DETERMINATION OF JUST-SUSPENSION SPEED FOR RUSHTON TURBINE USING TANK BOTTOM PRESSURE MEASUREMENTS.

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Tank bottom pressure was measured with manometers at five specific locations for a 0.2 m diameter standard cylindrical vessel stirred with Rushion Turbine (6DT). Glass Ballotini bits at 10, 20, 30, 40, 50 and 60 wt/wt % were be suspended in water and compressed air at 1, 3 and 5 mm/s superficial gas velocities were used. Plots of pressure versus impeller speed indicates that near the just-suspension speed, the base pressure values show a tendency to either decrease or remain constant after increasing with speed at lower impeller speeds. It was also observed that at the last point of suspension, i.e. at the center of the tank for 6DT, a marked reduction in pressure values occurs after the particles were all suspended, indicating that the tank bottom pressure could be used as an objective means of determining the just-suspension speed.

Introduction

The required degree of suspension in agitated vessels varies according to the purpose of the operation. For example, when a suspension is mixed prior to being fed to a reactor, a high degree of homogeneity is required. In many cases however, it is sufficient if the solid surface is fully exposed to the continuos phase, which occurs when the entire solid is lifted from the tank bottom. The agitation speed at which the solid is just suspended is termed as ‘just-suspension speed’ (N_{S} for ungassed condition and N_{SG} for gassed conditions). Many researchers in this field such as Chapman et al (1), Baldi et al (2), Nienow (3) and Zwirting (4) have studied the conditions which affect the just suspension-speed. Such conditions include the solid and liquid properties, relative quantity of the solid and liquid phases, impeller and vessel geometry and the presence of gas.

There are various criteria available for just suspension speed. The most common being the 1-2 criterion defined by Zwirting (4). The condition is determined by visual observation of the tank bottom. It may be difficult to determine the values accurately and objectively by visual observation as particles may settle temporarily at the tank bottom and remain there for a short time. The method is also very subjective to the individual observing it. In industries where the vessels are big in size, complex in shape and commonly made of opaque materials and the operations are of dynamic nature, visual observations may not be a practical way to determine just-suspension speeds.

Zehner and Tebel (5) defined just-suspension speed as the agitator speed at which the suspended particles reach 90% of the suspension height. Musil et al (6) introduced
another criterion and method where a conductivity probe was fixed at a point just above the solid particle level and as the agitation speed increases the solid concentration at this point increase gradually and reach a maximum when complete suspension occurs. Further agitation would cause solid concentration to level up or drop down. Bourne and Shama (7) also used the same method in their work.

More novel methods of determining the suspension condition include measurement of indirect parameters such as conductivity, radiation and frequency. Such probes require calibrations and may only be applicable for the conditions it is calibrated for.

Drewer et al. (8) reported an observation relating tank bottom pressure and agitation speed in a stirred vessel for solid-liquid systems. In that work it was reported that there was a clearly observable pressure trend at just-suspension speed if the pressure is measured at a particular optimum location and suggested that the tank bottom pressure could be used for determining just-suspension speed. An attempt was also made by the workers to predict the pressure values at optimum locations using fluidization theory.

Brucato et al. (9), reported on the development of a similar pressure technique to determine the fraction of unsuspended / suspended solids in stirred tanks operating below the complete suspension speed.

The aim of this work is to explore the tank bottom pressure as a criterion for defining just-suspension condition more objectively than those presently available, and to evaluate the pressure technique in determining just-suspension speed for two and three phase systems for a range of experimental parameters and set up as discussed in following section.

Material and Methods

The experimental setup used is as shown in Figure 1. A 0.2 m diameter cylindrical Perspex tank with flat bottom was used for the experiments. Agitation was done with 4 kW motor suspended with a counter weight in order to measure the power drawn by the impeller using load cell although power is not critical for this study. The tank bottom pressure was measured using manometer tubes at five locations (termed 'sensor' hereafter).

The locations of the sensors are shown in Figure 2. Sensor 3 is located at the center of the tank. The distance between adjacent sensors is D/6. Therefore sensor 2 and 4 are at the same radial distance but sensor 2 is in between two baffles while sensor 4 is in line with a baffle. Similarly for sensors 1 and 5 which are nearest to the vessel wall. The detail of pressure tapping at the tank bottom is shown in Figure 3. Nylon mesh is stuffed into the manometer opening to ensure a continuity of liquid between the tank and the manometer tubes while retaining the solid from the tank from going into the manometer tubes. The dimensions of the impeller used are shown in Figure 4.

Tap water and spherical Ballotini particles with an average diameter of 0.25-mm and density of 2530 kg/m³ were used as the liquid and solid medium respectively. Experiments with solid were conducted for 10, 20, 30, 40, 50 and 60 % of the weight of
water at a level, equivalent to the diameter of the tank (H=T). For three phase experiments, oil free compressed air at 2.0 bar was fed at superficial velocities, \( U_g \) of 1, 3, and 5mm/s.

Under each condition, i.e. solid concentrations and gas flow rate, the impeller speed was increased gradually from zero. The five manometer pressures were recorded and the suspension condition were observed from the base of the tank at each 100 rpm increment in impeller speed using speed inverter. Sufficient time (at least a time period of five minutes) was given for the sensors to achieve steady state before recording the pressure values. Plots of pressure versus speed were made for each case.

**Results and Discussions**

i. General Trends of the Pressure Curves

An example of pressure versus impeller speed plot for all five sensors at 30% solid and \( U_g = 1 \) mm/s is shown in Figure 6. In this figure the impeller speed range have been divided into 4 distinct “zones”.

Zone 1 covers the lowest speed range in which the pressure is almost the same for all sensors and the values do not change with impeller speed. This zone covers the speed range from 0 to 300-400 rpm. Visual observations showed that in this speed range the sensors were all completely covered with the bed of particles and there were no significant suspension of particles. Under gassed conditions, even at the lowest flow rate used here, no proper dispersion was achieved.

Zone 2 is between about 400 to 900, where the pressure increases gradually with the increase in impeller speed. The pressure rises more quickly for sensors 1 and 5 which are the furthest from the center, compared to the other sensors. Visual observation reveals that particles are gradually lifted from the bed as the agitation speed increases.

Zone 3 is shown as a narrow range where the pressure values reach a peak before starting to decrease or remain almost constant. This is the most critical speed zone because it is over this speed range that particles are seen to clear from the tank base. The \( N_{SG} \) observed visually fall in this range as indicated by the arrow in Figure 6.

Zone 4 is when the particles are all completely suspended, and with further increase in speed, the sensor pressure either:

- a. Increases slightly as for sensor 1
- b. reaches a plateau as for sensors, 2 and 4; with values that depend on the sensor location,
- c. decreases gradually as for sensor 5, or
- d. drops substantially as observed for sensor 3.

ii. Effect of hydrostatic and dynamic pressure

Even though the actual reasons for the difference in variation could not be quantified or justified at this point of time, the flow pattern generated by 6D model could offer some explanation for pressure profiles described above. Figure 7, shows the suspension pattern
and flow profile in the vessel as the agitation speed gradually increases until last particle is suspended.

The pressure measured by the manometer tube is the total of hydrostatic pressure from the liquid height and dynamic pressure from the liquid movement.
Total pressure = hydrostatic pressure + dynamic pressure

The solid particles sedimented at the bottom of the tank behave like a porous medium and therefore the level in the tank and the level in the manometer tube are the same as unagitated condition. However, when the impeller starts rotating, solid particles will be gradually suspended and the density of the suspension will start increasing. At this point the level in the in the manometer will increase as the density of the liquid medium remain unchanged due to the presence of the wire mesh which isolate the manometer from the solid particles. On the other hand, as the speed increases more particles will be suspended and the density of suspension reaches maximum when all the particles are suspended fully and the manometer level also increases up to this point. Until the complete point of suspension, the pressure measured by the manometer is only contributed by the hydrostatic pressure, which reaches maximum when the particle at the location is completely suspended.

Total sensor pressure = Hydrostatic pressure if sensor is still covered by solid particles.

When all particles are cleared from the base, the affected sensor is exposed to dynamic pressure as well. With hydrostatic pressure already at a maximum point, total pressure is now dependent on the dynamic pressure. At a location where there is a vortex formation, a negative dynamic pressure will be present and therefore the total pressure will be start reducing when agitation speed exceed the complete suspension speed at that location.

The explanation seems to fit all the sensors in Figure 6, where all the sensors show an initial increase in pressure when the agitation speed increases. For 6DT, the particles are suspended from the periphery first therefore initially sensor 1 and 5 (located at the outermost radial position) give higher pressure values compared to other sensors. But once localized complete suspension occur at these locations at around 700 rpm the pressure for sensor 1 continuously increases while for sensor 5 the net result is a decrease in the measured pressure value. The difference may be due to the vortex and flow mechanisms at these locations. Sensor 2 and sensor 4 show similar trends where after reaching localized complete suspension at about 1000 rpm the measured pressure remain unchanged indicating that perhaps the dynamic pressure at this locations is not contributing to the total pressure significantly. As for sensor 3, after reaching localized complete suspension, the measured pressure decreases continuously as vortex formation at the center produces negative dynamic pressure.

iii. The optimum sensor

The pressure behavior observed through the five sensor locations is directly related to the flow characteristics on the base of the tank, particularly at the verge of and upon
complete suspension of the particles. For a given fluid, the flow pattern is governed mainly by the impeller-to-tank geometry. In turn, this determines the distribution of particles on the tank base and the last point of suspension. Previous work by Ibrahim and Nienow (10) has shown that for 6DT particles suspend from the periphery to the center. The exception occurs if the impeller clearance is very low for the 6DT, which was not the case here. These distributions were confirmed in the experiments conducted for this work.

It is interesting to note that as the particles clear away from different parts of the tank base, the affected sensors show the pressure changes observed in zone 3 of the pressure curve. Hence, it can be said that over the speed range in zone 3, “localized” clearance of particles is taking place. However, the overall just-suspension really occurs when the last particles are just lifted from the bottom and does not remain stagnant for more than 1-2 second thereafter. In accordance with the center being the last point from which particles are lifted for 6DT, the pressure at sensor 3 was the last to start to decline. This means that to ascertain overall just-suspension, it would suffice to just observe the pressure at location 3. The visually observed ‘just-suspension speed’ was found to coincide with the point where the pressure for sensor 3 reaches the maximum before tapering down.

Figure 8, shows pressure variation for 30% solid at ungassed conditions. Even though there is slight difference in pressure profile and values for sensors 1, 2, 4 and 5, sensor 3 still shows a similar trend with the just-suspension speed occurring at the point where pressure for sensor 3 reaches maximum before descending. The variation for the other sensors could be due to the effect of gaseous phase on flow characteristics.

iv. Comparing the Ns and Ng based on visual observation and pressure measurement

Figures 9 and 10 are plots of pressure at sensor 3 (optimum sensor) for the 6DT at various concentrations for gassed (3 mm/s) and ungassed conditions. In both figures the visually observed just-suspension speed was found to coincide within ± 80 rpm from the point in the plot where the pressure start reducing after reaching a maximum.

Table 1 below gives detailed comparisons of the Ns and Ng values determined visually and by pressure technique (PT) in all the cases studied here.

<table>
<thead>
<tr>
<th>Solid %</th>
<th>U g = 0 mm/s</th>
<th>U g = 1 mm/s</th>
<th>U g = 3 mm/s</th>
<th>U g = 5 mm/s</th>
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<tbody>
<tr>
<td></td>
<td>Visual PT.</td>
<td>Visual PT.</td>
<td>Visual PT.</td>
<td>Visual PT.</td>
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<tr>
<td>10</td>
<td>780 800</td>
<td>940 950</td>
<td>1069 1010</td>
<td>1150 1160</td>
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<tr>
<td>20</td>
<td>880 900</td>
<td>1004 1050</td>
<td>1162 1110</td>
<td>1250 1230</td>
</tr>
<tr>
<td>30</td>
<td>982 1000</td>
<td>1072 1020</td>
<td>1191 1150</td>
<td>1311 1300</td>
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<td>1041 1050</td>
<td>1086 1100</td>
<td>1259 1139</td>
<td>1376 1400</td>
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<td>50</td>
<td>960 980</td>
<td>1131 1150</td>
<td>1290 1220</td>
<td>1395 1410</td>
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<tr>
<td>60</td>
<td>1070 1100</td>
<td>1180 1200</td>
<td>1370 1310</td>
<td>1460 1500</td>
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</table>

Table 1: Comparison of visually obtained just-suspension speed ( rpm ) with values obtained by pressure technique for various solid concentration and U g.
From Table 1 above, the difference in just-suspension speed values obtained from pressure versus impeller speed plot at the optimum sensor than the visually observed values can be safely said to lie within ± 80 rpm for gassed and ungassed conditions and for both low and high solid concentration as well. The results obtained give a good indication that the pressure technique can be used as an objective method to determining the just-suspension condition.

Conclusion

A simple technique has been developed to characterize and to determine just-suspension speed in a stirred vessel more objectively compared to presently available visual criteria and methods. The technique is based on measuring tank bottom pressure using simple water manometer tube at a location where the particles are suspended last. The sensor at this location is then termed as optimum sensor.

As the impeller speed increases, the pressure on the tank base also increases due to the increment in amount of solid suspended. The increase in pressure reached maximum value when all the particles are just suspended, i.e. at just-suspension speed. With a few exceptions, further increase in speed, caused the pressure to decrease. Similar trend is observed for all the cases.

This work has indicated that the technique is capable of determining just-suspension speed both for gassed and ungassed conditions for 6DT. The accuracy was found to be within ± 80 rpm when compared with visually observed values for both low and high solid concentrations.

Besides being able to determine the just-suspension speed, the technique also could offer an alternative criterion for defining just-suspension speed by using a directly measurable parameter which is the pressure.

References

5. Zehner, P. and Tebel, K.H., 1984, Hydrodynamik beim suspendieren in ruhrbehalter, Mischvorgänge, Freising

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>6DT</td>
<td>Six-Blade Disc Turbine (Rushton Turbine)</td>
</tr>
<tr>
<td>$N_{JS}$</td>
<td>Just-Suspension Speed under ungassed conditions, rpm</td>
</tr>
<tr>
<td>$N_{SG}$</td>
<td>Just-Suspension Speed under gassed conditions, rpm</td>
</tr>
<tr>
<td>H</td>
<td>Liquid Height, m</td>
</tr>
<tr>
<td>D</td>
<td>Impeller Diameter, m</td>
</tr>
<tr>
<td>C</td>
<td>Sparger Clearance, m</td>
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<tr>
<td>$U_g$</td>
<td>Superficial Gas velocity, m/s (Q/A)</td>
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<td>Q</td>
<td>Gas flow rate at the sparger, m$^3$/s</td>
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<tr>
<td>A</td>
<td>Cross sectional area of the tank, m$^2$</td>
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<tr>
<td>x</td>
<td>Impeller thickness, m</td>
</tr>
<tr>
<td>W</td>
<td>Blade width, m</td>
</tr>
<tr>
<td>L</td>
<td>Blade length, m</td>
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