QUANTIFICATION OF THE PERFORMANCE OF AGITATORS IN STIRRED VESSELS: Definition and Use of an Agitation Index

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An agitation index, based on velocity measurements obtained from laser Doppler velocimetry or other similar techniques, is proposed as an objective measure of the effectiveness of a particular agitator in inducing flow in a stirred vessel. This index is calculated by first generating a cell structure based on the measurement grid, and then assigning each velocity to the entire corresponding cell; the volume-weighted sum of velocities yields then the agitation index, which represents the volume-average velocity as a percentage of the impeller tip velocity. The usefulness of this objective measure of the quality of agitation in a stirred vessel is illustrated by applying it first to the case where three different agitators have to be graded in terms of effectiveness in inducing flow, and then to the case of determining the clearance of two agitators located on the same shaft corresponding to the optimum liquid circulation.

Keywords: agitation; agitation index; mixing; LDV; laser Doppler velocimetry; Rushton turbine; Mixel; Lightnin A310

INTRODUCTION
Simple paddles and later propellers were used for millennia to agitate and mix the contents of vessels; the necessity of optimizing the industrial application of this process led to the development and marketing of a variety of agitators, each one of them deemed appropriate for particular single-, two- or three-phase systems. An objective means of discriminating among the various designs would obviously be very helpful when optimizing the mixing process for particular applications. However, the characterization of the performance of each of these impellers was based mostly either on a qualitative judgement of the extent of flow induced in the vessel, based often on mere visual observation, or on some global characteristic, like for example the mixing time. The experimental techniques used to study flow patterns induced by the agitators in stirred vessels include, among others:

- liquid homogenization based on simple visual observations1–4 or/and conductivity5
- flow visualization by laser sheet6,7, by image processing based on laser sheet illumination and laser-induced fluorescence8,9, or by resistance tomography10
- by hot-wire anemometry11

Laser Doppler velocimetry (LDV) has emerged lately as a very important experimental technique for flow pattern studies; it allows the relatively straightforward determination of the three components of the velocity vector12–15—see reference 12 for a list of publications up to 1994. From these measurements, flow maps are usually drawn, to show (a) the principal movements of the fluid inside the vessel, using most often 2-D velocity vectors \( (U_{ij}) \) resulting from the geometrical addition of \( U_r \) and \( U_z \), and (b) the regions of high, medium and small velocities. Such illustrations are useful in delineating the main circulation loops established in the vessel, but often miss the strong tangential character of the flow, especially around the agitator. The magnitude of the velocity vector components have also been compared to the velocity at the tip of the agitator, \( U_{tip} = \pi ND \) to determine relatively fast or slow flows in the vessel; in the case of viscous liquids, velocities \( \leq 0.01U_{tip} \) constitute the ‘cavern’16,17 of fast-moving liquid which surrounds the impeller and which is considered as the only liquid which is agitated to an appreciable extent.

It is interesting that little else seems to have been done to quantify objectively the extent of mixing achieved in a stirred vessel, apart the definition of a mixing index based on conductivity measurements18.

In this work, a volume-weighted mean velocity and the distribution of velocity-related liquid volumes are proposed as objective measures of the extent of mixing provided by a given impeller.

DEFINITION OF THE AGITATION INDEX
Instantaneous velocities are usually measured at various points \( (i,j,k) \) of a grid \( G \), mostly on the plane of two opposite baffles \( (\theta = 0^\circ) \) or the mid-plane between two neighbouring ones \( (\theta = 45^\circ) \); it is assumed that the vessel under consideration conforms to the ‘standard’ 4-baffle vessel. These are then numerically averaged to yield the mean \( (U_{ijk}) \) and the r.m.s. \( (u_{ijk}) \) velocity of the \( k \)-th component of the local velocity vector \( (k = r,z,\theta) \).
From these, it is possible to calculate the composite mean local 2-D \((U_{ij})\) or 3-D \((U_{ijk})\) velocity for each grid point \(g_{ij}\):

\[
U_g = \left( \sum_k U^2_{ijk} \right)^{1/2}, \quad k = r, z, \Theta
\]  

(1)

depending on whether two or three of the velocity components (axial, radial and/or tangential) are used.

It is postulated that each such velocity \(U_g\) corresponds to a volume of liquid \((V_g)\), which is related to the vessel dimensions and the grid point co-ordinates. The volumes corresponding to the whole grid are summed, so that a volume-weighted average velocity is obtained:

\[
\bar{U} = \frac{\sum_i \sum_j V_i U_{ij}}{\sum_i \sum_j V_i}
\]

(2)

where the denominator corresponds approximately to the vessel volume minus the volume swept by the agitator. Dividing this volume-average velocity by the agitator tip velocity \((U_{tip})\) yields the agitation index:

\[
I = \frac{\bar{U}}{U_{tip}} \times 100\%
\]

(3)

which may be considered as representing the global mean velocity expressed as a percentage of the tip velocity. If the purpose of an agitator is to induce flow inside a vessel, then the agitation index \(I\) is a measure of its effectiveness: the better the agitator is, the higher the velocities inside the vessel will be, resulting in high \(I\) values.

A side benefit of this calculation is the determination of the distribution of liquid volumes associated with a particular velocity; this is achieved by summing the volumes \(V_g\) with related velocities \(U_g\) falling in a given velocity range \([U_{low}, U_{up}]\):

\[
f(V) = \sum_i \sum_j V_{ij} U_{ij} < U_g \leq U_{up}
\]

(4)

In principle, it is conceivable that some agitators will produce different velocity-volume distributions but similar means or agitation indices, making it difficult to discriminate among them; in such cases, the optimum agitator will be the one with a velocity-volume distribution with a larger fraction of vessel volume biased towards higher velocities.

APPLICATION OF THE AGITATION INDEX

In order to illustrate its applicability and usefulness, the agitation index will be calculated for several sets of experimental data.

Comparison of Impellers

The first set comprises measurements of radial, axial and tangential velocities performed in a dished-bottom, cylindrical agitated vessel of standard configuration \((H = T)\); the experimental details, as well as the data, have already been published\(^{1,2}\). Three agitators were used: a 6-blade Rushton turbine, and two propellers, the Lightnin A310 and the Mixel TT. Measurements were done in plain tap water and in a 1\% \((w/w)\) carboxy methyl cellulose (CMC) solution, which exhibited a non-Newtonian behaviour and had an apparent viscosity \((\mu_a)\) of 38 mPa.s. The measurement points were located in the vertical mid-plane between two neighbouring baffles \((\Theta = 45^\circ)\).

The Rushton turbine

Measurements of all velocity components \((U_r, U_z, U_c)\) were performed at various points \((g)\) on a 10×13 grid; these grid points— which are shown as crosses in Figure 1—are considered to correspond to 3-D cells \(c_{ij}\), with volumes \(V_{ij}\) calculated as shown in the Appendix.

Calculating \(U_{seg}\) (equation (1)) and applying equations (2) and (3) yielded an agitation index of 17.8\%, i.e., the global mean velocity is approximately 18\% of \(U_{seg}\). Thus, although some velocities—especially in the exit stream at the tip of the impeller—approach the value of \(U_{seg}\), the majority of the induced flow in the vessel is considerably lower, with an average velocity—for the whole vessel—of ~18\% of \(U_{seg}\).

Of particular interest is the distribution of volumes related to specific velocity subranges; for the purpose of these calculations, subranges of 0.05×\(U_{seg}\) were chosen, for example: 0.05 × \(U_{seg}\) < \(U\) ≤ 0.10 × \(U_{seg}\). As illustrated in Figure 2 (top), the largest fraction of volume is related to slow flows, with ~80\% of the vessel volume, excluding the agitator-swept region, having velocities less than 0.20 × \(U_{seg}\).

When these calculations are performed for the case of the viscous 1\% CMC solution, a similar distribution is obtained,

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (Top) Illustration of the LDV measuring grid (indicated by the crosses) and the superimposed volume-calculation grid (thin lines); \(T = 190\) mm, \(H = T\), \(D = T/2\), \(C = T/3\); Rushton turbine (Bottom) Illustration of the cell volume (solid of rotation).

\(^{\dagger}\) It should be noted that, as illustrated by CFD calculations and by measurements, velocities near the baffles will be different from those in the intersecting plane; however, the lack of more detailed data forces upon us the assumption that these velocity differences may be neglected without invalidating the definition and usefulness of the agitation index.

but slightly translated towards smaller velocities, reflecting the slowing of the flow in the vessel due to the high viscosity of the solution; as a result, the agitation index obtained is lower: \( I_g = 14.5\% \).

Thus, \( I_g \) reflects immediately the change in one of the parameters of the system—in this case of the viscosity of the agitated liquid—if this has a noticeable effect on the flow patterns inside the vessel.

The Mixel TT and Lightnin A310 Propellers

These calculations were repeated for two axial-flow impellers, the Mixel TT and the Lightnin A310, again for water and the 1% CMC solution, in the same vessel (results are presented in Table 1). As already observed by data analysis\(^{12}\), the flow induced by these two agitators is considerably slower than the turbine-induced flow and this is well reflected by the values of the agitation indices, as well as from the distribution of velocity-related volumes (Figure 3).

The usefulness of the agitation index becomes again apparent: the velocity data obtained by laser Doppler velocimetry may be used to obtain an objective characterization of the three agitators for the same vessel configuration and the same medium: in water, \( I_g \) varies from 17.8% for the Rushton turbine to 12.0% for the Mixel TT and to 8.5% for the Lightnin A310. Therefore, it is now possible to grade objectively the performance of each one of them, in terms of the agitation achieved.

In the viscous 1% CMC solution, flow is slowed down, and this is reflected by the lowering of \( I_g \) in the case of the Mixel TT propeller; for the Lightnin A310, it is interesting to note that the velocity distribution was not appreciably affected (see Figure 3), yielding the same \( I_g \) for both cases.

It is interesting to note that the cumulative distributions of velocity-related volumes for each agitator are similar for water and the viscous liquid (Figure 4), i.e., it would appear that the performance of each agitator is characteristic of its design features and depends less on the physical properties of the medium.

At the same time, Figure 4 is illustrative of the relatively low impact that these agitators (in similar configurations) have on the vessel contents, with few regions exhibiting velocities higher than 20% of \( U_{tip} \).

The Problem of the Missing Data

Checking through the literature, one finds that few people have measured all components of the velocity vector, or have data for the whole vessel; in fact, sometimes measurements are restricted to a region around the impeller, in order to provide boundary conditions for subsequent CFD calculations, whereas often only two of the three

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**Table 1.** Agitation index (\( I_g \)) calculated for three agitators in water and in a 1% CMC solution (data from Mavros et al.\(^{12}\)).

<table>
<thead>
<tr>
<th>Type</th>
<th>Medium</th>
<th>( T )</th>
<th>( D )</th>
<th>( H )</th>
<th>( N )</th>
<th>( C )</th>
<th>( w )</th>
<th>( Re )</th>
<th>( I_g ) (tot)</th>
<th>( I_g ) (rz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rushton</td>
<td>water</td>
<td>190</td>
<td>95</td>
<td>190</td>
<td>180</td>
<td>63</td>
<td>19</td>
<td>27100</td>
<td>17.8%</td>
<td>14.5%</td>
</tr>
<tr>
<td>Rushton</td>
<td>1% CMC</td>
<td>190</td>
<td>95</td>
<td>190</td>
<td>120</td>
<td>63</td>
<td>19</td>
<td>480</td>
<td>15.8%</td>
<td>12.2%</td>
</tr>
<tr>
<td>TT</td>
<td>water</td>
<td>190</td>
<td>95</td>
<td>190</td>
<td>400</td>
<td>63</td>
<td>24</td>
<td>60500</td>
<td>12.0%</td>
<td>11.1%</td>
</tr>
<tr>
<td>TT</td>
<td>1% CMC</td>
<td>190</td>
<td>95</td>
<td>190</td>
<td>120</td>
<td>63</td>
<td>24</td>
<td>480</td>
<td>10.5%</td>
<td>8.8%</td>
</tr>
<tr>
<td>A310</td>
<td>water</td>
<td>190</td>
<td>95</td>
<td>190</td>
<td>400</td>
<td>63</td>
<td>12</td>
<td>60500</td>
<td>8.3%</td>
<td>7.8%</td>
</tr>
<tr>
<td>A310</td>
<td>1% CMC</td>
<td>190</td>
<td>95</td>
<td>190</td>
<td>120</td>
<td>63</td>
<td>12</td>
<td>480</td>
<td>8.5%</td>
<td>6.6%</td>
</tr>
</tbody>
</table>
components, usually the radial ($U_r$) and the axial ones ($U_z$), are measured.

In cases such as the latter, in order to overcome the problem of the missing of the third velocity ($U_h$) data, the two components ($U_r$, $U_z$) are used to calculate the 2-D composite velocity ($U_{rz}$); all subsequent calculations (equations (2) to (4)) and comparisons among agitators and/or systems are made using $U_{rz}$ and the resulting $I_{g(rz)}$. Figure 5, which illustrates the parity plots of $U_{rz}$ vs. $U_{rz,h}$ for the three agitators and both media, is drawn in order to test the hypothesis that it is possible to use $U_{rz}$ instead of $U_{rz,h}$. In fact, in the case of the Rushton turbine, the tangential character of the induced flow seems particularly strong and the resulting $U_{hz}$ is therefore somewhat lower than $U_{rz,h}$ since it lacks the effect of the tangential component. In the case of the two propellers, the tangential feature of the induced flow is less significant; in water, the 2-D and 3-D composite velocities have approximately similar values, whereas in the viscous liquid the effect of the lack of the tangential component becomes more pronounced.

Bearing these results in mind, the agitation index calculations were performed again but using $U_{rz}$ instead of $U_{rz,h}$; the results are presented in the last column of Table 1. As expected, the agitation indices are slightly lower, since one of the velocity components is missing, but the trend for the three agitators remains the same. It is therefore concluded that it is possible to use reduced sets of data, i.e., ones having only radial-axial velocity data, if comparisons are made consistently among agitation indices obtained only with these and not referring to or comparing with values obtained with 3-D velocity values.

**Comparison of Configurations**

In the section above, the agitation index was used to differentiate among three agitators, in order to determine the most effective in inducing flow in a stirred vessel. $I_g$ may also be used in other situations, such as when trying to position two agitators on a shaft, so that the optimum configuration—in terms of agitation achieved—is obtained.
**Tall vessels**

Tall vessels, i.e., with liquid height greater than its diameter ($H \geq T$) are widely used for various applications, e.g., fermenters or gas-liquid reactors. It is obvious that a single agitator is not able to provide sufficient fluid movement; hence at least a second one has to be used. This leads to the problem of optimum location of these impellers.

Extensive experimental work has been performed for the case of a double-height vessel ($H = 2T$), using two Mixel TT agitators and varying the lower-impeller clearance ($C$), as well as the inter-impeller one ($\Delta C$). The advantage or disadvantage of various positions were judged by visual observation of the 2-D circulation and flow patterns, as well as by mixing times. Four configurations were selected and LDV measurements were performed: configuration ‘A’ ($C = 2T/3$, $\Delta C = 2T/3$), configuration ‘B’ ($C = T/2$, $\Delta C = 5T/6$), configuration ‘C’ ($C = T/3$, $\Delta C = T$) and configuration ‘D’ ($C = 2T/2$, $\Delta C = 2T/6$); these correspond to a gradual separation of the two agitators. In configuration ‘A’, a single circulation loop seems to be established (Figure 6), with two slow-flow regions in the upper and lower part of the vessel. As the distance between the two agitators is gradually increased, a distinct circulation loop around each one of them are clearly formed, with slow-flow regions eventually found between them. It is obvious that mere visual observation cannot determine which one of these configurations achieve the optimum liquid circulation in the stirred vessel.

Equations (2)–(4) were applied in each case and the agitation index was calculated for each configuration; results are presented in Table 2 (for configuration ‘C’, $I_g$ was determined from both $U_{rz}$ and $U_{rz}h$, since all three velocity components were determined). In configuration ‘A’, the quasi-single circulation loop results in slow flows in large regions in the vessel, and this is reflected by the low agitation index: $I_g = 8.1\%$. As $\Delta C$ gradually increases, a larger fraction of vessel liquid is circulated, and $I_g$ correspondingly increases: to 10.6\% for configuration ‘B’ and even to 11.5\% for configuration ‘C’. This is also illustrated by the distribution of velocity-related volumes (Figure 7); in configuration ‘A’, over 70\% of the vessel volume corresponds to slow flow, i.e., with velocities $\leq 0.10 \times U_{tip}$; as $\Delta C$ increases, the distribution is gradually skewed towards higher velocities, indicating that increasingly more flow moves faster, and this possibly due to a clearer separation of the impeller action, i.e., the establishment of two distinctive circulation loops.

A further inter-agitator clearance increase—configuration ‘D’—yields interesting results: the value of $I_g (= 11.5\%)$ is the same as in ‘C’, i.e., the two configurations seem equivalent. The respective distributions of velocity-related volumes (Figure 7) are slightly different, with a slightly larger fraction of the vessel volume related to small velocities in ‘D’. Therefore, it seems that separating the two agitators by more than $\Delta C = T$ does not yield any appreciable effect, in terms of overall flow patterns.

Therefore, the agitation index is capable of discriminating among several agitator configurations, indicating the one probably yielding the optimum flow structure in the stirred vessel.

**Standard-height vessels**

The poor agitation provided by single impellers has long been recognized; this is especially true when agitating viscous liquids, where the upper part of the vessel is little if at all mixed. To counter this, it is often necessary to add a second impeller, to enhance liquid circulation in the upper part of the vessel. In order to illustrate this, experiments were performed with twin agitators located on the same shaft in standard vessels ($H = T$) in a viscous liquid. For these tests, two axial-flow Mixel propellers were used, the TT95 (a modification of the TT impeller) and the TTP95 (a modification, also, of the TTP agitator); their forms are illustrated in Figure 8.

In configurations ‘E’ and ‘F’, a 1\% CMC solution ($\mu_s = 55$ mPa.s) was agitated by either TT95 impellers (‘E’) or TTP95 ones (‘F’); the latter are slightly shorter in height than the TT95 or the original TT agitator. In configuration ‘G’, two TT95 impellers were used to agitate a 2.5\% CMC solution ($\mu_s = 535$ mPa.s). First of all, the effect of the viscosity increase on the flow patterns around the impellers is immediately noticeable, with a suction zone not only in the upper part of the agitators, as expected, but on the lower part as well; this has already been noticed in single-agitator configurations. The proximity of the two agitators disrupts this flow structure, and the lower suction zone of the upper one disappears, with the ejected liquid being drawn directly into and by the lower impeller. The further increase in viscosity (configuration ‘G’) causes a loss in axial flow and an increase in impeller radiality, with more flow directed radially by the (in principle) axial impeller.

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$^1$ It must be noted that clearance of the lowest agitator ($C$) is measured from the bottom of the vessel to the lowest horizontal plane of the impeller-swept region, whereas the inter-agitator clearance ($\Delta C$) is measured between the lowest horizontal planes of the two agitators.

$^2$ Details about the characteristics of these impellers may be obtained directly from the manufacturer (Mixel S.A., 48 rue de la Grange, F-69009 Lyon, France).

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**Figure 6.** 2-D flow maps for various 2-impeller configurations in a tall vessel ($H = 2T$); Mixel TT agitators. Data from Baudou.

**Table 2.** Agitation index in various configurations ($I_g$) for tall vessels ($H = 2T$).

**Table 3.** Agitation index in various configurations ($I_g$) for standard-height vessels ($H = T$).

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**Trans IChemE, Vol 75, Part A, November 1997**
The agitation index reflects these changes; for configuration ‘E’, $I_g = 12.2\%$, which is compared to the 8.8% for the single TT in a 1% CMC solution (Table 1), i.e., the twin-impeller system—with impellers (TT95) slightly larger than the TT—yields an enhanced circulation, compared to the single-impeller case. Using similar but slightly narrower impellers (TTP95), configuration ‘F’, results in a loss of flow circulation: $I_g = 10.6\%$. Finally, the use of the same impellers (TT95) but in a more viscous solution (configuration ‘G’) results in a loss of circulation, again: $I_g = 7.0\%$.

As expected, the addition of a second impeller improved the liquid circulation in the vessel; here, again, further investigation could possibly determine the optimum inter-agitator clearance, as in configurations ‘A’–‘D’—in fact, industrial applications favour the placement of the upper agitator very close to the surface of the vessel\(^\text{21}\), since this is the region with the poorest flow.

**DISCUSSION**

In calculating and applying the agitation index, several points should be noted:

- the usefulness of the agitation index lies in its ability to differentiate among several possible alternatives, either in terms of type of agitator or in terms of their placement in the vessel, but with overall liquid flow patterns principally in mind; this is an important problem either for agitator manufacturers, trying to grade their products, or for potential buyers examining alternative designs. It is evident that cases involving major sub-processes, like surface aeration, particle dispersion and sedimentation or complex reaction schemes, where the exact location of fast- or slow-flowing fluids are important for the overall vessel performance, would be outside the scope of application of the agitation index.

- it is obvious that the grid density, i.e., the number of cells $V_{ij}$ considered, will have an effect on the value of $I_g$, in a similar way that the number—and volume—of cells in a network of cells may affect the outcome of stirred vessel simulations\(^\text{22,23}\); ideally, an infinite number of infinitely small cells would yield the ‘true’ mean velocity:

$$U_{\text{true}} = \lim_{V_{ij} \to 0} \left( \frac{\sum \sum V_{ij} U_{ij}}{\sum \sum V_{ij}} \right)_{V_{ij} = 0}$$

Therefore, it would be interesting to investigate this effect, especially with data from automated 3-D tables, which

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**Table 2. Application of the agitation index to various agitator/vessel configurations (data from Baudou\(^\text{1}\)).**

<table>
<thead>
<tr>
<th>Config.</th>
<th>Medium</th>
<th>$T$ [mm]</th>
<th>$D$ [mm]</th>
<th>$H$ [mm]</th>
<th>$N$ [rpm]</th>
<th>Type</th>
<th>no</th>
<th>$C$ [mm]</th>
<th>$w$ [mm]</th>
<th>Re</th>
<th>$I_g$ (rzh)</th>
<th>$I_g$ (rz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>water</td>
<td>190</td>
<td>95</td>
<td>380</td>
<td>90.5</td>
<td>TT</td>
<td>2</td>
<td>125</td>
<td>24</td>
<td>13,600</td>
<td>—</td>
<td>8.1%</td>
</tr>
<tr>
<td>B</td>
<td>water</td>
<td>190</td>
<td>95</td>
<td>380</td>
<td>400</td>
<td>TT</td>
<td>2</td>
<td>95</td>
<td>24</td>
<td>60,200</td>
<td>—</td>
<td>10.6%</td>
</tr>
<tr>
<td>C</td>
<td>water</td>
<td>190</td>
<td>95</td>
<td>380</td>
<td>400</td>
<td>TT</td>
<td>2</td>
<td>63</td>
<td>24</td>
<td>60,200</td>
<td>12.7%</td>
<td>11.5%</td>
</tr>
<tr>
<td>D</td>
<td>water</td>
<td>190</td>
<td>95</td>
<td>380</td>
<td>300</td>
<td>TT</td>
<td>2</td>
<td>95</td>
<td>24</td>
<td>45,100</td>
<td>—</td>
<td>11.5%</td>
</tr>
<tr>
<td>E</td>
<td>1% CMC</td>
<td>190</td>
<td>95</td>
<td>190</td>
<td>300</td>
<td>TT95</td>
<td>2</td>
<td>317</td>
<td>24</td>
<td>820</td>
<td>—</td>
<td>12.2%</td>
</tr>
<tr>
<td>F</td>
<td>1% CMC</td>
<td>190</td>
<td>95</td>
<td>190</td>
<td>300</td>
<td>TTP95</td>
<td>2</td>
<td>95</td>
<td>25</td>
<td>84</td>
<td>—</td>
<td>7.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95</td>
<td>25</td>
<td>820</td>
<td>—</td>
<td>10.6%</td>
</tr>
</tbody>
</table>

* no baffles

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**Figure 7. Distribution of velocity-related volumes for the four tall vessel configurations (see Table 2 for the details); Mixex TT agitators. Data from Baudou\(^\text{1}\).**

produce large data sets and greatly facilitate the LDV-data-gathering process.

- the large number of data collected by LDV may include errors; therefore, the data consistency should be tested before the \( I_g \) calculations are performed; one such test would be the calculation of the mass balance around the impeller, e.g. by comparing the amount of liquid being drawn in and pumped out by the rotating agitator.

- cases of missing data should be treated according to how much data are missing: if, for example, a few velocities in the grid have not been measured, these could be calculated by interpolation, since all available data to date have not indicated any discontinuities in velocity profiles; on the other hand, if LDV data are available only for some regions, then agitation index calculations should not be performed.

- in calculating \( I_g \), all three components of the local velocity vector have been taken as of equal weight, since it is considered that all of them contribute to the establishment of the flow pattern in the vessel; it is obvious that in the various regions of the stirred tank, axial, radial or tangential flow may be predominant, depending upon the type of agitator used, but application of some weighting mechanism would invalidate the objectivity of \( I_g \).

- finally, it would be interesting to examine whether the agitation index may be correlated to some other global stirred vessel characteristic, like for example the power or flow number. However, this would necessitate the gathering and compiling of an extensive set of data from various researchers, which is beyond the scope of the present work.

\[ \frac{V}{V_{mol}} = 0.40 \]

\[ \frac{V}{V_{mol}} = 0.20 \]

\[ \text{base case} \]

\[ \text{Config. E} \]

\[ \text{TT95} \]

\[ 1\% \text{ CMC} \]

\[ \text{Config. F} \]

\[ \text{TT95} \]

\[ 1\% \text{ CMC} \]

\[ \text{Config. G} \]

\[ \text{TT95} \]

\[ 2.5\% \text{ CMC} \]

\[ U_{50}\% \]

\[ \text{Config. E} \]

\[ C = T/4, \Delta C = T/4 \]

\[ I_{mol} = 12.2\% \]

\[ \text{TT95} \]

\[ \text{Config. F} \]

\[ C = T/4, \Delta C = T/4 \]

\[ I_{mol} = 10.6\% \]

\[ \text{TT95} \]

\[ \text{Config. G} \]

\[ C = T/4, \Delta C = T/4 \]

\[ I_{mol} = 7.0\% \]

\[ \text{TT95} \]

Figure 8. Variations of the Mixel TT agitator used in the twin-agitator configurations ('E', 'F' and 'G') in viscous liquids (see Table 2 for details); data from Baudou.

Figure 9. 2-D flow maps for various 2-impeller configurations, compared to the single-impeller flow map, data from Baudou.

Figure 10. Distribution of velocity-related volumes for the standard \( (H = T) \) agitated vessel (see Table 2 for the details); configurations 'E', 'F': 1% CMC, configuration 'G': 2.5% CMC. Data from Baudou.
CONCLUSIONS

The agitation index, \( I_a \), i.e., the volume-weighted average velocity, is proposed as an objective measure of the extent of agitation induced in a stirred vessel by a single or several agitators; it uses the extensive velocity data made available nowadays by laser Doppler velocimetry or other similar techniques. The agitation index is calculated by dividing the whole vessel volume into a cell structure based on the velocity measuring grid and by assigning each cell with the velocity determined at the corresponding grid point; the sum of volume-weighted velocities yields the volume-average mean velocity.

This index represents an objective measure of the extent of mixing and agitation in the stirred vessel: for example, high velocities, resulting in intense flow and agitation in the vessel, will result and correspond to a high value of \( I_a \). This index may then be used as a means of objectively discriminating among various configurations, where a choice should be made about e.g. the positioning, the type or even the number of agitators yielding the optimum agitation in a stirred vessel.

In cases where different configurations yield similar values of \( I_a \), the distribution of vessel volumes related to particular velocities may help in determining the optimum configuration for a particular application.

APPENDIX: Calculation of Volumes

The starting point of the volume calculations is the grid of velocity measurement points, with co-ordinates \((r, \zeta)\) corresponding to the point \( g_{ij} \). The cell \( c_{ij} \) corresponding to \( g_{ij} \) is obtained as a solid of revolution:

\[
V_{ij} = \pi \int_{\zeta_1}^{\zeta_2} f(\zeta) \, d\zeta
\]

(A1)

which in this case becomes:

\[
V_{ij} = \pi \left[ r_{right}^2 - r_{left}^2 \right] \times \left[ z_{up} - z_{low} \right]
\]

(A2)

with

\[
r_{right} = \frac{r_i + r_{tip}}{2}, \quad r_{left} = \frac{r_{right} - r_i}{2}
\]

(A3)

\[
z_{up} = \frac{z_i + z_{tip}}{2}, \quad z_{low} = \frac{z_i + z_{tip}}{2}
\]

(A4)

The edge points need special consideration:

- for the points next to the shaft or the agitator tip, \( r_{up} = r_s \) or \( r_{down} = r_{tip} \);
- for the points close the vessel walls, \( r_{right} = r_{right} \); and
- for the points close to the top of the vessel, \( z_{up} = H \).

Finally, for the points closest to the bottom of the vessel, when the bottom is flat, \( z_{low} = 0 \), whereas if it is dished, the radius of curvature \( (R) \) should be taken into account:

\[
z_{low} = R - \left( R^2 - x^2 \right)^{1/2}
\]

(A5)

where \( x = r_{right} \) or \( x = r_{left} \).

NOMENCLATURE

| \( C \) | impeller clearance from the bottom of the vessel, m |
| \( D \) | impeller diameter, m |

REFERENCES


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The manuscript was received 17 February 1997 and accepted for publication after revision 29 July 1997.