EFFICACY OF PARTIAL BAFFLES FOR A VESSEL AGITATED BY A RUSHTON TURBINE IMPELLER

Article Highlights
- Standard baffling may not be the best approach for a vessel agitated by a Rushton turbine impeller
- Baffle efficacy is reflected by the bulk liquid flow affecting the impeller power consumption
- Partial baffles are effective in the flow and power, favorably comparing with full baffles

Abstract
For a vessel agitated by a Rushton turbine impeller, the efficacy of partial baffles was evaluated through examination of the liquid flow and impeller power characteristics. The bulk flow formed a pattern having circulation loops of different intensity and largeness depending on the baffle condition: the baffle length relative to the liquid depth for the vessel. Consequently, the liquid flow within the vessel affected the impeller power number. The characteristic circulation loops, which generally reflect the baffle efficacy, were assessed in terms of the discharge flow through the impeller and the energy transmission within the vessel based on the flow velocity profiles. The shorter length of baffles fitted partially in the upper half of the liquid phase was revealed to be effective, supported in combination by a comparable discharge flow and a successful energy transmission.

Keywords: agitation vessel, Rushton turbine impeller, partial baffles, liquid flow, impeller power.

When vessel-type apparatuses agitated by mechanically rotating impellers are used for lower viscosity liquids in turbulent flow regimes, the vessels have baffles in many cases. The standard is wall baffles which consist of four flat vertical plates, directed radially and spaced at 90° intervals around the vessel periphery, starting at the vessel bottom and running the length of the vessel side to the liquid top. This condition is often designated as fully baffled or standard baffle. Without the baffles for the vessel, formation of a central vortex results in poor mixing, with the free surface sagging downwards in the center. The full baffles destroy the vortex and keep the free surface flat. Then, the circumferential flow produced primarily by the rotating impeller is converted into axial flows, thereby improving mixing. For these reasons, baffled vessels are widely used in industrial applications. They have been configured as an object of related studies. Sometimes, however, when it is critical that the impeller draw in material, standard baffling may not be the best approach [1].

Unbaffled vessels have been studied much less satisfactorily than baffled vessels. Some applications are preferred with the former vessels [2-5] because of undesirable effects of the presence of the baffles. For the unbaffled vessel, the central vortex formation and the following free surface shape have been studied mainly in relation to the impeller power consumption [6,7]. The trailing vortices behind the blades of the turbine type impeller, which have a significant effect on the mixing performance, were observed in the unbaffled vessel as well as in the baffled one [8].

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compared the internal flow of the turbine type impeller between the conditions with and without baffles. The comparative results demonstrated that the absence of baffles made the impeller more efficient for energy transmission. Additionally, a characteristic flow is known to be derived near the vessel bottom. The resultant flow orientated radially inward along the bottom surface may be effective for circulation of the liquid within the vessel. Advantages over the baffled vessel were found for the liquid-phase mixing and solid-liquid dispersion. These findings could extend the potential application range of unbaffled vessels.

Between the fully baffled and unbaffled conditions, there exist partial baffle configurations. Vessels having such configurations were introduced to be non-standard by Siddiqui [13]. An example is wall baffles of different lengths, which are shorter than standard ones and are located at a certain distance from the vessel bottom or liquid top [14-16]. Although partially baffled vessels are used in industries producing polymers, pharmaceuticals and fine chemicals, they have been studied poorly and lack information on the mixing performance. While being recognized that baffling partially is incomplete to prevent the central vortex formation, the efficacy of shorter baffles has been discussed on the basis of the measurements of the power input [14,15] or those of the flow field [16] but the results should be developed for operational design. To attain the respective purposes in the related applications, a key to successful agitation is providing the proper flow field under the power input controlled. Therefore, for the partially baffled vessel, an examination of the hydrodynamics in energy consideration is primarily addressed and, conventionally, its attention is concentrated on the impeller round and distance regions. Then, regarding the baffle efficacy, we attempt to assess the flow field characterized along with the power input.

A main objective of this study is experimental clarification of the efficacy of partial (shorter) baffles for a vessel agitated by a disk turbine impeller with six flat blades: a Rushton turbine impeller. For partially baffled vessels and the fully baffled and unbaffled vessels, respectively, the liquid flows produced by the impeller were first visualized in conjunction with measurement of the impeller power consumption. Then, the flow measurements were made around the impeller rotational region and in the vessel bottom region. Based on the flow velocity profiles there, the baffle efficacy was evaluated considering the discharge flow through the impeller and the energy transmission within the vessel.

EXPERIMENTAL

A schematic diagram of the experimental agitation vessel is shown in Figure 1. A cylindrical vessel with a flat base made of transparent acrylic resin (300 mm inner diameter, D) was used. The liquid depth, H, was maintained at 300 mm (D). Four platy baffles 1 mm thick were fitted on the vessel wall. They were 30 mm (0.1D) wide and have different lengths of Lb. For

Figure 1. Schematic diagram of experimental agitation vessel and coordinate system for observations.
being adjusted to 0, 75, 150, 225 and 300 mm, the geometrical parameter \( L_b/H \) was varied in the range of 0-1, inclusive of the fully baffled \( (L_b = 300 \text{ mm}) \) and unbaffled \( (L_b = 0) \) conditions. The partial baffles \( (L_b \text{ of } 75, 150 \text{ and } 225 \text{ mm}) \) were located from the liquid top with the clearances above the vessel bottom. Standard designs of Rushton turbine impellers (90, 120 and 150 mm diameter, \( D \)) were used, respectively corresponding to \( D/D_t \) of 0.3, 0.4 and 0.5. The respective impellers were set at 150 mm height \((0.5D_t)\), \( H_i \) from the vessel bottom. The impeller rotation rate, \( N_i \), was varied from 50 to 150 rpm. The liquid phase was water. The impeller Reynolds number ranged in values of 7580-63200.

The impeller power consumption was ascertained by measuring the torque with strain gauges fitted onto the shaft [19]. Side-viewing visualization of the bulk liquid flow within the vessel was made using the particle suspension method. Polystyrene particles (approximately 0.5 mm in diameter, with 1030 kg m\(^{-3}\) density) were used as tracers. A 0.5 W laser light source was used in the form of a sheet for lighting. Lighting was collimated to illuminate the vertical plane immediately in front of the impeller shaft. A square jacket arranged around the vessel was also filled with water to reduce optical distortion in the observation of the tracer movement under agitation at \( N_i \) of 100 rpm by the impeller with \( D \) of 150 mm. Subsequently, images were recorded using a still camera to characterize the flow pattern [20].

Observation of the liquid flow using the particle suspension method was focused on two distinguishing planes: the vertical plane including the impeller shaft and the horizontal plane including the vessel bottom. On the respective planes, the flow velocities were measured using two-dimensional particle tracking velocimetry (PTV). The polystyrene tracer particle diameter was approximately 0.05 mm. The laser light sheet adjusted to 2 mm thickness illuminated the respective planes. The impeller with \( D \) of 150 mm was used; \( N_i \) was set to 100 rpm. In the region immediately around the impeller blade passing, the radial and axial velocities of liquid flow were examined based on pictures taken with a video camera set on a stationary tripod beside the vessel. Additionally, in the region immediately above the bottom surface, the circumferential and radial flow velocities were observed through the camera underneath the vessel. Further details of PTV analysis were described in the previous papers [20]. The coordinate system defined on the horizontal and vertical planes is given in Fig. 1. Cylindrical coordinates were used: the origins were designated as the intersection between the impeller shaft centerline and the vessel bottom surface. The circumferential angle was measured in the orientation as depicted in the figure. For the predetermined positions in the impeller and bottom regions, the liquid flow velocities were determined as vectors. The velocity vectors collected during 40 rotations of the impeller were averaged temporally.

RESULTS AND DISCUSSION

Bulk liquid flows and impeller power characteristics for vessels under different baffle conditions

The liquid flows produced by the Rushton turbine impeller were visually overviewed for the fully baffled, partially baffled and unbaffled vessels, respectively, in conjunction with evaluation of the impeller power characteristics. Figure 2 shows images of path lines depicted by the tracer particles, displaying the flow patterns within the vessels, under different baffle conditions \((L_b/H_b)\). In the fully baffled vessel \((L_b/H = 1)\), the flow field was characterized by a radially outward discharge stream [21]. Such a stream caused the flow to form one circulation loop on each half of the liquid phase, which are represented roughly with bold solid lines on the related picture in the figure. In the absence of baffles \((L_b/H = 0)\), the tracer trajectories were intermissive, implying that the circumferential flow was dominant compared with the radial and axial ones: a strong swirling flow could remain. Because this is comprehended to make the circulation loop difficult to detect, the bulk flow having weak circulation loops is represented with bold dotted lines. With the partial baffles of \(L_b/H = 1/4\), the upper and lower halves of the liquids flowed similarly to the circulation loop under the fully baffled condition (solid line) and that under the unbaflled one (dotted line), respectively. When the baffle length was increased by \(1/2 \text{ of } L_b/H\), the circulation loop in the upper half part was observed to be intensified and the swirling flow in

![Figure 2. Bulk liquid flow patterns under conditions of different baffle lengths relative to liquid height, \(L_b/H_b\).](image-url)
the lower half part was apparently reduced. Furthermore, with 3/4 of $L_b/H$, a detectable circulation loop was poorly formed, enlarging in the lower half.

Note that the bold lines shown on the pictures represent roughly the circulations in the upper and lower halves of the liquid phase. The actual flows are three-dimensional but the description used in Figure 2 is useful for overviewing the difference of bulk liquid flow depending on the baffle condition, in a qualitative manner [22]. The impeller power consumption, $P_m$, was expressed as the power number, $N_p$, in a dimensionless form. Its change with variation of the impeller diameter and rotation rate, $D_i$ and $N_r$, was investigated in terms of the impeller Reynolds number, $Re_m$. Figure 3a shows the relations between $N_p$ and $Re_m$ for different baffle conditions. $N_p$s under the fully and partially baffled conditions were almost unchanged with variation of $Re_m$, but those under the unbaffled condition tended to decrease with increase of $Re_m$. The dependence of $N_p$ on $Re_m$ is regarded as reflecting the shape of the free surface related to the bulk flow as depicted in Figure 2. The fully and partially baffled vessels had a practically flat surface. They provided nearly constant $N_p$ values, suggesting satisfaction of Newton’s law on the flow resistance of the impeller. Without the baffles, the vortex surface was formed with the bulk flow producing approximate solid-body rotation. Because the extent of such a rotation increases concomitantly with increased $Re_m$, the load on the impeller indicated by $N_p$ can decrease with $Re_m$. For the effect of baffle condition, results showed that the $N_p$ values with the full and partial baffles were higher than that without the baffles. Figure 3b shows the relation between $N_p$ and relative baffle length, $L_b/H$, where the $N_p$ value was plotted after average with respect to each baffle condition. With the baffles, even though it had only partial fitting, $N_p$ exhibited notably larger values than that observed without the baffles. Additionally, $N_p$ tended to increase gradually with increase of the baffle length. To the figure, the data reported by Karcz and Major [14] were added for comparison. Although differences exist in the impeller-to-vessel configurations between our study and theirs, the results were almost similar in terms of their tendencies. In relation to the flow pattern, the intensified and enlarged circulation loop is considered to produce the increase of $N_p$ [23]. Then the behavior of the circulation loops in the flow pattern could generally reflect the variation of the baffle efficacy. Kratena et al. [24,25] measured the dynamic pressure affecting the full baffle of the vessel agitated by the Rushton turbine impeller. Such measurements of the force on the baffles of different lengths may be a parameter reflecting the baffle efficiency. The further search of the more quantitative reflector concerned is believed to be important.

**Evaluation of baffle efficacy as viewed from discharge flow**

The behavior of the circulation loops in the flow pattern can be measured first by evaluation of the impeller discharge characteristics. In view of this behavior, the liquid flow was examined typically around the impeller rotational region. Figure 4 depicts profiles of the flow velocity in the region immediately around the blade passing. Under the fully baffled and unbaffled conditions, the inflow and outflow through the impeller were nearly symmetric to the blade centerline, the characteristic discharge stream being positioned around the centerline. With the partial baffles, the flow through the impeller was vertically asymmetric. The discharge stream tended to shift axially downward. The smaller the baffle length, $L_b/H$, was, the higher this tendency became. Such a change in the flow pattern might result from the generation of the downward flow as a reaction of an increased lift in

![Figure 3](image-url)
force upward on the impeller because of the swirling flow in the lower half [26].

Figure 4. Flow velocity profiles in region around blade passing.

From the velocity profiles depicted in Figure 4, the discharge stream was then represented in terms of the volumetric flow rate. A circular cylinder was defined for the impeller rotational region. The magnitudes of \( v_r \) and \( v_z \) in the orientations of the outflow from the cylinder were multiplied by the areas of the cylinder surfaces normal to the respective directions, \( S_r \) and \( S_z \). The obtained products were summarized; the volumetric flow rate, \( Q_d \), was calculated as [27]:

\[
Q_d = \sum v_r S_r + \sum v_z S_z
\]

and \( Q_d \) was expressed as the discharge flow number, \( N_d \), in a dimensionless form. Figure 5 shows the relation between \( N_d \) and the relative baffle length, \( L_b/H \). The tendency for \( N_d \) to increase with \( L_b/H \) corresponded to that for \( N_p \) as shown in Figure 3b. The increase of the discharge flow rate could be related to the flow pattern with the intensified and enlarged circulation loop. To Figure 5, a dimensionless parameter, \( N_d/N_p \), was added as a measure of the shear action due to the impeller. \( N_d/N_p \) under the unbaffled condition was larger than those under the fully and partially baffled conditions: In the unbaffled vessel, the discharge flow produced by the impeller is perceived to have only small turbulence because of smaller trailing vortices [8]. Stated another way, the impeller can function insufficiently for generation of the turbulence. With the baffles, \( N_d/N_p \) was almost unchanged with variation of \( L_b/H \). When the impeller is assumed to perform the role of an actuator fully with the specific \( N_d/N_p \) value in the fully baffled vessel [28,29], the baffle length, affecting the behavior of the circulation loops in the flow pattern, is recognized as a minor factor; The baffle length should be determined considering another characteristic parameter.

Figure 5. Relationship between impeller discharge flow number, \( N_d \), and relative baffle length, \( L_b/H \).

Evaluation of baffle efficacy as viewed from energy transmission

As described above, viewed on the vertical plane, the Rushton turbine impeller exhibits a flow pattern having the circulation loops on one level or another in the intensity and largeness depending on the baffle condition. Near the bottom being located downstream in the lower loop, the flow was regarded as remaining in existence along the bottom surface almost without the axial velocity component. Such a liquid flow was examined specifically in the vessel bottom region for the behavior of the circulation loops to be measured in view of the energy transmission within the vessel. Figure 6 depicts the profiles of the flow velocity at 1 mm height above the vessel bottom (Z). Exploration of the velocity profiles revealed that the velocities without the baffles were larger overall than those with the full baffles [30,31]. Flows observed near the unbaffled vessel bottom were the circumferential flow with orientation identical to that of impeller rotation and the inwardly radial flow from the vessel wall toward its center. The fully baffled vessel had flows weakened locally. In the intermediate region between the baffles, the counter circumferential flows were observed to mutually collide. Consequently, the
profile in the fully baffled vessel was non-uniform in the circumferential direction compared with that in the unbaffled vessel. Such a flow field can provide poor mixing, as demonstrated for off-bottom solids suspension in impeller-agitated vessels [32]. The partial baffles maintained the circumferential uniformity but decreased the flow velocities concomitantly with increased length, $L_b/H$. These tendencies are perceived as a product of the dominant circumferential flow because of the absence of the baffles on the bottom surface.

Examination of the liquid flow in the vessel bottom region proved that its velocity differed at the circumferential and radial positions. The position-dependent profile of the flow velocity was coordinated in terms of the circumferential and radial components averaged for the circumferential direction. Figure 7 shows changes of average velocities, $v_{\theta}$ and $v_r$, with radial distance, $R$. The region on the center side of the $R$ range under about 30 mm should be out of inspection because there the flows along the bottom surface are shifted to the vertical flow to return to the impeller. Comparing the velocity magnitudes at the same radial positions among the vessels, both $v_{\theta}$ and $v_r$ exhibited maximum values under the unbaffled condition. The velocity magnitudes became smaller as the baffle length, $L_b/H$, was increased. The values had only a small difference between the conditions of the full baffles and partial baffles of $L_b/H = 3/4$. Without the baffles, a dominated circumferential flow is regarded as an influence of impeller rotation reaching the vessel bottom region directly [33]. Additionally, an inwardly radial flow can be derived because of a larger pressure gradient decreased from the vessel.
wall toward its center. For the partially baffled vessels, such a characteristic flow near the vessel bottom is anticipated to some degree. The baffled vessel had poor radial and circumferential flows and in the region near the vessel wall, even the circumferential flow in an orientation opposite to the impeller rotation as shown with the negative values of $v_0$ [34]. The latter result can be attributed to the generation of a secondary flow through the vortex region formed behind the baffles [35].

From the velocity profiles depicted in Figure 6, the flow characteristics in the vessel bottom region were then represented in terms of the energy dissipation rate. For a thin layer on the bottom, the viscous sublayer, the relation to express the energy dissipation can be in accordance with Newton’s viscous law. There, the axial motion of fluid particles is assumed to be reduced because of the influence of stationary bottom: The liquid flows two-dimensionally along the vessel bottom surface. Then, the local energy dissipation rate per unit mass of liquid, is given as the following equation:

$$\varepsilon = \frac{2\mu}{\rho} \left\{ \left(\frac{\partial v_z}{\partial r}\right)^2 + \frac{1}{r} \left(\frac{\partial v_r}{\partial \theta} + v_r\right)^2 \right\} + \frac{\mu}{\rho} \left\{ \left(\frac{\partial v_z}{\partial z}\right)^2 + \left(\frac{\partial v_r}{\partial \theta} + \frac{1}{r} \frac{\partial v_r}{\partial r}\right)^2 + \frac{1}{r^2} \frac{\partial v_r}{\partial r} \left(\frac{\partial v_r}{\partial r}\right) \right\}$$

In the equation, $\rho$ and $\mu$ denote the density and viscosity of liquid, respectively. In this work, applying the velocity data at 1 mm height above the vessel bottom (Z) to Eq. (2), $\varepsilon$ was calculated for fully baffled, partially baffled and unbaffled vessels. For calculations, the velocity gradients in the axial direction were estimated by dividing the velocity values at $Z = 1$ mm by 1 mm of the distance, which implies that approximate gradients were evaluated when the velocity value on the bottom was regarded as 0 because the linear velocity profile might form in a viscosity-controlling region closer to the bottom surface. Although such a calculation is lacking rigor to some degree, the results are meaningfully helpful for comparison of the liquid flow characteristics among the vessels different in the baffle condition.

By integrating the respective $\varepsilon$ over the control volume, the energy dissipated locally per unit time, $P_c$, was determined for the vessel bottom region of 2 mm height. Concurrently, the energy dissipation rate averaged over the control volume, $\varepsilon_l$, was calculated by dividing $P_c$ by the related volume. For calculations, the velocity gradients in the axial direction were estimated by dividing the velocity values at $Z = 1$ mm by 1 mm of the distance, which implies that approximate gradients were evaluated when the velocity value on the bottom was regarded as 0 because the linear velocity profile might form in a viscosity-controlling region closer to the bottom surface. Although such a calculation is lacking rigor to some degree, the results are meaningfully helpful for comparison of the liquid flow characteristics among the vessels different in the baffle condition.

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CONCLUSION

For partially baffled vessels agitated by a Rushton turbine impeller, bulk liquid flows and impeller power consumptions were examined in comparison with those for fully baffled and unbaffled vessels. The difference of flow pattern depending on the baffle condition was characterized schematically by the behavior of the circulation loops in the pattern. Correspondingly, the power number changed with variation of the baffle length relative to the liquid depth for the vessel. The baffle efficacy was evaluated as viewed from the two standpoints based on the flow power consumption, $P_m$, corresponds to the energy supplied totally to the liquid within the vessel per unit time. To Figure 8, the energy ratio, $P_l/P_m$, was added as an energy transmission index. The index for the unbaffled vessel was significantly larger, differing by one order of magnitude from that for the baffled vessels. Such a larger energy transmission is considered to result from the contribution of the circumferential flow extended axially to the vessel bottom region. In other words, related to the circulation loop, conversion of the circumferential flow into the axial one by baffles might be disadvantageous for the transmission of the energy of impeller rotation. The index decreasing with fitting the baffles tended to be almost unchanged in the $L_J/H$ range over 3/4. These results of comparisons proved that the energy transmission from the impeller region to the bottom one was potentially successful for vessels with shorter length of baffles to cover the upper half of the liquid phase. In combination with comparable characteristics of impeller discharge as shown in Figure 5, application of such partial baffles to the vessel is expected to be effective for enhancement of the liquid-phase mixing with design of the impeller-vessel configuration, including the baffle geometries [36-40].
velocity profiles: the discharge flow through the impeller and the energy transmission within the vessel. When the baffles were used under different conditions, the dimensionless parameter indicating the discharge flow was found to have a small change. Additionally, the ratio of the energy dissipated locally near the bottom of the vessel to that supplied totally to the liquid within the vessel indicated a larger energy transmission concomitantly with decreased baffle length. The combined efficacy was clarified for shorter length of baffles fitted partially in the upper half of the liquid phase, which can engender modification and design of impeller-vessel configurations.

Nomenclature

- $D_i$: impeller diameter (mm)
- $D_v$: vessel diameter (mm)
- $H$: liquid depth (mm)
- $H_i$: impeller setting height (mm)
- $L_b$: baffle length (mm)
- $N_p$: impeller power number = $P_m/P_{Nr}$
- $N_{di}$: liquid discharge flow number = $Q_d/NrDi$
- $N_r$: impeller rotation rate (rpm)
- $P_{L}$: local energy dissipation rate (W)
- $P_m$: impeller power consumption (total energy supply rate) (W)
- $Q_d$: volumetric flow rate of discharged liquid (m$^3$s$^{-1}$)
- $R$: radial distance (mm)
- $R_{em}$: impeller Reynolds number = $\rho N D_i^2 \mu (-)$
- $S_1$: area of surface normal to radial direction (m$^2$)
- $S_2$: area of surface normal to axial direction (m$^2$)
- $v_r$: radial velocity component of liquid flow (m s$^{-1}$)
- $v_z$: axial velocity component of liquid flow (m s$^{-1}$)
- $v_\theta$: circumferential velocity component of liquid flow (m s$^{-1}$)
- $Z$: axial distance measured from vessel bottom surface (mm)

Greek letters

- $\varepsilon$: specific energy dissipation rate (W kg$^{-1}$)
- $\varepsilon_l$: specific local energy dissipation rate (W kg$^{-1}$)
- $\Theta$: circumferential angle (rad)
- $\mu$: viscosity of liquid (Pa s)
- $\rho$: density of liquid (kg m$^{-3}$)

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NAUČNI RAD

EFIKASNOST PARCIJALNIH ODBOJNIKA SUD SA RUSHTONOVOM TURBINSKOM MEŠALICOM

Efikasnost parcijalnih odbojnika u sudu sa Rushton turbinskom mešalicom je pro- 
jenjena istraživanjem karakteristika strujanja tečnosti i snage mešanja. Glavna stuja teč-
nosti je formirala tok sa cirkulacionom petljom različitog intenziteta u zavisnosti od 
odnosa dužine odbojnika i visine tečnosti u sudu. Shodno tome, protok tečnosti kroz sud 
uticao je na broj snage mešanja. Karakteristične cirkulacione petlje, koje generalno 
obražavaju efektivnost odbojnika, procenjene su prema protoku koji indukuje mešalica i 
rasute energije unutar suda na osnovu profila brzine strujanja. Utvrđeno je da je kraća 
dužina odbojnika u gornjoj fazi efikasna zbog kombinacije poredljivog protoka 
dukovkovanog mešalicom i uspešnim rasipanjem energije.

Ključne reči: sud sa mešanjem, Rushton turbinska mešalica, parcijalni odbojnici, 
strujanje fluida, snaga mešanja.