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TITLE: HEAT TRANSFER INVESTIGATIONS IN A SLURRY BUBBLE COLUMN

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__Objective__: To investigate the heat transfer characteristics in two slurry bubble columns (10.8 and 30.5 cm diameter) equipped with heat transfer probes of different sizes and configurations as a function of system and operating parameters.

__Technical Approach__: The 10.8 cm diameter Plexiglas slurry bubble column along with its associated units viz., the air supply system, slurry circulation loop, temperature and pressure measurement systems, on line data acquisition and analysis system, heat transfer probes and probe bundle, is completely functional and a variety of measurements have been completed. The gas holdup is measured for two- and three-phase systems in semi-batch and continuous modes of operation. The liquid is simulated by water and gas by air at ambient temperature and pressure conditions. Glass beads and iron oxide particles of different sizes in slurries of varying concentrations have been used. Measurements of phase holdup are conducted with single tube, five-tube and seven-tube bundles in the bubble column. These correlations are compared with the predictions of various correlations available in the literature.

Heat transfer coefficient for an immersed surface and surrounding two- and three-phase dispersions are measured for all the above mentioned systems and bubble column configurations. The heat transfer coefficient values thus generated for two- and three-phase systems as a function of air velocity, solids concentration and solid particle sizes are compared with the predictions of available correlations and models. The temperature - history records of a local element on the probe surface are taken for different operating conditions and the same are interpreted to understand the mechanistic details of the heat transfer process

A larger 30.5 cm internal diameter slurry bubble column is installed to take similar hydrodynamic and heat transfer data at higher temperatures. Data have been generated for the air-water and air-water glass bead system as a function of air velocity, temperature, glass bead size in the slurry, and slurry concentration for a single tube and seven-tube bundle configurations. These data are analysed in terms of mathematical models and correlations.

Significant Accomplishments: Based on measurements of gas holdup and heat transfer coefficient under varying operating conditions in these two bubble columns with different internals several important conclusions have been drawn. These are: (a) the gas holdup depends uniquely not only on the value of the air velocity but also how this value is approached and whether or not the liquid is stationary or moving. This is particularly true for foamy systems. (b) The prediction of gas phase holdup by correlations is in general unsatisfactory and the correlations are particularly inadequate for three-phase systems and in accounting for the properties of the phases. (c) The temperature dependence of the gas-phase holdup is not reproduced by the available correlations. (d) The gas phase holdup data is shown to be sensitively dependent on the nature of internals present in the bubble columns. (e) The heat transfer coefficient data generated for the two-phase and three-phase systems have indicated for the first time its different type of qualitative dependence on different operating and system variables. (f) The available models and correlations are inadequate to represent the measured data. (g) The heat transfer coefficient are found to be quite sensitive to the nature of internals present in the bubble columns.

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INTRODUCTION

Two-phase bubble columns and three-phase slurry bubble columns are employed in a variety of industrial applications[1]. However, model representation of hydrodynamic and heat transfer behavior of these columns is quite difficult because of the involved and complicated flow and dispersion patterns of the different phases. This makes it difficult and rather impossible to reliably scaleup such reactor operations. To assist in this difficult task, we have set up two well instrumented bubble columns and measurements on these columns are in progress. The smaller column is 0.108 m in diameter and is adequate for operation at ambient conditions both in the continuous and semi-batch mode[2-4]. The other larger column[5] is 0.305 m in diameter and can be operated over a wide temperature range. The measurements conducted in this column with air-water and air-water-glass beads in the temperature range 297-343 K are reported here. Powders of glass beads of three average diameters 50.0 , 90.0 and 143.3 μm are used and their concentrations in the slurry have been varied up to 20 weight percent. The engineering design details of the larger bubble column and of the associated air supply and measuring units are given earlier by Saxena et al.[5] ; hence the major emphasis of the present work is in reporting and interpreting the experimental data. These data are employed to evaluate and assess most of the correlations and model based equations proposed for the estimation of gas-phase holdup and heat-transfer coefficient in two- and three- phase bubble columns. Comparison of these data obtained on the larger column with those generated on the smaller column under identical conditions has revealed the type of differences one would expect in these two properties with the change in reactor size.

EXPERIMENTAL EQUIPMENT

The major component of the experimental facility is the bubble column, 0.305 m in height, and equipped with a perforated gas distributor plate. The column has a conical section serving as a calming section to smooth out the gas flow. In this section, gas enters through a specially designed stainless steel gas distributor plate assembly, 203.2 mm in diameter and provided with sixtyone bubble caps arranged on concentric circles with an equilateral triangular pitch of 28.6 mm. The upper end of the column terminates into a diverging section^5 which is now further extended by a straight cylindrical section and closed by a flat steel sheet through a flange join.. A side connection with a flexible 102 mm diameter duct pipe with two liquid traps joins the column to the main exhaust system. This arrangement became necessary for operation of the column at temperatures higher than the ambient.

A stainless steel seven-tube bundle is used in this work to simulate the heat transfer surface and constitutes the internal. Each tube of the bundle is 19 mm in diameter and 3.25 m in length. Work is planned with a much bigger bundle as shown in Figure 1. The configuration of the bundle is such that each tube is located on the vertices of an equilateral triangle, 36.5 mm to a side. The tube bundle is mounted in the column with the help of two specially designed three-arm clamps. Two arms of each of the two clamps are equipped with telescopic studs as shown in Figure 1. The clamp can accommodate thirtyseven tubes in three equilateral triangles with a common vertex located along the column axis. The sides of these triangles are 36.5 , 73.0 and 109.5 mm. The measurements reported here are confined to seven tubes occupying the central and the vertices of the next set of six triangles.

Three of these seven tubes contain single phase 240 V AC , 4 kW calrod heaters of length 1.22 m , shown as H1, H2 and H3 in Figure 2. These will be referred to as heater probes. The midpoints of these heaters are 0.741, 1.118 and 1.490

m above the gas distributor plate. The remaining four heat transfer probes, P1, P2, P3 and P4 in Figure 2, are provided with a 0.361 m long brass section housing a 0.34 m long calrod heater. The brass section is connected on either side by two 40 mm long Teflon threaded connectors. On the brass test surface, six thermocouples are cemented into milled groves at various angularly staggered axial positions. The locations of these brass sections on the heat transfer probes (P1.....P4) are shown in Figure 2. The other design features of these probes are identical to those given by Saxena et al.[5] in connection with a single probe.

The three heater probes (H1, H2 and H3) provide the necessary thermal energy to heat the column contents to the desired temperature. These heaters are energized with three Payne engineering model 18 thyristor power controls with the zero-fire proportion option, and the temperature is controlled with the help of three Payne engineering model 18A4 thermocouple temperature controllers. The operation involves setting a particular controller to the desired temperature. This in turn energizes the 250 V AC/20 A receptacle, to which the control heater is connected. A T-type thermocouple is positioned in the column at the point where the temperature is to be maintained constant. This thermocouple is attached to its respective thermocouple connector and it provides the feedback to the Payne control unit. The locations of these heater probes and heat-transfer probes in the tube bundle is indicated in Figure 1.

With the above arrangement, the column is heated and maintained at four temperature levels, up to 343 K with water and glass beads. The column is always filled with an unaerated water column height of 1.8 m, and the measurements of air holdup and heat-transfer coefficient are made with decreasing air velocity. The heat transfer coefficient is measured for the probe P1 and accordingly these measurements refer to a column height of 52.1 cm above the column plate. The air velocity is computed in all cases on the basis of the unblocked cross-sectional area of the column. The air volume is computed at a pressure corresponding to the midpoint of the unaerated water column. The details of the measurement methods and computation of the air holdup and heat-transfer coefficient are the same as reported earlier[5] and hence only the final results and their discussion is presented in the following sections.

EXPERIMENTAL RESULTS

Figure 3 graphs the data for the air-water system at four temperatures in the range 297-343 K. The holdup data exhibit a characteristic qualitative dependence on air velocity[2,3,6]. Its value at a particular gas velocity decreases with increase in temperature, the rate is faster at lower temperatures and the values are almost identical at the two higher temperatures , particularly at higher air velocities. Also shown for comparison in Figure 4 are the earlier[5] air holdup data for the single 19 mm diameter axial heat transfer probe only at 291 K. These values are systematically smaller than the seven tube bundle values. This trend suggests that the air bubble size is smaller in the column at a given air velocity for the case when a seven-tube bundle is present than for the single tube case. The corresponding data taken in the small column for a single tube[6] and a seven-tube bundle[7] are also shown and these are in good agreement with the corresponding data for the larger column. This would suggest that the hydrodynamic conditions in the two columns are quite comparable. This is not surprising as the distributor plate design in both the columns is similar These conclusions are strictly valid for bubble column operations at ambient temperature and pressure conditions.

A few comments concerning the bubble formation, bubble circulation, and bubble coalescence are in order in relation to the air holdup data displayed in Figures 3 and 4. At room temperature (297K), as the air velocity is increased from zero to 0.04 m/s, uniform bubbles, spherical in shape, are observed throughout the column in increasing number. As the air velocity is further increased up to about 0.06 m/s, the air bubbles descend down near the column wall to be swept up in the inner region of the column and thereby indicating the establishment of a local liquid circulation pattern. This is observed in the upper-half section of the column only. With further increase in the air velocity the liquid circulation pattern descends down in the lower-half section of the column. It is observed up to 0.3 m above the distributor plate at an air velocity of 0.1 m/s. Further, in this air velocity range, the bubble coalescence sets in and 4-5 mm diameter bubbles coalesce to form larger bubbles, about 1 cm in diameter, which rise in the central region of the column along its axis. This bubble dynamic pattern explains the initial increase of air holdup with air velocity and its still rapid increase as the air velocity is increased beyond 0.05 ± 0.01 m/s. As the air velocity is increased beyond 0.1 m/s, the bubble coalescence increases and the size of the coalesced bubbles is up to about 3 cm in diameter. In this bubble coalescing regime, the air holdup decreases with increase in air velocity. The coalesced bubbles assume a maximum stable size at an air velocity of about 0.17 m/s. Further increase in air velocity results only in the increase of the number of coalesced bubbles and hence of the air holdup.

The nature of internals present in the column are primarily responsible for this characteristic variation of air holdup with air velocity for this bubble column configuration. The dashed curve representing the data for the small column with seven-tube bundle in Figure 4, represents similar characteristic variation of air holdup with air velocity. On the other hand, both these columns, equipped with only a single tube, produce a different bubble pattern and dynamics in the column and hence a somewhat different qualitative and quantitative dependence of air holdup on air velocity is observed as discussed by Saxena and Rao[6]. Briefly, the coalesced bubbles are much larger for the single tube case so that the gas holdup is uniformly smaller than for the seven-tube bundle over the entire air velocity range. A bundle of tubes helps in limiting the size of the coalesced bubbles.

As the temperature is increased the region of uniform bubbling shrinks a little bit , the bubble coalescence sets in earlier at an air velocity of about 0.08 m/s and occurs at a relatively rapid rate. The size of coalesced bubbles is larger than at room temperature. This results in an apparent monotonic increase of air holdup with air velocity. These qualitative trends decrease in magnitude with further increase in temperature so that the air holdup values exhibit a relatively smaller change as the temperature is increased from 323 to 343 K. The air holdup values are listed in Table 1, as a function of air velocity and temperature.

The values of air holdup for a 143.3 μm average diameter slurry of glass beads in water for solids concentrations of 5, 10 and 20 weight percent, as a function of air velocity at temperatures of 297, 323 and 343 K, are shown in Figure 5. The presence of solids at 297 K reduces the air holdup considerably at all the three solids concentrations. With an increase in temperature above 297 K, the variation of air holdup with air velocity, for the air-water system, is monotonic. The variation of air holdup for this three-phase system with temperature above 297 K and for the solids concentrations investigated here is almost negligibly small. In Table 1, we report these concentration averaged air holdup values at each of the three temperatures as a function of air velocity. In Figures 6 and 7, similar data are presented as in Figure 5 for 90 and 50 μm average diameter glass bead slurries for the solids concentration of five weight percent. It is seen that at all temperatures the air holdup variation monotonically increases with air velocity and is not much different from the corresponding two-phase air-water system other than at 297 K. These qualitative features highlight the probable effect of particle diameter on slurry viscosity as further compounded with the influence of temperature. It appears that the bubble dynamic pattern for systems of particles greater than 100 μm at [illegible] temperature is different than those involving particles smaller than 100 μm, as also commented by Pandit and Joshi[8]. Smoothed values of air holdup for these two systems are reported in Table 1. In Figure 8, we show the air holdup values averaged for slurries containing particles of average diameters 50 and 90 μm over the entire temperature range, 297-343 K. Similar additional values for slurries containing particles greater than 100 μm will be useful.

Measured values of heat transfer coefficient as a function of air velocity for the air-water system at temperatures of 297, 323 and 343 K are shown in Figure 9. Qualitatively, the heat transfer coefficient at a given temperature increases with air velocity, first rapidly in the bubbling regime, less rapidly in the bubble coalescing regime, and approach a constant value in the coalesced bubble regime. At a given air velocity, the heat transfer coefficient increases monotonically with temperature. The influences of tube bundle and column diameter on heat transfer coefficient are displayed in Figure 10. The single-tube heat transfer coefficient values of Saxena et al.[5] are seen to be in good agreement with the present seven-tube bundle values measured at 297 K. This we believe is due to the fact that liquid churning and circulation of liquid at the heat transfer surface is essentially the same in the two cases, though as discussed earlier, the bubble sizes and air holdup in the two cases are widely different. The seven-tube bundle heat transfer coefficient values, as obtained in the smaller bubble column, are in good agreement with the data obtained on the larger column. This would suggest only a small effect, if any, of column diameter on heat transfer coefficient as long as the liquid is well mixed and adequately circulated around the heat transfer surface. The single-tube data in the smaller column is significantly smaller than the corresponding seven-tube bundle data. This is due to the poor liquid mixing for the single-tube case as compared to that in the presence of the seven-tube bundle.

The heat transfer coefficient data for the slurry of 143.3 μm average diameter glass beads in water, at three concentrations of solids in the slurry, are presented in

Figure 11 at three temperatures. Also shown in this figure are the air-water system data. Several interesting qualitative trends follow from these plots. In general, the three-phase data follow the same qualitative trends mentioned earlier for the two-phase system. In addition, it may be noted that at a given air velocity and temperature the solids concentration has a negligible influence on heat transfer coefficient. This conclusion is well valid even when the solids concentration is zero. It may be emphasized that the large increase in the observed heat transfer coefficient values with temperature for the air-water system is well substantiated by the data of air-water-glass bead system, both qualitatively and quantitatively.

Figures 12 and 13 present the heat transfer data for smaller size glass bead slurries of average diameters 90 and 50 µm respectively. The slurry concentration in both cases is 5 weight percent. The difference in the two- and three-phase values seem to be appreciable at room temperature. The differences decrease considerably as the temperature increases. All other characteristic trends are similar to those as seen in the case of Figure 11. Figure 14 is a graph of the heat transfer coefficient values at each temperature, averaged for the various solids concentrations (including zero) and particle sizes. The vertical bars represent the range of maximum variation. We have employed these averaged values to assess the various theoretical models and correlations discussed in the next section.

The smoothed values of heat transfer coefficient for air-water and air-water-glass bead system at each of the temperatures, as a function air velocity, are reported in Table 2 for slurries of three different average particle sizes. The values for 143.3 µm particles are averaged for all the three slurry concentrations.

DISCUSSION OF EXPERIMENTAL GAS HOLDUP AND HEAT TRANSFER DATA

The experimental air holdup data for the two ph er, are compared with the predictions of available correlations in Figure 3. In view of our experimental results, only those correlations which exhibit temperature dependence are considered. The various correlations for gas holdup are listed in Table III. The correlations of Reilly et al.[9], Sada et al.[10], Hikita et al.[11], Smith et al.[12], and Kumar et al.[13] reproduce the present data rather poorly. All these correlations[9-13] predict a dependence of gas holdup of less than 5 percent for the temperature range of our data. However, the experimental data suggest a more pronounced dependence, particularly for the range of air velocities where liquid circulation sets in, in the bubble coalescing regime at lower temperatures. It follows from this comparison of experiment and theory that the temperature dependence of gas holdup cannot be predicted only through the temperature dependence of the thermodynamic and transport properties used in the development of these correlations[9-13]. This is not surprising as these correlations were developed and tested mostly on data around 300 K or for a narrow band of temperatures around this value. A more detailed discussion of these correlations is given by Saxena and Rao[6].

Correlations of Grover et al.[14] and Zou et al.[16] were developed to correlate the gas holdup data at elevated temperatures for the two-phase systems. Both these groups of workers[14,16] realized that the temperature dependence of the gas holdup cannot be simulated only through the dependence on temperature of thermodynamic and transport properties of the phases involved. Grover et al.[14] correlation is a modification of the Hikita et al.[11] correlation and has the same dimensionless groups and an additional term containing vapor pressure of the liquid at that temperature. Grover et al.[14] measured the gas holdup for the air-water, and air-aqueous solution of NaCl (or Cu Cl_2) in the temperature range 303-353 K. A 10 cm internal diameter bubble column, 1.5 m in height, was used in the semi-batch mode for air velocities up to 0.045 m/s. A sintered glass disc with a mean pore size of 100-120 μm was used as an air distributor plate. They[14] found the air holdup to decrease substantially with increase in temperature up to 323 K and the influence was only marginal beyond this temperature. They determined the six constants of the correlation on the basis of their experimental data. Our data are not satisfactorily reproduced by this correlation and the disagreement increases as the air velocity increases. Obviously this correlation is inadequate to represent quantitatively the gas phase holdup over a wide range of operating variables.

Zou et al.[16] also developed their correlation on the basis of the Hikita et al.[11] correlation after dropping the density and viscosity ratio terms of the two phases involved and adding a term containing vapor pressure of the liquid and the total system pressure. They[16] represented their data by such a correlation by adjusting four parameters. Zou et al.[16] have employed a stainless steel bubble column, 0.1 m in diameter and 1.05 m in height. The gas and liquid were introduced in the column by a single nozzle of 10 mm inside diameter. Data were generated in the continuous mode with gas and liquid flowing in cocurrent streams. The gas and liquid velocities ranged up to 0.16 m/s and 0.007 m/s respectively Air-water, air-alcohol and air-50% NaCl systems were studied and the maximum temperature range was 298.2-369.7 K. They[16] found the air holdup to increase with increase in temperature at all air velocities. This temperature dependence of air holdup is opposite to that found by Grover et al.[14] , and also to that of the present experimental work. The predictions based on Zou et al.[16] correlation in Figure 3 are seen to be in poor agreement with our data and an opposite qualitative dependence of air holdup on temperature is obvious. It appears that gas holdup data for well defined two-phase systems as a function of temperature will be very useful to develop a quantitative correlation.

In Figure 5, the experimental air holdup data for the slurries of 143.3 μm glass beads and solids concentrations of 5, 10 and 20 percent by weight are compared with the predictions of the correlations due to Reilly[9], Smith et al.[12], and Roy et al[15]. Of all the correlations listed in Table III, these are the only correlations which are developed for three-phase systems. The Reilly et al[9]. correlation exhibits practically no dependence of air holdup on temperature, while those of Smith et al.[12] and Roy et al.[15] predict an increase and decrease of 3 and 5 percent, respectively, in air holup with increase in temperture in the range of our persent measurements. Thus, even the qualititative dependence of air holdup for these systems is not reproduced by these correlations. The quantitative dependence is poor for all the correlations and particularly inadequate for the case of Roy et al.[15]. These correlations developed from data mostly around ambient conditions are incapable of explaining the dependence of gas holdup on temperature and solids concentration. The failure of the Roy et al.[15] correlation is mostly due to the fact that it has column diameter as one of the parameters while measurements, present as well as those available in the literature, have shown that gas holdup is almost independent of column diameter, as long as it is greater than about 10 cm. Further, the correlations due to Reilly et al.[9] and Roy et al[15]. do not include slurry (or liquid) viscosity as a parameter, while our present work suggest it to be one of the important parameters in a realistic correlation. The solids concentration in the slurry and temperature seem to be somewhat related parameters as judged from the data of Figures 5A, 5B and 5C. Slurry viscosity could link all these parameters together and it would follow that sound knowledge of the properties of the phases involved are crucial in the development of an accurate correlation. Experimental data of the nature produced here will help in identifying these parameters.

In Figures 6 and 7 are given similar comparisons of theory and experiment for slurries of particle diameters 90 and 50 μm and 5 weight percent respectively as in Figure 5 for slurries of 143.3 μm particles. The disagreements between correlation based air holdup values and the experimental data are of the same nature as those in Figure 5. None of the three correlations have particle diameter as a parameter, while our data at 297 K show that the gas holdup changes significantly when the size is reduced. In Figure 8, we present the data for the 5 weight percent slurries of two smaller size particles as averaged for the particle size and temperature ranges. The experimental values are consistently smaller than the correlation based values for the entire air velocity range. Smith et al.[12] correlation is most successful of all the correlations in reproducing the data. The Roy et al.[15] correlation leads to a very poor reproduction of experimental data. A modified form of Smith et al.[12] correlation will be appropriate to develop for slurries involving particles smaller than 100 µm as more three-phase data become available.

Heat transfer coefficient values for the air-water system at three temperatures are compared with the predictions of the correlations due to Hikita et al.[18], Pandit and Joshi[8], Kim et al.[19], and Suh and Deckwer[20] in Figure 9. These correlations are listed in Table IV and only computations performed at the two extreme temperatures, 297 and 343K are shown in Figure 9, to avoid over crowding. The computed values based on Hikita et al.[18] correlation lead to values which are in poor qualitative agreement with the experimental data. The calculated values of heat transfer coefficient, while smaller than the experimental values at the higher temperature, are much larger than the experimental values at the lower temperature. The Pandit and Joshi[8] correlation based values are considerably smaller than the experimental values at the higher temperature over the entire air velocity range. On the other hand, at the lower temperature, the computed values are smaller than the experimental values at low air velocities and this trend reverses with the increase in air velocity. In general, the correlation would appear to be inadequate. The Kim et al.[19] correlation predicts values which are consistently smaller than the experimental values, and the disagreement seems to increase rapidly with increase in temperature. The qualitative shape of the dependence of heat transfer coefficient on air velocity is adequately reproduced. However, this correlation will need substantial refinement before reliable predictions may be possible. One such effort was made by Suh and Deckwer[20]. This did improve the agreement between theory and experiment, but still the differences are large enough to warrant further refinement of theory. We think this will be in order as some more data on different systems become available.

Zehner[21,22] proposed a heat transfer model for two-phase systems in the discrete bubbling regime and computed values of heat transfer coefficient from his expression given in Table IV for the data of Figure 9 are much smaller than the experimental values. At 303 K, the values range between 0.578 to 4.13 kW/m^2 K for the air velocity range of 0.01 to 0.30 m/s. For the same air velocity range at 343 K, the values range between 0.765 to 5.47 kW/m^2 K. Thus, the predicted values are an order of magnitude smaller at low air velocities and are about half as large at the highest air velocity. One would have expected a better agreement at lower air velocities and the agreement to deteriorate as the air velocity increases due to bubble coalescence and increasing turbulence.

The Mersmann[23] correlation developed for the maximum heat transfer in analogy to the phenomenon of free convection, listed in Table IV, predicts values in this temperature range which vary from 4.22 to 4.87 kW/m^2 K. These values are somewhat smaller than our experimental values and the difference increases as the temperature increases. This conclusion is in agreement with our[6] earlier finding at ambient temperature.

The heat transfer coefficient values for the air-water-glass bead system averaged over the slurry concentration and particle size range, as shown in Figure 14, are compared with the predictions of four models[8,17,19,20] in Figures 15A, B and C at the three temperatures of 297, 323 and 343 K respectively. The Pandit and Joshi[8] correlation has the same deficiency for this three-phase system at all the three temperatures as discussed earlier for the two-phase air-water in connection with Figure 9. The correlation underpredicts the data and has an improper qualitative dependence on air velocity. The Deckwer et al.[17] correlation leads to values which are increasingly smaller than the experimental values as the temperature increases.

However, the shape of qualitative dependence of heat transfer coefficient on air velocity is well reproduced. The Kim et al.[19] model leads to values which are still smaller than the predicted values based on the Deckwer et al.[17] correlation. Attempts of Suh and Deckwer[20] to improve the correlation of Kim et al.[19] seem to be only partially successful. This correlation does reproduce the qualitative shape of the dependence of heat transfer coefficient or air velocity, and quantitatively leads to values which are in best agreement with the experimental data of all the four correlations. However, the degree of disagreement between theory and experiment is large and the predictions are systematically smaller than the observed values. It would be appropriate to refine this model as more data becomes available.

Kolbel et al.[24] and Kato et al.[25] have proposed correlations which also include the particle size. We discuss these correlations for slurry bubble columns because our measurements suggest very small dependence on particle diameter. Both these correlations predict much higher values than the experimental data. The Mersmann et al.[23] correlation as generalized by Saxena et al.[26] for the three-phase systems is given in Table IV. It leads to the maximum heat transfer coefficient values which are smaller than the experimental values. The disagreement, which is about 35 percent at 303 K, increases to about 60 percent at 343 K In summary, the available heat transfer models and correlations are inadequate to predict the experimental data, particularly as the temperature increases above the ambient.

CONCLUSIONS

Based on gas holdup and heat transfer experimental data generated in a 0.305 m diameter slurry bubble column, equipped with either a single tube or a seven-tube bundle, and similar data obtained in a 0.108 m diameter column, and the theoretical analysis in terms of correlations and models, several interesting conclusions may be drawn and these are summarized below. The systems investigated here are air-water and air-water-glass bead and our results indicate that similar general conclusions can be drawn for two- and three- phase systems, as far as the dependencies of gas holdup and heat transfer coefficient on air velocity, column temperature, column diameter and internals in the column are concerned. More specific conclusions are as follows.

The magnitude of the gas holdup does not seen to be much dependent on the column diameter as long as it is larger than 0.10 m, but the gas holdup is found to be dependent on the nature of internals present in the column. The gas holdup increases if the internals in the column prevent bubble coalescence and thereby limit the size of coalesced bubbles.

The influence of temperature is to decrease the gas holdup with increase in temperature for two-phase systems, this dependence is quite pronounced and the gas holdup values tend to assume constant values at higher temperatures. The gas holdup increases with an increase in air velocity at all temperatures. For three-phase systems, the particle diameter plays an important role while solids concentration has a relatively weaker influence. For particles greater than about 100 µm, the gas holdup at ambient temperature is significantly different than at higher temperatures, where it assumes constant values. The difference in the gas holdup values with temperature decreases as the solids concentration increases. On the other hand, for slurries of particles smaller than 100 µm, the influence of temperature is relatively much smaller. The gas holdup for three phase systems also increases with air velocity at all temperatures.

The status of available correlations in representing the temperature dependence of gas holdup for two- and three-phase systems is inadequate and poor. Many of the available correlations which have been successfully used to represent experimental data at temperatures close to ambient temperatures due to Reilly et al.[9], Sada et al.[10], Hikita et al.[11], Smith et al.[12], Roy et al.[15] and Kumar et al.[13] are unsatisfactory as revealed by this work. The temperature dependence of gas holdup is much more pronounced than demonstrated by these correlations. The two correlations[14,16] developed specifically to represent temperature dependence of gas holdup on temperature for two-phase systems are found entirely inadequate for the data generated for the air-water system. It is clear that development of a reliable correlation is urgently needed and such an undertaking will be in order as soon as a reliable data base becomes available. All these comments apply equally well to the three-phase systems except for slurries containing particles smaller than 100 μm, the dependence of air holdup on temperature is weak and the reproduction by the correlation of Smith et al.[12] is fair but it needs refinement for good quantitative estimation. This will be attempted as soon as some more data is available.

The dependence of heat transfer coefficient on air velocity and column temperature is quite pronounced for these systems as revealed by our measurements. The influence of internals in the larger column is negligibly small but its influence is significant for the smaller column. The values of heat transfer coefficient for the larger column are greater than for the smaller column, unless the internals are such that their presence enhances liquid mixing and circulation. The influence of slurry concentration and particle size is small and is particularly so at higher temperatures and at higher gas velocities.

The correlations are found to be incapable of reproducing the experimental data, particularly at temperatures above ambient, both for two- and three-phase systems. The correlations underestimate the experimental data over the entire air velocity range. The refinements and development of a new correlation will be in order as soon as more experimental data become available.

Very briefly, experimental data for gas holdup, heat transfer coefficient, and related transport and thermodynamic data for the different phases are needed to develop reliable models and correlations.

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NOMENCLATURE

Ar	Archemedes number = $d_b^3 (\rho_L - \rho_g)\, g\, \rho_L/\mu_L^2$, dimensionless
Bo	Bond number = $gD^2 \rho_L/\sigma_L$, dimensionless
C_p	slurry heat capacity, J/kg K
C_{pL}	liquid heat capacity, J/kg K
C_{ps}	solid heat capacity, J/kg K
d_b	bubble diameter, m
d_o	smallest average diameter of the sand sample, 0.04 mm
d_p	mean particle diameter, m
D	column diameter, m
Fr	Froude number = $U_g^2/g\, d_p$, dimensionless
g	acceleration due to gravity, m/s^2
Ga	Galileo number = $g D^3 \rho_L/\mu_L^2$, dimensionless
h_w	heat transfer coefficient, W/m^2 K
$h_{w\,max}$	maximum heat transfer coefficient, W/m^2 K
$\bar{k}$	slurry thermal conductivity, W/m K
k_g	gas thermal conductivity, W/m K

k_L	liquid thermal conductivity, W/m K
k_s	solid thermal conductivity, W/m K
l	mean distance between bubbles, m
Nu	Nusselt number = $h_W d_p/k_L$, dimensionless
P	total pressure of system, Pa
P_v	vapor pressure of liquid phase, Pa
Pr	Prandtl number = $C_{pL} \mu_L / k_L$ or $\bar{C}p \bar{\mu}/\bar{k}$, dimensionless
Re	Reynolds number = $U_g d_p \rho_L/\mu_L$, dimensionless
$\overline{\mathrm{Re}}$	Reynolds number = $U_g d_p \bar{\rho} / \bar{\mu}$, dimensionless
Re_T	Reynolds number = $U_g D \rho_g/\mu_g$, dimensionless
St	Stanton number = $h_W/\rho_L C_{pL} U_g$, dimensionless
T	temperature, K
$U_{b\infty}$	slip velocity of a single bubble, m/s
U_g	Superficial gas velocity, m/s
v_F	eddy velocity, m/s
v_L	liquid volume fraction in slurry, dimensionless
v_s	Solid volume fraction in slurry, dimensionless
W_L	weight of liquid in slurry, kg
W_s	weight of solids in slurry, kg
w_L	weight fraction of liquid in slurry, dimensionless
w_s	weight fraction of solids in slurry, dimensionless

Greek Symbols

ϵ_g	average gas-phase holdup, dimensionless
ϵ_L	average liquid-phase holdup, dimensionless
ϵ_s	average solid-phase holdup, dimensionless
μ_g	viscosity of gas, kg/ms
μ_L	viscosity of liquid, kg/ms
μ_b, μ_{sL}	viscosity of slurry, kg/ms
ρ_g	gas density, kg/m^3
ρ_L	liquid density, kg/m^3
ρ_s	solid density, kg/m^3
ρ_{sL}	slurry density, kg/m^3
σ_L	liquid surface tension, N/m
σ_w	water surface tension, N/m