Effect of Impeller Clearance on Power Consumption of Unsteadily Forward-Reverse Rotating Multiple Impellers in an Unbaffled Agitation Vessel

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Key words: power consumption; unbaffled agitation vessel; unsteadily forward-reverse rotating impellers; multiple impeller system; impeller clearance

Abstract

Power consumption of unsteadily forward-reverse rotating multiple impellers, a new cross type of impellers with four delta blades (CDs), was experimentally studied in an unbaffled agitation vessel containing water with a liquid height-to-diameter ratio of 2. The effect of clearance on the power number of forward-reverse rotating double and triple CDs was compared with that of unidirectionally rotating disk turbine impellers with six flat blades (DTs) in the baffled vessel. The result was discussed in relation to the difference in bulk flow pattern between the unbaffled vessel with CDs and the baffled vessel with DTs. The study also revealed that the value of power consumption for the forward-reverse rotating multiple CDs in the unbaffled vessel can be evaluated as the value for the single CD system multiplied by the number of impeller stages over a wide range of impeller clearances.

1. Introduction

Power consumption of impeller in agitation vessels is an important parameter not only required in selecting and designing the drive unit but also needed in characterizing the difference in transport phenomena within the vessel. For example, the volumetric mass transfer coefficient, a significant measure for scale-up of aerated agitation vessels, is closely related to the power consumption per unit volume or mass of liquid, i.e., the specific power input (Van't Riet, 1979). In other words, when an improvement in the volumetric coefficient is planned by varying operation conditions including the way of attachment of impellers in multi-stage configuration system, the magnitude of the intended volumetric coefficient is predicted through estimation of changes in the specific power input. In industrial agitation operations, deep vessels which have multiple impellers characterized by a liquid height-to-diameter ratio considerably larger than unity are frequently employed. For such a system, the importance is well known of the selection of impeller design and the determination of impeller arrangement. A number of studies have already been carried out on the relationship between the power consumption of steadily (=unidirectionally) rotating multiple impellers and their clearance in conventional vessels with baffles attached to avoid the formation of a purely rotational flow (Takeda *et al.*, 1968b; Taguchi and Kimura, 1970; Nishikawa *et al.*, 1976; Hudcova *et al.*, 1989; Armenante and Chang, 1998). These results can successfully be applied to design and operation of baffled vessels having steadily rotating multiple impellers.

On the other hand, there has recently been a growing interest in using the method that gives unsteady agitation action to fluid either by changing the direction or speed of impeller rotation, i.e., that allows the impeller to rotate unsteadily in liquid. In fact, some papers have been reported the operational characteristics of this kind of agitation vessel having unsteadily rotating impeller in relation to the specific power input (Lamberto *et al.*, 1996; Ogawa *et al.*, 1996; Nomura *et al.*, 1997; Yao *et al.*, 1998). As has been pointed out, improvement in performance (operational characteristics) of the agitation vessel is achievable under low power consumption by using unsteadily rotating impeller. However, these works dealt with the vessels having only unsteadily rotating single impeller and the results were not developed into the vessel having multiple impellers, which is likely to be more important from the viewpoint of industrial (=practical) application. In other words, this suggests that the previous works can hardly give knowledge on the power characteristics necessary as the basic data for design and operation of the vessel having unsteadily rotating multiple impellers, or more

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concretely, useful information on the effect of clearance on the power consumption of unsteadily rotating multiple impellers, etc.

Previously, as a novel type of aerated agitation vessel, we proposed an unbaffled vessel having unsteadily forward-reverse rotating multiple impellers, a cross type of impellers with four delta blades (CDs), whose rotation reverses its direction periodically (Yoshida *et al.*, 1996), and this type of gas-liquid agitator was named "AJITER". A forward-reverse agitation in which a constant-angle impeller rotates changing its direction alternately provides sufficient dispersion of the fluid in the vessel without using baffles. The effect of clearance on the power consumption of unsteadily forward-reverse rotating multiple CDs must be elucidated so that we can design and operate AJITER as a novel type of agitation vessel with multiple impellers. In this work, we first investigated experimentally the effect of clearance on the power consumption of the forward-reverse rotating multiple CDs while comparing with that of the unidirectionally rotating impellers in a baffled vessel. We then tried to explain differences in the dependence of power number on the clearance between the unsteadily and steadily rotating impellers in terms of the difference in bulk flow pattern within the vessel. Furthermore, we discussed the advantage in designing when the present type of forward-reverse rotating CD is used in multi-stage configuration on the basis of the results obtained, in comparison with the vessel having unidirectionally rotating disk turbine impeller (DT).

2. Methods

A schematic diagram of the experimental set-up for forward-reverse rotation mode is shown in Fig. 1. The vessel of 250 mm inner diameter, D_t, was used. The depth of liquid, H, was held at D_t (250 mm) for single impeller configuration system and at twice D_t (500 mm) for multiple impeller configuration system, respectively. As the impeller, geometrically similar cross type of impellers, i.e., impellers with four delta blades (CDs), 120-240 mm in diameter (D_i), were employed in single-, and two- and three-stage configurations for the vessel without baffles. A conventional impeller, a disk turbine impeller with six flat blades (DT), was adopted as the unidirectionally rotating impeller. Two different but geometrically similar sizes of DTs, 90 and 120 mm in D_i, were used under the fully baffled condition (four baffles, $0.1D_t$ in width, see Fig. 2). CDs, 120 and 160 mm in D_i, were also employed in unidirectional mode of operation for comparison. The geometrical conditions such as D_t and H were the same as those for forward-reverse rotation mode. The distance from the bottom of the lowest impeller, C_b, was 75 mm. For multi-stage

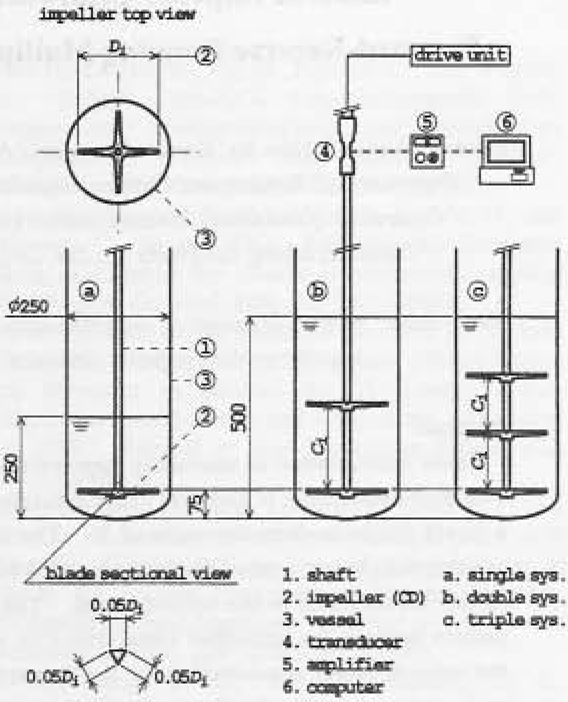

Figure 1. Experimental apparatus for forward-reverse rotation mode (Dimensions in mm).

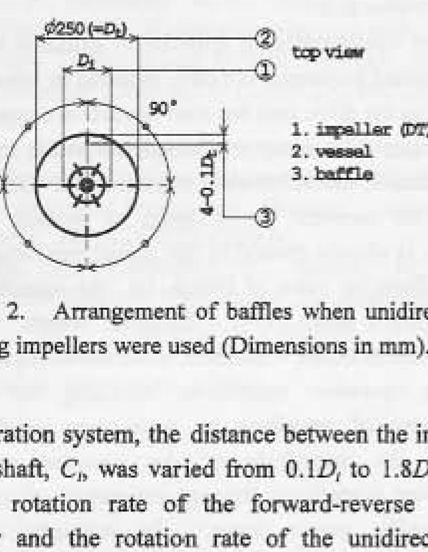

Figure 2. Arrangement of baffles when unidirectionally rotating impellers were used (Dimensions in mm).

configuration system, the distance between the impellers on the shaft, C_i, was varied from $0.1D_i$ to $1.8D_i$. The average rotation rate of the forward-reverse rotating impeller and the rotation rate of the unidirectionally rotating impellers, N_r, ranged from 75 to 400 rpm. All experiments for the two agitation modes were performed using deionized water at 298 K.

The agitation power, P_m, was determined by measuring the torque with strain gauges fitted on the shaft. For the forward-reverse rotating impeller, the average values over one cyclic time of forward-reverse rotation of impeller were employed as P_m. The dimensionless numbers such as the power number, N_p, and the Reynolds number, Re_m, were calculated by the following equations, respectively:

$$N_p=P_m/\rho N_r^3 D_i^5 \quad (1)$$

$$Re_m=\rho N_r D_i^2/\mu \quad (2)$$

These parameters of the forward-reverse rotating impeller system were based on the average impeller rotation rate.

3. Results and Discussion

3.1 Power Consumption of Single Impeller

Before investigating the power consumption of multiple impellers, the power consumption of single impeller was first examined in terms of power number. Figure 3 shows the relationship between the power number, N_{p1}, and the impeller Reynolds number, Re_m, for the forward-reverse rotating CD and the unidirectionally rotating impellers such as DT and CD. N_{p1} differed depending on impeller design and agitation mode, but was almost independent of Re_m. Comparison of N_{p1} of the unidirectionally rotating impellers between the two impellers of different designs showed that the values of N_{p1} for the DT tended to be large compared with those for the CD. That is, the impeller with wider and larger number of blades exhibited higher N_{p1} values. This result seems to suggest that form drag plays a dominant role in the resistance of liquid against the motion of both impellers (Shirakura and Ohashi, 1984). For the difference between the two agitation modes, the value of N_{p1} for the forward-reverse rotating CD tended to be high compared with that for the unidirectionally rotating CD as can be seen from the figure. This may be attributed mainly to the phenomenon that the disturbed flow region behind the blades, a factor relating to the magnitude of the resistance of liquid against the motion of impeller, extends due to the unsteady motion of impeller (Okajima *et al.*, 1997).

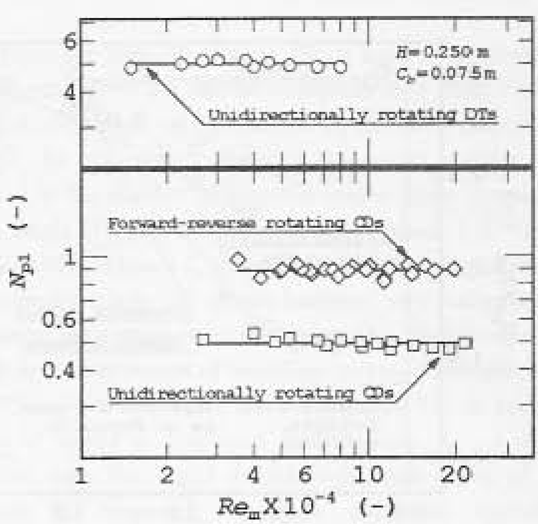

Figure 3. Relationship between N_{p1} and Re_m.

The differences in impeller design and agitation mode yield not only the difference in power number but also that in the bulk flow pattern within the vessel. Figure 4 shows the liquid flow patterns produced by the respective impellers. The flow pattern for the unidirectionally rotating CD was similar to that for the unidirectionally rotating DT, the well-known pattern having circulation loops with the characteristic radial discharge stream [Fig. 4 (a)]. When there is a difference in strength between the upper and lower loops, the discharge flow from the impeller deviates somewhat in the axial direction (Takeda *et al.*, 1968a). As demonstrated in Fig. 4 (b), this phenomenon was observed also for the present type of CD. On the other hand, when the CD was allowed to rotate in forward-reverse mode, the tendency for the discharge flow to shift from the radial direction to the axial direction was more significant [Fig. 4 (c)].

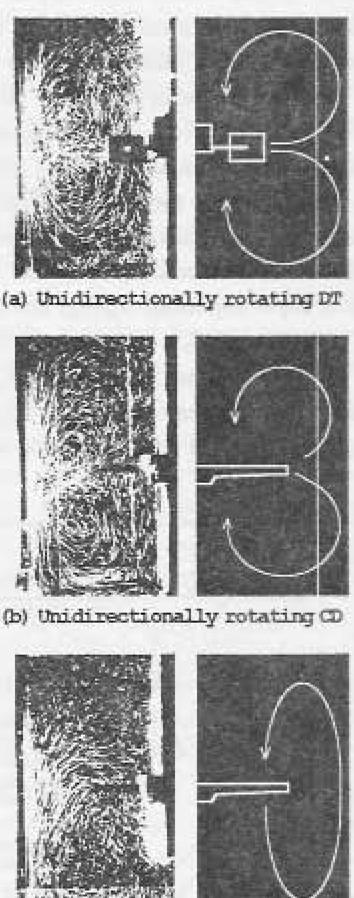

Figure 4. Flow patterns produced by single impeller.
(a) baffled vessel with D_i/D_t=0.48, (b) baffled vessel with D_i/D_t=0.64, and (c) unbaffled vessel with D_i/D_t=0.64, at N_r=3.33 s^{-1}.

3.2 Power Consumption of Multiple Impellers

For most cases where the unidirectionally rotating impeller was used in the baffled vessel, roughly one to one and a half impeller per the liquid depth equal to the vessel diameter is attached on the agitation shaft. On the basis of this fact, the power number was investigated when two and three impellers were used for the vessel with the liquid height-to-diameter ratio of 2. Figure 5 shows the relationship between the power number of dual impellers, N_{p2}, and the clearance of impellers, C_i. In the figure, N_{p2} is divided by the power number of single impeller, N_{p1}, and C_i is divided by the impeller diameter, D_i. For the unidirectionally rotating DT, N_{p2} tended to decrease monotonically with decrease in C_i. This tendency is common to the result by Nishikawa *et al.* (1976) and that by Hudcova *et al.* (1989). For the unidirectionally rotating CD, N_{p2} first decreased slightly with decrease in C_i, then reached to a minimum at a certain value of C_i and tended afterward to reincrease. The difference in the dependence of N_{p2} on C_i between the impellers of different designs may be attributed mainly to that in impeller-impeller flow pattern interaction due to the different impeller design such as with or without disk (Nishikawa *et al.*, 1976). The value of N_{p2} was found for the forward-reverse rotating CD to remain almost constant when C_i was varied. Figure 6 shows the relationship between the power number ratio of triple impellers, N_{p3}/N_{p1}, and the specific clearance of impellers, C_i/D_i. Although the dependence of N_{p3} on C_i was similar to that of N_{p2}, for the unidirectionally rotating impellers, the degree of its effect on N_{p3} was somewhat large compared with that on N_{p2}. On the other hand, N_{p3} of the forward-reverse rotating CD exhibited an almost constant value independent of C_i.

Here, let's note the difference of the power number ratios, N_{p2}/N_{p1} and N_{p3}/N_{p1}. The values of N_{p2}/N_{p1} and N_{p3}/N_{p1} for the unidirectionally rotating CD lie in the range close to 2 and 3, respectively, in contrast with those for the DT. The forward-reverse rotating CD gives the almost constant power number ratios, 2 and 3, in two- and three-stage configurations, respectively. When N_{p2}/N_{p1} and N_{p3}/N_{p1} are equal to 2 and 3, respectively, namely the power numbers for multiple impellers are equal to the number of impeller stages times the value for single impeller, each impeller is regarded to act independently without impeller-impeller flow pattern interaction (Takeda *et al.*, 1968b; Taguchi and Kimura, 1970; Nishikawa *et al.*, 1976; Hudcova *et al.*, 1989; Armenante and Chang, 1998). As shown in Fig. 4, the liquid flow with the largest axial component was observed for the forward-reverse rotating CD among the impellers used. Figure 7 shows the liquid flow patterns produced by the respective multiple impellers. The differences in the flow patterns due to changes in the axial component in the discharge flows from impellers were observed. An increased axial component would result in a series of discharge flows between the adjacent impellers leading to a decreased impeller-impeller flow pattern interaction (Mochizuki *et al.*, 1995). A less dependence of power number of the forward-reverse rotating multiple CDs on their clearance in the unbaffled vessel may be attributed mainly to the bulk flow with larger axial component.

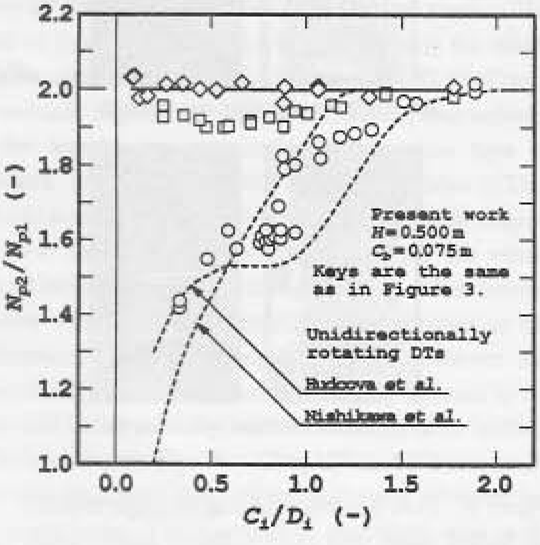

Figure 5. Relationship between power number ratio and specific impeller clearance for double-impeller system.

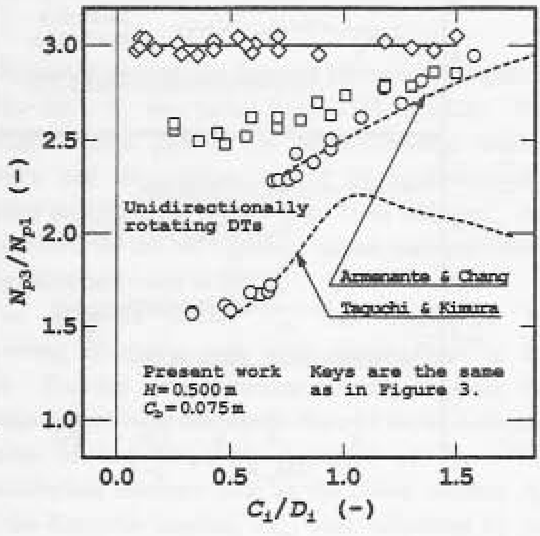

Figure 6. Relationship between power number ratio and specific impeller clearance for triple-impeller system.

D_i = impeller diameter, m
D_t = vessel diameter, m
H = liquid depth in vessel, m
N_p = impeller power number, -
N_{p1} = impeller power number in single impeller system, -
N_{p2} = impeller power number in dual impeller system, -
N_{p3} = impeller power number in triple impeller system, -
N_r = rotation rate of impeller, s^{-1}
P_m = power consumption of impeller, W
Re_m= impeller Reynolds number, -

Greek letters

μ = liquid viscosity, Pa s
ρ = liquid density, kg/m^3

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Received: December 27, 2000 (by Editor-in-Chief) - August 10, 2001 (by Subject Editor).
Accepted for publication: January 3, 2002.
Recommended by Subject Editor A. Cuitiño.