7. GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In the earlier sections, a detailed discussion of the heat transfer data generated for individual systems under varying operating conditions and column configurations is presented, and the conclusions derived on the basis of these individual systems are also noted. The inadequacy and paucity of the literature available data are emphasized. The general inability of the theoretical correlations to predict reliable values is universally observed for all the systems. A brief mention of general conclusions emerging from this work is made in the section on executive summary. Here, in the following we list the general conclusions in the context of the need they indicate for future research work both experimental and theoretical. We discuss heat transfer from simulated heat transfer surfaces in the slurry bubble column first and then the gas holdup. This is because the major thrust of the present work is on the former and the latter is considered only to characterize the bubble column operation so that our heat transfer data may be appropriately selected for the design of larger-scale production systems.

A major portion of our effort has concentrated with aqueous systems involving air as the gas-phase. This is primarily due to the operational convenience as we conducted a variety of experiments to disentangle the effect of gas velocity, liquid column height, temperature of operation, solid phase physical properties, solid particle size and size distribution, and slurry concentration. In addition, the column diameter effect and the influence of column internals, size and configuration, are also investigated. These elaborate experimental studies have provided a number of interesting and useful characteristics of significant value in judging the slurry bubble column behavior and these are briefly enumerated in the following.

The heat transfer coefficient increases rapidly as the gas velocity is increased and the column hydrodynamic behavior shifts from discrete bubbling to bubble coalescing regime, and the liquid mixing in the column improves. The rate of heat transfer increase in the churn-turbulent flow regime is much slower and it gets to a constant value as the flow becomes fully developed and liquid mixing is at its optimum state. In this context in an unbaffled column, the heat transfer coefficient is relatively larger for a column of greater diameter than for a narrower column (less than about 10 cm) as the liquid mixing in the former is much better than in the latter. Certainly, this is dependent on the gas sparger design and our literature analysis has revealed that single nozzle air spargers are inadequate and lead to poor liquid mixing and smaller heat transfer rates. Our above comments and subsequent analysis assumes that the gas is introduced in the column through judiciously spaced nozzles or bubble caps, or through a perforated plate of appropriate pressure drop. This will bring about a well distributed uniform gas flow through the slurry in the bubble column. As a rough guide, a linear gas velocity of about 12 cm/s will bring the heat transfer coefficient at its maximum optimum value. Unfortunately, the existing models and correlations do a poor job in predicting this value and particularly so for nonaqueous systems involving liquids of higher viscosity. A good basic theoretical study oriented towards improving the ability of a design engineer to estimate this maximum heat transfer coefficient in general will be superbly appropriate and is an essential component in the art of understanding the bubble column behavior.

The influence of temperature is pronounced on heat transfer rate. Qualitatively, heat transfer coefficient increases appreciably with increase in temperature at the same air velocity. The increase is enough to influence any design and economic study. Quantitatively, none of the existing theories can even approximately predict these values. We have presented only a semitheoretical approach which has the potential to correlate the data at a given temperature only. The scheme is uncertain for its ability to synthesize data at different temperatures or predict the same. We recommend, that a thorough theoretical effort focused in this direction will be extremely useful and rewarding. The experimental data generated in this effort will be useful in providing guidance for the development of this theory as well as will constitute a basis for testing it.

The influence of internals on heat transfer rates at different temperatures is quite involved. Based on limited data generated in this effort it appears that at room temperature at all U_g values, a loosely packed configuration of internal tubes will not influence the heat transfer rates. A tightly packed column with tube internals on the other hand gave lower heat transfer rates for velocities smaller than those where churn-turbulent regime sets in and higher rates for larger velocities. This can be understood on the basis of liquid mixing. At a higher temperature (70°C) the behavior is different. Increasing tubes in the column leads to decrease in heat transfer rates. This would suggest relatively less efficient liquid movement at the tube surfaces as the temperature is increased. Holdup data suggest larger number of smaller air bubbles for thirty-seven tube bundle which will impede liquid circulation rate and hence the heat transfer coefficient. More experimental effort will help if it is supplemented with the measurement of bubble diameter also.

Our heat transfer rate measurements conducted in the lower (0 - 0.7m) and upper (1.0 - 1.7 m) sections of the column revealed that the same are independent of the height in the column for the seven-tube bundle while for the thirty-seven tube bundle rates are higher for the upper section than for the lower section. These data are presented in Fig. 7.1 to 7.3 and these also suggest that these variations in heat transfer rates are not dependent on temperature.

The addition of a third solid phase changes the heat transfer rates only in a minor way as compared to the rates for the corresponding two-phase system. This is highlighted in Fig. 7.4. Our work from micron size range particles to as high as 140 μm suggest only a weak dependence of particle size on heat transfer coefficient. The solid phase concentration increase influences the heat transfer only feebly at solids concentration by weight up to thirty percent but the increase thereafter is more pronounced as the weight fraction of solids in the slurry is increased. The physical properties of the solids such as density, specific heat and thermal conductivity have a relatively weak influence on the heat transfer characteristics, Fig. 7.4. More detailed investigations of these aspects do indicate some trends which are only of limited importance to a design engineer. However, the available models and correlations fail to simulate any of these observed features.

The empirical approach to correlate the experimental data by a power function in gas velocity successfully employed in this work need to be further investigated. Attempts will be in order to develop explicit expressions for the constants a and b of the empirical model in terms of the operating parameters and system characteristics in the light of existing theory of Deckwer and coworkers along with Kolmogoroff's theory of isotropic turbulence. A detailed tabulation for these constants generated in this work for different systems and parameters will be particularly useful in this endeavor.

Slurry bubble column dispersion rheology plays a very important role in heat

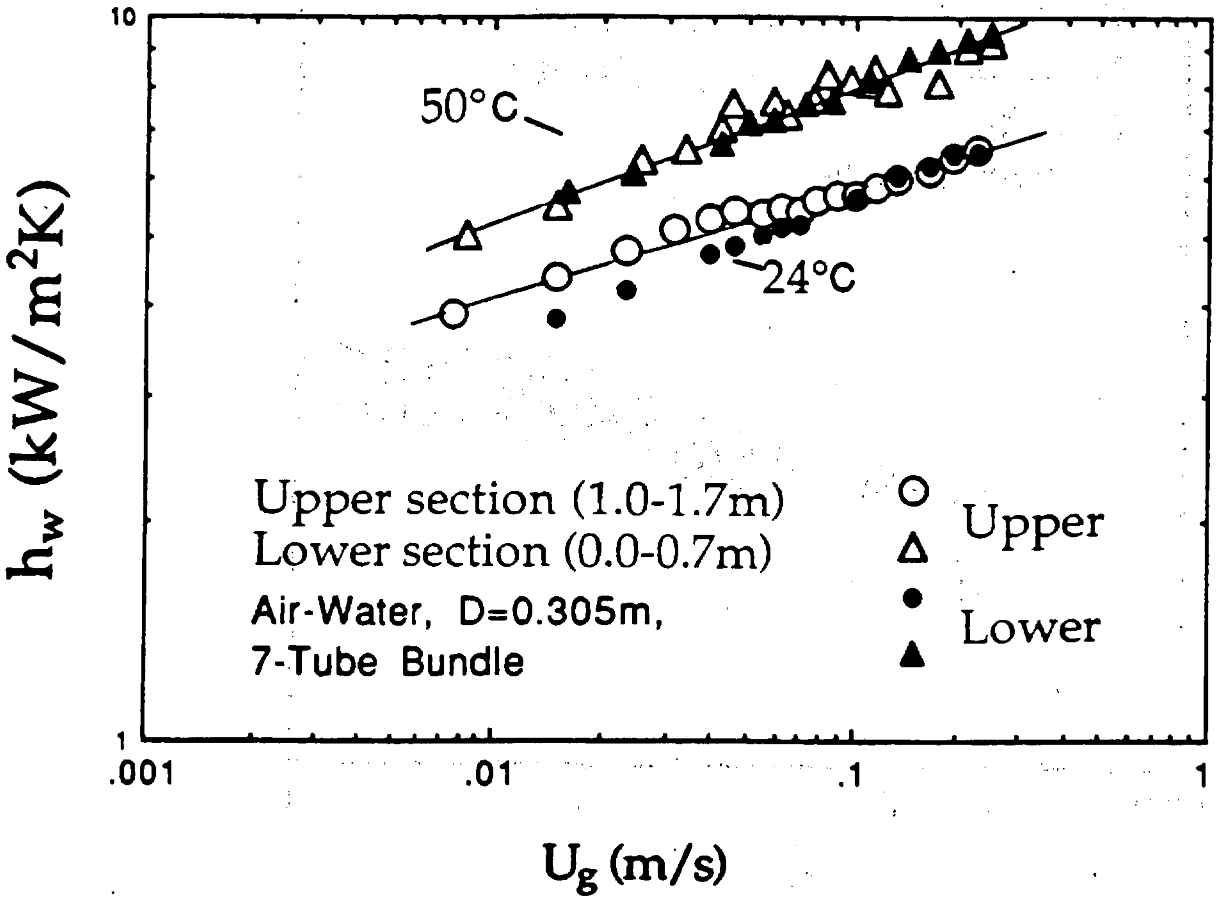

Fig. 7.1. Variation of h_W with air velocity and probe location.

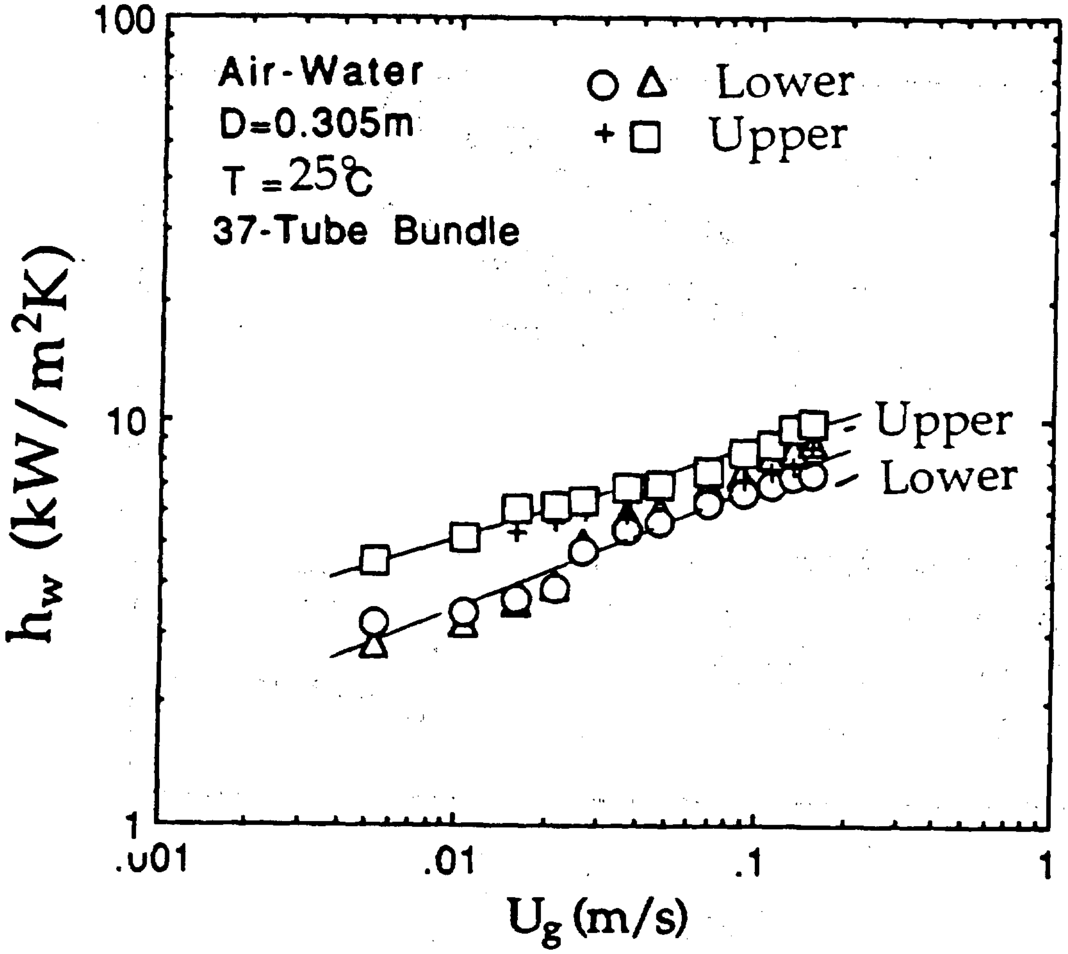

Fig. 7.2. Variation of h_W with air velocity and probe location.

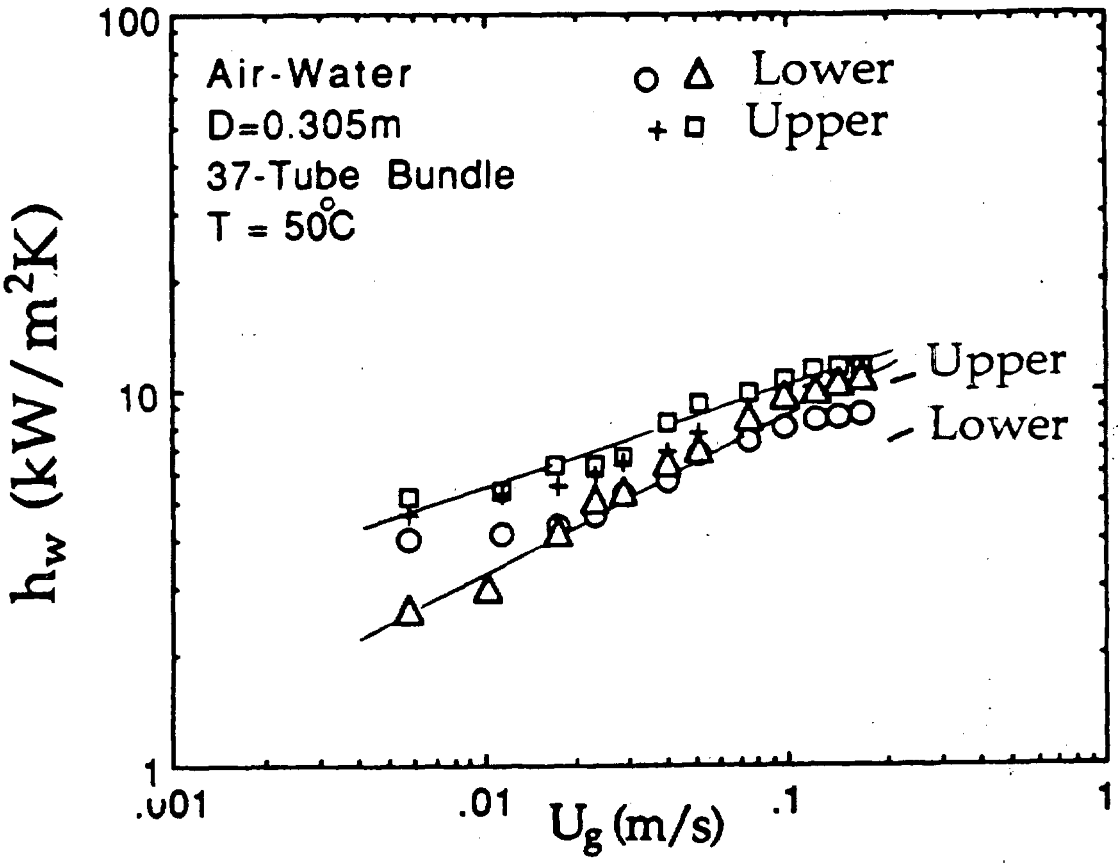

Fig. 7.3. Variation of h_W with air velocity and probe location.

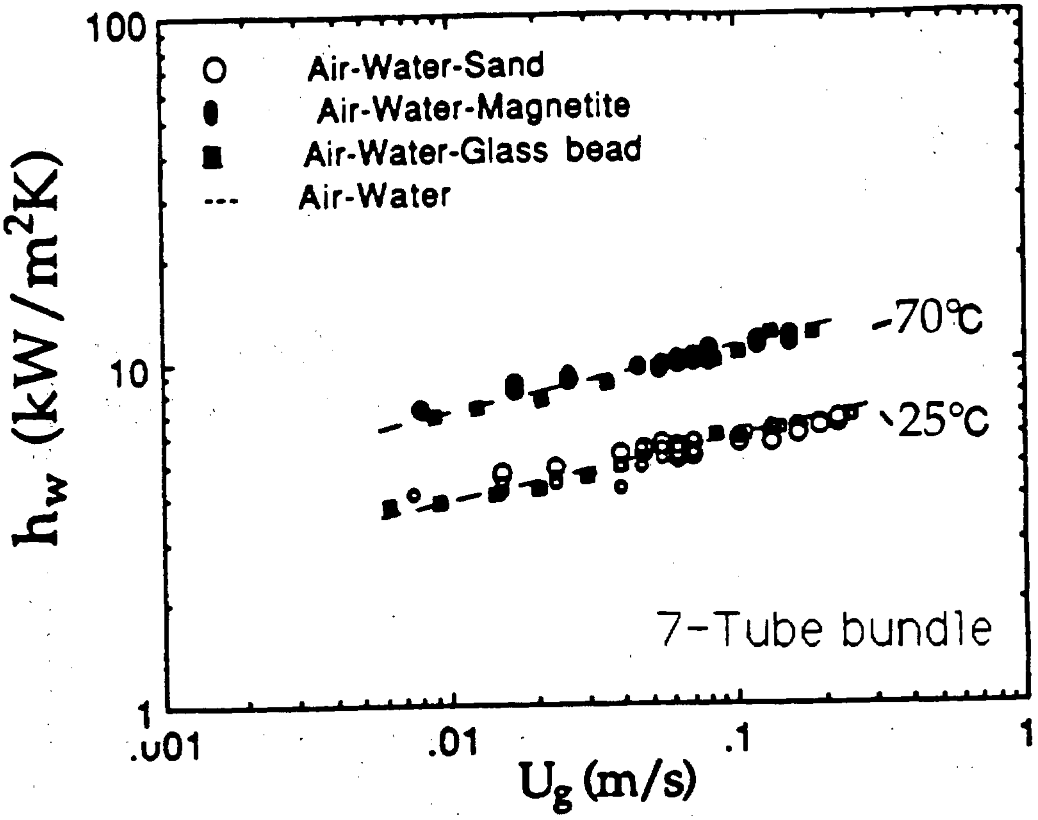

Fig. 7.4. Variation of h_W with air velocity and temperature for different systems.

transfer process through the prevailing hydrodynamics. To establish this explicitly a much more viscous heat transfer fluid, Therminol-66, was investigated. Experiments somewhat analogous to aqueous systems have been performed though on a relatively smaller scale. These experiments on the whole have indicated a qualitative dependence on different parameters which is identical to that observed for aqueous systems. Quantitatively the differences are appreciable and significant. Thus, as displayed in Fig. 7.5, h_W for Therminol-66 systems are more than an order of magnitude smaller than aqueous systems. This brings to light the importance of the liquid phase properties in establishing heat transfer rates in slurry bubble columns.

The dependence of such systems on different parameters is in some cases distinctly different in relative magnitudes than what is observed in aqueous systems. For example, addition of solids enhances the heat transfer rates much more than in an aqueous system, and this enhancement exhibits a systematic increase with increase in solids concentration. In Fig. 4.40, a similar result is displayed for single tubes of different diameters. The temperature increase reduces this enhancement in heat transfer rates with increase in concentration. This will suggest that liquid viscosity plays a very significant role. With increase in temperature, the viscosity decreases and the system tends to behave ~~more~~ like an aqueous system. At 523K the viscosity of Therminol-66 is about the same as that of water at 323K. The thermal conductivity of Therminol-66 is much smaller (by a factor of five) than that of water while it is comparable to that of solids. It would therefore suggest that solids will have more influence in removing heat in Therminol-66 than in water. Similarly, the specific heat of water is more than twice that of Therminol. This will again suggest that water will play a dominant role in removing heat than Therminol in the presence of solids. Solids specific heat is about one-sixth of water and about one-half to one-third that of Therminol. It would be appropriate to undertake some work on heat transfer with liquids of different viscosities to understand and quantify the heat transfer rates in terms of the properties of the system. The single tube internals at room temperature exhibit a bit more pronounced effect than found for aqueous systems. This need to be further investigated.

A similar body of data is generated for the gas holdup. For aqueous systems,

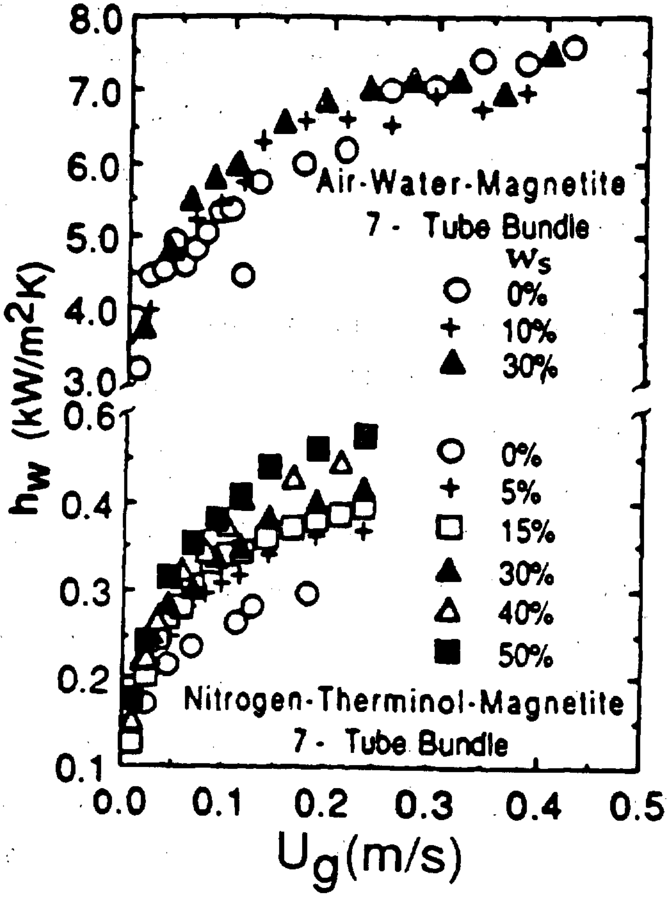

Fig. 7.5. Comparison of h_W data for two systems with widely different viscosities for the liquid phase.

the gas holdup increases rapidly in the discrete bubbling regime, the increase slows down in the bubble coalescence regime, and further slows down in the churn-turbulent regime. The hysteresis effect is encountered whenever foaming is observed and we have taken data with decreasing air velocity. The influence of slow (< 1.0 cm/s) cocurrent liquid flow influences the holdup insignificantly in relation to the values obtained with decreasing air flow velocity in the absence of foam. The existing correlations are found to be inadequate in predicting these experimentally observed air holdup values. A modified drift-flux theory approach has been successful in correlating the data.

The presence of internals (tube bundles) enhances the air holdup and eliminates the hysteresis effect. At room temperature, with either a single tube or a seven-tube bundle, the air holdup is found to be independent of column diameter, 0.108 and 0.305m. The effect of temperature on air holdup is to decrease it with increase in temperature, and above 323K it is almost constant. In Fig. 7.6., it is demonstrated that at room temperature, the air holdup is about the same for a seven and thirty-seven tube bundle, while at a higher temperatures in the range 50 - 70°C, the thirty-seven tube bundle gives a higher value than the seven-tube bundle. This would suggest that bubble diameters be measured in baffled columns as a function of temperature to mechanistically understand this phenomenon.

The addition of solid particles of different physical properties and sizes (1 to 140 μm) always decreases the gas holdup as compared to the corresponding values in the absence of solids. The air holdup increases with increase in air velocity, and decreases with increase in slurry concentration. The hysteresis effects are negligibly small and particle size has a weak dependence. Our detailed work with air-water-magnetite system indicates that with increasing particle size in the powder, the air holdup decreases. The dependence for air-water-glass bead system for air holdup on powder size is not evident. If these differences are realistic, it appears that particle density and wettability play an important role. The air holdup for the magnetite system is smaller as compared to the glass bead system. Further careful work will be essential to resolve these observations. Data obtained at room temperature with internals indicate that holdup increases with internals in the column. This is obviously because of the smaller bubbles. The influence on holdup by the presence of internals seem to decrease as the particle size in the slurry increases.

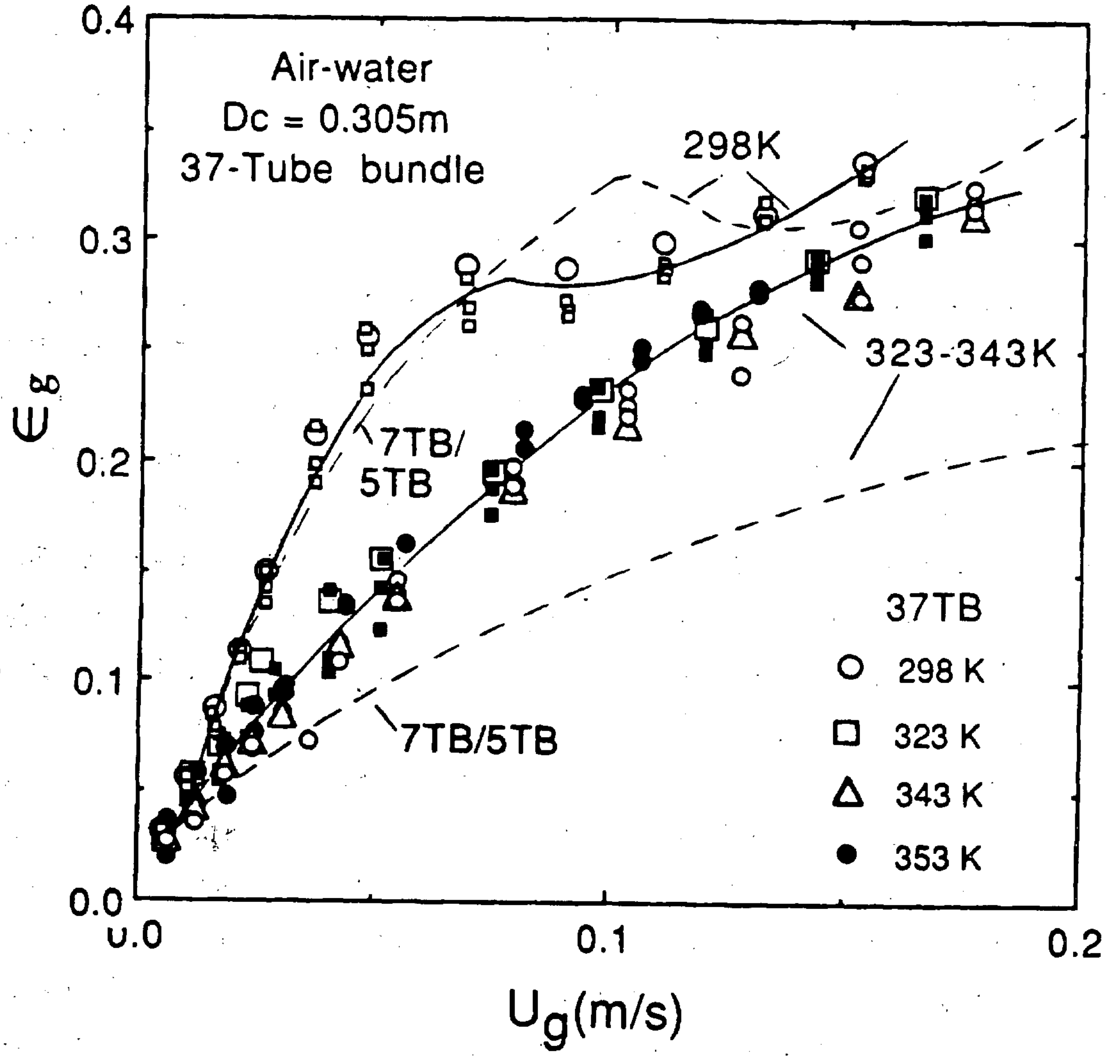

Fig. 7.6. Variation of air holdup for air-water system with air velocity at different temperatures for a column equipped with either a five-tube, a seven-tube or a thirty-tube bundle. $D_c = 0.305$ m.

The temperature has an appreciable effect on air holdup for three-phase systems as the temperature is raised above the ambient. For aqueuos systems, the air holdup decreases as the temperature increases to about 50°C and thereafter the decrease is negligibly small as the temperature rises to about 70°C. At higher temperatures, the influence of slurry concentration on air holdup is not appreciable and this has been confirmed with measurements using internals of varying sizes in the column. The available models have generally not been successful except the correlation uses a slurry viscosity expression and its reliability needs to be established. In this context, it may be pointed out that measurements of slurry viscosity are essential to fully establish the potential of these two correlations. The drift-flux theory in its modified form has been generally successful in at least correlating the data which at best can be regarded as an empirical approach at the present time. More theoretical work is in order in this direction.

The three-phase systems involving more viscous fluids than water have been investigated with a particular system nitrogen-Therminol-magnetite (or red iron oxide). At room temperature with red iron oxide, the nitrogen holdup is influenced to a small extent (± 5 percent). The holdup decreases at smaller nitrogen velocities (<0.08 m/s) as the red iron oxide powder is added up to 50 weight percent, but this decrease reduces at the higher nitrogen velocities where the holdup becomes almost identical to that for the two-phase system. The presence of internals (seven-tube) in the small column has decreased the nitrogen holdup in sharp contrast to low viscous slurries where the holdup increased with internals. This would suggest that the influence of internals on gas holdup is viscosity dependent. It implies that bubble dynamics of systems with internals involving relatively more viscous fluids need to be investigated and properly correlated with the geometry of internals. For magnetite powders in the average size range, 27.7 - 45.5 μm, the influence of particle size on gas holdup is negligible. A similar conclusion is reached about the slurry concentration for all the internals investigated. Unlike small red iron oxide particles here the holdup for seven-tube bundle is not much different from the data for these single-tubes. The reason for this may be in the nature of slurry rheology involving fine and large particles.

It is interesting to compare the relative values of gas-phase holdup for less and more viscous fluid systems. In Fig. 7.7 such a comparison is presented. It is

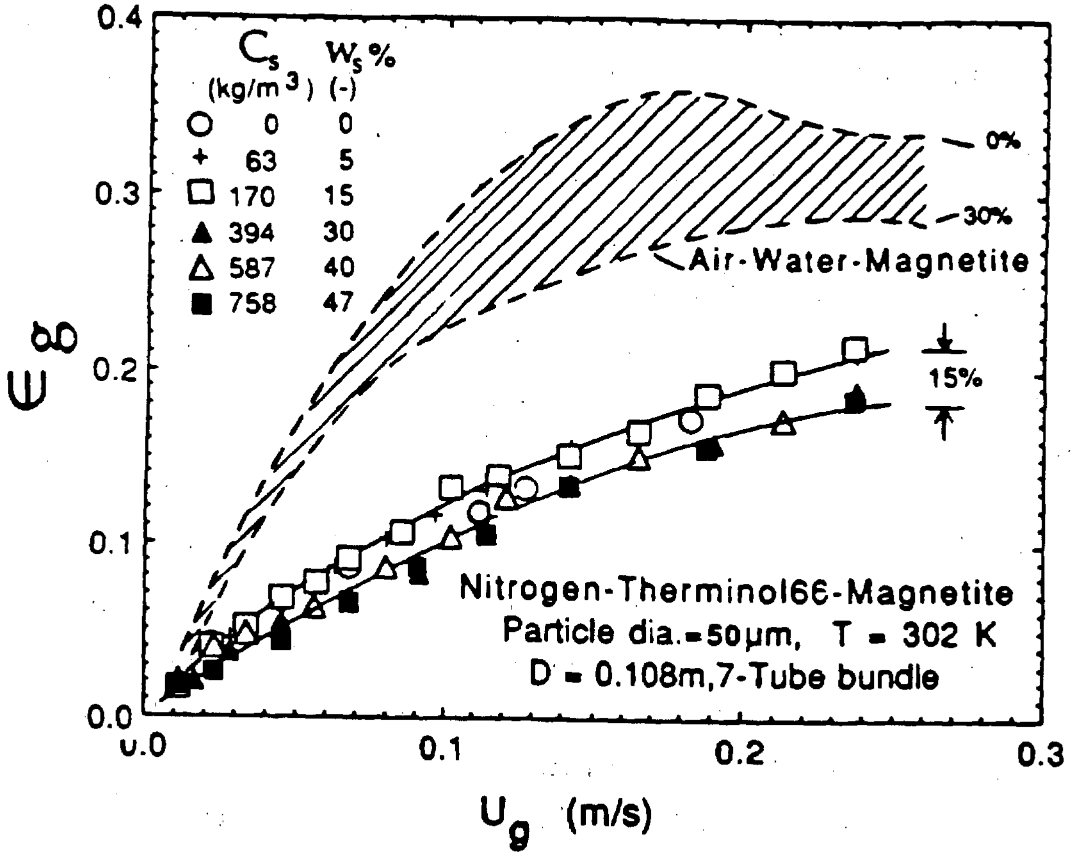

Fig. 7.7. Variation of nitrogen holdup as a function of nitrogen velocity in slurries of different concentrations of 50 μm average diameter powder.

important to note that the holdup for viscous systems is much smaller than for less viscous systems. This result is valid both for two and three-phase systems, and the effect of slurry concentration is more for less viscous systems than for viscous systems.

The influence of temperature on systems involving viscous fluids is investigated in the large column with thirty-seven tube bundle and 36 μm magnetite powder. For nitrogen-Therminol system, the nitrogen holdup increases with nitrogen velocity but the influence of temperature is involved. The holdup slightly decreases as the temperature is raised from 296K to 309K and thereafter it increases with temperature up to 428K. At this temperature and beyond up to 523K, the foam formation is observed and holdup remains constant. For three-phase systems a monotonic increase in gas holdup is observed with increase in temperature in the nonfoaming regime. In the foaming regime the holdup is constant. The addition of solids at room temperature decreases the holdup, while the change is negligible at higher temperatures till the foaming sets in. In the foaming regime (428 - 523K), the influence of solids concentration is negligible up to thirty weight percent but the holdup decreases as the solids concentration is further increased. It would be very useful to launch a careful experimental program of research involving such viscous fluids over a temperature range encompassing both the foaming and nonfoaming regimes.

8. NOMENCLATURE

A	cross-sectional area, m^2
a, b, c, d	numerical constants of Eqs. (6.51) and (6.54)
C_{pL}	liquid heat capacity, J/kg K
$\overline{C}_p$ or $C_{p, SL}$	slurry heat capacity, J/kg K
C_{ps}	solids heat capacity, J/kg K
C_s	solids concentration, kg/m^3
d_b	bubble diameter, m
d_o	particle diameter as defined in Eq. (6.18), m
d_p	particle diameter, m
d_{pi}	mean particle diameter in the range d_{pi-1} to d_{pi}, m
D_c	column diameter, m
D_T	heat transfer probe diameter, m
G	mass flow rate, kg/m^2s
g	acceleration due to gravity, m/s^2
H	section height, m
H_e	expanded dispersion column height, m
H_S	slumped liquid column height, m
H_{sl}	slumped slurry column height, m
H1, H2, H3, H4	heaters
h	height above the gas distributor plate, m

h_W	heat transfer coefficient, W/ m^2 K
$h_{W, max}$	maximum value of heat transfer coefficient, W/m^2 K
I	current through the heating element, A
k_L	liquid thermal conductivity, W/mK
k_s	solid thermal conductivity, W/mK
$\bar{k}$ or k_{SL}	slurry thermal conductivity, W/mK
l	distance between successive bubbles, m
P	total pressure, Pa
P_v	vapor pressure, Pa
P_v	$= g\ U_g\ \rho_L$, energy dissipation rate per unit volume, kg/ms^3
ΔP	pressure drop across a section, Pa
P1, P2, P3, P4	heat transfer probes
Q	power input to heat transfer probe, W
T_c	column temperature, K
T_s	surface temperature, K
ΔT	temperature difference, K
$U_{b\infty}$	bubble terminal rise velocity, m/s
U_g	superficial gas velocity, m/s
U_o	drift velocity, m/s
U_{SL}	superficial slurry velocity, m/s
V	electrical voltage, V

V_c	liquid circulation velocity, m/s
V_L or U_L	superficial liquid velocity, m/s
v_a	axial component of V_c, m/s
v_F	eddy velocity as defined in Eq. (6.5), m/s
v_L	volume friction of liquid in slurry, dimensionless
v_S	volume friction of solids in slurry, dimensionless
W_L	mass of liquid in slurry, kg
W_s	mass of solids in slurry, kg
w_L	mass fraction of liquid in slurry, dimensionless
w_S	mass fraction of solids in slurry, dimensionless
x_i	mass fraction solids of average size, d_{pi}, dimensionless
1TB, 5TB, 7TB, 37TB	1,5,7, or 37 tube bundle

Dimensionless Numbers

Ar = $d_b^3 (\rho_L - \rho_g) g \rho_L / \mu_L^2$, Archimedes number

Bo = $g D_c^2 \rho_L / \sigma_L$, Bond number

Fr = $U_g^2 / d_b g$, Froude number

Ga = $g D_c^3 \rho_L^2 / \mu_L^2$, Galileo number

Nu = $h_W d_p / k_L$, Nusselt number

Nu' = $h_W d_p \in_L / k_L (1 - \in_L)$, Nusselt number

Pr = $\mu_L C_{p,L} / k_L$ or $\mu_{SL} C_{p,SL} / k_{SL}$, Prandtl number

Re = $U_g d_p \rho_L / \mu_L$ or $U_g d_p \bar{\rho} / \bar{\mu}$, Reynolds number

Re$'$ = $U_L d_p \rho_L / \mu_L (1 - \epsilon_L)$, Reynolds number

St = $h_W / \rho_L C_{pL} U_g$ or $h_W / \rho_{SL} C_{p,SL} U_g$, Stanton number

<u>Greek Symbols</u>

ϵ_g	average gas holdup, dimensionless
ϵ'_g	local gas holdup, dimensionless
ϵ''_g	gas holdup in continuous mode of operation, dimensionless
ϵ_L	average liquid-phase holdup, dimensionless
ϵ_s	average solid-phase holdup, dimensionless
μ_b	apparent effective slurry viscosity, kg/ m s
μ_g	gas viscosity, kg/m s
μ_L	liquid viscosity, kg/ m s
$\bar{\mu}$ or μ_{SL}	slurry viscosity, kg/ m s
$\mu_{SL,W}$	slurry viscosity at surface temperature, kg/ m s
ρ_g	gas density, kg/ m^3
ρ_L	gas density, kg/ m^3
ρ_m	manometer liquid density, kg/ m^3

ρ_s	solid density, kg/ m^3
$\bar{\rho}$ or ρ_{SL}	slurry density, kg/ m^3
ρ_w	water density, kg/ m^3
σ_L	liquid surface tension, N/m
σ_w	water surface tension, N/m