Abstract. The addition of solids or liquids into solutions is a very important issue in industrial processes. The effectiveness of these industrial processes is improved if efficient dispersion and dissolution of the additives is achieved. It is known that current bench scale tests do not always represent the industrial scale behavior. A new stirred tank geometry was designed to provide a better representation of the industrial process, the Shear and Sedimentation Test Cell (SSTC). The SSTC (T=7.6 cm, H=3T) provides more uniform intensity of mixing over the volume of the tank, uses a much smaller volume of sample than the traditional stirred tank, and allows for the possibility of a sedimentation step after the mixing step with no sample transfer required. The geometry of the SSTC allows a more uniform turbulence distribution, which is not obtained in the other bench scale tests. Mean velocity profiles were measured at different axial positions in the tank using a Laser Doppler Velocimeter. Several impeller shapes, impeller diameters and fluids were used in order to check their effect in the flow. The SSTC was able to keep the flow turbulent even at Re as small as 2000. These results have implications both for scale-up and for industrial applications with surface feed or with dip pipes in the top third of the tank.

Keywords: SSTC, turbulence, flow pattern, LDV.

1. INTRODUCTION

The addition of solids or liquids into solutions is a very important issue in industrial processes such as oil sands, drinking water treatment, cosmetics and personal care products, and paints and coatings. The effectiveness of these industrial processes is improved if efficient dispersion and dissolution of the additives is achieved. One of the main challenges of developing a chemical process is to properly represent the industrial scale when the process is tested at the bench scale [1], and it is known that current bench scale tests do not always represent full scale behavior. The jar test, which has been used in the water treatment industry for over 80 years, is a good illustration of how difficult this can be. The industrial scale process operates in the turbulent regime with impellers which are several meters in diameter. On the bench scale, impellers are limited to approximately 10 cm in diameter, and the rotational speed of the impeller is limited by mechanical vibration and air entrainment; so the bench scale flow regime is often limited to transitional instead of turbulent flow. The jar test uses a large paddle impeller with a peak energy dissipation, or mixing intensity, 4-6 times higher in the impeller zone than in the bulk of the tank. Since the local mixing intensity influences dispersion and dissolution of additives, drop coalescence, break-up of particles and formation and breakage of flocs, this inhomogeneity leads to some very significant uncertainties about the process mixing requirements. A stirred tank with a more conventional impeller which is geometrically similar to full scale mixing vessels used in the fine chemicals industry can have a maximum mixing intensity 100 times higher than the bulk value [2, 3].
Besides the turbulence distribution, it is important to know in which regime the tank is operating. An impeller Reynolds number (Re>20000) is often cited as the limit of fully turbulent flow and the point where the power number becomes constant with increasing Re. There are documented cases, however, where this is not the case [4]. A more rigorous definition of fully turbulent flow involves the scaling of velocity profiles with a characteristic velocity scale. Mean and rms velocity profiles are expected to scale exactly with the tip speed ($\pi ND$) at locations where the flow reaches fully turbulent conditions [5]. Velocity profiles and turbulence intensities do not scale exactly with the tip speed in the transitional flow regime because both viscous and inertial forces play a role. Bittorf and Kresta [4], [6] showed that up to one third of the volume of a stirred tank operating at Re=20000 may not be active and the flow in this part of the tank is in the transitional regime. This is a very important result for scale-up operations when the feed point is located in the non active portion of tank, since transitional flow is not easily predicted and is not scalable.

1.1 Design of the Shear and Sedimentation Test Cell (SSTC)

In order to better represent the industrial scale, a new bench scale stirred tank has been developed: the Shear and Sedimentation Test Cell (SSTC). The SSTC provides a more uniform mixing intensity over the volume of the tank, uses a much smaller sample volume than the traditional stirred tank, and allows for the possibility of a sedimentation step after the mixing step with no sample transfer required. The unique geometry of the SSTC allows a more uniform turbulence distribution, which is not obtained in the other bench scale tests. The SSTC is relatively longer and thinner ($H = 3T$) when compared to standard stirred tanks used industrially ($H = T$), as shown in Figure 1, where $H$ is tank height and $T$ is tank diameter. The SSTC has a set of 5 or 6 impellers with relatively large diameters ($D=T/2$ or $D=2T/3$) to provide a more homogenous turbulence distribution over the full tank volume. As there are more impellers than in a standard stirred tank and these impellers have a large diameter, the turbulence is provided at several positions in the tank resulting in more uniform energy dissipation rate. The impeller tip speed and peak energy dissipation are both smaller than in a regular stirred tank operation [7], which is desirable in processes where coalescence is a goal or where the goal is to avoid the breakup of particles. In a regular stirred tank, the peak energy dissipation may be 100 times higher than the average [3]. In the SSTC, results show that the peak is less than 10 times higher than the average.

![Figure 1. Geometric differences between SSTC and a regular stirred tank. SSTC (left) is relatively longer and thinner than a standard stirred tank (right). Furthermore, the impellers at SSTC have a bigger diameter (D = T/2 to 2T/3) and occupy a bigger portion of the tank volume.](image)

Table 1 shows the dimensionless numbers and the power per volume consumption determined using three different sets of impellers: Rushton, Intermig and A310 [7]. The power number ($N_P$) was determined for the full set of impellers in the SSTC and the result was divided by...
the number of impellers in the set. The flow number (N_Q) and momentum number (Mo) were measured for each impeller and there was no difference between the impellers. The momentum number was calculated using the definition by Machado et al. [8]. The last four columns of Table 1 show a comparison of the ratio \( \varepsilon_{max}/\varepsilon_{average} \) and the ratio of impeller swept volume/tank volume between the SSTC and the regular stirred tank. The SSTC impeller swept volume is considerably higher than the standard stirred tank. Adding to this the impeller discharge streams and the wall jets, the quiescent bulk of the tank in the SSTC is reduced to a very small portion of the total tank volume.

Table 1. Dimensionless numbers and power per volume for different impellers operating in the SSTC.

<table>
<thead>
<tr>
<th>Impeller</th>
<th>( N_P^* )</th>
<th>( N_Q^* )</th>
<th>Mo*</th>
<th>( \varepsilon_{average} ) **</th>
<th>( \varepsilon_{max} )</th>
<th>( \varepsilon_{max}/\varepsilon_{average} ) stirred tank [9]</th>
<th>( V_{SWEPT}/V_{STIRRED TANK} ) [8]***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rushton</td>
<td>4.4</td>
<td>0.52</td>
<td>0.41</td>
<td>15.5</td>
<td>160</td>
<td>15 - 138</td>
<td>0.053</td>
</tr>
<tr>
<td>Intermig</td>
<td>0.45</td>
<td>0.27</td>
<td>0.1</td>
<td>1.5</td>
<td>7.3</td>
<td>N/A</td>
<td>0.169</td>
</tr>
<tr>
<td>A310</td>
<td>0.5</td>
<td>0.41</td>
<td>0.22</td>
<td>1.8</td>
<td>13.7</td>
<td>13 - 46</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Value per impeller ** Re = 30 000 using water *** PBT T/3

2. EXPERIMENTAL CONDITIONS

Mean and rms velocities were measured throughout the SSTC using an LDV. Three sets of impeller geometries were used: A310, Rushton and Intermig. Sets of five (Rushton and A310) or six (Intermig) impellers of a relatively large diameter (D=T/2 for Rushton and A310 and D=2T/3 for Intermig) were used. The off-bottom clearance of the lowest impeller was one third of the impeller diameter (C=D/3) and the submergence of the highest was equal to one impeller diameter (S=D). The other impellers were equally spaced on the shaft. Two fluids were used in the tank: water (1cp) and triethylene glycol (6 cp); to check the effect of the fluid viscosity. The Reynolds number was varied from 1100 to 43000. The power consumption of all sets of impellers was determined over the same range of Reynolds numbers.

3. RESULTS

Figures 2, 3 and 4 show several velocity profiles using 3 different sets of impellers. The velocity profiles were measured in the impeller discharge stream and close to the surface of the liquid for all impeller shapes. All the results were scaled with the tip speed (\( \pi ND \)) in order to determine whether or not the flow is fully turbulent. Machado et al. [7] showed that the impeller discharge stream is the same for all the impellers except for the lowest and the highest in the tank. For this reason, the impeller located in a mid-position in the tank (third impeller considering that the lowest one is the first impeller) was chosen for this part of the study.

3.1. A310 impellers

Figure 2a shows that the dimensionless velocity profiles scaled quite well when Re\( \geq 6000 \) in the impeller discharge stream, but some parts of the profile were in the transitional regime for Re\( \leq 4200 \). The transition from transitional to turbulent regime in the SSTC happens at a Reynolds number considerably lower than the well established limit used for bench scale stirred tanks (Re=20000). As the Reynolds number goes down, the dimensionless velocity
profile deviates more from the turbulent behavior. Figure 2b shows the velocity profiles in the upper part of the tank and these results showed that fully turbulent behavior may be expected for Re≥12100, while the curves tend to have a higher deviation when the Reynolds number decreases. Again, the limiting Re for the SSTC is much lower than for the stirred tank.

Figure 2. Velocity profiles obtained using A310 set of impellers. (a) Axial mean velocity profile 2 mm under the 3rd impeller (impeller discharge stream section). (b) Axial mean velocity profile 30 mm from the surface of the tank.

3.2. Intermig impellers

Intermig impellers were designed to be up- and down-pumping at the same time. The inner part of the impeller pumps the fluid upwards while the outer part of the impeller pumps the fluid downwards. Figure 3a shows that at 2 mm under the impeller the fluid is sucked upwards at the center of the impeller and is pushed down over the outer third of the blade. The results collapsed very well for all Reynolds numbers in the suction area and close to the tank wall (Re≥2000), but the region where the fluid was pushed down shows transitional behavior for Re<7500. Figure 3b shows that the fluid is flowing downwards in the region close to the shaft in the upper part of tank, even though the impeller is pumping the fluid up. This indicates that a secondary recirculation loop forms in the upper part of the stirred tank when a set of Intermig impellers is used. All of the profiles collapse for r≤0.44T. Further from the shaft, the measurements using TEG deviate significantly while the results obtained using water collapsed well even for low Reynolds numbers. This suggests that fluid properties may impact flow, even when the Re is above the turbulent limit for water.

Figure 3. Velocity profiles obtained using Intermig set of impellers. (a) Axial mean velocity profile 2 mm under the 3rd impeller. (b) Axial mean velocity profile 30 mm from the surface of the tank.
3.3. Rushton impellers

Figure 4a shows the impeller discharge stream for the third Rushton impeller in the stirred tank. Rushton impellers generate radial flow and because of that the radial component of the impeller discharge stream was measured 2 mm away from the impeller tip. Figure 4a shows that Rushton impellers are able to keep the flow fully turbulent even at very low Reynolds numbers (Re\(\geq\)1800) over most of the profile. At the peak of the velocity profile, a much higher Reynolds number (Re\(\geq\)6000) is necessary. This is still considerably lower than the limit used for stirred tanks (Re=20000). The fact the profiles do not collapse at the center of the impeller discharge stream is due to the strong vortex structures in that region [10]. Figure 4b shows that the results for water scale well at the top of the tank even at Re=1800, but when TEG was used, the velocity profiles do not follow the turbulent profile.

![Figure 4. Velocity profiles obtained using Rushton set of impellers. (a) Radial mean velocity profile 2 mm away from the 3rd impeller (impeller discharge section). (b) Axial mean velocity profile 30 mm from the surface of the tank.](image)

3.4. Implications for scale-up

When a industrial process is replicated at the bench scale, it is important to make reasonable assumptions in order to correctly represent the process. The current design of the bench scale stirred tanks contain regions where the flow is transitional or quiescent instead of turbulent. This introduces a large degree of uncertainty into the accuracy of scale up assumptions based on fully turbulent flow. The lack of knowledge of the flow is the main cause of uncertainty in the design of reactors [11], and having transitional instead of turbulent flow will affect any process which depends on feed at points in the transitional areas.

The SSTC provide a more homogenous turbulence distribution throughout the tank and has some significant advantages for replication or design of industrial process on the bench scale. It has been successfully applied to studies of demulsifier effectiveness [12] in cases where the stirred tank gave inconclusive results. Table 2 contains a summary of the results presented in this paper. The fully turbulent Reynolds number for each set of data is shown, giving the range of Re where the velocity profiles collapse, both at the impeller, and close to the surface. This limit changes even at the same measurement profile with different fluids. These results help to explain some of the results in the literature which report fully turbulent behavior at low Reynolds numbers for standard stirred tanks [13].

Table 2. Summary of Results.

<table>
<thead>
<tr>
<th>Type</th>
<th>Re(_T) at impeller discharge stream</th>
<th>Re(_T) at surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>A310</td>
<td>4200 - 6000</td>
<td>12100</td>
</tr>
<tr>
<td>Intermig</td>
<td>2000 - 7500</td>
<td>2000 - N/A</td>
</tr>
<tr>
<td>Rushton</td>
<td>1800 - 6000</td>
<td>1800*</td>
</tr>
</tbody>
</table>

*TEG and water had distinct behaviors for this set of data.
4. CONCLUSIONS

The Shear and Sedimentation Test Cell (SSTC) was able to keep the flow fully turbulent even at Reynolds numbers much lower than the stirred tank transitional limit cited in the literature.

These results are quite promising since the bench scale stirred tank is not able to provide fully turbulent flow in the bulk of the tank even at Re>20000, while the SSTC is fully turbulent over most of the vessel at Reynolds numbers considerably lower than this.

5. REFERENCES


