Movement of Solid Particles on and off Bottom of an Unbaffled Vessel Agitated by Unsteadily Forward-Reverse Rotating Impeller*

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Abstract
An unbaffled agitated vessel having an unsteadily rotating impeller was employed as an apparatus mixing liquid and solid particles with the density larger than that of liquid. For this type of vessel, the movement of solid particles on and off the vessel bottom was studied in relation to the liquid flow produced by the impeller. When a disk turbine impeller with six flat blades was rotated in the forward-reverse mode, the liquid flow and the particle movement were visualized. Concurrently, the agitation requirement for complete solid suspension where no particle remains on the vessel bottom for more than a short period and all particles are in motion was determined as a minimum rotation rate of impeller. The liquid flow and the particle movement around a tiny heap of solid particles configured on the vessel bottom were characterized through measurement of their velocities by the particle tracking velocimetry (PTV). The relative velocity of rising with off-bottom suspension of solid particles was uniform in its distribution and wholly large in its magnitude, compared with that in a baffled vessel with a unidirectionally rotating impeller of the identical design, which revealed an effectiveness of this type of vessel as an apparatus for the solid-liquid mass transfer.

Key words: Unbaffled Agitated Vessel, Unsteadily Rotating Impeller, Solid-Liquid Dispersion, PTV

1. Introduction
Dispersion of solid particles in liquids is often involved in operations for process productions in chemical industries, ranging from mass transfer operations such as dissolution, crystallization, etc., to reaction operations treating catalysts. For these systems, cylindrical vessels that are agitated by unidirectionally rotating impellers are generally adopted as an apparatus for mass transfer or reaction. In the conventional vessels, vertically long plates, so-called baffles, are attached flush to the vessel wall to avoid occurrence of the forced vortex, resulting in decrease of the vertical flow necessary for mixing of the liquid-phase within the vessel. However, attachment of the baffles causes such problems as formation of insufficient mixing zone behind them, possible scale adhesion to them and necessity of their periodical cleaning, etc. In contrast, if an impeller
is allowed to rotate unsteadily with alternation of its direction, sufficient mixing could be expected without the baffles, which alleviates concerns about problems encountered with conventional baffled vessels.

Recently, there has been a growing interest in unsteady agitation modes either by changing the rotation direction or speed of impeller. In fact, some papers have reported their mixing characteristics of this kind of vessel agitated by an unsteadily rotating impeller, which requires no baffles even when low-viscosity liquids are treated. The researchers treated relatively high viscous liquids found out that controlled periodic fluctuation of the flow field provides bulk liquid with an effective mixing, referring to the chaotic mixing. On the other hand, for the case of turbulent conditions, a few publications have been available, where a unique deformation action in the unsteady flow produced by the impeller is expected for enhancement of the mixing. As pointed out in common in those papers, improved performance of the agitated vessel is achievable using the unsteadily rotating impeller. Few literatures on application of the unsteadily rotating impeller vessel to solid-liquid dispersion system is found out although such a system is industrially of importance as mentioned above.

Previously, we designed an agitator with an impeller whose rotation alternates periodically the direction, i.e., an unsteadily forward-reverse rotating impeller. Figure 1 shows a process in one cycle when a disk turbine impeller with six flat blades that is one of typical impellers for agitators is rotated in the forward-reverse mode. Starting at location S1, the impeller first rotates at an increasing speed, exhibiting a maximum velocity at its angular displacement of 45°. After that, it rotates with a decreasing speed, stopping at its angular displacement of 90°, location S2. The impeller then reverses direction, rotating with a velocity of opposite sign, and returns to the initial location S1. That is, the impeller completes one forward-reverse rotation cycle and starts a following cycle. The unbaffled vessel agitated by the forward-reverse rotating impeller was applied to a system treating liquid and solid particles with the density larger than that of liquid to be developed to a new type of solid-liquid apparatus.

As a primary characteristic of solid-liquid apparatus, the minimum rotation rate of impeller is mostly considered for complete solid suspension where no particle remains on the vessel bottom for more than a short period (e.g. 1-2 s) and all particles are in motion. The cause for that is that under such state, all the surface of solid particles is contacted with liquid, ensuring avail of the interfacial area at a maximum for heat and mass transfer and chemical reaction. However, the agitation requirements evaluated in such a way characterize indirectly the movement of solid particles and relating accurately them to mass transfer characteristics, etc. is unreasonable. Direct evaluation of the particle
movement through measurement of its velocity would enable to make more reasonable relation and thereby consideration\(^{(15), (16)}\).

In this work, for an unbaffled agitated vessel with a forward-reverse rotating impeller, the liquid flow produced by the impeller was first visualized based on the photograph showing the path lines of tracers. Additionally, the particle movement on and off the vessel bottom was observed visually and concurrently the agitation requirement for complete solid suspension was determined as a minimum rotation rate of impeller. The velocity of liquid and that of solid particles were then measured near the vessel bottom. Furthermore, the relative velocity between liquid and solid particles in this type of vessel was compared with that in a baffled vessel with the unidirectionally rotating impeller. Thereby, the relation between the solid-liquid mass transfer rate and the velocity was discussed.

2. Nomenclature

\[
\begin{align*}
C_b &: \text{Impeller height [mm]} \\
C_L &: \text{Concentration of solute in liquid phase [gL]} \\
C_L^* &: \text{Concentration in liquid phase saturated with solute [gL]} \\
D_i &: \text{Impeller diameter [mm]} \\
D_v &: \text{Vessel diameter [mm]} \\
N_{fr} &: \text{Frequency of forward-reverse rotation of impeller [Hz]} \\
N_r &: \text{Rotation rate of impeller [s\(^{-1}\)]} \\
R &: \text{Radial distance in coordinate system [mm]} \\
t &: \text{Time [s or min]} \\
v_z' &: \text{Relative velocity of particle rising [m/s]} \\
v_{Lz} &: \text{Axial velocity of liquid flow [m/s]} \\
v_{sz} &: \text{Axial velocity of solid particle movement [m/s]}
\end{align*}
\]
3. Experimental Setup

A schematic diagram of the experimental apparatus is shown in Fig. 2. An unbaffled vessel with a flat base made of transparent acrylic resin (300 mm in inner diameter, \(D_t\)) was used. The liquid depth was set at \(D_t\): 300 mm. A disk turbine impeller with six flat blades (paddle type radial impeller with six flat blades fitted to disk), as shown in Fig. 3, was used with the diameter (\(D_t\)) of \(D_t/2\), 150 mm. The impeller was fitted on a shaft at the height (\(C_b\)) of \(D_t/3\), 100 mm, as measured from the vessel bottom to the impeller blade centerline. For solid phase, namely, model solid particles, glass (density, 2.457 g/cm\(^3\)) particles were employed at the concentration of 0.5 wt%. The particle diameter was 0.425 mm. Liquid phase was water and its temperature was maintained at 298 K in all the experiments. Moreover, control experiments were carried out using the turbine type impeller in the unidirectional rotation mode under the fully baffled condition (Fig. 4). This work was performed in the range of impeller rotation rate up to that giving the complete solid suspension mentioned above. Agitation requirements for it were determined by visual observation according to Zwietering’s criterion\(^{14}\). The rotation rate of the forward-reverse rotating impeller was described as the average over one cyclic time of its movement. As shown in Fig. 1, when the angular displacement is expressed in a form of cosine function, the rotation rate is given by the sine function. Then, the average impeller rotation rate, \(N_r\), is related to the amplitude, \(\theta_o\), and the frequency, \(N_f\), of the forward-reverse rotation that is the operating conditions as follows:

\[
N_r = (2/\pi) \theta_o N_f
\]  

In the mechanism for transmitting motion in the drive unit employed here, \(\theta_o\) is \(\pi/4\).

Visualization of the liquid flow and that of the solid movement were made independently. The liquid flow was examined with polystyrene particles (approximately 0.5 mm diameter) as tracers in the system without the glass particles. The liquid phase was NaCl solution, with density equal to that of the tracers (1.04 g/cm\(^3\)). In this system, tracers could serve as flowers for bulk liquid flow\(^{17}\). A 0.5 W laser light source was used for lighting. The thickness of light sheet was set at 3 mm in the location of vessel center. One picture was taken with the camera set on a stationary table underneath the vessel under
lighting that was collimated to illuminate the horizontal plane including undermost the vessel bottom. The other picture was taken with the camera set on a stationary tripod beside the vessel under lighting that was collimated to illuminate the vertical plane including centrally the shaft center. The images were recorded using a still camera over one-half forward-reverse rotation or one unidirectional rotation. The solid movement in the system treating water and the glass particles was examined with themselves as tracers. The pictures were taken with a flare of flashlight of xenon lamp on the horizontal and vertical planes.

Measurement of the liquid flow and that of the solid movement were also made independently. The tracers for liquid flow and those for solid movement were the same as the respective ones in the visualization experiments. For lighting, being common to the cases of liquid and solid, the laser light sheet was set as mentioned above. The images were recorded using a video camera (frame time, 1/250 s) during 8 s. Image analysis was made to determine the velocity of liquid and that of solid particles by the two-dimensional particle tracking velocimetry (PTV)\(^{(18)}\). The details of setting on analysis in PTV were described in the previous paper\(^{(19)}\). After set of the two instantaneous pictures in series, the velocities through the test section were determined as the vectors based on the difference in position of the tracers identified on the composite picture and the frame time. The velocity vectors in the section collected for the 1999 pictures were averaged with weighted for the distance between the measured point and the section center.

There are some possible error sources in the measuring system and measurement uncertainty is difficult to calculate precisely. The error is determined by the position measurement of the tracer particles, the time between frames of the video camera, the traceability of the particles to the liquid flow and pathline averaging effect, etc. Among these error sources, the uncertainty due to the position measurement is expected to be dominant and was estimated to be on average 3 % from the results of the camera calibration. The repeatability of data was about 95 %.

The rate for benzoic acid to transfer from its solid particles to water, namely, the rate of dissolution of benzoic acid in water, was assessed as a process reflecting the solid-liquid mass transfer\(^{(20)}\). The change of the benzoic acid concentration in the liquid phase, \(C_L\), was analyzed against the time from rapid release of the particles into water agitated at the measured impeller rotation rate. \(C_L\) was evaluated by measuring the electrical conductivity of the solution with the electrode.

4. Results and Discussion

4.1. Flow of liquid and movement of solid particles

It is fundamental to observe the liquid flow near the vessel bottom to understand off-bottom suspension of solid particles. The liquid flows produced by the forward-reverse and unidirectionally rotating impellers were first visualized and comparison between the impeller rotation modes was made of the liquid flow along the vessel bottom. Figures 5 show the pictures taken with a long exposure for the forward-reverse (a) and unidirectional (b) rotation modes, respectively. Upper photographs are on the vertical plane including the shaft; lower ones are on the horizontal plane including the vessel bottom. Those images give the outline of the liquid flow displayed by the path lines of tracers. Liquid discharged through the unidirectionally rotating impeller flows from the vessel wall side to its center along the bottom. Beneath the impeller, the region of flow having almost no radial component was then formed. In the forward-reverse rotation mode of the impeller, the direction of the liquid flow resembles that in the unidirectional one. On the other hand, almost no circumferential component was observed in the liquid flow along the vessel bottom.
The movement of solid particles on and off the vessel produced by the liquid flow through the impeller was then observed. When the impeller rotation rate was increased, the final solid particles to be suspended came from a tiny heap on the vessel bottom, whose position was the region beneath the impeller, irrespective of the impeller rotation mode. Figures 6 show off-bottom suspension of solid particles from side and bottom views. The impeller rotation rates in the respective modes are 0.9-fold the minimum rates for complete solid suspension corresponding to a state slightly before complete one. The significant difference between the impeller rotation modes was observed in the configuration of heap. This is considered to be attributed to the difference in the vessel structure with and without the baffles and that in the magnitude of circumferential component in the liquid flow. In any impeller rotation modes, the behavior was observed for solid particles to travel toward the heap horizontally with motion from the vessel wall side to its center and to travel away from the heap vortically with upward motion.

On the basis of these results, the test sections for determining the velocity of liquid flow and that of particle movement were set as shown in Fig. 7. Around the heap of solid particles configured on the vessel bottom, the flow and movement toward it are...
characterized on the horizontal plane including the vessel bottom, and those away from it are characterized on the vertical plane including the shaft center, respectively. In cylindrical coordinates where an origin was designated as the intersection between the centerline of the shaft and the plane including the vessel bottom, the sections were 20 × 20 mm on the horizontal plane and 20 × 37.5 mm on the vertical one.

4.2. Velocities of liquid and solid particles

For the forward-reverse and unidirectional rotation modes, respectively, the velocity vectors of liquid flow are overprinted on the images displaying the flow patterns in Figs 5. The magnitude of vector was scaled relative to that of the blade tip velocity of impeller as calculated with Eq. (1). In any impeller rotation modes, the directions of velocity vectors were almost same, irrespective of the impeller rotation rate. Additionally, the relative magnitudes of the vectors were unchanged. From these, the velocity of liquid flow was found to be proportional to the impeller rotation rate.

The velocity vectors of particle movement are overprinted on the images displaying the heap configuration on the vessel bottom in Fig. 6. The relative magnitudes of velocity vectors on the horizontal plane differed depending on the impeller rotation rate, among the positions around the heap. Such dependence on the impeller rotation rate is interpreted as rate controlling of off-bottom suspension of solid particles by the flow or movement toward the heap. On the other hand, at the respective positions on the vertical plane, the relative magnitudes of the vectors were comparatively equal. Thereby, the velocity for solid particles to rise with suspension was shown to increase nearly in proportion to the impeller rotation rate.
Moreover, many workers\textsuperscript{(21)} employ the magnitude relative to that of the blade tip velocity of impeller to characterize the transport phenomena in the vessels agitated by the impellers. Additionally, the blade tip velocity of impeller is selected as a measure in scale-up of the vessel, in some application\textsuperscript{(22)}. From these, the results obtained in this work are expected to be applicable to the vessels with different scales, when the solid-liquid conditions are not varied.

From the viewpoint of the solid-liquid mass transfer, the relative velocity between liquid and solid particles, particularly the velocity for solid particles to rise relatively to liquid in flow, as given by Eq. (2), is an important parameter.

\[
V_z' = v_{sz} - v_{Lz}
\]  

(2)

where \(v_{Lz}\) is axial liquid velocity and \(v_{sz}\) is axial solid velocity. Figure 8 shows the plot of the relative velocity of particle rising, \(V_z'\), against the impeller rotation rate, \(N_r\). A small dependence of \(V_z'\) on \(N_r\) was common to the impeller rotation modes. In the unidirectional rotation mode, the velocity difference due to the position on the vertical plane was more remarkable. Although a regularity in the distribution was not recognized, a cause seems to be for the liquid flow velocities to have the outward or inward radial components, which are large compared with those in the forward-reverse rotation mode. On the other hand, for the forward-reverse rotation mode, the velocity distribution was found to have a uniformity. Additionally, its magnitude in the latter mode was on the whole larger and ranged up to about fourfold enlargement.

4.3. Relation between solid-liquid mass transfer rate and velocity

The solid-liquid mass transfer was then investigated in relation to the relative velocity between liquid and solid particles. Figure 9 shows the time-course of dissolution of benzoic acid in water as an example of solid-liquid mass transfer process. The concentration of benzoic acid in the liquid phase, \(C_L\), was determined at the position of \(R=37.5\, \text{mm}\) and \(Z=40\, \text{mm}\) on the plane of \(\Theta=90\, \text{deg}\) in the coordinate system (Fig. 7). As can be seen in Fig. 9, \(C_L\) increased leveling off with the time, \(t\), and reached the saturated value, \(C_L^*\). In a middle stage of the dissolution process, the values of \(C_L\) for the forward-reverse rotation mode was about 25 % large compared with those for the unidirectional rotation mode. That is, the dissolution rate in the forward-reverse rotation mode was found to be higher than that in the unidirectional rotation mode. The correlation between the solid-liquid mass transfer rate and relative velocity has been generally recognized in that the liquid flow controls the boundary layer on the mass concentration around solid particle\textsuperscript{(23)}. Higher dissolution rate in the forward-reverse rotation mode is
considered to be attributed to larger relative velocity between liquid and solid particles as shown in Fig. 8. The characteristic marks on the velocity in forward-reverse rotation of the impeller was demonstrated for effective enhancement of the solid-liquid mass transfer.

Moreover, the result shown in Fig. 9 is an example revealing the enhancement of the solid-liquid mass transfer with the forward-reverse rotating impeller. To establish a sounder and more generalized basis by which the mass transfer characteristic of the solid-liquid apparatus agitated by the forward-reverse rotating impeller can be predicted, further examinations in different solid-liquid systems are necessary.

5. Conclusion

In the unbaffled agitated vessel with the forward-reverse rotating disk turbine impeller with six flat blades, the movement of solid particles with the density larger than that of liquid was investigated through visualization and measurement on and off the vessel bottom. When the impeller rotation rate was increased in the range of the rate lower than the minimum one for complete solid suspension, off-bottom suspension of solid particles was observed with travels toward and away from the tiny heap produced by the liquid flow through the impeller. The velocity vectors of the liquid flow and those of the particle movement were determined around the heap by PTV. The relative velocity of particle rising, which is considered to be related to the rate of enhancement of the solid-liquid mass transfer, was compared between this type of vessel and the baffled vessel with the unidirectionally rotating impeller of the identical design. The characteristic marks on the velocity in the former were clarified to be more uniform distribution and wholly larger magnitude, effective for the mass transfer.

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References


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