Effect of Solids on Gas-Liquid Mass Transfer and Bubble Characteristics in Three-Phase Systems

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ABSTRACT - The effect of the solids on the mass transfer characteristics in a bubble column was studied experimentally for the system air/water/beads of calcium alginate. Volumetric liquid side mass transfer coefficient, k_La, specific interfacial area, a, and liquid side mass transfer coefficient, k_L, were determined under different solid concentrations, gas flow rates and solid sizes. Bubble characteristics were obtained using an image analysis technique. The presence of solids affect negatively k_La, decreasing both a and k_L and the effect is more pronounced for the smaller particles. For these particles the variation of k_La is due to the variation of its two components, while for larger particles k_La variation is due, essentially, to changes in k_L as no significant differences in a were observed.
An optical probe technique was also used to obtain gas holdup radial profiles for higher solids loadings and gas flow rates. It was observed that increasing the solids loading, the gas holdup decreases and the shape of the gas holdup profiles is also influenced by the solids concentration.

KEYWORDS: Bubble column; image analysis; optical probe; mass transfer; multiphase reactors; solids.

1. INTRODUCTION

Bubble columns are frequently used in industry as gas-liquid and gas-liquid-solid contactors. Chemical or biochemical reactive operations, separation of mixtures by rectification, absorption, and waste-water treatment, can serve as examples of their application (Hong and Brauer, 1989). Recently, bubble columns have also gained importance in the field of biotechnology (Álvarez, 2000). Frequently, in multiphase systems, gas-liquid mass transfer is the rate determining step for the overall process. Therefore, the knowledge of gas-liquid mass transfer rates characterized by volumetric gas liquid mass transfer coefficients (k_La) is required for reliable design and operation of such reactors (Ozkan, 2000). A full understand of the influence of the operating parameters on each component of k_La, the liquid side mass transfer coefficient (k_L) and the interfacial area (a), is required. In three phase systems, the presence of solid phase is an important parameter that may have a positive or negative effect on the mass transfer process. Thus, the effect of solid characteristics such as loading, size, density, shape and surface properties on gas-liquid mass transfer has been a challenging task for researchers. Yagi and Yoshida (1974) verified that the effect of dead microorganisms on k_L was negligible. However, the presence of such substances caused remarkable change in the bubble size distribution, and consequently decreased the gas holdup, the interfacial area a, and the k_La. To study the effect of solids concentration on k_La, Albal et al. (1983) added glass beads and oil shale particles to water. For low values (2-5 vol.%) of the solids concentration, k_La increased about 10%-30% and then decreased with further increases in the solids concentration. Sada et al. (1986) observed that the influence of fine suspended particles on bubble column performance depends upon the particle size. More recently, Freitas and Teixeira (2001) showed that k_La diminishes with the increase in solids loading, especially for high airflow rates, due to an increase in bubble coalescence. Solid density also affects k_La.

Several methods exist for measuring the interfacial area in gas-liquid systems, such as, light attenuation, ultrasonic attenuation, photographic, double-optical probes and chemical absorption methods. But these methods are effective only under certain conditions (Kiambi et al., 2001).

In our case of gas-liquid-solid system, two different techniques were used:

Photographic and subsequent image analysis technique was use to determine different bubble characteristics such as superficial area, volume, size and shape. Volumetric mass transfer coefficients were obtained for different gas flow rates, solids loading and size. The influence of these variables on the liquid side mass transfer coefficient (k_L) and interfacial area (a) was analyzed.

For higher solids loadings and gas flow rates, an optical probe technique was used to obtain gas holdup radial profiles.

2. EXPERIMENTAL

2.1. Experimental Set-Ups

In the **mass transfer and image analysis experiments** the contact device was perspex cylindrical bubble column of 84 mm internal diameter, 3 mm thick and 600 mm high. A perspex rectangular box covers the column. The space between the columns is filled with the liquid under study to avoid optical effects. The gas enters in a gas chamber and then passes through a sparger where the bubbles are formed. The sparger consists of 13 uniformly spaced needles with an inner diameter of 0.3 mm. The shape and size of the needles ensure the formation of small and well-defined bubbles.

In the **optical probe experiments** were performed in a perspex cylindrical bubble column of 72 mm internal diameter and 500 mm high. The column was equipped with a perforated plate with 0.6 mm orifices and relative free area 1%.

2.2. Mass transfer experiments

Oxygen mass transfer experiments were performed in two and three-phase systems. Air and water were the gas and liquid phases, respectively, and calcium alginate beads (with a mean diameter – d_p - of 1.2 mm and 2.1 mm) were the solid phase. The experiments were done for several gas flow rates (up to 15 cm^3/s), and solid concentrations (0, 5, 10 vol.%). In this procedure, liquid is deoxygenated by bubbling nitrogen and, after total removal of oxygen, dry air is fed into the column. The dissolved oxygen concentration is measured along time (t), using an O_2 electrode and recorded directly on a PC, through a data acquisition board. The mass balance for oxygen in the liquid is written as:

(1)

where k_La the volumetric mass transfer coefficient, and C^* and C, respectively, the oxygen solubility and the oxygen concentration in the liquid. Assuming the liquid phase homogeneous and the oxygen concentration at t=0, the integration of the previous equation leads to:

(2)

The volumetric mass transfer coefficient (k_La) can now be determined by plotting $ln(C^*-C)$ against time (t).

2.3. Image analysis experiments

To obtain the bubbles characteristics, images were grabbed with a monochrome video digital camera (Sony XCD-X700), which was connected to a Matrox Meteor II – 1394 board. Sets of images (1024×768 Pixels) were recorded for varying gas flow rates, solids loadings and sizes, for the same conditions used in mass transfer experiments. The most suitable lightning system was found to be backlight through a diffusing glass. The images were automatically treated, analyzed and several object descriptors were obtained for each bubble using a program running under Visilog™5.4 software (Noésis, les Ulis, France). After the image treatment, several shape and size characteristics of the bubbles were determined (Pons et al., 1997).

4. Optical probe experiments

Gas holdup radial profiles were obtained with a monofiber optical probe with conical tip developed at LEGI. Air and water were the gas and liquid phases, respectively, and calcium alginate beads (with a mean diameter – d_p = 2.1 mm) were the solid phase. Experiments were performed for four gas flow rates (67; 110; 156 and 187 cm^3/s) and solid concentrations up to 30 vol.%.
The tip of the optical probe was located 28 cm high from the perforated plate.
The measurement principle is based on liquid/gas phase detection by an optical probe. A monochromatic light is transmitted through an optical fibre to the sensing conical tip. When the tip is dipped into a gas phase, the light is manly reflected and travels back to the detector through a Y junction and it is converted into an electrical signal. When the tip is immersed in a liquid environment, the light is scattered and almost no light is reflected back to the emitter/receiver apparatus leading to a weak electric signal (Boyer and Cartellier, 1999).

3. RESULTS AND DISCUSSION

Figure 2 shows how **volumetric mass transfer coefficient, k_La,** varies with gas flow rate, Q_g, solid loading and solid size, for calcium alginate beads of 2.1 mm diameter (algI) and 1.2 mm diameter (algII).

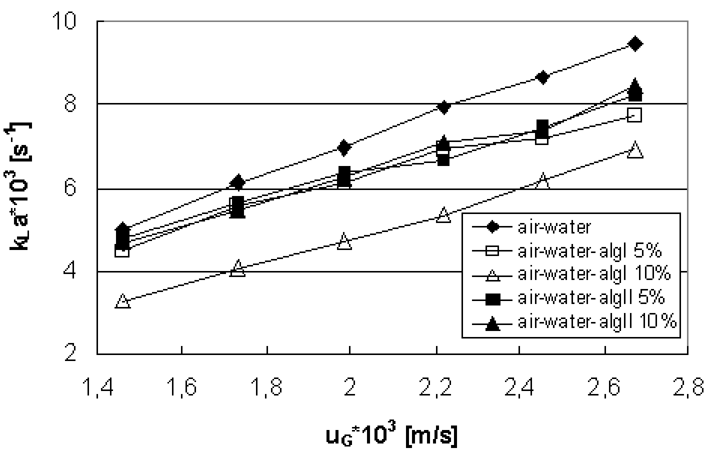


Figure 2 - Dependence of k_La on superficial gas velocity, solids loading and solids size.

It can be seen from this figure that k_La increases with gas flow rate. For the larger particles, the effect of the solids increases with the flow rate, being this increase independent from solids concentration. In the case of the smaller beads, k_La clearly decreases with the solid concentration and this effect is much stronger than for larger particles. These results are reproducible with an average relative error of 5%.

Zahradnik et al. (1992) studied the effect of some operating parameters on hydrodynamics and mass transfer characteristics of multi-stage three-phase slurry reactors and found that increasing concentration of solid particles (in the range 0-5 wt%) reduced the k_La values. Freitas and Teixeira (2001) working with a three-phase internal loop airlift reactor noticed a similar behaviour for the effect of solids.

For all visualization experiments, several average bubble descriptors were obtained by image analysis, namely the projected area and the Feret diameters. According to bubble characteristics, these were classified as elongated or flattened spheroids, and the respective superficial area and volume calculated

as (Pereira, 1997).
The **bubbles shape** is affected by the gas flow rate, solids concentration and size and is expressed by the F_{max}/F_{min} ratio (see Figure 3).
The concentration of solids is the parameter with the strongest effect on the bubble shape. The presence of solids makes the bubbles more rounded and this effect is more pronounced for the higher solids loading and for the smaller particles, where the bubble sphericity goes close to 1.

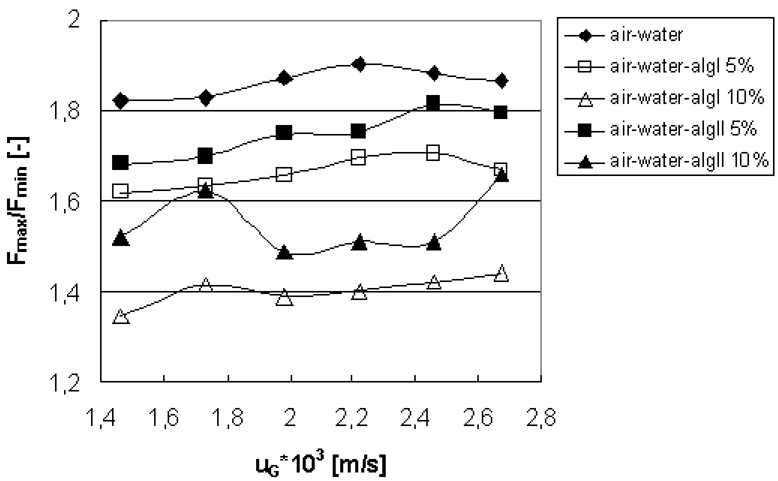
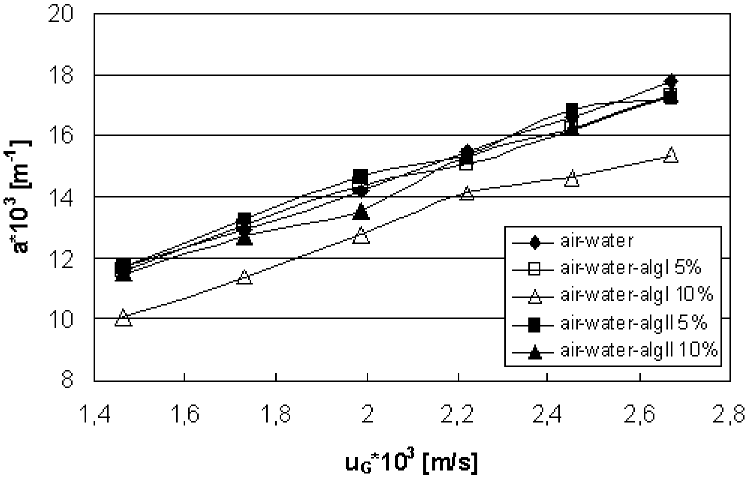


Figure 3 - F_{max}/F_{min} ratio for the different experimental conditions.

The **specific interfacial area**, ***a***, is calculated using the following equation:

(Eq. 5)

where N_b is the number of bubbles in the column at a certain instant, A_{sup} is the mean superficial area of the bubbles and V_L is the liquid volume. The rise velocity of bubbles is calculated according to (Wesselingh and Bollen,1999) and is used for determine N_b. Figure 4 show the results for the two solid sizes used. The results are reproducible with an average relative error of 4%.



As foreseen (Vasquez et al., 2000; Quicker et al. 1984), interfacial area increases with gas flow rate. Even as bubbles become larger, since the number of bubbles formed increases, and at this bubble size range the rise velocity is nearly constant, the total superficial area also increases.

Figure 5 - Dependence of interfacial area on superficial gas velocity, solids loading and solids size.

For the larger particles as well as for the smaller particles at lower concentration the solid effect is negligible. For the smaller particles one notices a significant decrease of interfacial area at the higher solids loading. This may be due to an increase of bubble coalescence leading to a decrease in total superficial area (Zahradnik et al. 1992). Yagi and Yoshida (1974) reported a similar effect in systems containing dead yeast cells.

The **liquid side mass transfer coefficient**, k_L, can be calculated from the values of k_La and a previously determined. Figure 6 present the results for the two solid sizes used. k_L values reflect the previously reported values of k_La and a. It is observed a conjugate effect of the solids size and concentration on k_L, similar to k_La behaviour. The strongest effect occurs for the smaller particles and at higher concentrations.

Keeping in mind the previous analyses, the contributions of a and k_L on k_La behaviour can now be examined. For the larger particles, the k_La variation is almost only due to the k_L variation, which shows a negligible dependence on solids concentration. The effect of solids on interfacial area is negligible, and the effect on mass transfer coefficient seems to be more pronounced as the gas flow rate increases.

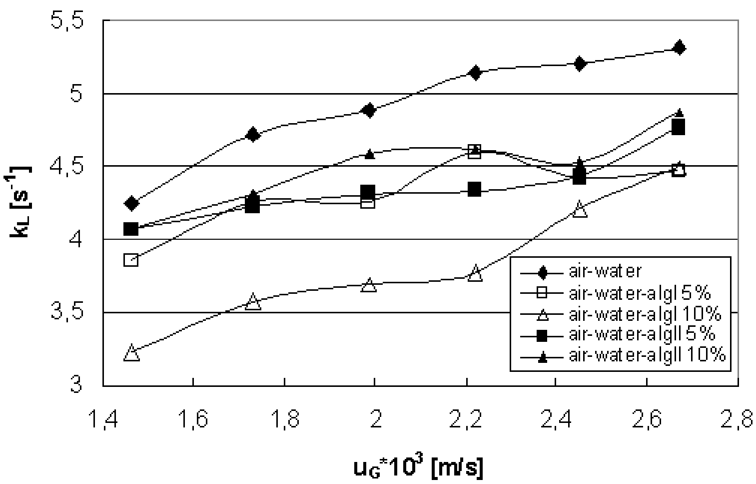


Figure 6 - Dependence of Liquid side mass transfer coefficient on superficial gas velocity, solids loading and solids size.

For the smaller particles, the $k_L a$ variation is due to the simultaneous variation of a and k_L in the same direction. The presence of solids reduces the interfacial area and the mass transfer coefficient and the effect is more pronounced at the higher solid concentration.

The **optical probe experiments** were performed for higher gas flow rates and for a higher solids loadings. Figures 7 and 8 show the radial profiles for solids loadings up to 30% and for the superficial gas velocities 0.038 and 0.046 m/s, respectively.

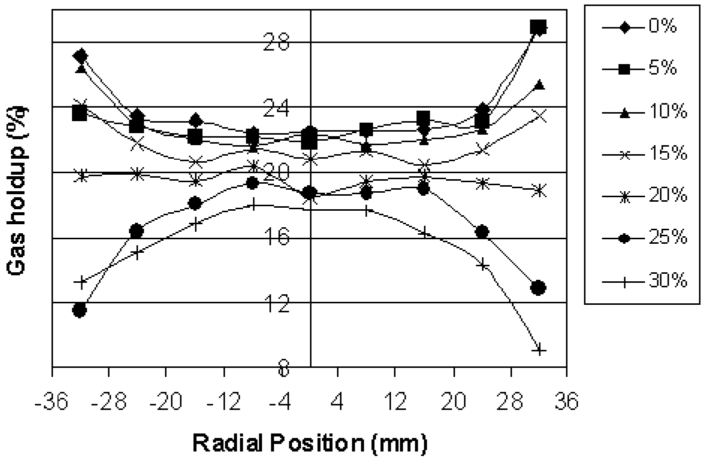


Figure 7 – Gas holdup radial profile for u_G = 0.038 m/s and solids loadings up to 30%v/v.

These pictures demonstrate that, in general, the global gas holdup decreases with the solids loading. From 0 to 20 % of solids the profiles are flat or exhibit a positive parabolic curve. This increase near the wall can be attributed to the peaking effect, being this effect more pronounced for lower gas velocities. From 20% of solids content the profiles exhibit a negative parabolic curve with the maximum at the center, typical from the heterogeneous flow regime transition. This radial profile change clearly shows a transition of flow regimes due to the increase of the solids loading. For lower solids content (0-20%) the homogeneous regime prevails while for higher solids concentrations the heterogeneous regime is dominant.

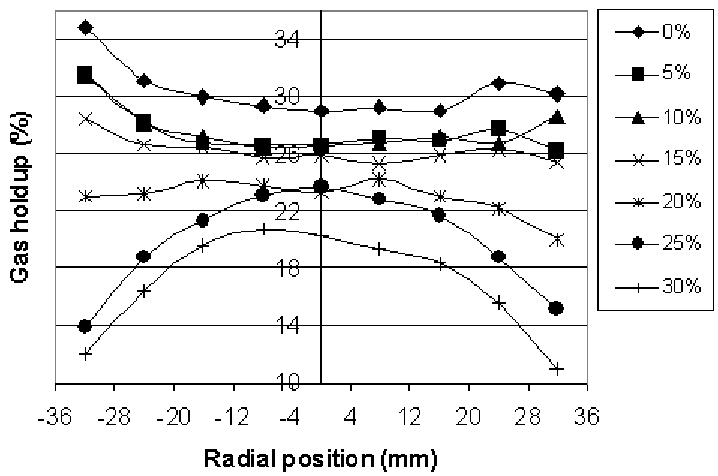


Figure 8 – Gas holdup radial profile for u_G = 0.046 m/s and solids loadings up to 30%v/v.

4. CONCLUSIONS

An image analysis technique was used to study the bubble characteristics, in two and three phase systems. In the range of operating conditions used (gas flow rate, solids loading and size), this technique shows to be suitable and practical, since the determined values of the specific interfacial area are reproducible. The solids affect negatively the volumetric liquid side mass transfer coefficient, k_La. This effect increases with the solid concentration and is more pronounced for the smaller particles used. The bubble shape is also affected by the presence of the solids. The bubbles become more rounded as the solid concentration increases and the solid size decreases. The influence of the solids on k_La was separated in its components, a and k_L. The image analysis results show that the solids tend to decrease the total interfacial area, and this effect is more pronounced for higher solid concentrations and smaller particle sizes. Determining k_L from the experimental values of a and k_La, one can infer that k_L increases with gas flow rate and decreases with solid concentration, this last effect being more important for the smaller particles. Finally, one can conclude that k_La variation is due to simultaneous variations of a and k_L in the same direction for smaller particles, while for larger particles that variation is almost only attributed to k_L variation.

An optical probe technique was used to obtain gas holdup radial profiles for higher solids loadings and gas flow rates. The experimental results demonstrate that increasing the solids loading, the gas holdup decreases and the gas holdup profiles are also influenced by the solids content.

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