5. DISCUSSION OF EXPERIMENT AND THEORY: GAS HOLDUP

5.1 Available Data and Correlations for Two-Phase Systems

Akita and Yoshida [53] measured gas holdup (air, helium,oxygen and carbon dioxide) in liquids (water, glycol, methanol, carbon tetrachloride and sodium chloride and sodium sulfate solutions) in the temperature range 283-303 K for gas velocities of 0.007-0.15 m/s in a column 0.152 m in diameter equipped with a single nozzle (5 mm diameter) gas distributor plate. They also report limited data in a 0.60 m column. They found negligible influence of gas density on gas holdup. The effect of liquid velocities up to 0.044 m/s was found to be negligible on gas holdup. On the basis of their data, they [53] proposed the following correlation:

$$\epsilon_g = C_1 (1 - \epsilon_g)^4 \, Bo^{1/8} \, Ga^{1/12} \, Fr \qquad 5.1$$

where C_1 is 0.20 for nonelectrolytes and is 0.25 for electrolytes.

Hughmark [54] measured the air holdup in a 2.54 cm column for water, sodium sulfate solution, kerosine, and a light oil in the bubbling regime. Air velocities ranged up to 0.305 m/s, and liquid velocities up to 0.09 m/s. His correlation is :

$$\epsilon_g = \frac{1}{2 + (0.35/U_g)\left[\left(\rho_L/\rho_w\right)\left(\sigma_L/\sigma_w\right)\right]^{1/3}} \qquad 5.2$$

for semibatch operation and zero liquid flow velocity. For continuous operation when the gas and liquid are in co-current flow, he found

$$U_g = \epsilon_g \left[\left(U_g/\epsilon''_g\right) - \left(V_L/1 - \epsilon''_g\right)\right] \qquad 5.3$$

On the basis of other workers data, he concluded that the column diameter has an effect on gas holdup as long as its value is less than 7.62 cm and is independent of its value for values greater than 10.2 cm.

Hikita et al. [55] measured gas holdup in a 10 cm diameter column with single-nozzle gas sparger at temperatures in the range 283-304 K. They used seven gases (air, hydrogen, carbon dioxide, methane, propane and the mixtures of hydrogen and nitrogen) and six liquids (water, sucrose solutions, methanol, n-butanol, aniline and i-butanol). They also employed nine electrolyte solutions with air. They determined gas holdup for three sections of the column and found it to be constant throughout the column height except for the lowest section (15 cm) where its value was lower due to larger gas bubbles and jetting gas stream. They found ϵ_g to be dependent on gas density but assumed it to be independent of nozzle opening, column diameter and ungassed liquid column height. Their correlation is:

$$\epsilon_g = 0.672 \left(U_g \mu_L/\sigma_L\right)^{0.578} \left(\mu_L^4 g/\rho_L \sigma_L^3\right)^{-0.131} \left(\rho_g/\rho_L\right)^{0.062} \left(\mu_g/\mu_L\right)^{0.107} \qquad 5.4$$

Reilly et al. [56] measured gas holdup in a 0.3 m diameter column for three different gas spargers at temperatures in the range 288-313 K. Three different gases (air, helium and argon) and three different liquids (deionized water, Esso Solvent Varsol DX 3641 with and without the addition of an antifoam agent, and a technical grade trichloro-ethylene) were used. They proposed a correlation which could represent their data as well as the literature data within ± 20 percent. The correlation is:

$$\epsilon_g = 0.009 + 296\, U_g^{0.44}\, \rho_L^{-0.98}\, \sigma_L^{-0.16}\, \rho_g^{0.19} \qquad 5.5$$

Zahradnik and Kastanek [48] reported air holdup data for air-water system as obtained in two columns for diameters 0.152 and 0.292 m equipped with perforated plate air spargers with hole diameters ranging from 0.0005 to 0.003 m with corresponding open plate area ranging between 0.1 to 1.0 percent. The air flow rate ranged form 0.031 to 0.276 m/s. Their results were correlated by:

$$\epsilon_g = U_g/(0.3 + 2.0\, U_g) \qquad 5.6$$

For a two-phase, gas-liquid, system Smith et al. [57] proposed the following

correlation:

$$\epsilon_g = \left[2.25 + \frac{0.379}{U_g}\left(\frac{\rho_L \sigma_L}{72}\right)^{0.31} \mu_L^{0.016}\right]^{-1} \qquad 5.7$$

Kumar et al. [59] generated air holdup data in columns of diameters 5.0, 7.5, and 10.0 cm and orifice plate distributors having 21-49 holes of diameters in the range 0.087 - 0.309 cm. As liquids, they employed water, kerosene and 40 percent glycerol, and air velocities in the range 0.2 - 13.83 cm/s. Their correlation is:

$$\epsilon_g = 0.728\, U_g' - 0.485\, U_g'^2 + 0.0975\, U_g'^3 \qquad 5.8$$

where

$$U'_g = U_g\left[\rho_L^2/\{\sigma_L(\rho_L - \rho_g)g\}\right]^{1/4} \qquad 5.9$$

Sada et al. [60] introduced the effect of gas density on holdup by modifying the correlation of Akita and Yoshida [53] on the basis of their data as

$$\epsilon_g = 0.32\left(1 - \epsilon_g\right)^4 Bo^{0.121}\, Ga^{0.086}\, Fr\left(\rho_g/\rho_L\right)^{0.068} \qquad 5.10$$

The data were obtained in a 7.3 cm diameter column provided with a single nozzle gas sparger of diameters 1.5, 2.7 and 5.7 mm. Helium and nitrogen were used as gases; and water, sodium nitrate, methanol, and a mixture of lithium chloride and potassium chloride as liquid media. The experiments were conducted in the temperature range 298-723 K for gas velocities in the range 0.005-0.11 m/s.

Hills [61] measured air holdup for air-water system in a 150 mm diameter column equipped with either a single 51 mm diameter orifice of a cylindrical sparger cap with 60 holes 3.1 mm diameter arranged in five rows with twelve holes in each row. The air velocity was varied in the range 0.07-3.5 m.s and that of the liquid in the range 0-2.7 m/s. For liquid velocities less than or equal to 0.3 m/s, he found that

$$\left(U_g/\epsilon''_g\right) - \left(V_L/\left(1-\epsilon''_g\right)\right) = 0.24 + 4.0\ \epsilon_g^{1.72} \qquad 5.11$$

and

$$\epsilon_g = U_g\left[0.24 + 4.0\ \epsilon_g^{1.72}\right]^{-1} \qquad 5.12$$

Correlations of Grover et al. [62] and Zou et al. [63] were developed to correlate the gas holdup data at elevated temperatures for the two-phase systems. Both these groups of workers [62, 63] 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. [52] correlation is a modification of Hikita et al. [55] correlation and has the same dimensionless groups and an additional term containing vapor pressure of the liquid at that temperature. Grover et al. [62] measured the gas holdup for the air-water, and air-aqueous solution of NaCl (or $CuCl_2$) in the temperature range 303-353 K. A 10 cm 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 [62] 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. The correlation is:

$$\epsilon_g = \left(\frac{1 + a\,P_v}{b\,P_v}\right)\left(\frac{U_g\,\mu_L}{\sigma_L}\right)^{0.76}\left(\frac{\mu_L^4\,g}{\rho_L\,\sigma_L^3}\right)^{-0.27}\left(\frac{\rho_g}{\rho_L}\right)^{0.09}\left(\frac{\mu_g}{\mu_L}\right)^{0.35} \qquad 5.13$$

where

$a = 1.1 \times 10^{-4}$, and $b = 5 \times 10^{-4}$

Zou et al. [63] also developed their correlation on the basis of the Hikata et al. [55] 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 [63] represented their data by such a correlation by adjusting four parameters. Zou et al. [63] 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 concurrent 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 [63] found the air holdup to increase with increase in temperature at all air velocities. Their form is:

$$\epsilon_g = 0.17283 \left(\frac{\mu_L^4 g}{\rho_L \sigma_L^3} \right)^{-0.1544} \left(\frac{U_g \mu_L}{\sigma_L} \right)^{0.5897} \left(\frac{P + P_v}{P} \right)^{1.6105} \qquad 5.14$$

The temperature dependence of air holdup given by the correlation of Eq. (5.14) is opposite to that of the relation of Grover et al. [62], Eq. (5.13).

5.2 Available Data and Correlations for Three-Phase Systems

Some of the important gas holdup correlations developed for three-phase systems are due to Reilly et al. [56], Smith et al. [57], and Roy et al. [64]. All these correlations have been developed by considering the data for two and three-phase systems. It is clear from these expressions that the correlations of Reilly et al. [56], and Smith et al. [57] predict negligible dependence of gas-phase holdup on temperature, and their predictions at best can be regarded as only in approximate agreement with the experimental data.

Roy et al. [64] on the basis of their fractional gas holdup data for three-phase systems (air-water-quartz, air-compressor oil-quartz, air-light diesel oil-quartz, and air-water-coal) proposed two-regions of gas holdup characterized by Reynolds number based on the column diameter, $Re_c = D_c G / H_g$ as

$$\epsilon_g = 3.88 \times 10^{-3} [Re_C (\sigma_w / \sigma_L)^{1/3} (1 - v_s)^3]^{0.69} \text{ for } Re_C < 350 \qquad 5.15$$

and

$$\epsilon_g = 1.72 \times 10^{-2}\left[Re_C\,(\sigma_w / \sigma_L)^{1/3}(1 - v_s)^3\right]^{0.44} \text{ for } Re_C > 500 \qquad 5.16$$

where

$$v_s = \frac{(W_s / \rho_s)}{(W_s / \rho_s) + (W_L / \rho_L)}$$

These authors [64] found that the fractional gas holdup values decreased with increasing concentration of the solids in the system. However, for coal the ϵ_g values were considerably higher than those for the systems containing quartz. This was attributed to the very different solid-liquid interface behavior for coal than for quartz. Ying et al. [65] found that the reduction in ϵ_g values because of the presence of solids in the column was dependent on the column diameter. The effect was negligible for a 2-in. diameter column, but for a 5-in. diameter column, ϵ_g values decreased in the presence of solids.

On the basis of works by Hughmark [54] and by Smith and Ruether [66], Smith et al. [57] have proposed for three-phase bubble columns:

$$\epsilon_g = \left[2.25 + \left(\frac{33.9}{U_g}\right)\left(\frac{\rho_L\,\sigma_L}{72}\right)^{0.31}\mu_{SL}^{0.16}\right]^{-1} \qquad 5.17$$

Barnea and Mizrahi [58] correlation was used to estimate the slurry viscosity from liquid viscosity, μ_L, according to the following relation:

$$\mu_{sL} = \mu_L \exp\left[\frac{(5 / 3)\,v_s}{(1 - v_s)}\right] \qquad 5.18$$

μ_{sL} and μ_L are in centipoise.

Roy et al. [56] correlation given in the previous section will also be employed here for the analysis of three-phase systems. This is in view of their [56] recommendation that solid particles have only negligible influence on gas holdup. They also felt similarly for gas and liquid viscosities and hence did not

at the highest air velocity. In the remaining portion of the column the uncertainties are ±5 and ±35 percent for the lowest and highest air velocities respectively.

Additional new data on air-water system are taken and these are displayed in Fig. 5.1. Two different procedures are adopted for measuring the air holdup. In one procedure, an initial unaerated water column of 1.10 m in height (H_s) is employed and the holdup is determined as a function of decreasing air velocity. In this case the expanded height (H_e) of the air-water dispersion is different at each air velocity. In the procedure, the air holdup was measured for an expanded aerated water column height of 1.70 m and again for decreasing air velocity. Typical results of these two procedures are shown in Fig. 5.1 as set A and set B respectively. The two sets of air holdup values agree with each other for air velocities up to about 0.08 m/s and thereafter set B is consistently greater than set A for the entire air velocity range.

Uniform bubbles, spherical in shape, moving almost vertically up in the column are observed up to air velocity of 0.05 m/s. At the air velocity of about 0.05 m/s, air bubbles are observed to move downwards near the column wall in small sections of upper column region ($h > 0.5$ m). This establishes a cellular flow pattern in the column. The overall region of liquid circulation in the column descends further down with increase in the air velocity, and it extends up to 0.3 m at the air velocity of 0.08 m/s. For air velocities greater than 0.08 m/s, the bubble coalescence is observed and at column heights of greater than 1 m, the coalesced bubbles escape from the middle of the column. The region of coalescence in the column increases with air velocity and more bubbles are observed to be swept down in the local circulating water eddies. The opposite influence of coalescence and circulating eddies on air holdup almost balance for the range of air velocities between 0.10 to 0.17 m/s, and a somewhat constant holdup is observed for set A. The degree of coalescence increases with an increase in air velocity , and the coalesced bubbles almost slug the top portion of the column for air velocities greater than 0.3 m/s. However, the number of bubbles and their residence time in the column due to water circulation is such that the increased holdups are consistently observed with increase in air velocity over the entire range. The higher holdup values of set B data than that of set A

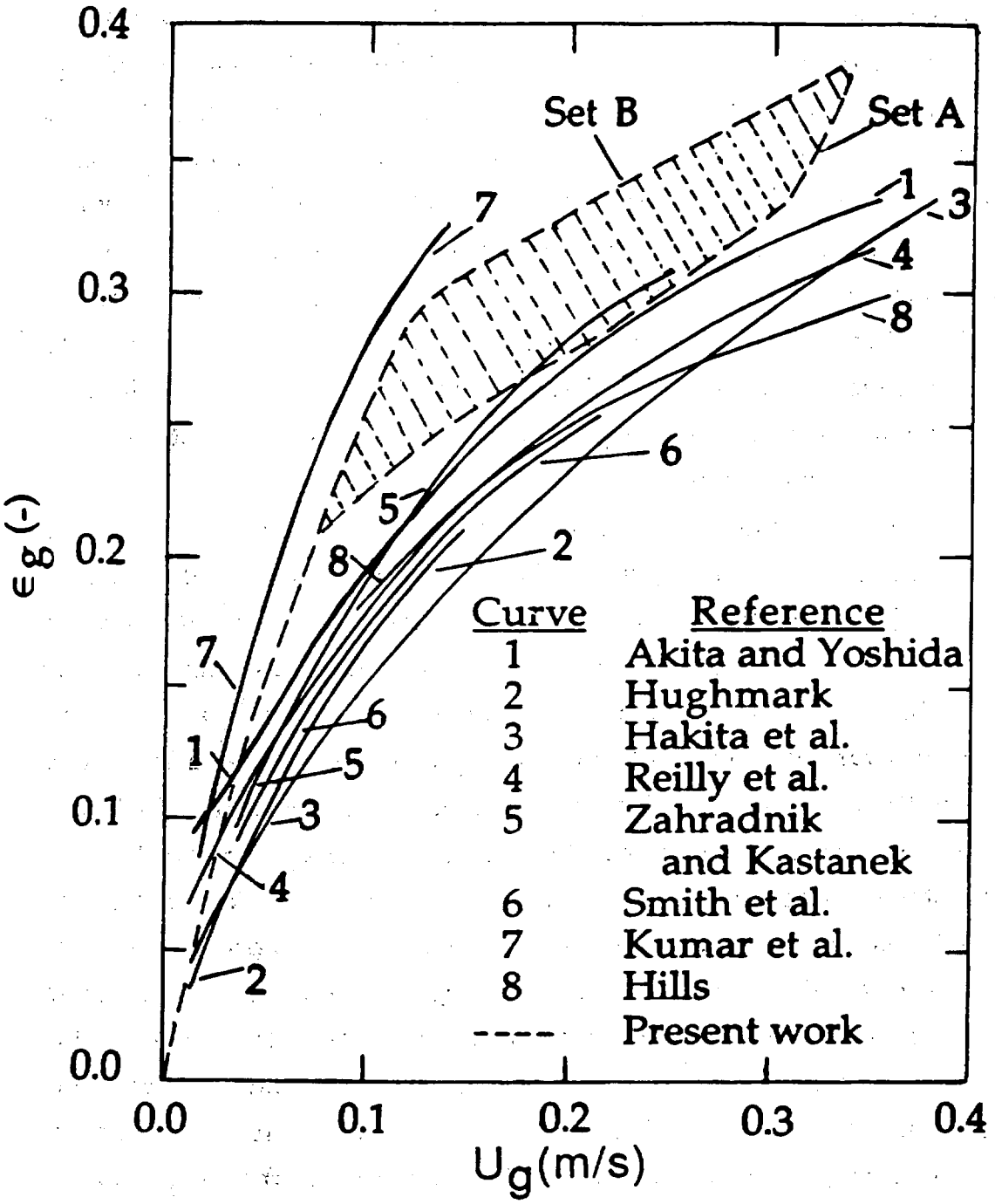


Fig. 5.1. Comparison of experimental and computed air holdup values for the air-water system as a function of superficial air velocity at 309K.

are partly due to a larger water column height and associated bubble dynamics. Our systematic measurements of air holdup for unaerated water column heights between 70 to 110 cm reveal that air holdup increases with increase of the water column height. Repeated measurements corresponding to sets A and B did represent some scatter and the dashed curve represents only the extreme values. The degree of foaming observed in the column has also varied in these runs and this also has partly been responsible for variation of the air holdup at the same air velocity. Our present holdup data are compared with the predictions of the air holdup values based on different correlations listed in section 5.1.

The computed values based on Akita and Yoshida's [53] correlation, Eq. (5.1), are shown in Fig. 5.1 as curve 1. Except for the very low air velocities (< 0.04 m/s), the computed values are generally smaller than our measured values. Hughmark's [54] correlation of Eq. (5.2) leads to values shown as curve 2 in Fig. 5.1, and these are systematically smaller than our measured values. The differences are significant and this correlation is not considered adequate for predicting the present air holdup values. Predictions based on Hikita et al.'s [55] correlation, Eq. (5.4), are shown as curve 3 in Fig. 5.1. This correlation like that of Hughmark's [54], underestimates the measured values of air-water system, and are systematically smaller than the computed values based on Akita and Yoshida's [53] correlation. For electrolytes, the air holdup is found to be greater than given by the above correlation and a multiplicative factor is introduced to represent the experimental data. Computed values from Reilly et al.'s [56] correlation, Eq. (5.5) are graphed in Fig. 5.1 as curve 4. These predictions are in better agreement with our data than those based on correlations of Hughmark [54], and Hakita et al. [55]. However, Akita and Yoshida's [53] correlation is relatively better in reproducing our data than that of Reilly et al.'s [56]. Zahraknik and Kastanek's correlation [48] based values are shown as curve 5 in Fig. 5.1 and these represent our data nearly as well as that of Eq. (5.1) by Akita and Yoshida [53]. Calculated values from Eq. (5.7) of Smith et al. [57] are shown as curve 6 in Fig. 5.1. These values are also lower than our measured values. Smith et al. [57] have examined the relation of Eq. (5.7) on the basis of data taken in a 0.108 cm diameter column for nitrogen and four liquids (water, silicone oil, glycol and aqueous ethanol). Calculated values from the correlation

of Kumar et al. [59] are shown as curve 7 in Fig. 5.1 and set B is reproduced well by this correlation. Predictions based on Sada et al.'s [60] correlation, Eq. (5.10), are almost identical with those obtained from Eq. (5.9). Hills's [61] correlation based values, Eq. (5.12), are shown as curve 8 in Fig. 5.1, and these consistently underestimate our data.

Lastly, we examine the approach of Nicklin [73] for correlating the gas holdup data in two-phase systems using the concept of drift velocity, Wallis [75]. This approach in the absence of liquid flow yields [74]:

$$\epsilon_g = U_g \left[U_g + U_o\right]^{-1} \qquad 5.19$$

Here, U_o is the drift velocity and in the churn turbulent regime, O'Dowd et al. [75] have proposed to express it as

$$U_o = U_g + U'_{b\infty} \qquad 5.20$$

$U_{b\infty}$ may be identified with the terminal rise velocity of bubbles and we have treated it as an adjustable parameter in correlating the gas holdup data. Equation (5.19) may then be written as

$$\epsilon_g = U_g \left[2U_g + U'_{b\infty}\right]^{-1} \qquad 5.21$$

The extreme sets A and B of experimental gas holdup data are examined in Fig. 5.2 on the basis of Eq. (5.21) and a constant value of 0.241 m/s for $U_{b\infty}$. This parity plot of gas holdup well substantiates the approach for correlating the data outlined here and the implicit assumption in Eq. (5.20).

In summary, we find that most of the correlations predict values of air holdup which are generally smaller than those obtained in our repeated measurements. We think that the column hydrodynamics plays a significant role and in particular the presence of a 19 mm axial probe in the column and the air sparger plate design has increased the residence time of bubbles, and hence the larger air holdup. Unaerated water column height and the mode of

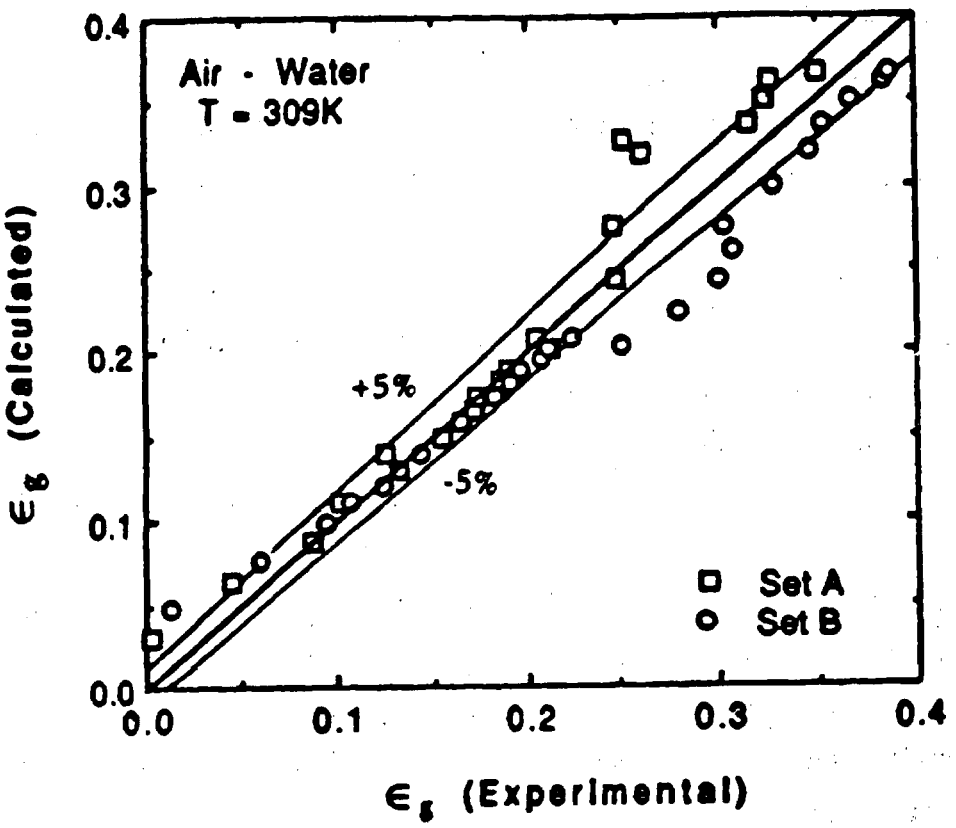


Fig. 5.2. Parity plot for gas holdup.

measurement (sets A and B) also influence the data significantly as the air velocity is increased. The air holdup knowledge is important for characterizing the column and in this perspective we attach special significance to such measurements. Heat transfer data reported later are taken for such a column operation as discussed above.

The knowledge of bubble size and bubble size distribution is particularly useful not only in interpreting the gas holdup data but also in establishing the magnitude of interfacial area. This parameter is essential for computing the mass transfer from bubble to the liquid phase. We [77] have taken limited data using high speed photographic and an image carrying fiber optic probe techniques. Saxena et al. [78] have reviewed the different techniques employed to obtain bubble size distributions in multiphase reactors. Patel et al. [79] have recently discussed the dynamic gas disengagement technique used to obtain these parameters. Obviously considerable research and development work needs to be done in this area to assist the development of a variety of chemical and biochemical processes performed in such bubble column reactors. Some relevant results obtained in our preliminary effort [77] are quoted here. In Figs. 5.3 through 5.8 are given the various measured bubble size frequency distributions and histograms. Based on these data, following conclusions may be drawn.

(a) The bubble size does not vary much with gas flow rate, at least in the air velocity range of 3.6 to 9.2 cm/s. A mean value of 6.1 ± 0.3 mm for air bubble diameter in water at ambient temperatures seems appropriate. This conclusion is based on the measurements made on the larger 30.5 cm diameter column.

(b) The bubble size is found to be dependent on the column diameter as judged from the data on the two columns at one gas velocity, 3.2-3.6 cm/s. The bubble diameter is smaller in the smaller baffled column than in the larger column where the baffles are relatively much less congested. O'Dowd et al. [76] have reported smaller bubbles in a baffled column than in the unbaffled column at lower gas velocities.

(c) The bubbles at the column wall are relatively smaller in size as recorded by the fiber optic probe than those farther away from the wall as observed in the photographic film. This is in agreement with detailed measurements made using a conductivity probe (O'Dowd et al. [76]), though in this technique bubble

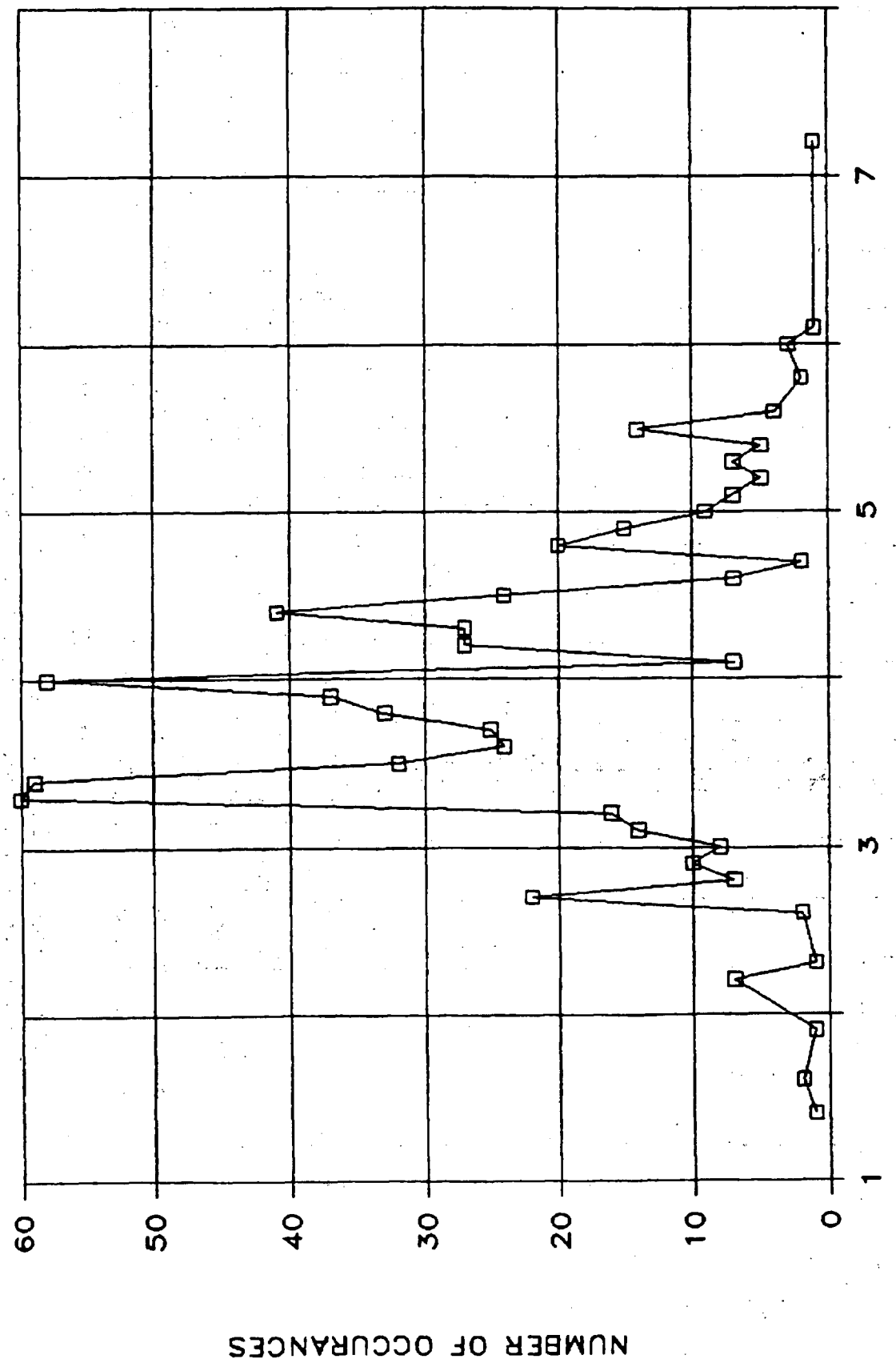


Fig. 5.3. Bubble size frequency distribution in the 10.8 cm diameter bubble column for the air-water system. Air velocity = 3.2 cm/s.

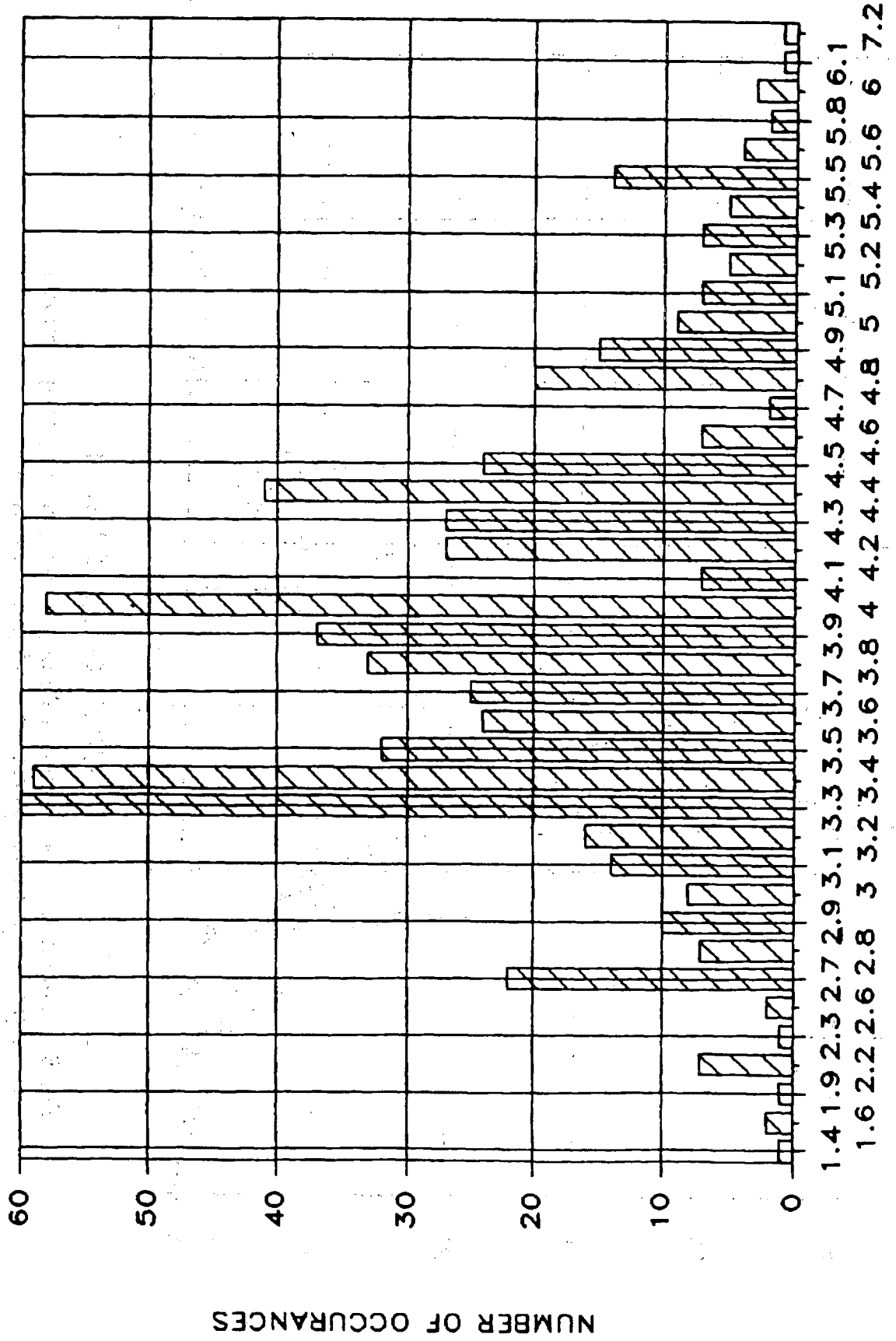


Fig. 5.4. Histogram of bubble-size distribution in the 10.8 cm diameter bubble column for the air-water system. Air velocity = 3.2 cm/s.

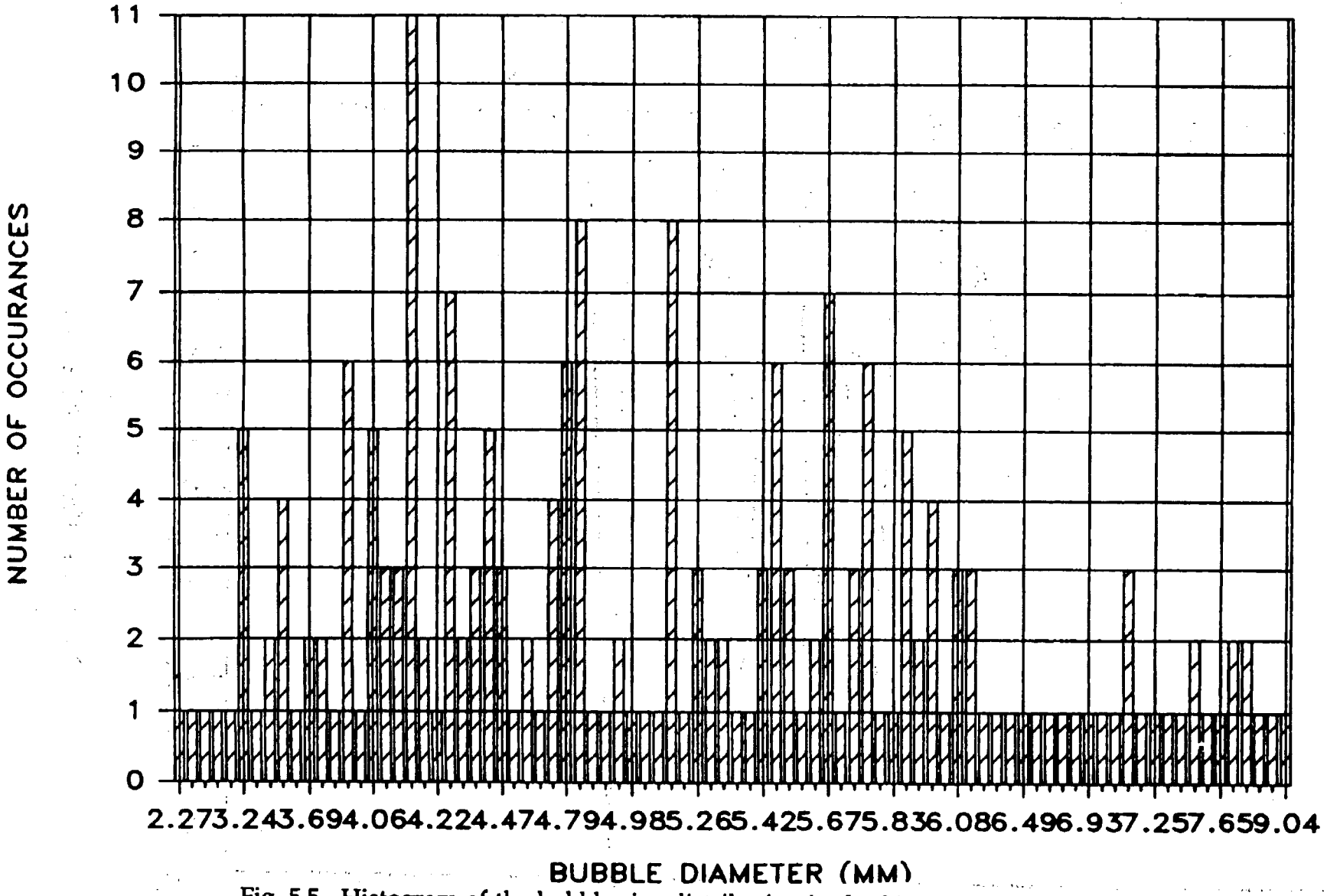


Fig. 5.5. Histogram of the bubble-size distribution in the 30.5 cm diameter bubble column for the air-water system. Air velocity = 3.2 cm/s.

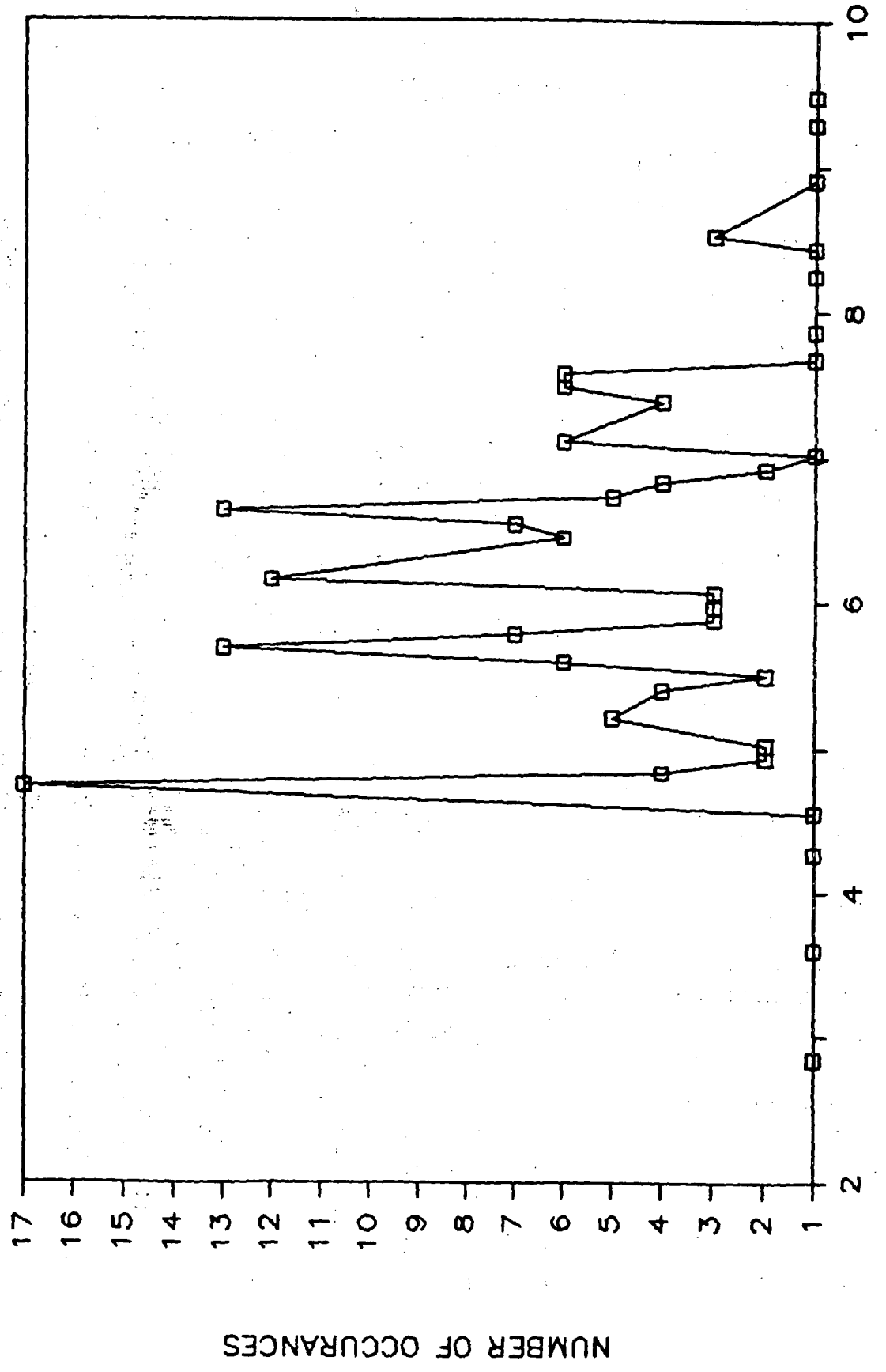


Fig. 5.6. Bubble size frequency distribution in the 30.5 cm diameter bubble column for the air-water system. Air-velocity = 3.6 cm/s.

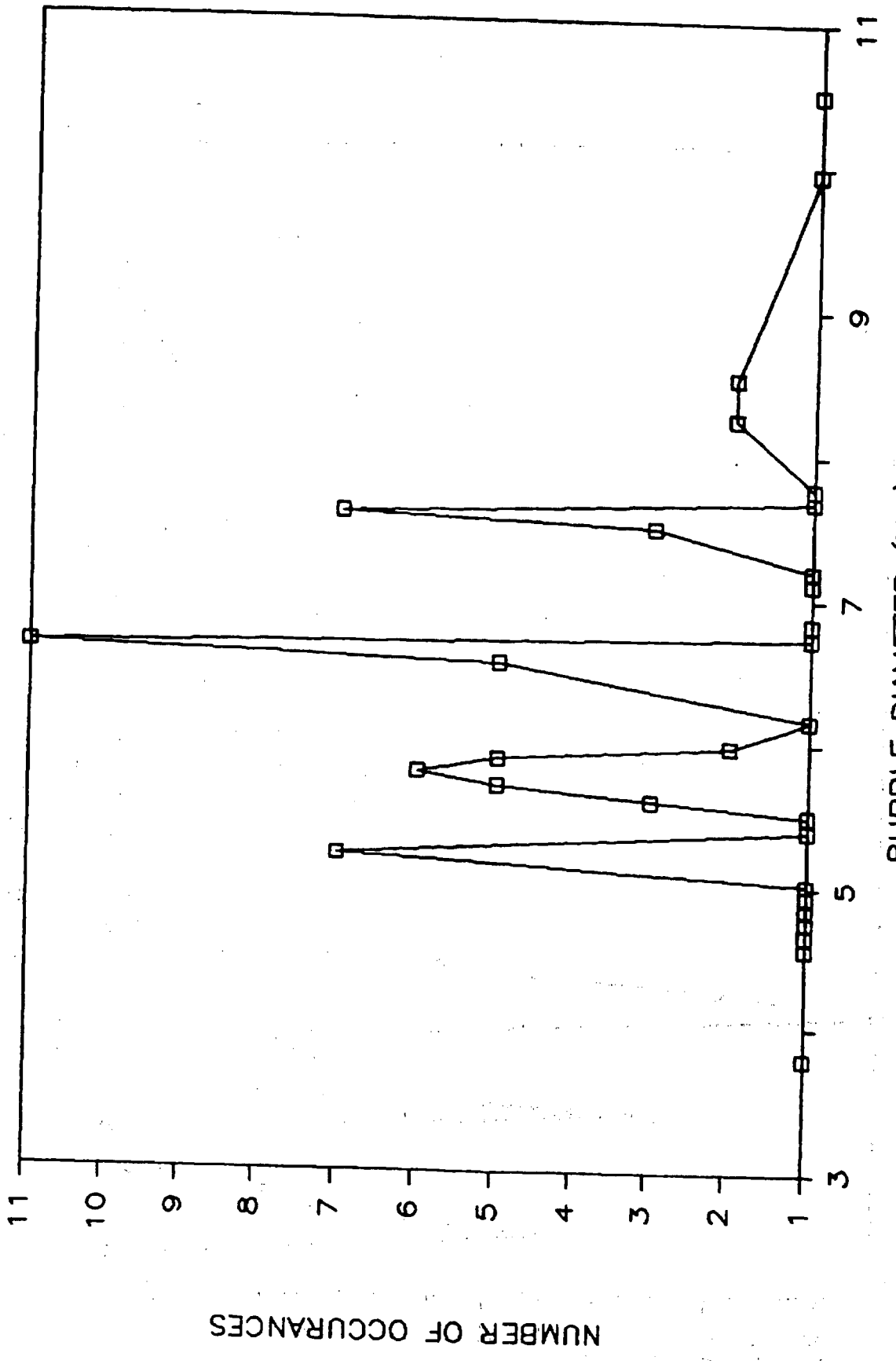


Fig. 5.7. Bubble size frequency distribution in the 30.5 cm diameter bubble column for the air-water system. Air velocity = 5.8 cm/s.

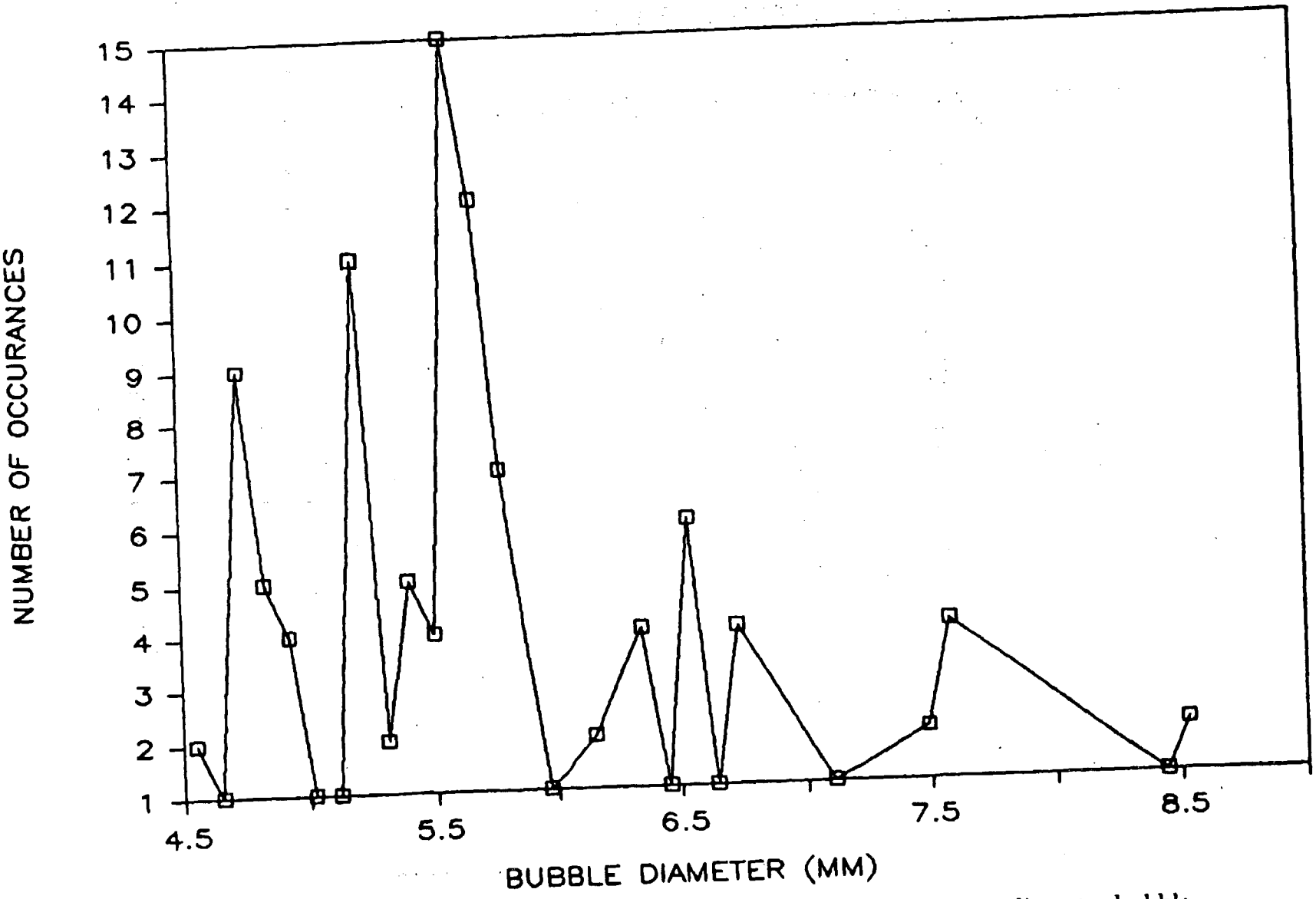


Fig. 5.8. Bubble size frequency distribution in the 30.5 cm diameter bubble column for the air-water system. Air velocity = 9.2 cm/s.

size distribution is measured at a point.

In Fig. 4.4, we have presented the data of holdup for the small column equipped with a single probe and a seven-tube bundle. The presence of a tube bundle inhibits to some extent bubble coalescence and therefore the holdup is larger and is independent of the initial column height. The models and correlations developed for unbaffled column operations will not be appropriate to represent these data. Additional data for air-water system are taken by Saxena and Patel [80] in this smaller bubble column equipped with a single 19 mm probe, and with a seven-tube bundle, and these have been correlated following the drift-flux theory of Wallis [75] as discussed by Zuber and Findlay [81] and detailed earlier in this section. This leads to $U_{b\infty}$ values listed in Table 5.1, and experimental gas holdup values are shown compared with the calculated values in Fig. 5.9. The agreement of theory and experiment is considered reasonable.

The experimental air holdup data taken at various temperatures in the larger column are compared with the predictions of available correlations in Fig. 5.10. In view of our experimental results, only those correlations which exhibit temperature dependence are considered. The correlations of Reilly et al. [56], Sada et al. [60], Hikita et al. [55], Smith et al. [57] and Kumar et al. [59] reproduce the present data rather poorly. All these correlations 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. This is not suprising as these correlations have been developed and tested mostly on data around 300 K or for a narrow band of temperatures around this value.

Grover et al. [62], and Zou et al. [63] have developed correlations to predict gas holdup for temperatures up to 370 K. Zou et al. [63] have reported the air holdup to increase with an increase in temperautre at all air velocities. This temperature dependence of air holdup is opposite to that found by Grover et al. [62], and also to that observed in the present experimental work. The predictions

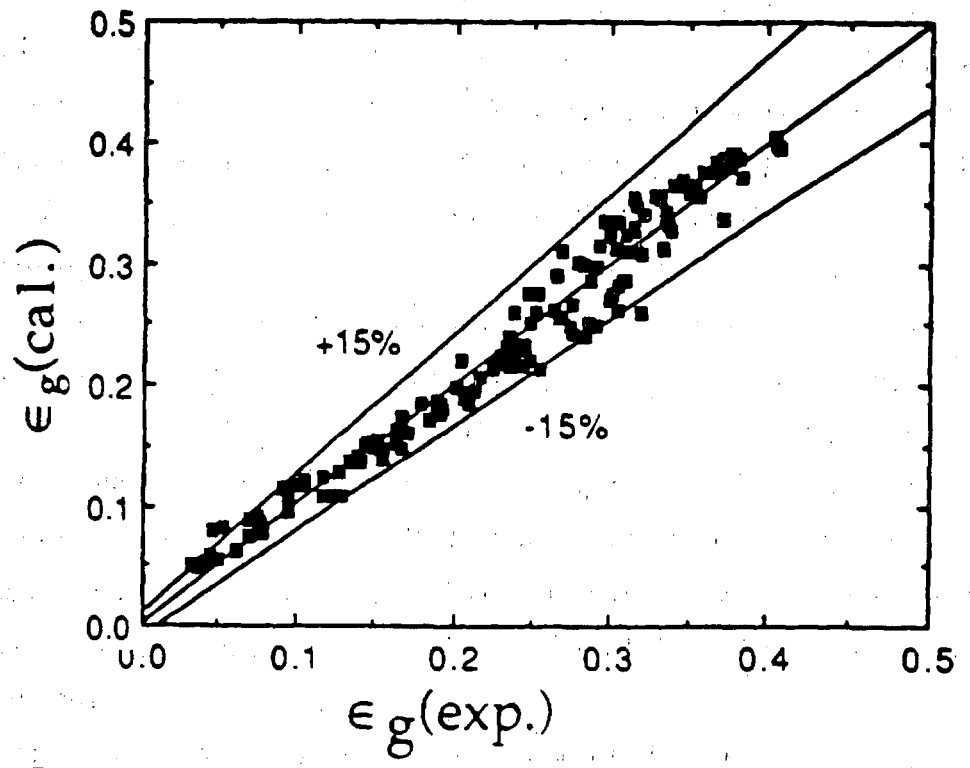


Fig. 5.9. Comparison of experimental and calculated gas holdup values.

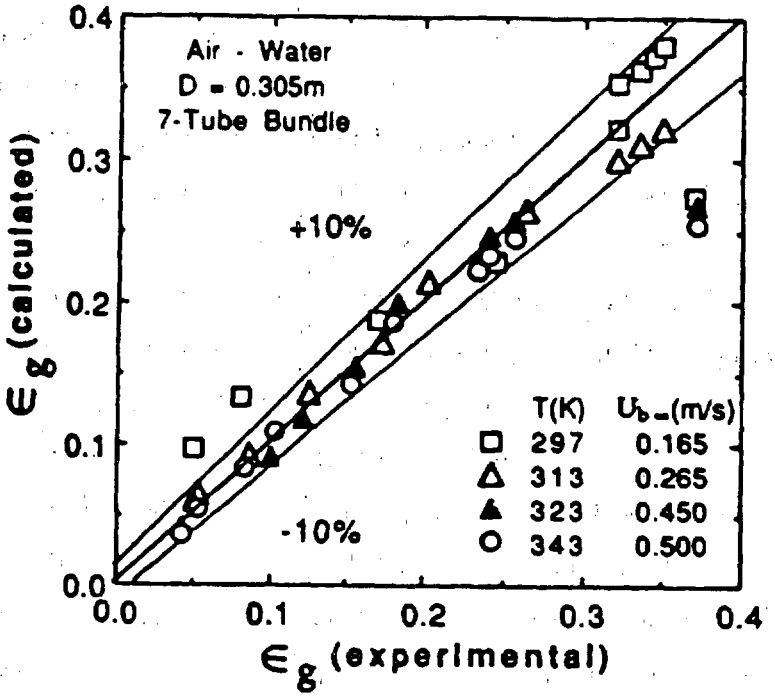


Fig. 5.11. Parity plot for the air-water system gas holdup data. Calculated ϵ_g values are according to Eq. (5.21).

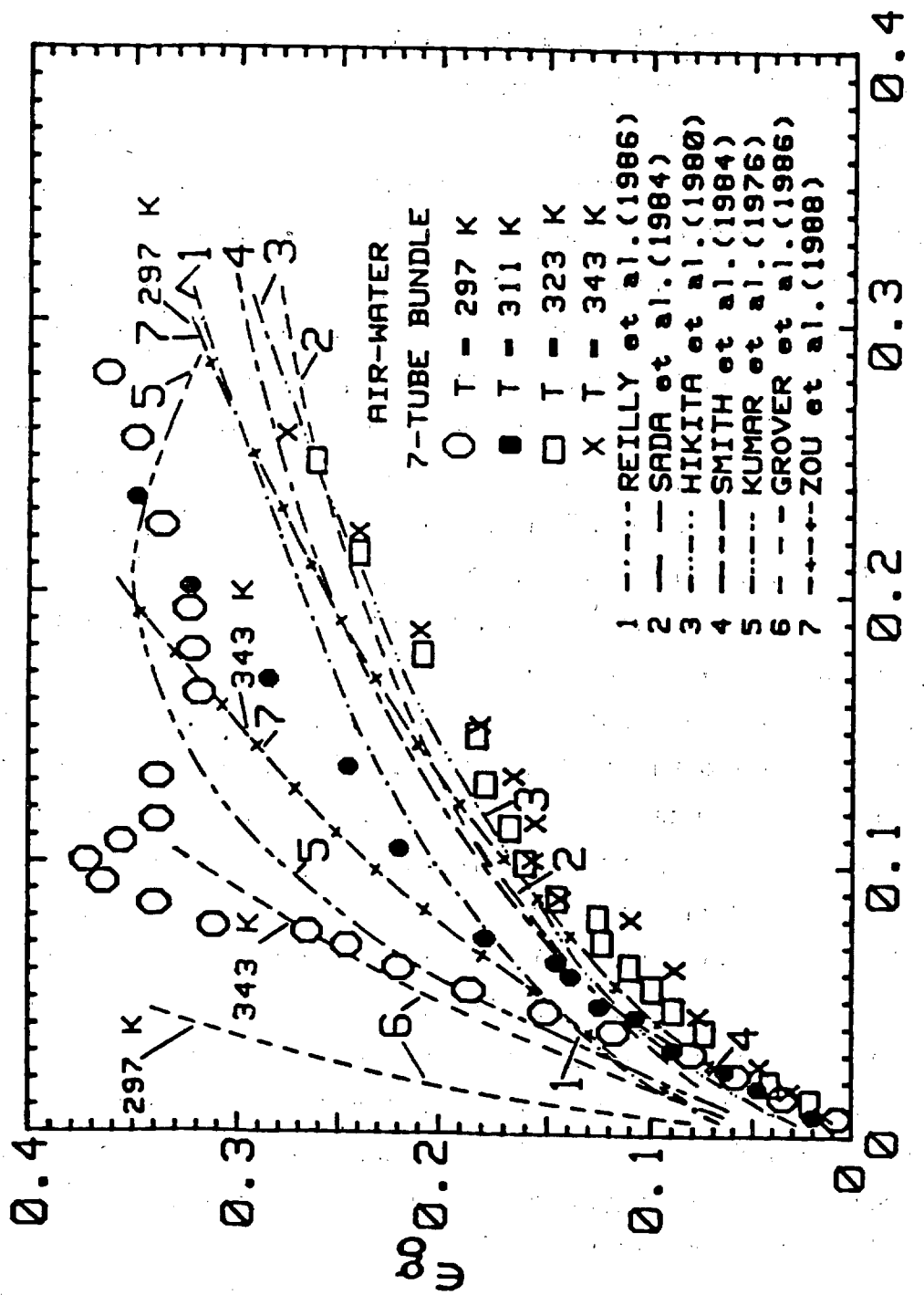


Fig. 5.10. Comparison of experimental air holdup values as a function of air velocity at different temperatures with the predictions based on different correlations.

based on Zou et al. [63] in Fig. 5.10 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.

Computing values of ϵ_g with $U_{b\infty}$ as an adjustable parameter are compared with the corresponding experimental values in Fig. 5.11. $U_{b\infty}$ values are also listed in this figure for the four temperatures of measurement and it is noted that $U_{b\infty}$ values monotonically increases with increase in temperature. This increase in $U_{b\infty}$ values with temperature suggests larger coalesced bubbles which result in smaller gas holdup. These results are in accordance with the visual observations of bubble size and the measured gas holdup values.

Experimental gas holdup data taken in the larger column with thirty-seven tube bundle as shown in Fig. 4.47 are compared with the predictions of correlations due to Grover et al. [62], Zou et al. [63], Reilly et al. [56], Smith et al. [57], and Roy et al. [64] in Fig. 5.12. The continuous curve 1 is a smooth plot through the four sets of experimental data points at four temperatures. Grover et al. predictions are always appreciably greater than the experimental values and exhibit a different dependence on air velocity. Zou et al. predictions are much lower than the experimental values at 298 K and increase with the increase in temperature much more rapidly than the experimentally observed trend according to which the values decrease with increase in temperature. Reilly, et al. and Smith et al., correlations lead to similar values than the experimental data and further these exhibit almost no temperature dependence in contradiction to the observed trend. Roy et al.correlation does predict the gas holdup values which decrease with increase in temperature in agreement with the observed trend. However, the absolute magnitude of values is appreciably different than the measured values. The drift-flux theory approach, as outlined above, leads to values which are in good agreement with experiment . These are shown in Fig. 5.13 where $U_{b\infty}$ values are also listed.

The experimental data of gas holdup for nitrogen-Therminol taken in the small column [82] with the 19 mm probe presented earlier in Fig. 4.6 are compared with the predictions of three correlations [56, 57, 64] in Fig. 5.14A. Figure 5.14A shows a poor prediction by all the three correlations and the Smith

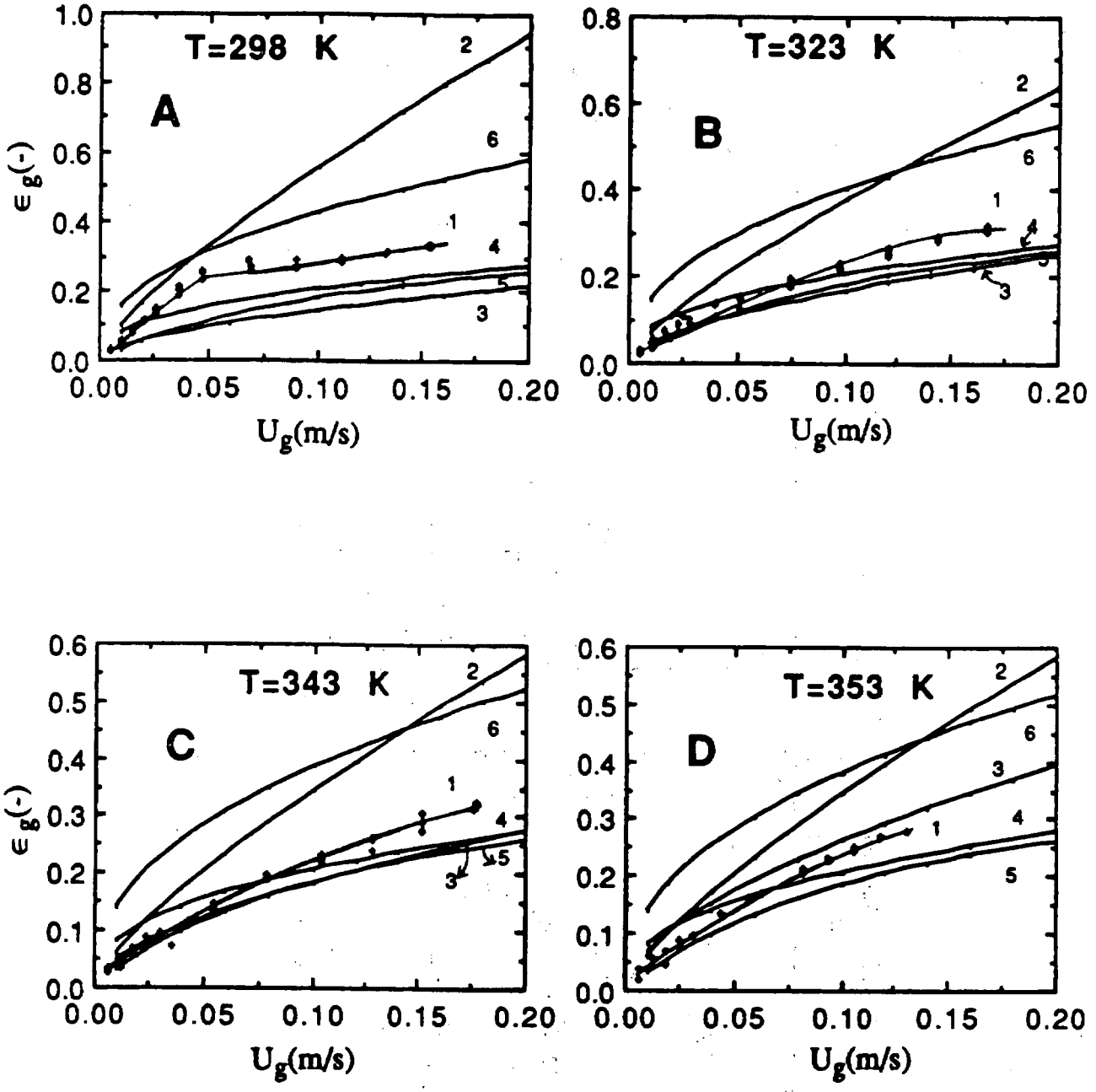


Fig. 5.12. Comparison of the four sets experimental data of air holdup of air - water system with the predictions of different models at four temperatures (1- Experiment, 2 - Grover et al., 3 - Zou et al., 4 - Reilly et al., 5 - Smith et al., 6 - Roy et al.).

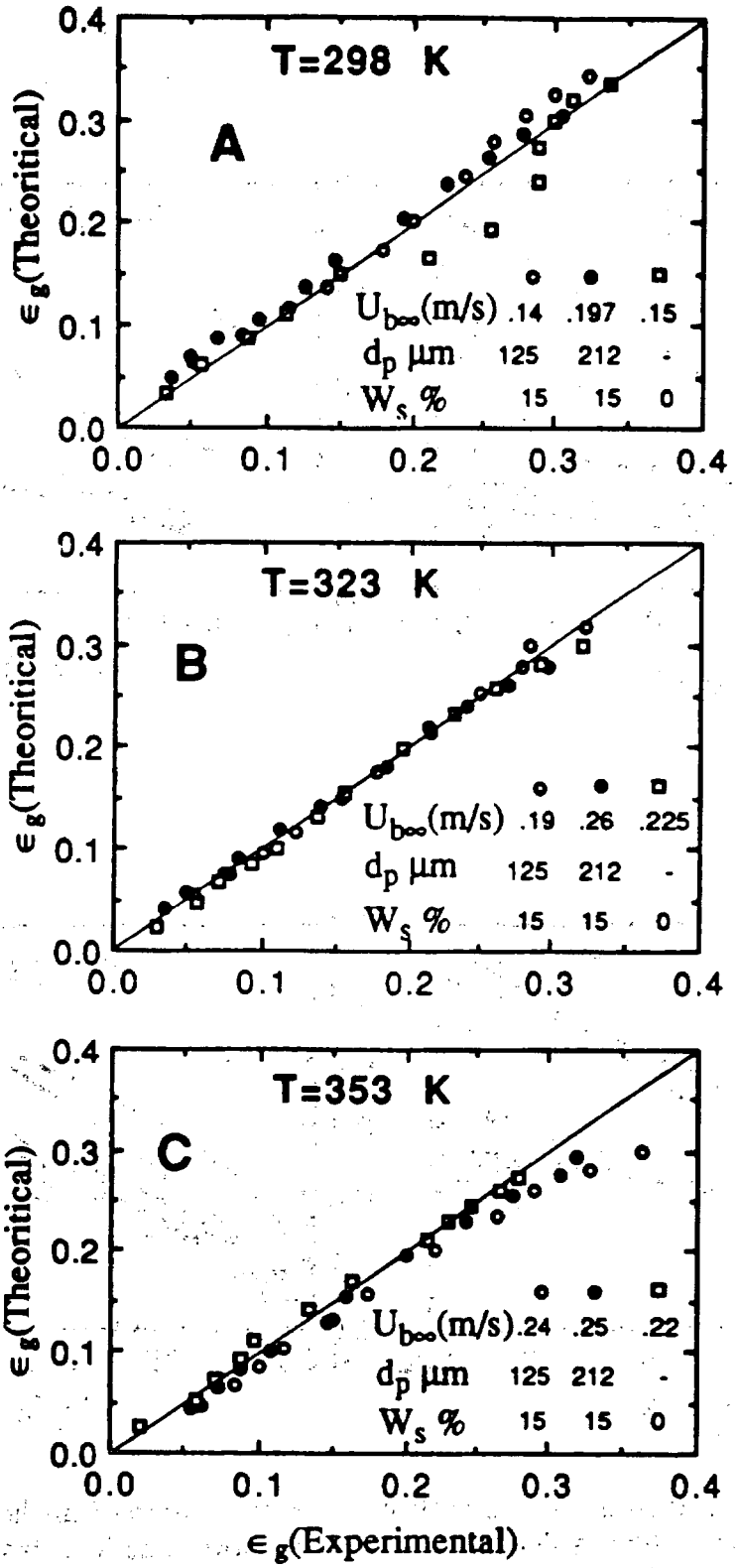


Fig. 5.13. Comparison of experimental air holdup data with the predictions of modified Nicklin's model for air-water and air-water-glass bead systems.

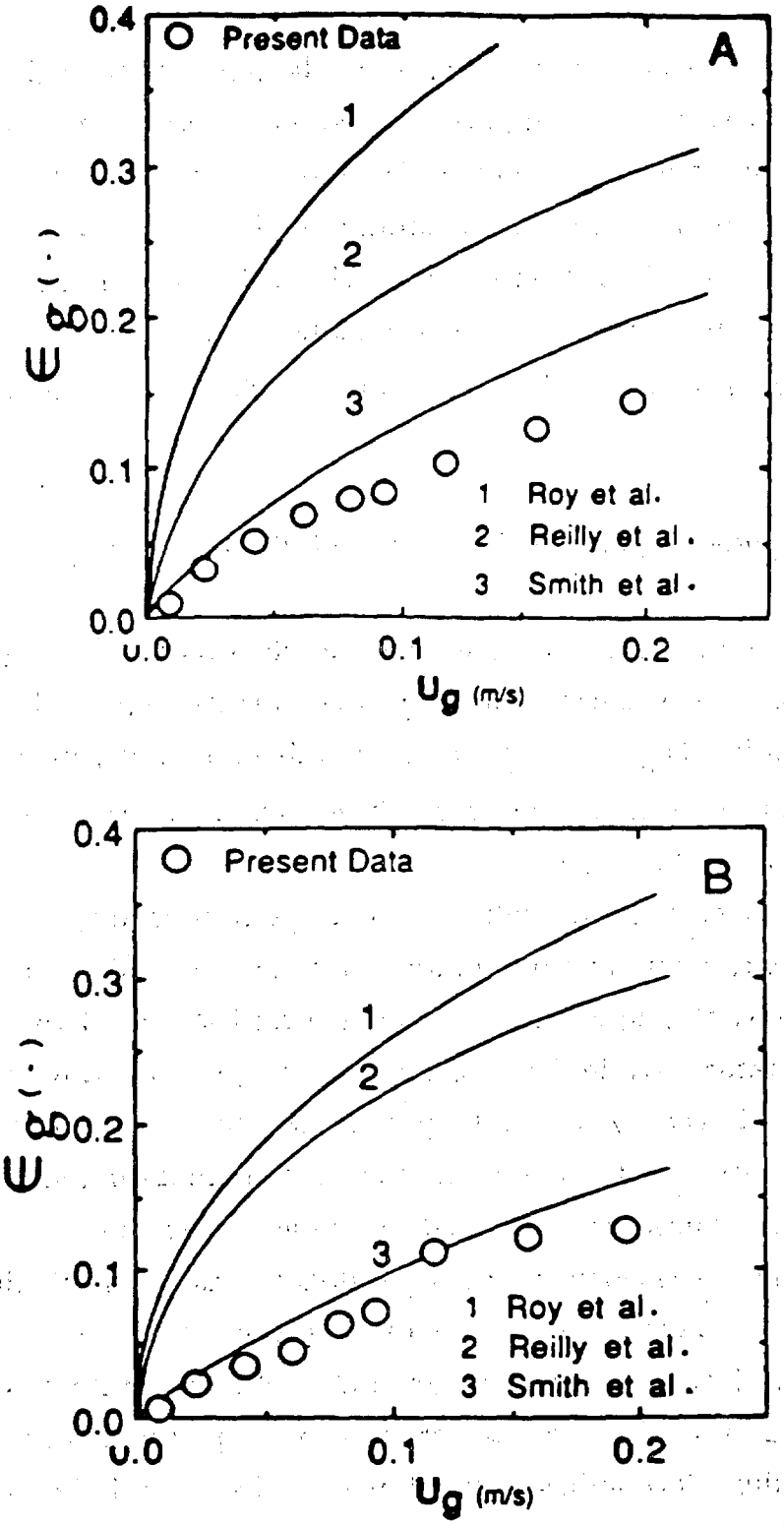


Fig. 5.14. Comparison of 19 mm probe internal nitrogen holdup data with the predictions of correlations for nitrogen-Therminol system: (A) without and (B) with solids.

et al. [57] correlation is the best of all though it overpredicts the data over the entire velocity range. It appears that liquid viscosity is not adequately accounted in these correlations; Reilly et al. [56] and Roy et al. [64] correlations do not have any liquid viscosity term while Smith et al. [57] correlation has only a very weak dependence on liquid viscosity. The drift-flux theory approach leads to satisfactory agreement with experimental data as seen in Fig. 5.15. The $U_{b\infty}$ values obtained for the four different internals in the column are listed in Table 5.2.

5.4 Comparison of Present Three-Phase Data with Theory

Saxena and Patel [80] have correlated their data, Fig. 4.9 and Table 4.8, on the drift-flux theory approach with the results reported in Fig. 5.9. The corresponding $U_{b\infty}$ values are listed in Table 5.1. The agreement between theory and experiment is satisfactory. The various correlations are found to be inadequate for this purpose.

The air holdup data taken in the large column for the air-water-glass bead system are compared with the three correlations [56, 57, 64] in Figs. 4.51 and 4.52. The Reilly et al. [56] correlation exhibits practically no dependence of air holdup on temperature, while those of Smith et al. [57] and Roy et al. [64] predict an increase and decrease of 3 and 5 percent, respectively, in air holdup with increase in temperature in the range of our present measurements. Thus, even the qualitative 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. [64]. 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. [64] 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 at al. [56] and Roy et al. [64] do not include slurry (or liquid) viscosity as a parameter, while our present work suggests it to

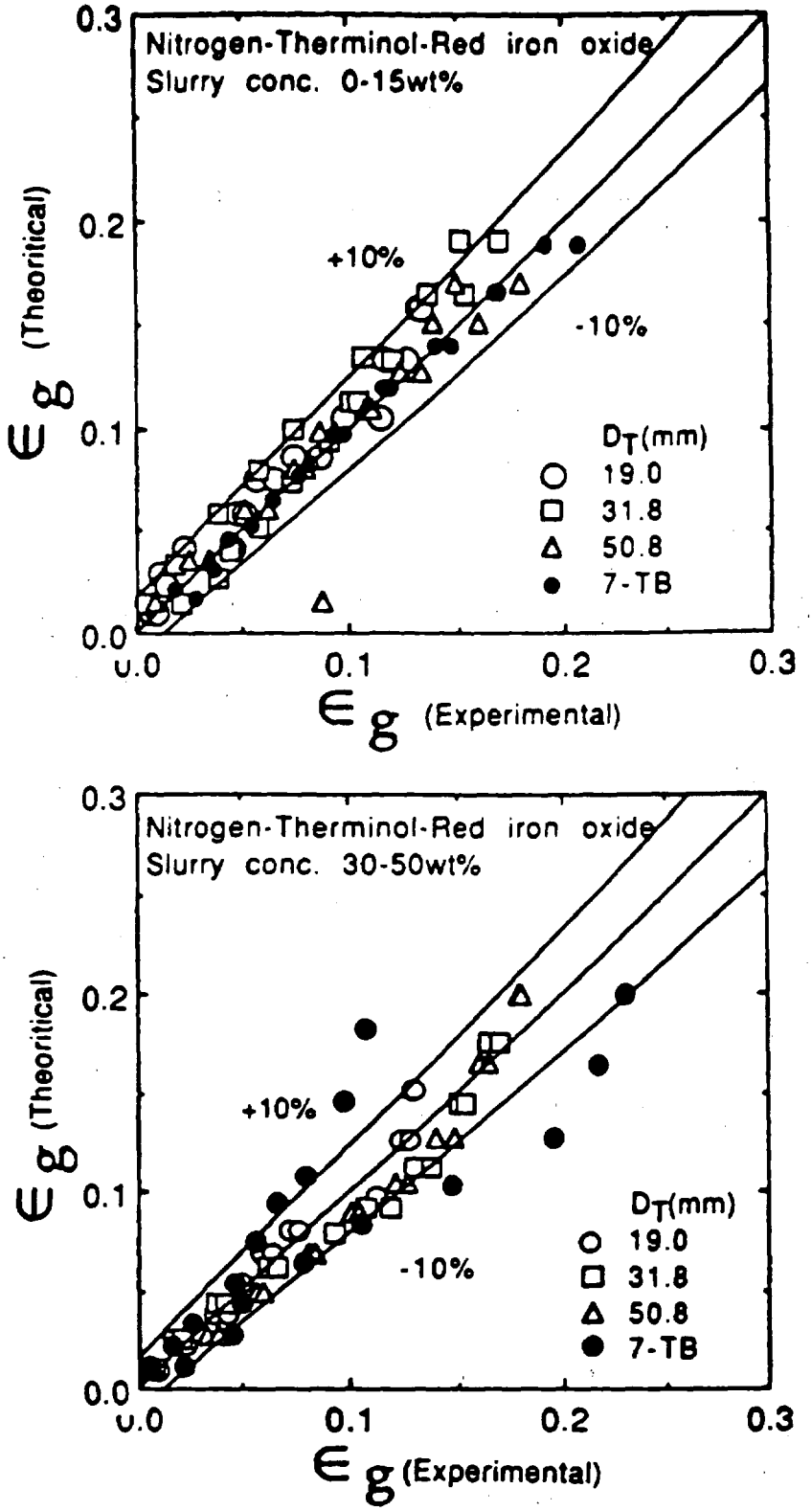


Fig. 5.15: Comparison of experimental nitrogen holdup data for 19 mm probe internal with the predictions based on the drift-flux theory.

Table 5.1. Values of $U_{b\infty}$ based on Eq. (5.21) and determined from experimental gas holdup data for air-water and air-water-glass bead systems at 309K in 0.108 m bubble column.

Single-tube configuration

d_p (μm)	0	50	119	143
w_s (%)	0	10	10	10
$U_{b\infty}$ (m/s)	0.314	0.433	0.420	0.473

Seven-tube bundle configuration

d_p (μm)	0	50	50	119	119	143	143	143	143
w_s (%)	0	5	10	5	10	5	10	20	30
$U_{b\infty}$ (m/s)	0.205	0.236	0.255	0.224	0.233	0.222	0.218	0.291	0.410

Table 5.2. Values of $U_{b\infty}$ based on Eq. (5.21) and determined from experimental gas holdup data for nitrogen-Therminol and nitrogen-Therminol-red iron oxide systems in 0.108 m bubble column at ambient temperature.

Internal	solids concentration (weight percent)			
	0	15	30	50
19.0 mm	0.864	0.998	1.08	1.07
31.8 mm	0.798	0.956	0.841	0.858
50.8 mm	0.796	0.914	0.791	0.749
7TB	0.718	0.812	0.709	0.682

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 Figs. 4.51A, 4.51B and 4.51C. 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 Figs. 4.52A and 4.52B are given similar comparisons of theory and experiment for slurries of particle diameters 90 and 50 μm and 5 weight percent respectively as in Fig. 4.51 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 Fig. 4.51. 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 Fig. 5.16, 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. [57] correlation is most successful of all the correlations in reproducing the data. The Roy et al. [64] correlation leads to a very poor reproduction of experimental data. A modified form of Smith et al. [57] correlation will be appropriate to develop for slurries involving particles smaller than 100 μm as more three-phase data become available.

In Fig. 5.17, these data are shown compared with computed values obtained on the approach based on modified drift-flux theory detailed in section 5.3. It is to be noted that data are well reproduced within ±10 percent. The $U_{b\infty}$ values are also listed in these figures and these again increase with temperature as observed for the two-phase, air-water, system.

The corresponding data [112] of air holdup with thirty-seven tube bundle, reported in Figs. 4.53-4.57, are shown compared with these model predictions in Fig. 5.18. Roy et al. [64] correlation based values are systematically greater than the experimental data, and their dependence on slurry concentration is more pronounced than that observed in the experiments. Reilly et al. [56] predictions are underestimates for air velocity values greater than about 0.07 m/s, and

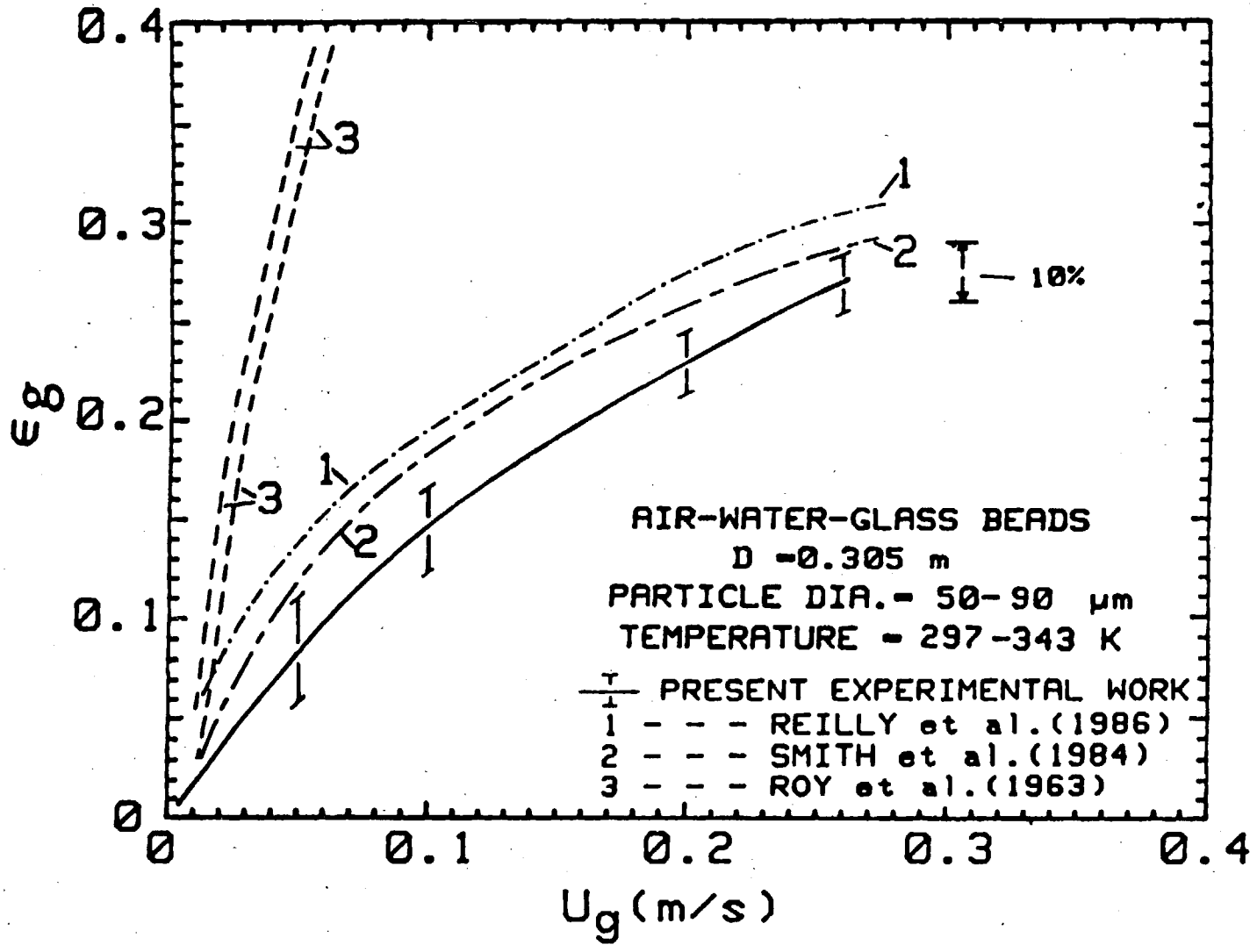


Fig. 5.16. Comparison of the averaged air holdup values for a range of particle sizes, slurry concentrations and temperatures as a function of air velocity with the predictions of different correlations.

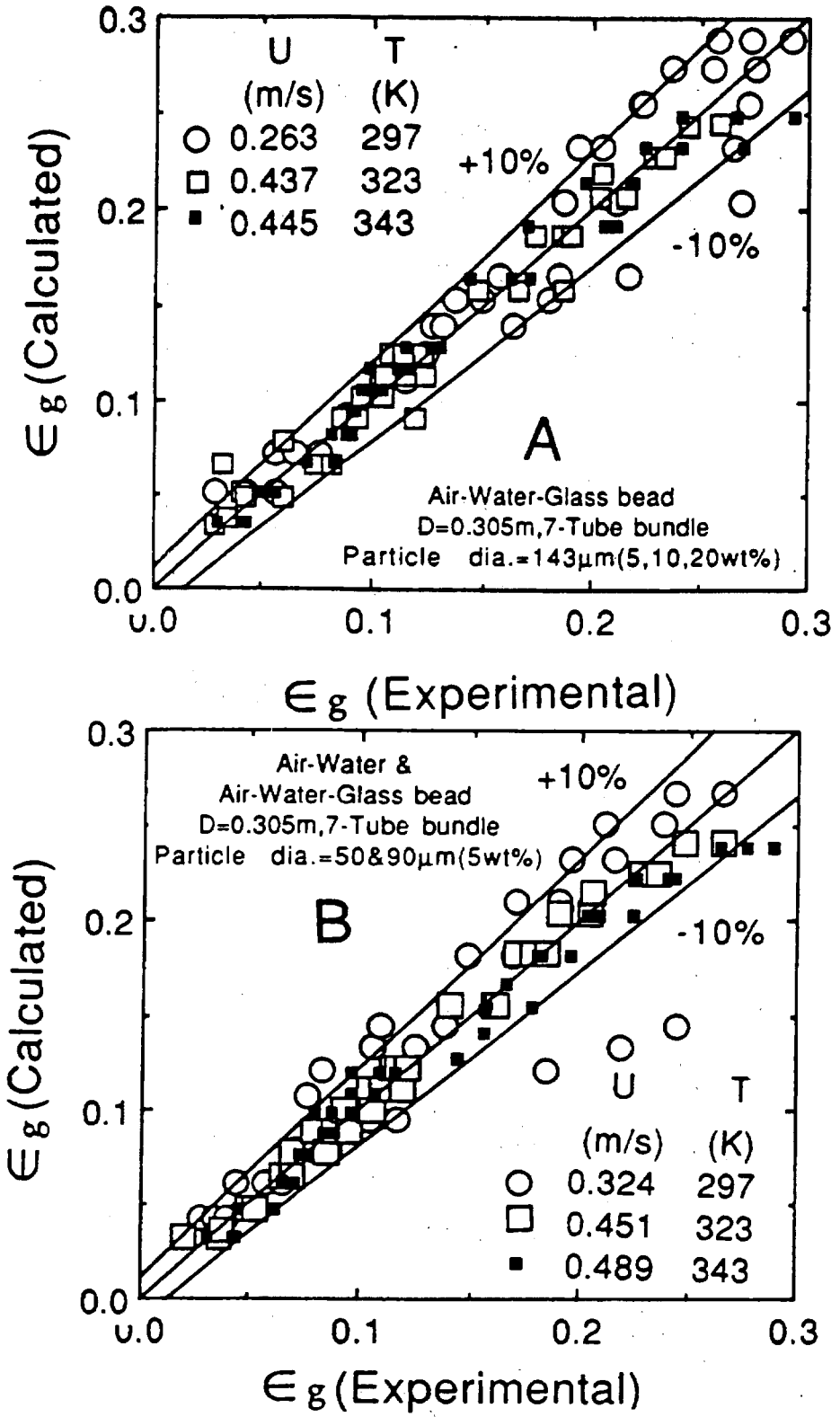


Fig. 5.17. Comparison of experimental air holdup data with the modified drift-flux theory approach.

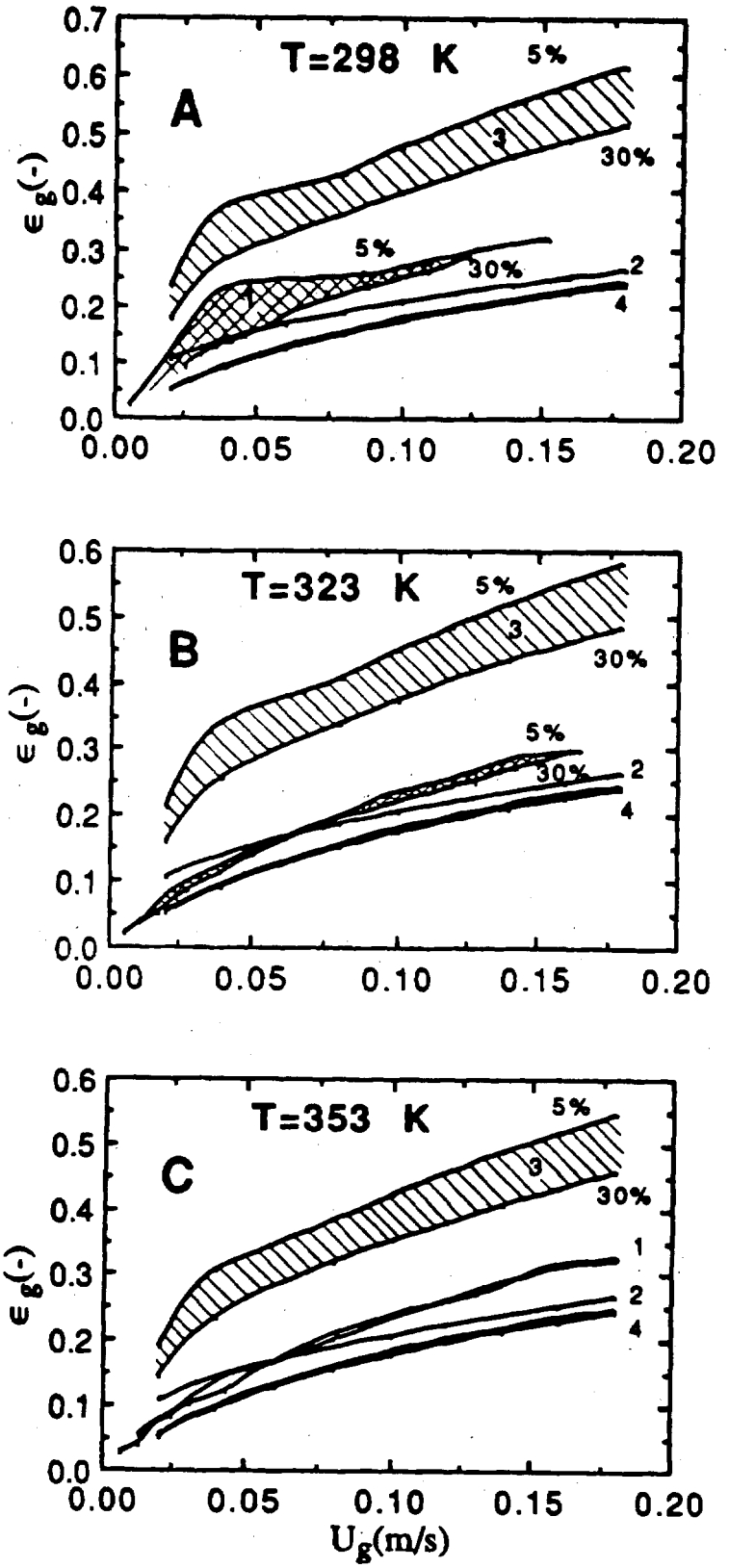


Fig. 5.18. Comparison of experimental air holdup data with the predictions of different models for the air-water-glass bead system (1 - Experimental, 2 - Reilly et al.[56], 3 - Roy et al.[64], 4 - Smith et al.[57].)

predict no dependence of slurry concentration. Smith et al. [57] values are systematically smaller than the experimental values and exhibit a very weak dependence on slurry similar to that implicit in our measured values. These data are shown compared with the modified drift-flux theory approach in Fig. 5.13. The $U_{b\infty}$ variation with temperature is the same as obtained with data on seven-tube bundle.

A comparison of experimental air holdup data for air-water-magnetite system in the small column with a single 19 mm heat transfer probe [105] with the computed values from the three correlations [56, 57, 64] is presented in Figs. 4.10A through 4.10F. In all cases, we find that Roy et al. [64] correlation based values (curves 1) reproduce rather poorly the experimental data and are always greater than the experimental values, the disagreement increases with increase in air velocity. We think that the inclusion of Reynold number based on column diameter is responsible for this discrepancy. Further, this correlation suggests a decrease in the value of gas holdup as solids concentration is increased in the slurry.

Reilly et al. [56] correlation which is based only on gas and liquid properties lead to values (curves 2) which are in fair agreement with the experimental data for slurries of smaller particles and small concentrations over the entire range of air velocities. The reproduction is relatively poorer for larger particles and for higher slurry concentrations. The small dependence of gas holdup found here on particle diameter and slurry concentration is implicitly built into this correlation for data of this nature were employed in the development of this correlation. We recommend this correlation for estimating the upper bound of the gas holdup for three-phase systems based on the present work.

Smith et al. [57] modified correlation of Hughmark [54] leads to values which are underestimates of data for small particles but the reproduction is better as the particle size increases and particularly for the bubbling regime. This correlation also gives a weak dependence on slurry concentration, the gas holdup decreases as the concentration of solids increases in the slurry. Again, based on present data, it appears that this correlation is a good estimate of the lower bound of the experimental gas holdup data.

Computed values from the drift-flux theory approach are shown compared

with the experimental values in Fig. 5.19. The corresponding $U_{b\infty}$ values are listed in Table 5.3. Data of this nature can help in understanding the dependence of $U_{b\infty}$ on d_p and w_s. However, work in this direction could not be pursued in the current contract period.

The experimental data on the larger column, Fig. 4.58 and Saxena et al [113], are shown compared with the predictions of all the four approaches [56, 57, 64 and 76] in Figs. 5.20 and 5.21. It is clear that the correlations of Reilly et al. [56] and Smith et al. [57] predict negligible dependence of gas-phase holdup on temperature, and their predictions at best can be regarded as only in approximate agreement with the experimental data. The correlation of Roy et al. [64] predicts the experimental data rather poorly though it has the right qualitative dependence on temperature. The main reason of the failure of this model is due to the inclusion of column diameter in the correlation. The computed values based on O'Dowd et al.'s [76] approach are given in Fig. 5.21. The agreement between the theory and experiment is good. $U_{b\infty}$ values determined from the experimental data are also reported in Fig. 5.21. These are dependent on temperature for a given slurry-gas system, and at temperatures above the ambient these are also apparently dependent on slurry concentration and particle size. $U_{b\infty}$ values increase with increase in temperature (as in the two-phase system), but decrease with increase in solids concentration in the slurry. The influence of particle size cannot be uniquely established from these data. Probably $U_{b\infty}$ may increase with increase in particle size and further experimental work will be useful.

The air holdup data for the air-water-silica sand system of Saxena et al. [114] graphed in Fig. 4.50 are compared with the computed values based on these four approaches [56,57,64 and 76] in Figs. 5.22 and 5.23. The nature of disagreement between the theory and experiment is almost identical for the two slurry concentrations. The Smith et al. [57] correlation based values give the best agreement with experimental values though these systematically overpredict them.

Reilly et al. [56] values are greater than the experimental results by larger magnitudes than the Smith et al. [57] values. Roy et al. [64] correlation based

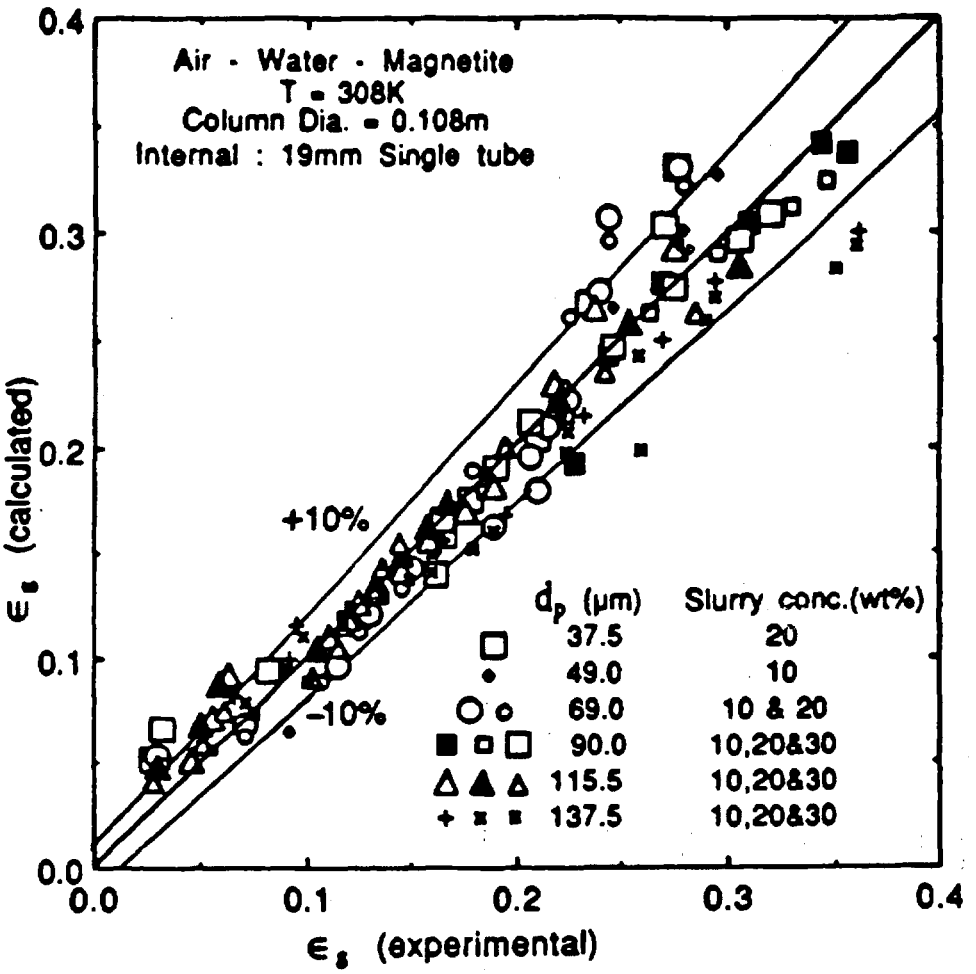


Fig. 5.19. Parity plot for gas holdup. ϵ_g (calculated) are according to the relation of Eq. (5.21).

Table 5.3. Values of $U_{b\infty}$ based on Eq. (5.21) and determined from experimental gas holdup data for air-water magnetite system in 0.108 m in bubble column equipped with a 19 m tube. The data was measured at 308K for particles in the size range 35.7 - 137.5 μm and slurry concentrations in the range 10 - 30 wt%.

Table 1. Values of $U_{b\infty}$ Determined from Experimental Gas Holdup Data

d_p	35.7	49	58	69	69	90	90	90	115.5	115.5	115.5	137.5	137.5	137.5
w_s(%)	20	10	10	10	20	10	20	30	10	20	30	10	20	30
$U_{b\infty}$	0.260	0.265	0.330	0.250	0.275	0.320	0.360	0.410	0.353	0.375	0.450	0.400	0.425	0.460

Table 5.4. Values of $U_{b\infty}$ based on Eq.(5.21) and determined from experimental gas holdup data for nitrogen-Therminol-magnetite system for different internals in 0.108 m bubble column at ambient temperature.

Internal	Solids concentration (weight percent)			
(mm)	0	15	30	50
19.0	0.864	0.875	0.800	0.785
31.8	-	0.888	1.000	1.300
50.8	-	0.800	1.070	1.000

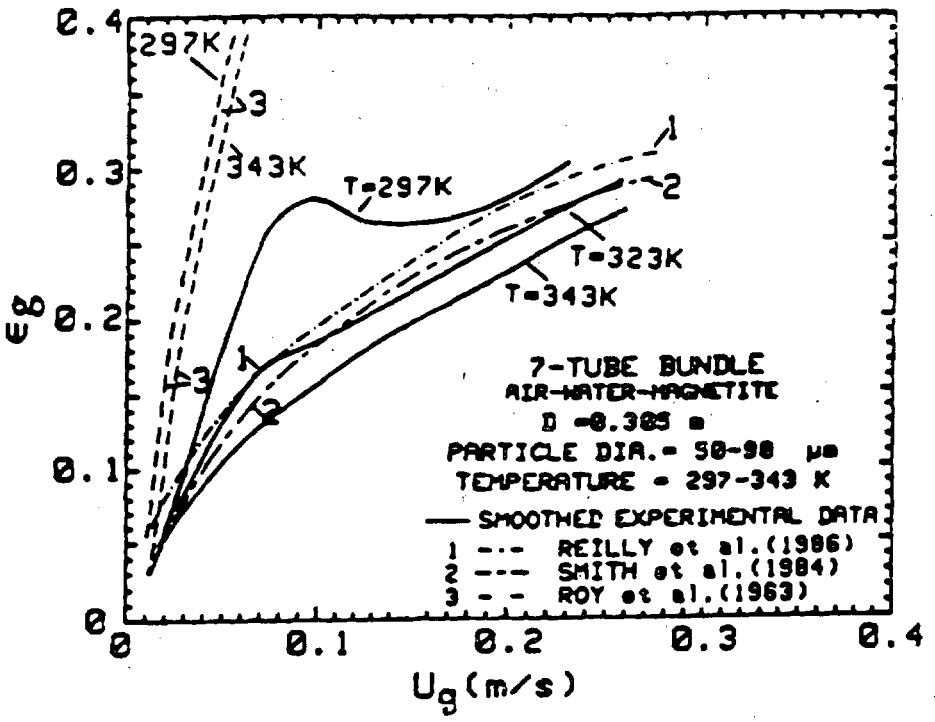


Fig. 5.20. Comparison of averaged experimental air holdup values with the calculated values.

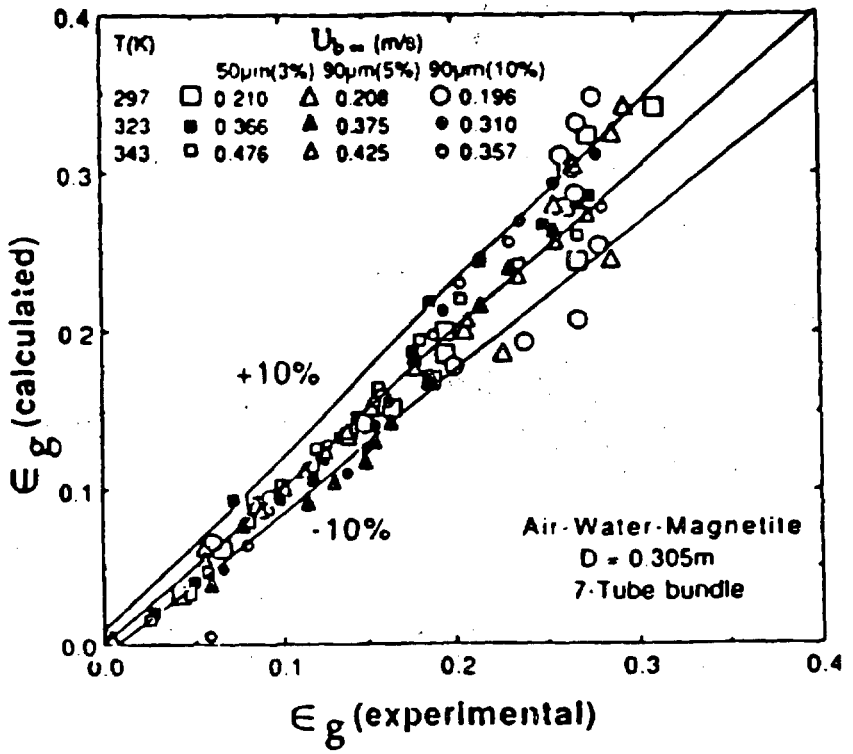


Fig. 5.21. Comparison of experimental and calculated air holdup values on Nicklin's approach.

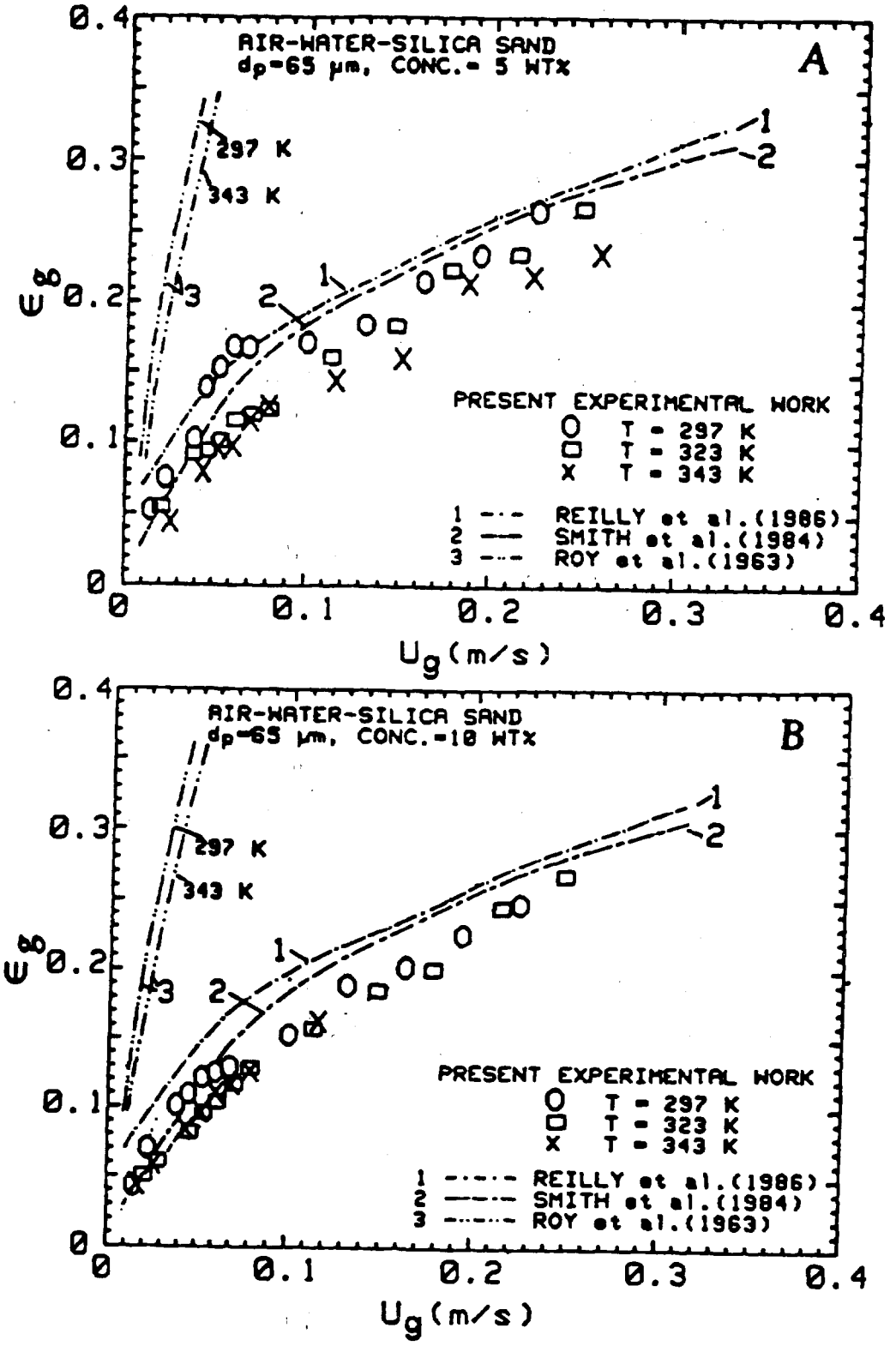


Fig. 5.22. Comparison of air holdup values for air-water-silica sand system over a range of slurry concentrations and temperatures as a function of air velocity with the predictions of different correlations.

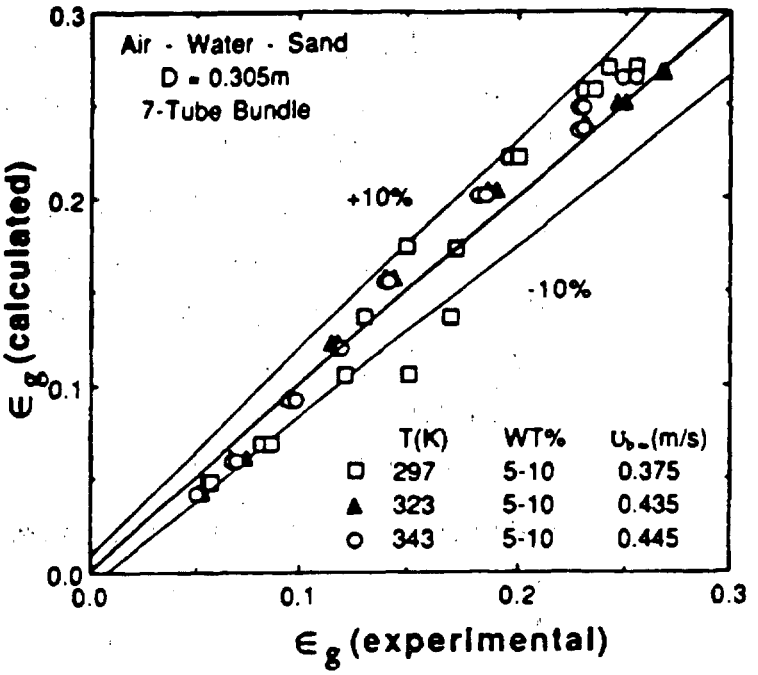


Fig. 5.23. Parity plot for the air-water-silica sand system gas holdup data. Calculated values are based on Eq. (5.21).

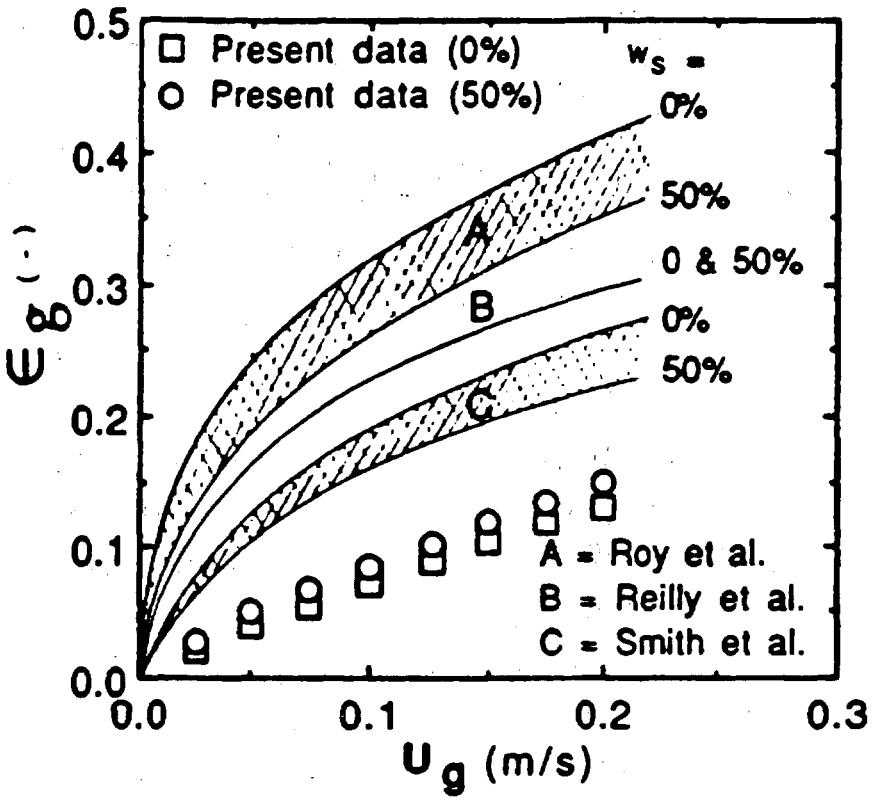


Fig. 5.24. Comparison of experimental data (□ 0%, ○ 50%) for the 19.0 mm probe with the predictions of correlations.

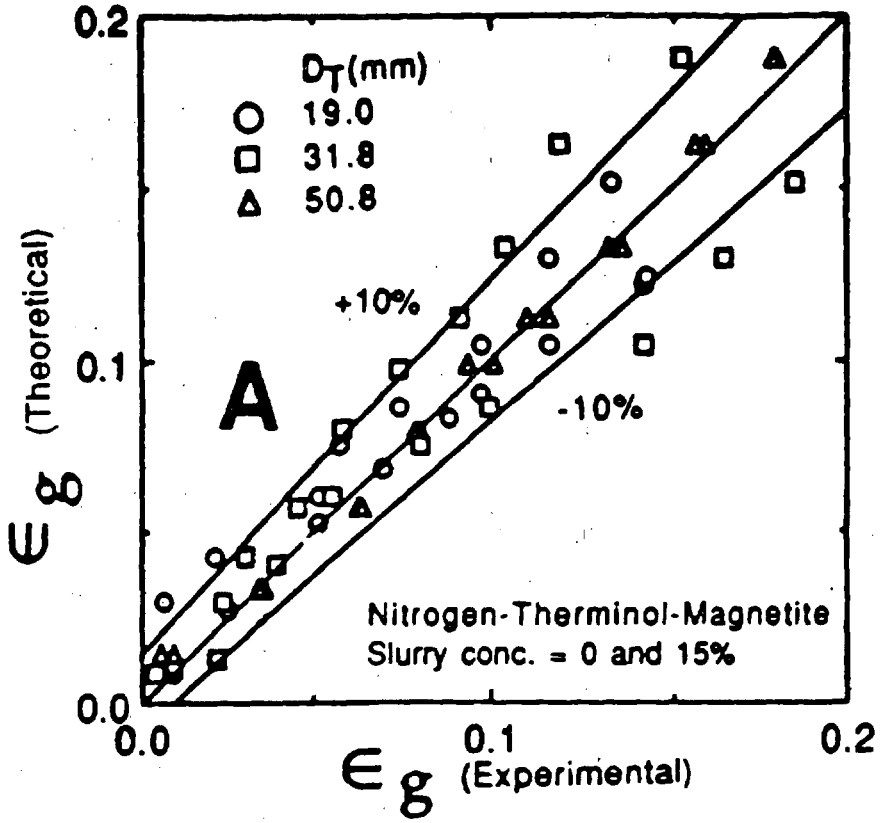
values are in poor agreement with the experimental data both qualitatively as well as quantitatively. This is probably because of the involvement of column diameter as one of the parameters in the correlation.

The drift-flux approach leads to satisfactory results for the air-water-sand system also. The $U_{b\infty}$ values, listed in Fig. 5.23, are again found to be temperature dependent, but these are much less pronounced for the three-phase system than their corresponding two-phase gas-liquid system.

A comparison of nitrogen holdup for the nitrogen-Therminol-red iron oxide system as obtained by Saxena et al. [82] is presented in Fig. 5.14B with the predictions based on the models of Roy et al. [57]. Smith et al.'s correlation [57] is the best of all and reproduces the data satisfactorily. Figure 5.15 presents the comparison of these data with the drift-flux theory [76] which is quite successful. The $U_{b\infty}$ values listed in Table 5.2 exhibit a clear dependence of $U_{b\infty}$ on slurry concentration and its variation with the internal geometry of the column is consistent with its physical meaning.

A comparison of nitrogen holdup data as reported in Figs. 4.15 through 4.17 for nitrogen-Therminol-magnetite system (Saxena et al. [114]) are compared with the model predictions in Fig. 5.24. Two points are to be noted. The experimental data are considerably smaller than the computed results. Further, Roy et al. [64] and Smith et al. [57] correlations predict a larger slurry concentration dependence (0-50 weight percent) than is experimentally observed. Reilly et al.'s correlation [67] has no slurry dependence. It appears that these correlations are not adequate for systems involving highly viscous liquids. A similar shortcoming was observed for nitrogen-Therminol-red iron oxide (1.7 μm) system. Smith et al. [57] correlation gives the best reproduction both as regards to the gas velocity and slurry concentration variations. It may be pointed out that the holdup predictions for less viscous systems, air-water-magnetite [105], by Smith et al.'s [57] correlation were much more satisfactory.

In Fig. 5.25 are presented the computed nitrogen holdup values as compared to the experimental values obtained by following the procedure outlined by O'Dowd et al. [76]. The $U_{b\infty}$ is treated as a disposable parameter and adjusted on the basis of experimental data. These values are listed in Table 5.4 for different size probes and slurry concentrations. The plots in Fig. 5.25 are separated from



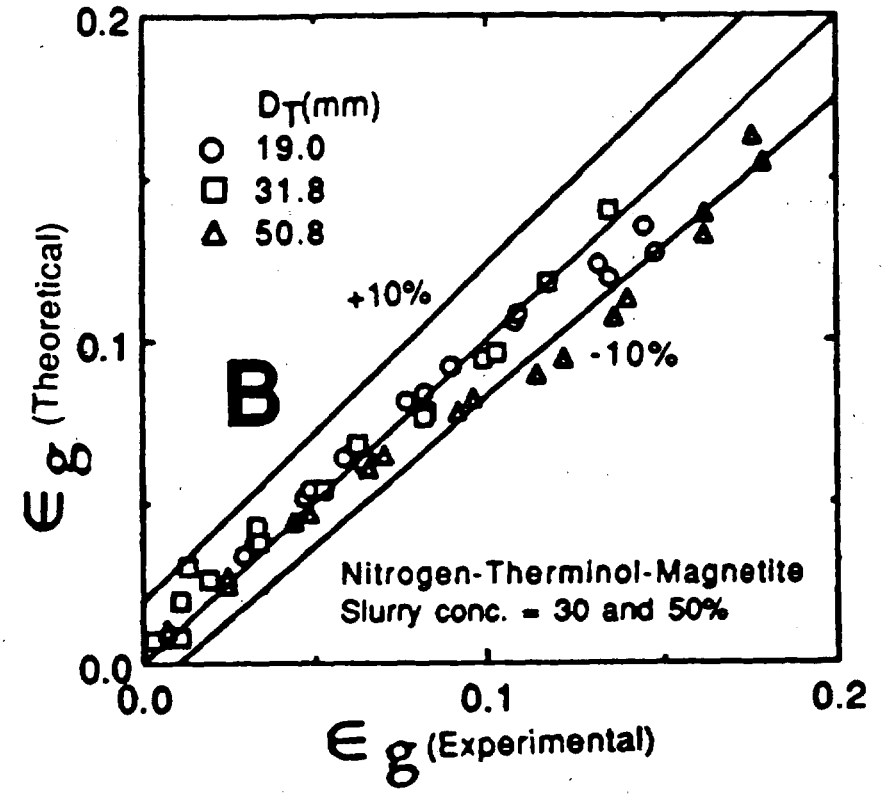


Fig. 5.25. Comparison of experimental and calculated nitrogen holdup values based on drift-flux theory.

one another only to avoid overcrowding. It is clear that this approach could correlate the data within an estimated uncertainty of about ten percent. It appears to be a reasonable approach for data correlation at the present time.

Saxena et al. [115] have also measured the nitrogen holdup for the nitrogen-Therminol-magnetite system in the small column equipped with a seven-tube bundle at ambient conditions and for slurries in the range 0-50 weight percent. These data are compared with the three models [56, 57 and 64] in Fig. 5.26, and with O'Dowd et al.'s [76] approach in Fig. 5.27. In all cases, the models predict the data rather unsatisfactorily. The computed values are much larger than the experimental values and will be poor estimates for any design work. Roy et al.[64] and Reilly et al. [56] fail to predict even the dependence of ϵ_g on w_s. Gas holdup correlations must be developed by taking into account the effect of liquid viscosity. The reproduction by the drift-flux theory is good but real confidence in this theory will have to await a good physical interpretation of the terminal rise velocity of a single bubble in an infinite medium ($U_{b\infty}$) which has been treated here as an adjustable parameter.

5.5 Conclusions and Recommendations

The measurements of gas holdup reported here for two liquids of widely different viscosities in bubble columns equipped with internals of different configurations and employing solids of different sizes and concentrations reveal certain interesting trends, which are mentioned here. Viscosity has a profound influence on gas holdup which decreases as the viscosity increases. The presence of solids also decreases the gas holdup. The temperature has an involved dependence and our data suggest that with increase in temperature the holdup decreases and the magnitude of this decrease reduces with increase in temperature for less viscous liquids. For liquids of high viscosity the above mentioned qualitative trend changes at some temperature beyond which the holdup increases with increase in temperature. These trends can be explained with the changes in the rheology of the system and hence proper knowledge of viscosity for the system under consideration is essential. Viscosity of the suspension influences the bubble dynamics in the column and hence the gas

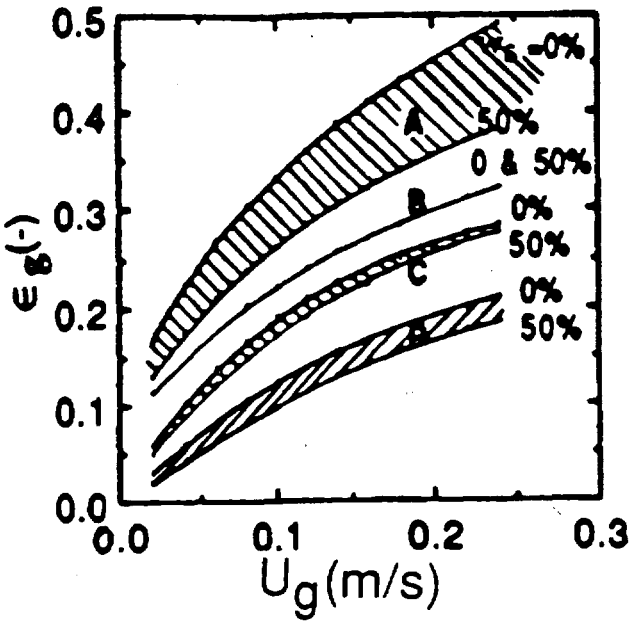


Fig. 5.26. Comparison of ϵ_g with model predictions.
A - [64], B - [56], C - [57], and P- Present data.

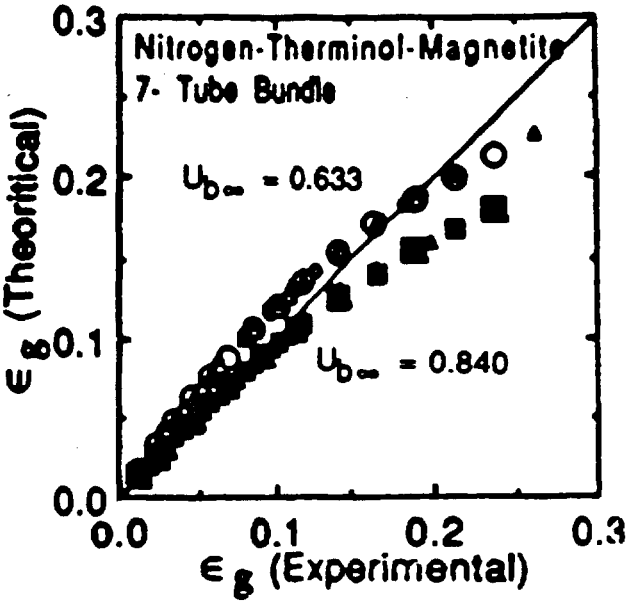


Fig. 5.27. Comparison of experiment and theory [76] for ϵ_g.

holdup. Internals are found to influence the bubble coalescence and thereby the gas holdup. Holdup data in bubble columns are insensitive to column diameter.

Existing correlations are extensively tested and are found to be inadequate to reproduce or predict the gas holdup. The modified drift-flux theory approach is found successful in correlation the experimental data and this success suggests that a more basic approach to develop a sound theory for the evaluation of $U_{b\infty}$ in terms of system and operation parameters is in order. The information generated here will help in achieving this goal. Gas holdup data are important to characterize the slurry bubble column operation, and in establishing the mass transfer and mixing characteristics.