TEMPERATURE EFFECTS ON THE GAS HOLD-UP IN AGITATED VESSELS

Richard Schaper, André B. de Haan and John M. Smith
University of Surrey, Guildford (U.K.), University of Twente, Enschede (NL.)

Previous work found the gas hold-up in a tall, 0.15 m$^3$ vessel, agitated by three impellers, to decrease considerably with temperature. This was attributed to either a decrease in liquid viscosity, a decrease in surface tension or a decrease in gas density. The aim of this work was to investigate the influence of gas density on the gas hold-up. First of all, it was attempted to reproduce the data found in literature. It was shown that contaminants had a significant impact on the gas hold-up. Experiments with increasing and decreasing amounts of tap water (as source of the contamination) found the gas hold-up to be affected by a strongly absorbing non-ionic surface active agent. Experiments in a system exhibiting low conductivity and low gas hold-up showed that the gas hold-up decreased 15 % for temperatures between 295 K and 350 K. Experiments with helium as sparging gas found that gas density does have a lowering effect on the gas hold-up. The gas hold-up increased again for temperatures above 350 K, which may be due to the increased presence of micro-bubbles in a near-boiling system.

Keywords: Sparged, Hot sparged, Agitated, Gas Hold-up, Temperature-effects

1. INTRODUCTION

Sparged agitated vessels have become a standard method of contacting gases and liquids, if a large liquid bulk is required. Research into this area focuses mainly on the mass transfer coefficient, as this is the key performance indicator for sparged agitated vessels. An important design parameter is the gas hold-up, which is required to accurately size the equipment. Smith and Gao found the gas hold-up to decrease with temperature. They offered that this might be due to the increased bubble size in a hot sparged system, caused by increased coalescence. The bubble size is governed by the ratio of forces stabilizing the bubble and the forces acting to break-up the bubble. The bubble is stabilized by the surface tension forces and the viscous stresses inside the bubble and de-stabilized by the deformation due to the shear stresses. Bubble break-up will thus occur if the de-stabilizing forces are larger than the stabilizing forces:

$$
\tau \geq \frac{\sigma + \mu_G \cdot \sqrt{\frac{\tau}{\rho_G}}}{d_b}
$$

If the viscous stresses are not important, the bubble break-up criterion can be reduced to Weber equals unity. For this case, Calderbank derived an equation for the gas hold-up. On assuming that the equation would extend to a fictitious system with physical properties resembling a near-boiling air-water system, one can calculate that the gas hold-up is not expected to decrease. Therefore, any change in gas hold-up is likely to be governed by one of the parameters contributing to the viscous stresses inside the bubble, which are the liquid viscosity, the gas viscosity and the gas density. Of these, the gas density is the easiest to change without changing the other physical properties of the system. This can be done by sparging the vessel with a gas of different density, such as helium. The decreased gas density should then lead to an increased bubble size and thus a decreased gas hold-up.
The decrease in gas density with increasing temperature is caused on the one hand by the increased molar volume of the gas and, on the other hand, by a decrease in average molecular weight due to evaporation effects. There is an implicit assumption that the introduced gas almost instantly becomes saturated and the mol fraction of water vapour in the gas can thus be calculated from the ratio of vapour pressure and the total pressure. This mol fraction of water vapour can be used to determine the total gas loading (excluding recirculation effects).

\[ Q_i = Q_i \cdot \frac{p_i}{p_i - p_{vap}} \]

A decrease in gas density can also be caused by changing the sparging gas at ambient temperature. We have chosen to use helium as sparging gas, as this should cause a much lower gas hold-up at ambient temperature than in an air sparged system. The gas density of a helium sparged system can be expected to increase with increasing temperature, as evaporation causes an increase in average molecular weight. The difference in gas hold-up between a helium sparged system and an air sparged system at high temperature should thus be far less than at ambient temperature.

2. EXPERIMENTAL EQUIPMENT

The experiments were carried out in a tall vessel with multiple impeller configuration. The vessel had a 0.45 m diameter and was 1.10 meters high, as shown in figure 1. It was filled to a 0.87 m liquid height. Gas was sparged through a twelve-hole ring-sparger, located just below the lower impeller. The lower impeller was a Chemineer BT-6 turbine with asymmetrical concave blades for improved gas handling capability\(^{10}\), which was 0.176 m in diameter. The middle and top impellers were both MaxFlo axially up-pumping propellers and were 0.218 m in diameter. These impellers were spaced one impeller diameter from each other. This impeller configuration resulted in a rather good gas handling capacity and a relatively low decrease in RPD with increased gassing rate.

The gas hold-up was determined from the change in liquid height, as measured with a Krohne BM-100 FMCW radar probe. The radar probe was calibrated for use in a liquid system and in a gas-liquid system. The temperature dependency of the readings were checked as well. The probe was positioned some 0.05 m from the vessel wall, between two baffles. The specific power input was calculated from the impeller speed and the shaft torque, which were both measured with a Vibrometer TorqueMaster system. As the calculated power number was constant in the turbulent regime, both the torque measurement and the impeller speed measurements seem to be correct.

The temperature of the vessel was determined with an Automatic System Laboratories F25 high-precision thermometer. The sparging gas flow rates were measured with a KDG 2000 flow-meter for the air flow and a Nixon helium flow-meter for the helium flow.

3. CONSUMABLES

As traces of impurities are known to influence the results, we used purified water from a reverse osmosis unit. The water from this RO unit was of analytical grade, type II. The specific conductance was always less than 1.0 \( \mu \text{S/cm} \). The air used was taken from the university’s internal air header and the helium used was commercially obtained from BOC Gases. (Commercial grade A, 99.65 % pure)
4. RESULTS AND DISCUSSION

4.1 REPRODUCING SMITH AND GAO’S DATA
It proved impossible to reproduce Smith and Gao’s data. Without exception, the gas hold-up at ambient temperature found in this work was up to 40% lower than the gas hold-up reported by Smith and Gao. At high temperature (365 K), the gas hold-up found in this work was approximately equal to the gas hold-up reported by Smith and Gao. This difference could be due to either a change in carbon dioxide content of the sparging gas, impurities in the sparging gas or impurities in the water used. It was found that carbon dioxide does have an effect on the gas hold-up, but the effect was too small to explain the difference observed. It was found that the filters in the air supply line were functioning as per design. It was found that impurities, as found in tap water, have a large effect on the gas hold-up at ambient temperature, but hardly an effect at high temperature.

The conductance of the water in the vessel was too low to suggest an important effect of electrolytes, as electrolytes are said to change the gas hold-up only when in excess of 1 M. We estimated the concentration of CaHCO₃, as representative electrolyte, to be of the order of 10⁻³ M. Therefore, the effect of impurities is more likely to be caused by surfactants.

It is known that the effect of surfactants decreases with temperature, due to a decreased efficiency of adsorption onto the surfaces at high temperature. Therefore, we would expect the effect of impurities at high temperature to be significantly less than at low temperature.

The hysteresis in effect at ambient temperature between increasing and decreasing level of contamination, as shown in figure 2, indicates that the impurities are strongly adsorbing, non-ionic surfactants and may be difficult to remove. The results reported by Smith and Gao are roughly equivalent to the results one would obtain in tap water, see figure 3. It therefore is possible that the vessel used by Smith and Gao was contaminated with non-ionic surfactants and that their results are not valid for a purified water system. This contamination may have come from the practice of calibrating the equipment in tap water, before filling the vessel with purified water and starting the experiments.

4.2 EXPERIMENTS IN A PURIFIED WATER SYSTEM

4.2.1 Experiments with air
A purified water system could be obtained by draining and refilling the vessel several times with purified water. The purified water system featured a low specific conductance and a low gas hold-up when sparged. As can be seen from figure 4, the gas hold-up decreases some 10 to 15 % with increasing temperature, but increases again above 350 K. An explanation for the increase in gas hold-up has not been investigated. The increase might be due to the increased presence of micro-bubbles, formed by liquid film boiling near the heaters and by cavitation near the impellers.

4.2.2 Experiments with helium
Helium was used as sparging gas to assess the influence of gas density on the gas hold-up. At ambient temperature, the gas hold-up in a helium sparged system was some 25 % lower than in an air sparged system, see figure 5. As expected, the difference was marginal at high temperature. Based on the difference in gas density, the difference in gas density between cold air and a hot air-water mixture should result in a 14 % lower gas hold-up at 368 K. This is equivalent with the 15 % decrease measured.

4.2.3 Determination of the bubble size
A Kodak Ekatopro high speed video camera was used to record the bubble size in the vessel. The bubble size was then determined using Optimas Imaging Software. As can be seen from figure 6, the average bubble size in a helium sparged system is some 30% higher than in an air sparged system. This increase in bubble size causes the measured decrease in gas hold-up. In an hot air sparged system the average bubble size is approximately equal to the average bubble size in a cold air sparged system. The bubble size distribution, however, shows an increase in very large bubbles, see figure 7. Bubbles of more than 70 mm in diameter have been measured. It takes over 10,000 coalescence events of standard bubbles to create such a bubble. This indicates that the decrease in gas hold-up with increasing temperature is due to an increase in coalescence, precisely the mechanism through which gas density has an effect. It furthermore suggests that the decrease in gas hold-up with increasing temperature will be more pronounced in vessel configurations that promote coalescence. In the vessel used, the radial impeller causes an upward bubble flow near the vessel wall, the axial impellers cause a downward liquid flow near this vessel wall, thus resulting in a highly gassed area (as observed by Smith and Gao). Coalescence can more easily occur in this highly gassed area than in a situation where the distance between the bubbles is larger. We therefore would like to recommend further research into the decrease in gas hold-up with increasing temperature in a vessel configuration that does not create such a highly gassed area, e.g. a Rushton turbine.

5. CONCLUSIONS
In a purified water system, sparged with air, the gas hold-up decreases some 15% with increasing temperature. In a cold, helium sparged system, the gas hold-up is some 25% lower than in a cold, air sparged system. In a hot, helium sparged system, the gas hold-up is approximately equal to that in a hot, air sparged system. This indicates that the lower gas hold-up at ambient temperature is caused by a difference in density. Based on the experiments with helium, one would expect the difference between a cold, air sparged system and a hot, air sparged system to be around 14%, which is in good agreement with the observed 15%. It was shown that the average bubble size in a helium sparged system is some 30% higher than in an air sparged system, but that the average bubble size in a hot, air sparged system is approximately equal to that in a cold, air sparged system. The bubble size distribution showed that there are more very large bubbles in a hot, air sparged system than in a cold, air sparged system. These very large bubbles are capable of reducing the gas hold-up significantly. However, as the difference in gas hold-up between a helium sparged system and an air sparged system seems to be caused by a difference in average bubble size and the difference in gas hold-up between a hot, air sparged system and a cold, air sparged system seems to be caused by a difference in bubble size distribution, it is not certain that the mechanism or the root-cause of change in gas hold-up are the same.

Although the decrease in gas density with increasing temperature does seem to contribute to the decrease in gas hold-up with increasing temperature, it should be noted that the decreased effect of contaminants with temperature can have a much larger effect.

APPENDIX A: NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>db</td>
<td>bubble diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>pt</td>
<td>total pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>pvap</td>
<td>vapour pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>Qs</td>
<td>sparged gas flow rate</td>
<td>[m³/s]</td>
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<tr>
<td>Qt</td>
<td>total gas flow rate</td>
<td>[m³/s]</td>
</tr>
<tr>
<td>μG</td>
<td>viscosity</td>
<td>[kg/m s]</td>
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<tr>
<td>ρG</td>
<td>gas density</td>
<td>[kg/m³]</td>
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</tbody>
</table>
σ  surface tension [N/m]
τ  shear stress [kg/m s²]

REFERENCES

![Diagram](image)

Figure 1: Schematic representation of the vessel
Figure 2: Effect of impurities on the gas hold-up versus the level of impurities. Temperature is 295 K, Total gas flow rate is 100 l/min. Sparged with air. Purified water contaminated with various amounts of tap water.
Figure 3: Comparison of the results by Smith and Gao with the results in an air-tap water system. Total gas flow rate is 385 l/min. Sparged with air. Tap water (this work) and purified water (Smith and Gao)

Figure 4: Gas hold-up versus temperature in a purified water system. Total gas flow rate is 300 l/min. Sparged with air. Purified water
Figure 5: Difference in gas hold-up due to a different sparging gas. Temperature is 295 K. Total gas flow rate is 75 l/min. Purified water.

Figure 6: Average bubble size versus total gas flow rate for two different sparging gases. Temperature is 293 K. Purified water.
Figure 7: Bubble size distribution in a cold and a hot air sparged system. Total gas flow rate is 347 l/min. Purified water

\[ T = 295 \text{ K} \]
\[ T = 368 \text{ K} \]

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\(^1\) Octave Levenspiel
\(^{ii}\) Marko Zlokarnik