authors appreciate the experimental assistance of student colleagues (Hirohisa Sugiura and Hajime Okido).

Nomenclature

b	= width of impeller blade	[m]
D	= diameter of vessel	[m]
d	= diameter of impeller	[m]
m	= number of times of circulation of discharged liquid to reach the mixing time	[—]
N_p	= power number $P/\rho n^3 d^5$	[—]

N_{qd}	= discharge flow rate number q_d/nd^3	[—]
n	= rotational speed	[1/s]
n_B	= number of baffle plates	[—]
n_p	= number of impeller blades	[—]
P	= mixing power	[W]
q_d	= discharge flow rate	[m ³ /s]
Re	= Reynolds number $d^2 n \rho / \mu$	[—]
V	= volume of liquid in vessel	[m ³]
w_B	= width of baffle plate	[m]
α	= parameter for the effect of baffle dimensions	[—]
$\beta_{N_{qd}}$	= parameter for the effect of impeller dimensions on the discharge flow rate	[—]
$\beta_{N_{qdc}}$	= critical value of $\beta_{N_{qd}}$, given by Eq. (10)	[—]
θ_M	= mixing time	[s]
μ	= viscosity of liquid	[Pa·s]
ρ	= density of liquid	[kg/m ³]

<Subscript>

FBC = refers to fully baffled condition

Literature Cited

- Bertrand, J., J. P. Couderc and H. Angelino: *Chem. Eng. Sci.*, **35**, 2157 (1980).
- Hiraoka, S. and R. Ito: *J. Chem. Eng. Japan*, **8**, 323 (1975).
- Kamiwano, M., K. Yamamoto and S. Nagata: *Kagaku Kōgaku*, **31**, 365 (1967).
- Mar, G. R. Jr. and E. F. Johnson: *AIChE J.*, **9**, 383 (1963).
- Nagase, Y., T. Iwamoto, S. Fujita and T. Yoshida: *Kagaku Kōgaku*, **38**, 519 (1974).
- Nagata, S.: "Mixing. Principles and Applications," p. 24, p. 39 and p. 200, Kodansha, Tokyo, Japan (1975).
- Nagata, S., K. Yamamoto and M. Ujihara: *Kagaku Kōgaku*, **23**, 130 (1959).
- Nagata, S., K. Yamamoto, K. Hashimoto and Y. Naruse: *Kagaku Kōgaku*, **23**, 595 (1959).
- Nishikawa, M., Y. Okamoto, M. Samejima, S. Fujieda and K. Hashimoto: *Kagaku Kōgaku Ronbunshu*, **5**, 535 (1979).
- Okita, N. and Y. Oyama: *Kagaku Kōgaku*, **27**, 252 (1963).
- Sano, Y. and H. Usui: *J. Chem. Eng. Japan*, **18**, 47 (1985).
- Uhl, V. W. and J. B. Cray: "Mixing Theory and Practice," p. 184, Academic Press, New York (1966).
- Van de Vusse, J. G.: *Chem. Eng. Sci.*, **4**, 178 (1955).
- Yoshida, T., Y. Nagase, R. Kakumoto, T. Hasegawa and T. Matoba: *Kagaku Kōgaku*, **37**, 1038 (1973).