CHAPTER 5

RESULTS AND DISCUSSION

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This chapter displays the effect of superficial gas velocity, solid concentration of the slurry phase and the number of cooling tubes inside the bubble column on:

1- The gas hold-up

2- Dispersion coefficient, in the liquid phase

5-1-Gas Holdup

5-1-1-Two - Phase

Effect of superficial gas velocity on gas holdup in gas- liquid bubble columns:

5-1-1-1-With no Tubes

The effect of superficial gas velocity for gas holdup on the empty bubble column is shown in Fig. (5-1-a)

Generally the gas holdup increases as the superficial gas velocity increases. An increase followed by a decrease and then another increase in gas holdup is observed at a superficial velocity between 5 and 6.5 cm/s. This change in the gas holdup pattern is characteristic for bubble columns (Krishna et al, 1997) and is attributed to the transition from bubbly to churn- turbulent flow. When the bubble rise velocity is suddenly increased, thus, causes a decrease in the gas hold-up.

5-1-1-2-With Increasing the Number of Tubes

Figures (5-1-b) to (5-1-f) show the effect of increasing superficial gas velocity on gas holdup with successively increasing the number of tubes. The same trend of increasing the gas holdup with increasing superficial gas velocity is still observed but with less pronounced transition point. The gas holdup is slightly decreased as a result of increasing the number of tubes inside the bed. Increasing the number of tubes results in decreasing the free column cross sectional area available for bubble flow thus increasing bubble coalescence. The bigger the bubble size, the higher its rise velocity, therefore the lower is the gas holdup.

5-1-1-3- Comparison with Literature Correlations

Literature correlations of Wilkinson (1991) Equation(2-10), Hikita et al.(1980) Equation(2-3), Idogawa et al.(1985) Equation(2-5), Stern (1985)Equation(2-17), Deckwer & Schumpe (1993)Equation(2-18), and Hammer et al.(1984) Equation(2-4) for gas holdup in gas- liquid bubble columns are tested against the present experimental data. Figure (5-2) shows the predictions of the above mentioned correlations for air water systems in empty bubble column (Figure 5-2,a) and in bubble columns containing tubes Figures(5-2,b-f). It is clear that the experimental data are in good agreement with the tested correlations up to 6cm/sec

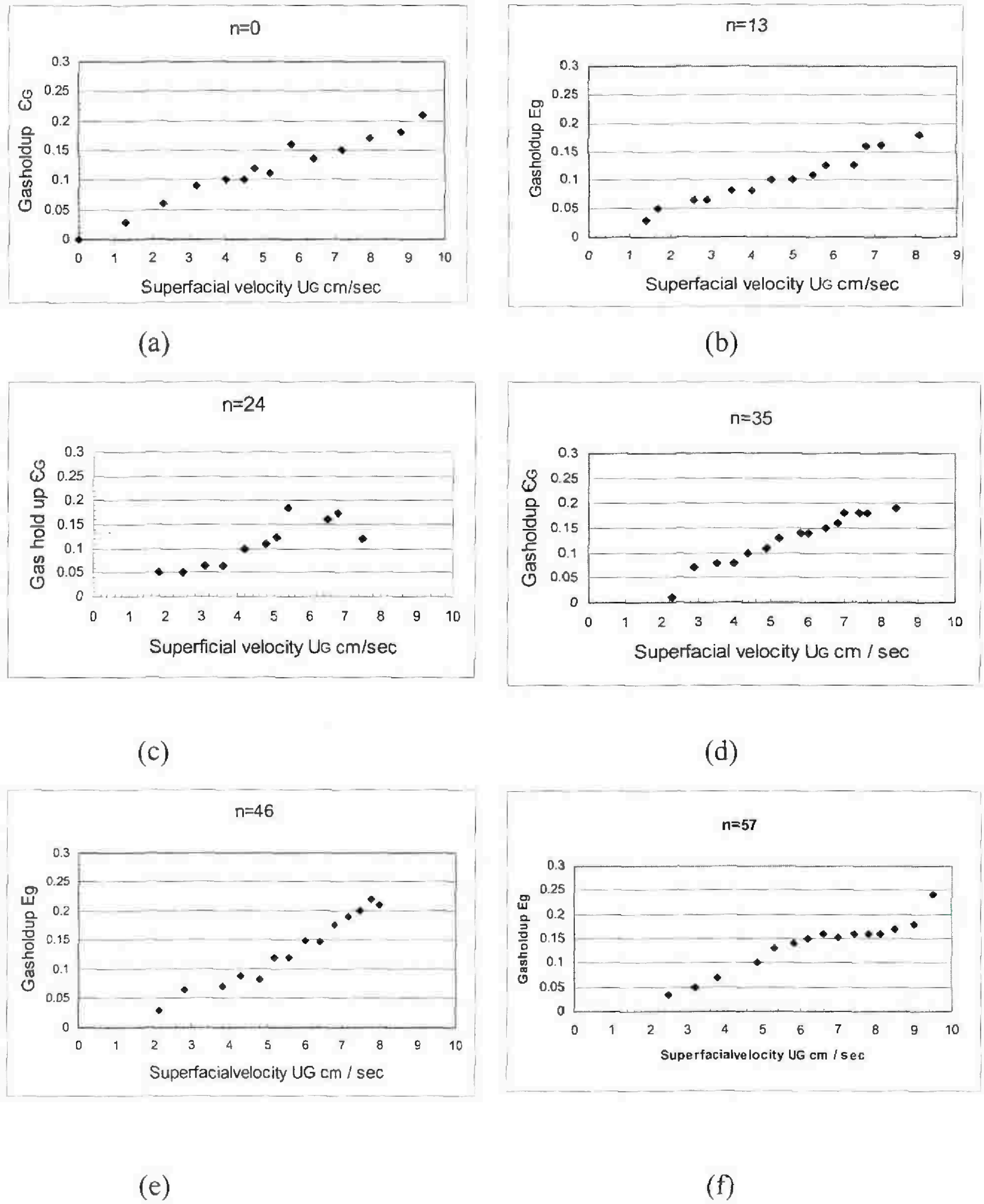
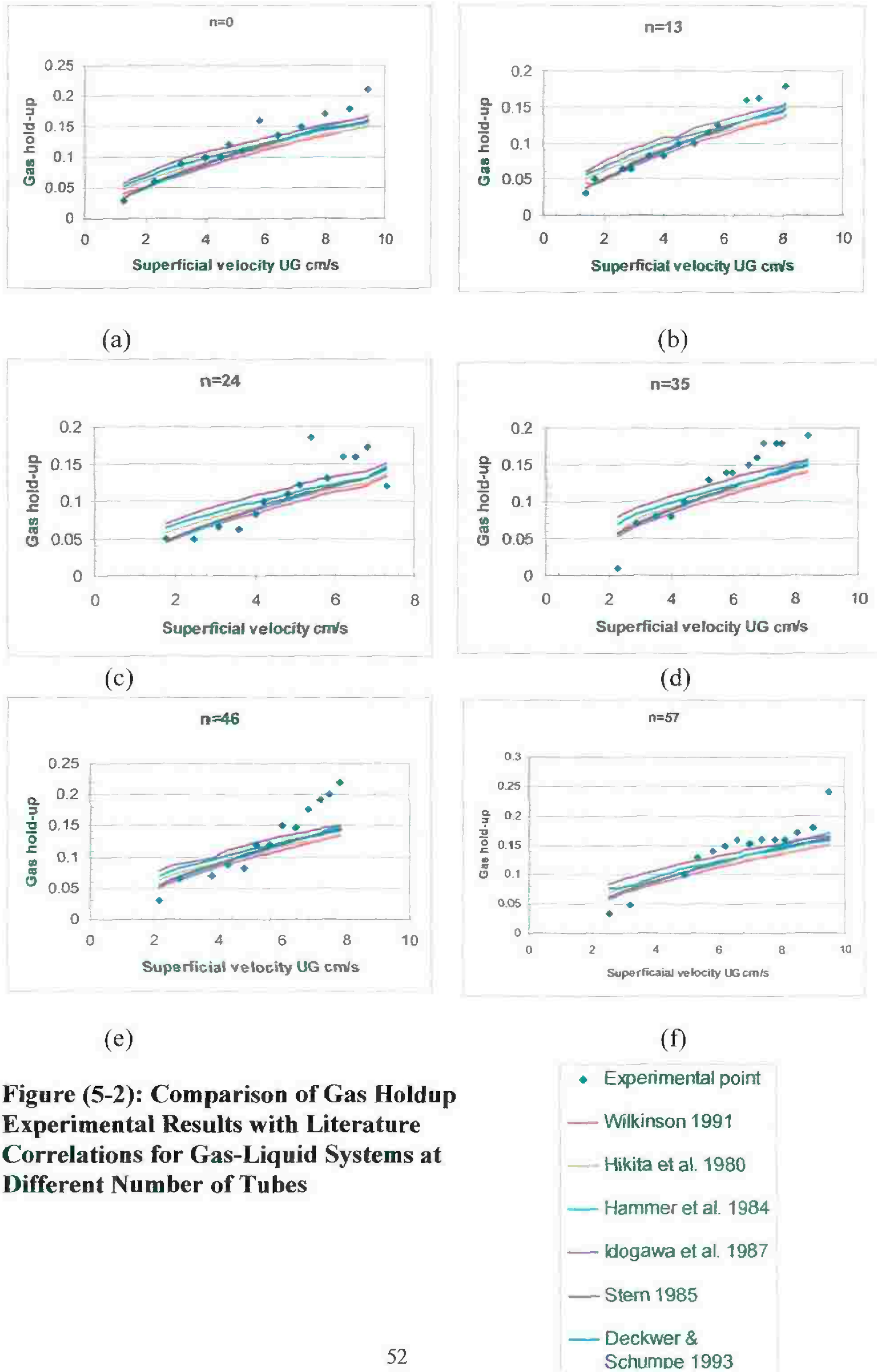


Figure (5-1): Effect of Increasing the Number of Cooling Tubes on Gas Holdup for Air-Water System



(a) (b) (c) (d) (e) (f)

Figure (5-2): Comparison of Gas Holdup Experimental Results with Literature Correlations for Gas-Liquid Systems at Different Number of Tubes

5-1-2-Slurry Phase Bubble Column

In this section the effect of adding solids to the bubble column is studied, firstly; for the empty bubble column (with no tubes), secondly; with successively increasing the number of tubes.

5-1-2-1-Effect of Solids Concentration on Gas Holdup for Empty Bubble Columns

The effects of adding solids with different initial concentrations (1, 2, 3, and 4 vol %) to an empty bubble column on gas holdup are displayed in Figures (5-3, b, c, and d) respectively. Fig (5-3-a) is for the case of two-phase bubble column. It is included here for comparison.

It can be observed that the starting gas velocity is shifted to higher values as the solids concentration is increased. Increasing the solids weight (or concentration) requires a higher momentum to ensure its complete suspension.

Investigating the above mentioned figures it can be observed that except for solids concentration of 2 % Fig (5-3-c) which shows slightly lower values for gas holdup at low gas superficial velocities and that of 4% which shows highest gas hold-up solids concentration has negligible effect on gas holdup. This is made clearer if we plot the five curves on the same figure as shown in Fig (5-4).

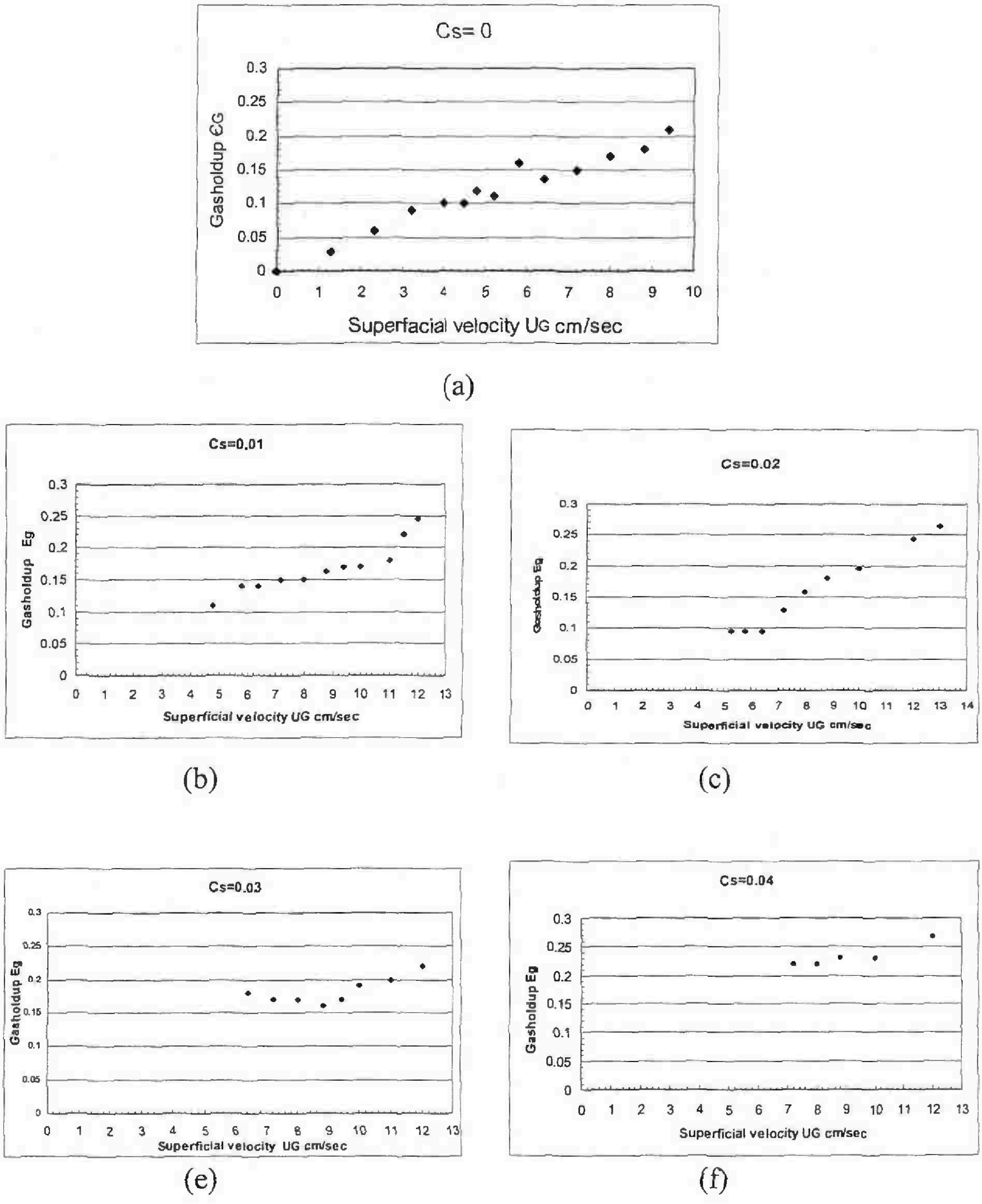


Figure (5-3): Effect of Solid Concentration on Gas Holdup for Empty Slurry Bubble Columns

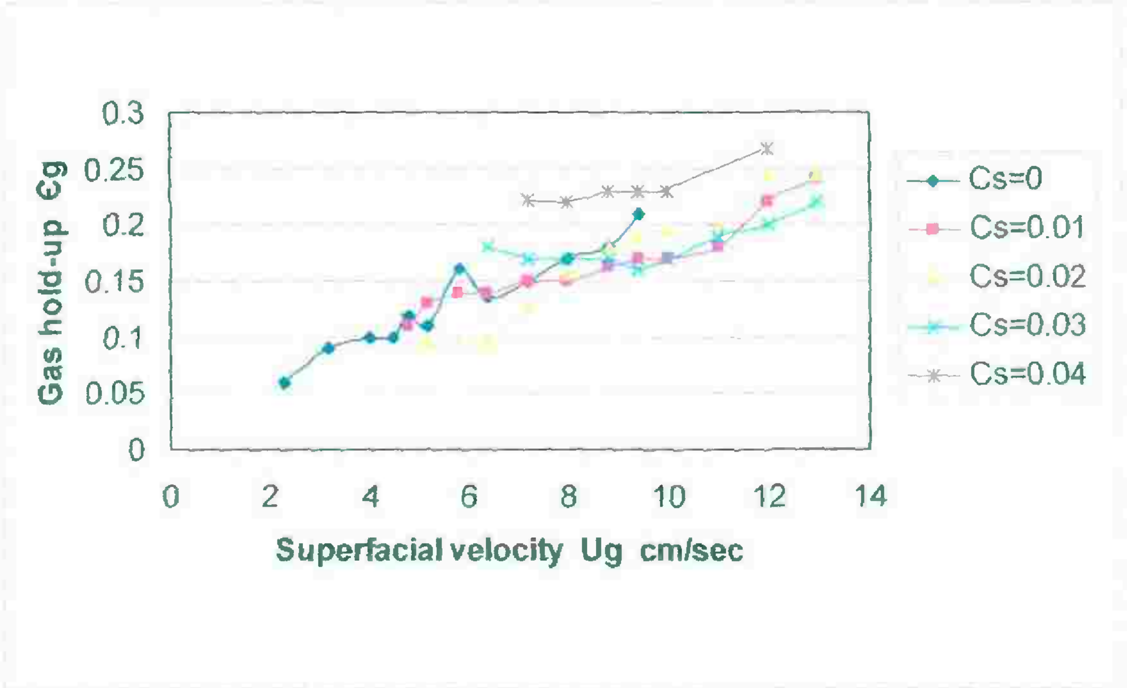


Figure (5-4): Effect of Solid Concentration on Gas Holdup for Empty Slurry Bubble Columns

The negligible effect of solids concentration on the gas holdup may be attributed to the low concentration of solids (maximum 3 %) in the slurry bed. However, the transition point from bubbly to churn turbulent regime is shifted towards higher air superficial velocities (between 8 and 11 cm/s) due to the presence of solids. The presence of solids slightly stabilized the bubble column i.e. it retards coalescence of the bubbles. This is contrary to what has been reported by Krishna et al (1997). However these authors used very small particle size ($\approx 50 \mu m$) and high solids concentration which reached 36 %. The reference conditions would promote bubble coalescence and hence higher bubble rise velocity and lower gas holdup. However, for initial solids concentration of 4 %, there is little change in gas holdup with superficial velocity. In this case the transition from bubbly to churn turbulent regime is not observed because the starting superficial air velocity coincides with the transition point, i.e. the bed starts in the churn turbulent regime.

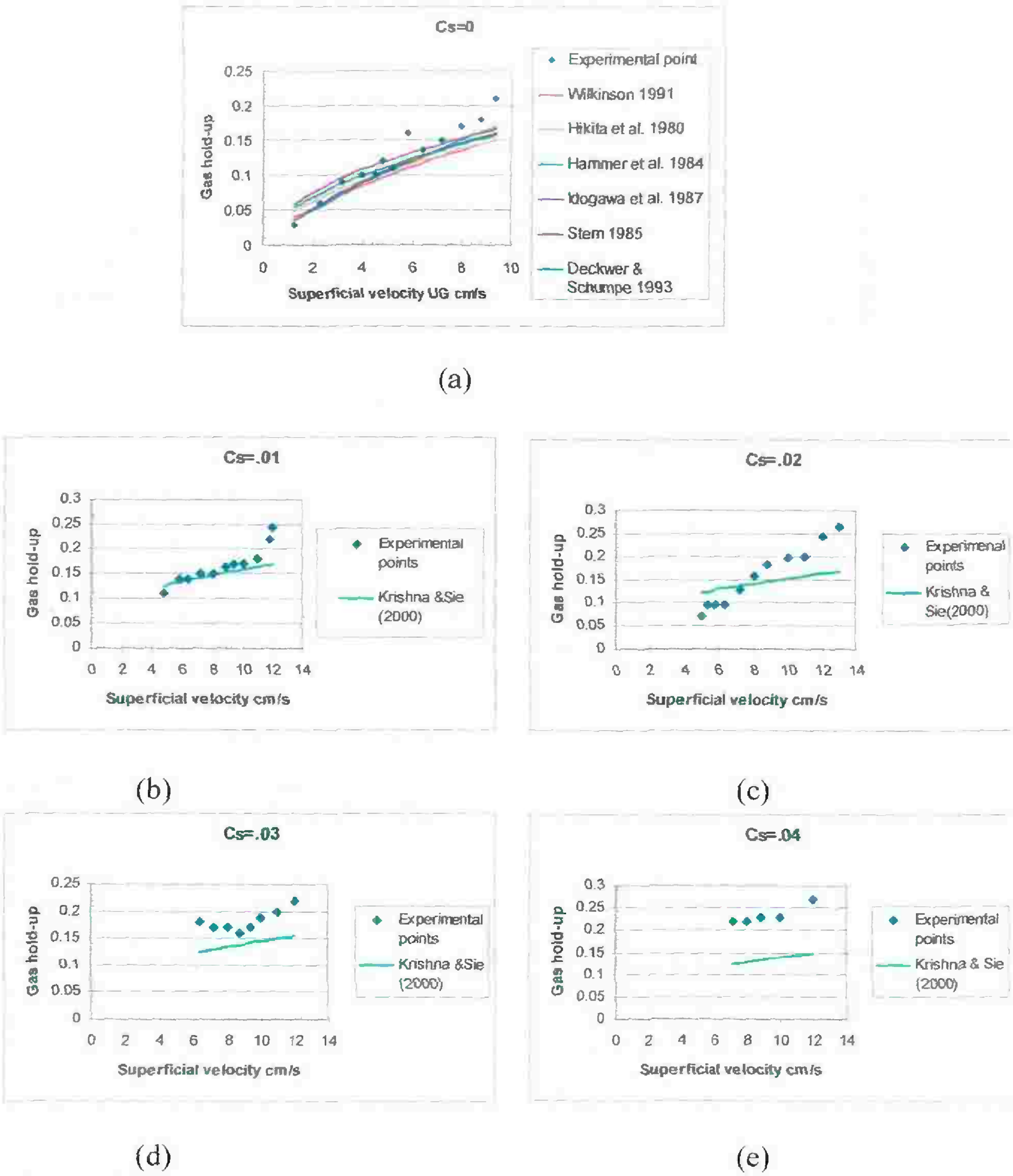


Figure (5-5): Comparison of Gas Holdup Experimental Results with Literature Correlations for Gas-Liquid-Solid Systems at Different Solid Concentrations

5-1-2-2- Comparison with Literature Correlations

To the author's attention only one correlation has appeared relating gas hold up in slurry bubble columns to solids concentration, this correlation is that of Krishna & Sie (2000), the two bubble class model Equations (2-11) to (2-16). The above mentioned correlation is tested against the experimental data as shown in figure (5-5, b-d). The predicted values though show good agreement for the case of solids concentration of 1%; they generally under estimate the gas holdup in the rest of the cases. The reason for the observed deviation may be attributed to that the reference's correlation was based on experimental results of smaller solids particle size (`~ 50μ) and higher solids concentration (~36 %) where bubble coalescence would have been prevailing.

5-1-2-3- Effect of Solids Concentration on Gas holdup in Presence of Tubes

To study the effect of solids concentration on gas holdups in slurry bubble columns in presence of tubes, different initial solids concentrations were studied in presence of tubes with a varying number. No noticeable effect on the gas holdup was observed due to the change in the number of tubes. An example of gas holdup in slurry bubble columns in presence of tubes is demonstrated in Fig (5-6) with n= 35 tube.

As in the case with no tubes the gas holdup pattern seems to be little affected by the presence of solid particles. This is made more clear if the five figures (5-6, a to e) are superimposed on each other in one collective figure, Fig (5-7).

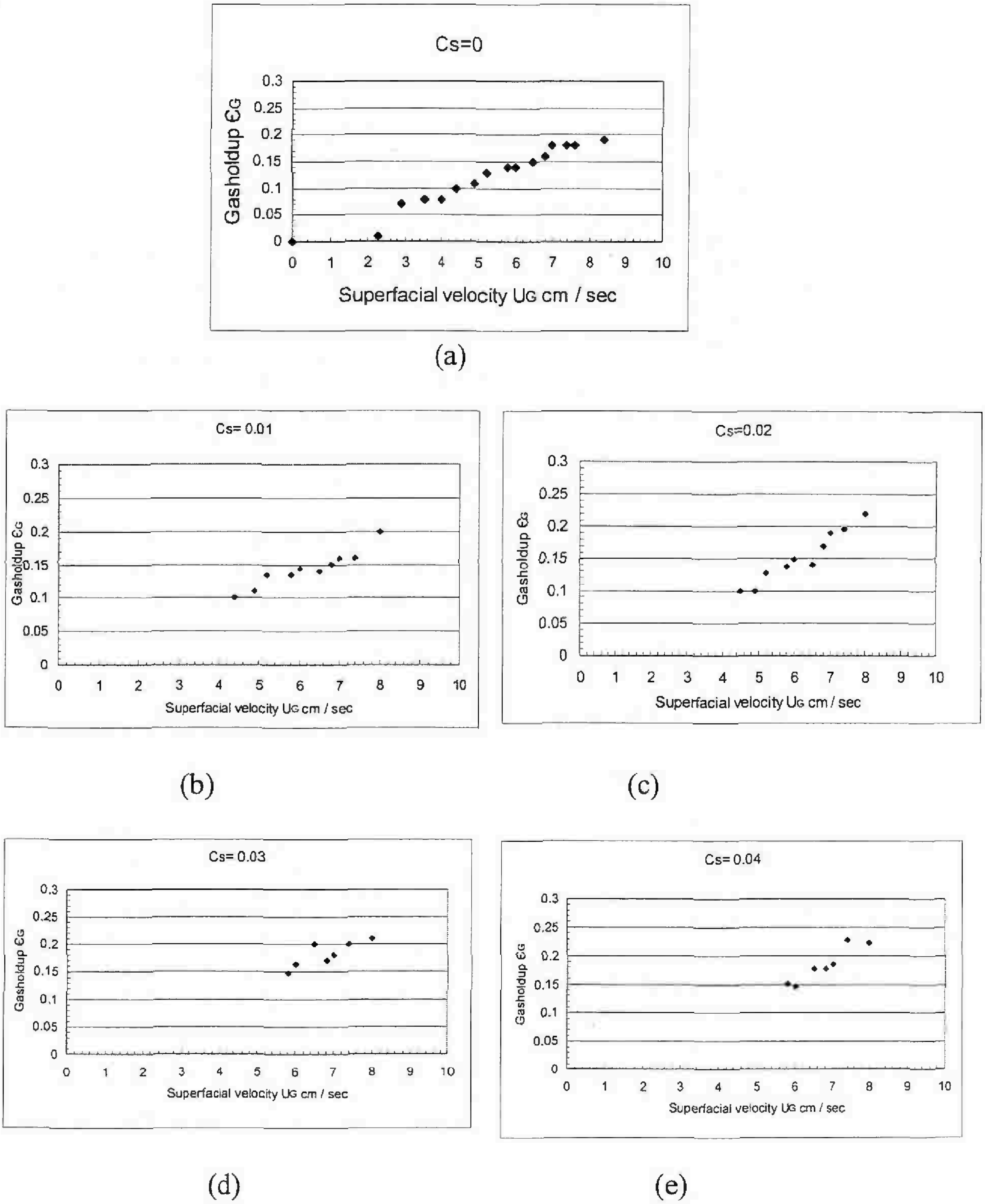


Figure (5-6): Effect of Solid Concentration on the Gas Holdup for Slurry Bubble columns Containing 35 Internal Tubes

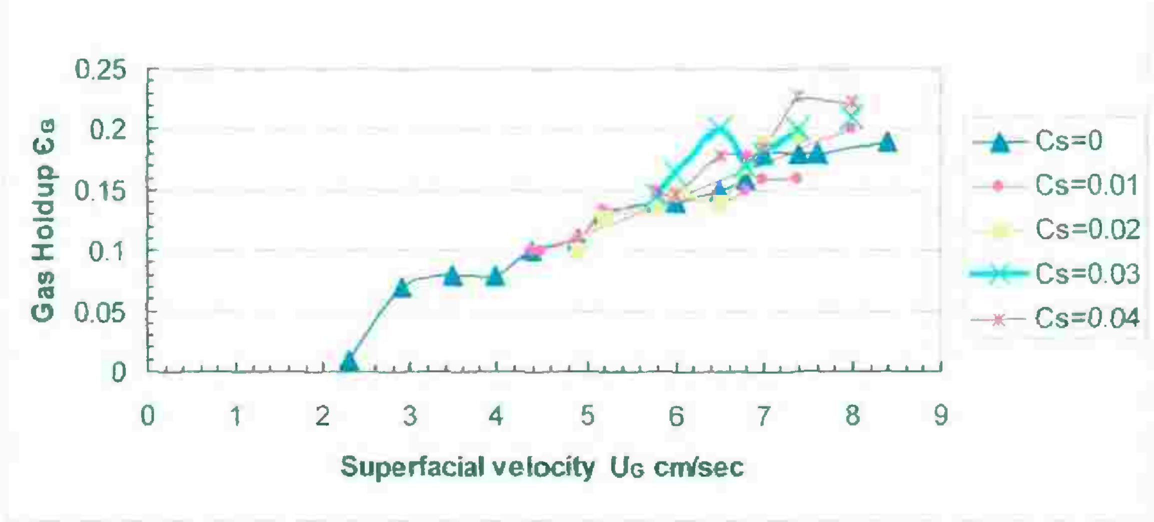


Figure (5-7): Gas Holdup at Different Solid Concentrations for Slurry Bubble Column Containing 35 Tubes

5-2- Liquid Phase Axial Dispersion coefficient

The axial dispersion coefficient in the liquid phase was calculated from RTD of the pulse tracer input as described in Chapter (3) [Theoretical Background] for two phase [gas-liquid] and three phase [gas-liquid-solid] bubble columns, both empty and containing varying number of cooling tubes. It is worth mentioning that to the authors' attention, except for only two articles (Forret et al. (2003) and Chen et al. (1999)) no work has been published on the effect of cooling tubes inside bubble columns. Even the above mentioned reference limited their studies to two-phase (gas-liquid) system.

As has been adopted in the study of gas holdup, liquid phase axial mixing has been studied for two-phase and three-phase system with and without cooling tubes as follows:

5-2-1- Two Phase (Gas –Liquid) Bubble Columns

Effect of superficial gas velocity on axial dispersion coefficient in Gas- liquid Bubble columns:

5-2-1-1-With No Tubes

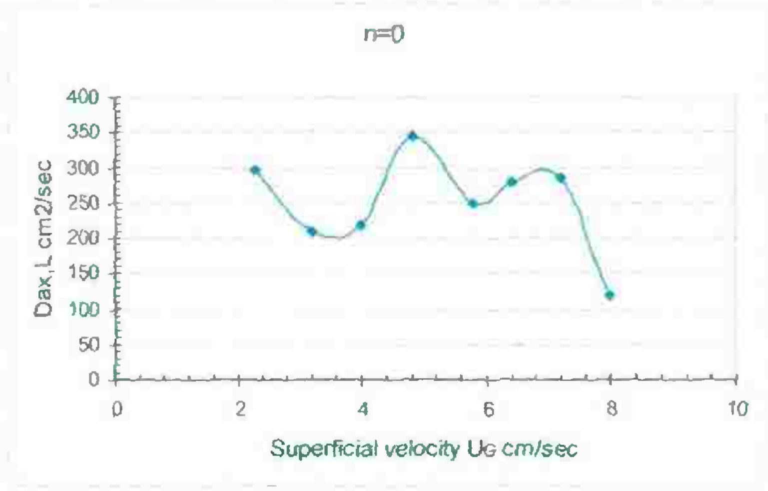
Figure (5-8-a) shows the effect of increasing superficial gas velocity on the liquid phase axial dispersion coefficient in empty bubble column i.e. containing no cooling tubes.

The dispersion coefficient fluctuates between 200-250 cm^2/s for superficial velocities between 2-7 cm/sec. It drops to ~ 100 cm^2/s as the superficial gas velocity reaches 8 cm/s. This may be due to the onset of slug flow.

5-2-1-2-With Increasing the Number of Tubes

Figures (5-8-b, c) show the effect of successively increasing the number of tubes to 35 and 57 respectively.

At low superficial air velocities, the liquid phase dispersion coefficient decreases as the number of tubes in increased. Also the maximum calculated value of dispersion coefficient is shifted towards higher superficial velocity as the number of tubes is increased. This may be due to the reduction of the effective column diameter where the dispersion coefficient increases with increasing the column diameter (see Table 2-2). Chen et al. (1999) reported a decrease in the turbulent eddy diffusivity both in the axial and radial directions in presence of cooling tubes as compared to bubble columns without tubes. This decrease in turbulent eddy diffusivity was attributed to the reduction of the length scale of the turbulent eddies because the presence of tubes restrict the flow in the radial direction.



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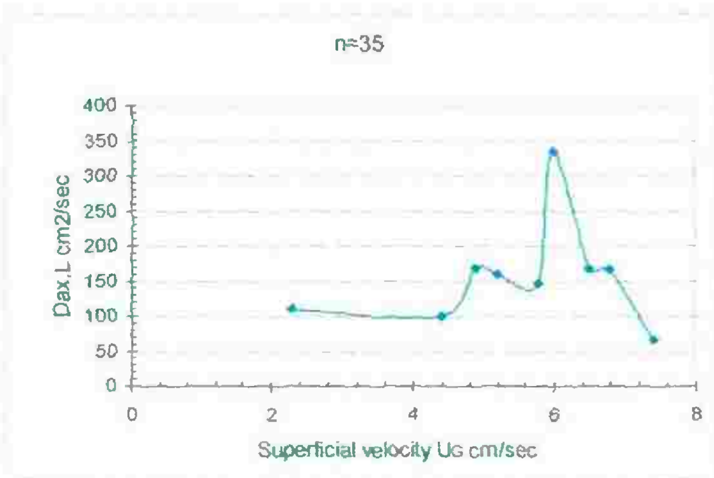

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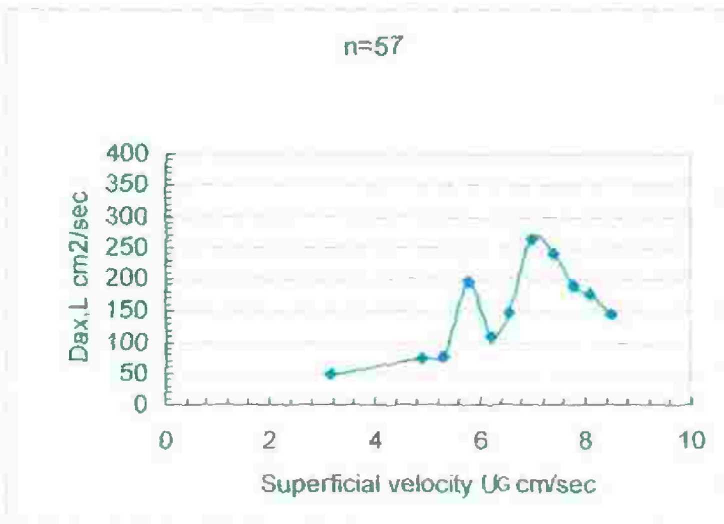
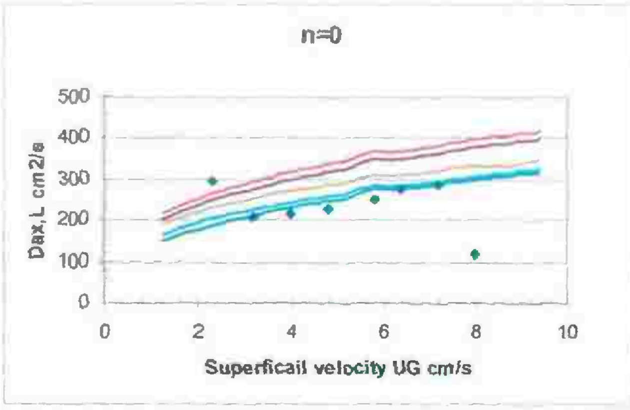


(c)

Figure (5-8): Effect of Number of Cooling Tubes on the Axial Dispersion Coefficient for Gas-Liquid Systems



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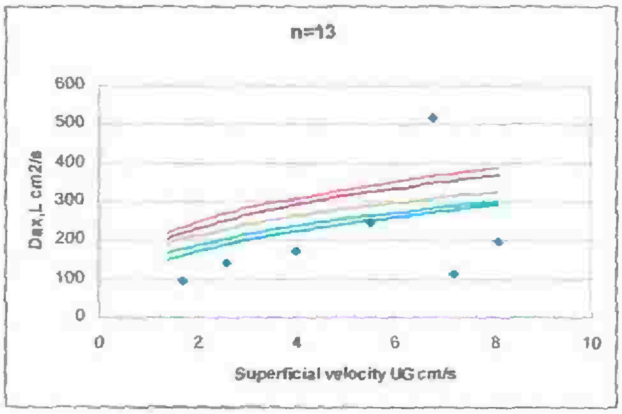

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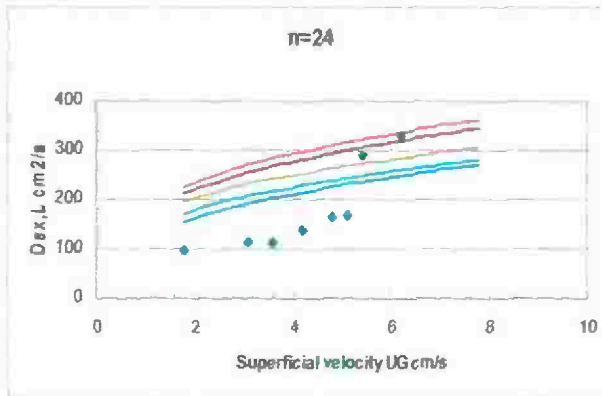

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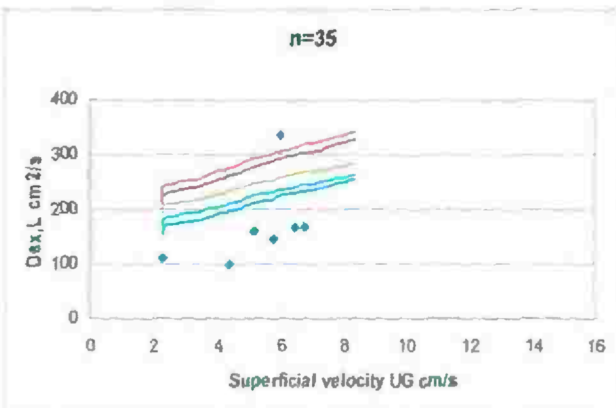

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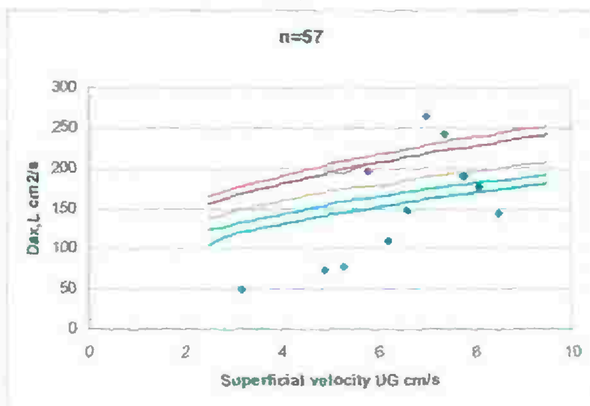


(e)

Figure (5-9): Comparison of Experimental Results for Liquid Phase Axial Mixing Coefficient with Literature Correlations for Gas-Liquid Systems at Different Number of Tubes

5-2-1-3- Comparison with Literature Correlations

Literature correlations (see Table 2-2) of Bukur (1983), Deckwer et al. (1973), Stern (1985), Baird & Rice (1975), Deckwer & Schumpe (1993), and Krishna (2000), for the estimation of liquid phase axial dispersion coefficient in gas-liquid bubble columns are tested against the present experimental data. Figure (5-9) shows the predictions of the above mentioned correlations for air- water systems in empty bubble columns (Figure 5-9,a) and in bubble columns containing tubes Figures(5-9,b-e). In case of bubble columns containing tubes, the column diameter was calculated based on the free cross sectional area, as $((D_T^2 - nd_t^2)^{0.5})$. It is clear that the experimental data are in good agreement with the tested correlations for the cases of empty column. However the experimental points fall below the correlations' predictions in the cases where the column contains tubes. Based on the explanation given by Chen et al. (1999) for the reduced scale of turbulent eddies in case of columns containing internals, special attention should be directed for the choice of the characteristic length scale incorporated in the correlations.

5-2-2-Liquid Phase Axial Mixing in Slurry Bubble Columns

Liquid phase axial mixing in three phase (Air-Water-Sand) bubble columns:

5-2-2-1-Effect of Solid Particles Concentration in Empty Bubble Columns

The effect of increasing solid particles concentration from 0 to 4% by volume is depicted in figure (5-10 a - e) for empty bubble columns. The same irregular humped curves once obtained for solids-free system figure (5-10 a) is repeated as the solids volume percentage is increased. However the peak value seems to be lower for bubble columns containing solids.

5-2-2-2- Comparison with Literature Correlations

Since no specific correlations are available for predicting dispersion coefficients in slurry bubble columns, literature correlations for two- phase gas- liquid systems are considered. The correlations of Bukur (1983), Deckwer et al. (1973), Stern (1985), Baird & Rice (1975), Deckwer & Schumpe (1993), and Krishna (2000),(see Table 2-2)for the estimation of liquid phase axial dispersion coefficient in gas-liquid bubble columns are tested against the present experimental data. Figure (5-11) shows the predictions of the above mentioned correlations for air- water systems (Figure 5-11,a) and for slurry bubble columns, Figures (5-11, b-d). While these predictions are in good agreement with the experimental points for two-phase systems, they over estimate the experimental values for the dispersion coefficients in case of slurry bubble columns, these correlations therefore need some refinement to accommodate the presence of solid particles.

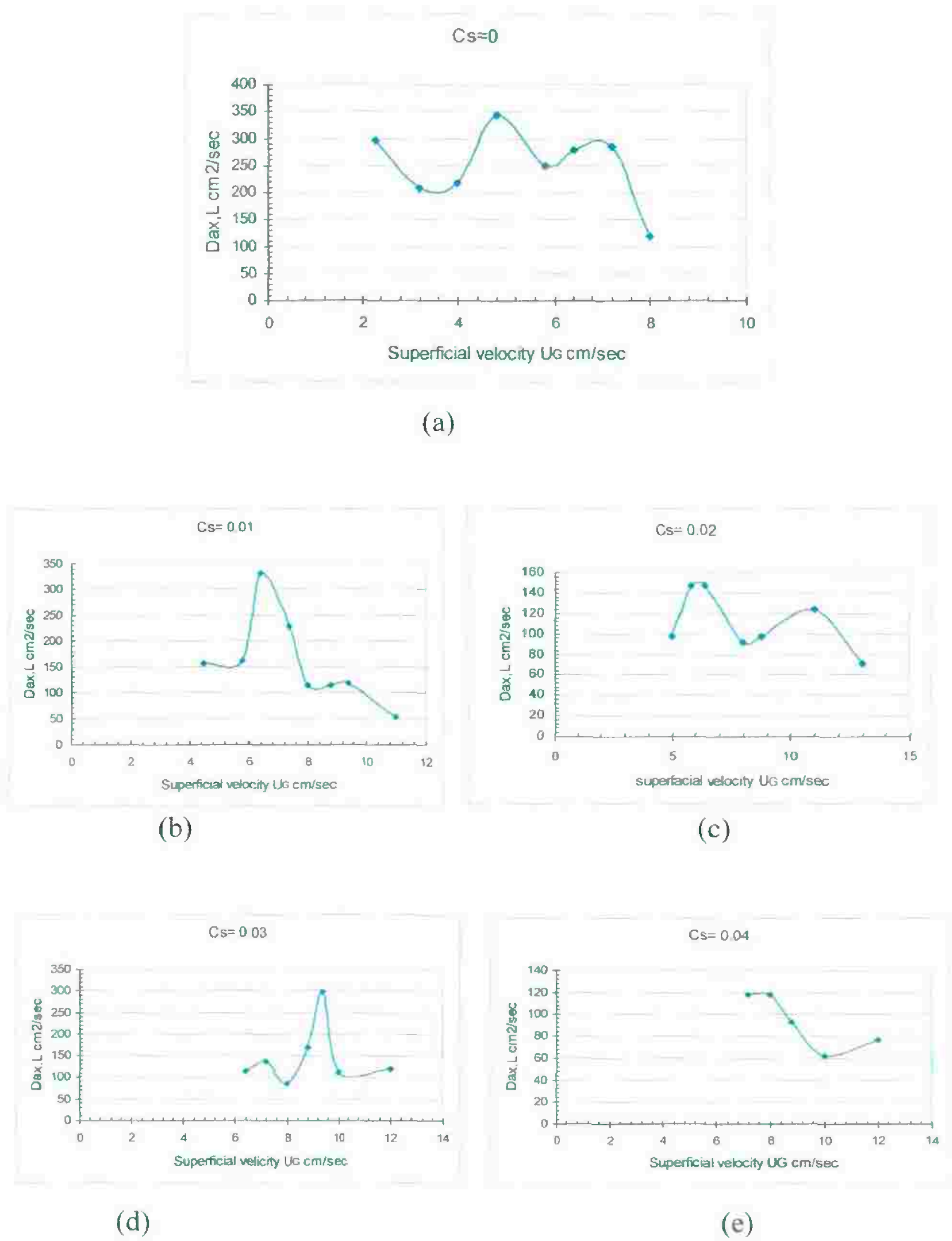
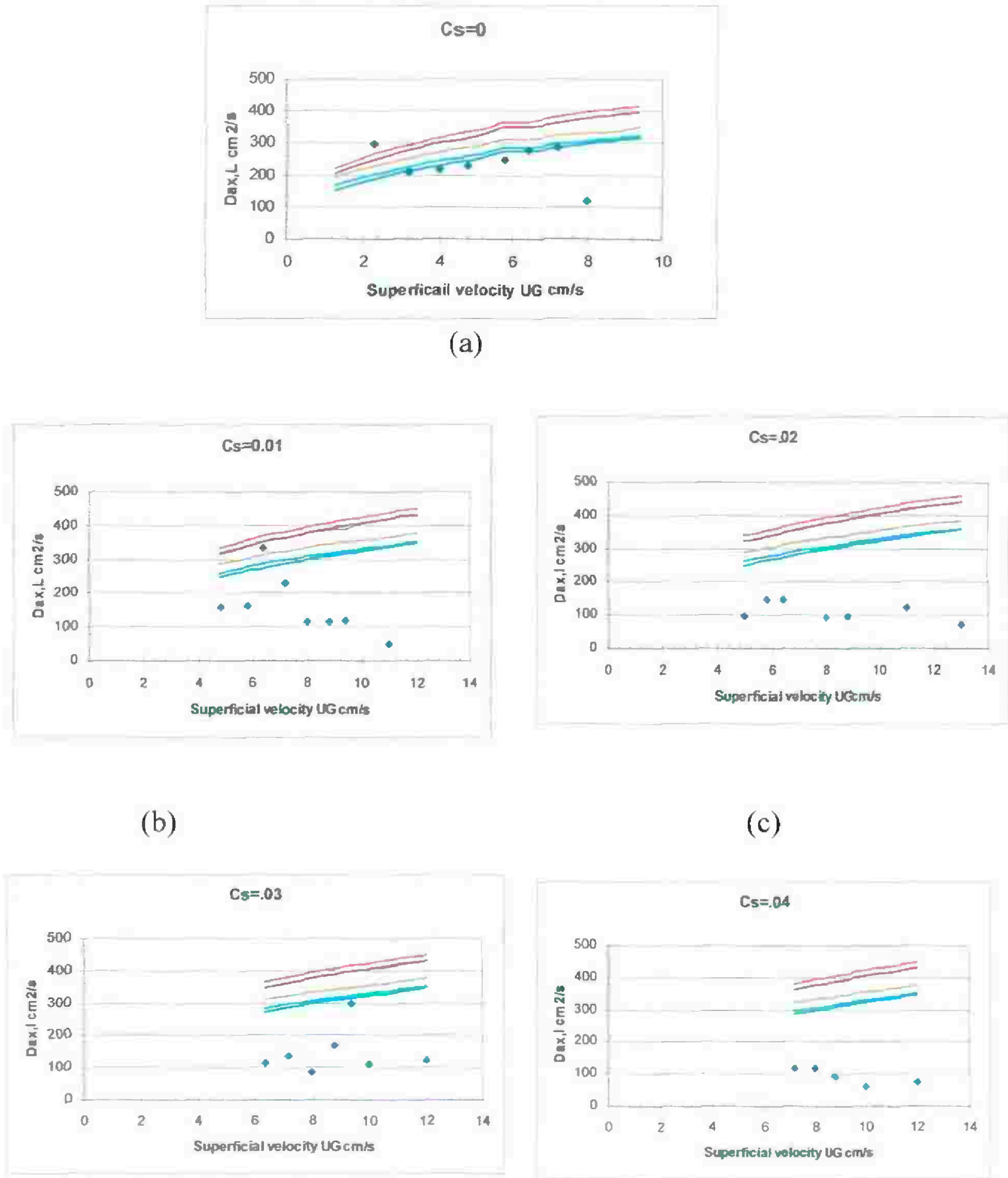


Figure (5-10): Effect of Solid Concentration on the Dispersion Coefficient for Empty Slurry Bubble Columns



(d) (e)

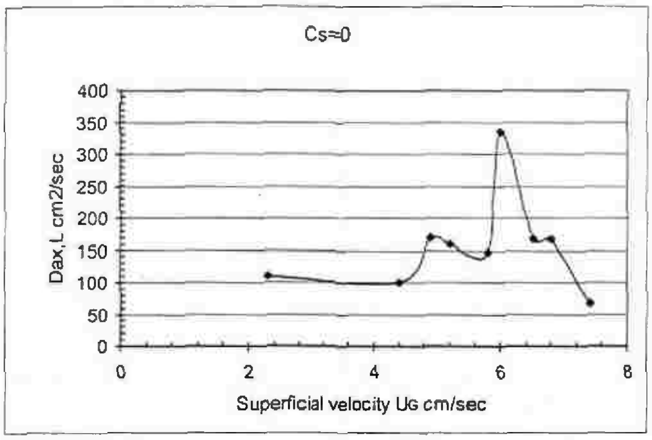
Figure (5-11): Comparison of Experimental Results for Liquid Phase Axial Dispersion Coefficient with Literature Correlations for Gas-Liquid-Solid Systems at Different Solid Concentrations

5-2-2-3-Effect of Solid Particles Concentration on Liquid Mixing in Bubble Columns Containing Cooling Tubes

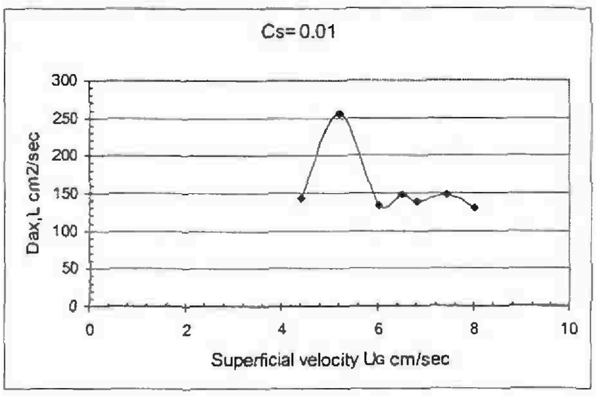
The effect of increasing solid particles concentration from 0 to 4% in bubble columns containing 35 and 57 cooling tubes is illustrated in figure (5-12 a to e) and (5-13 a to e). As with the case of empty bubble columns, the liquid dispersion coefficient exhibits a peak value between 5 and 7 cm/s superficial air velocity. For the case of 35 cooling tubes, this peak value is lower for three-phase bubble columns than for solids free systems. Exactly the reverse behavior is observed for the case of 57 cooling tubes as solids concentration is raised from 0 to 2%.I.e. The peak dispersion coefficient is higher for bubble columns containing solids than for solid free systems.

The decrease in axial dispersion coefficient with increasing solids concentration as observed for the case of empty bubble columns and for bubble columns containing 35 tubes may be attributed to that the momentum of the moving bubbles was completely transferred to the liquid phase in case of particles-free systems while part of it is utilized to suspend the particles in systems containing solids. Systems containing the highest solids content in empty bubble columns and in bubble columns containing 35 and 57 tubes show the lowest calculated dispersion coefficients.

The increase in the peak value of the liquid phase dispersion coefficient in case of 57 tubes still needs explanation.



(a)



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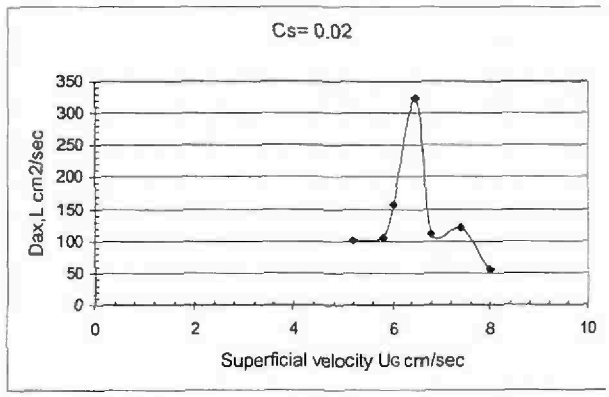

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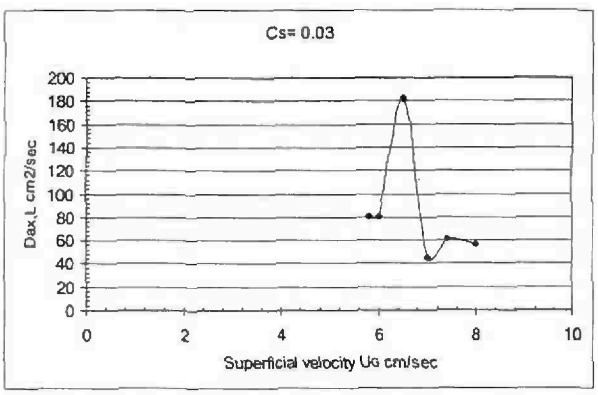

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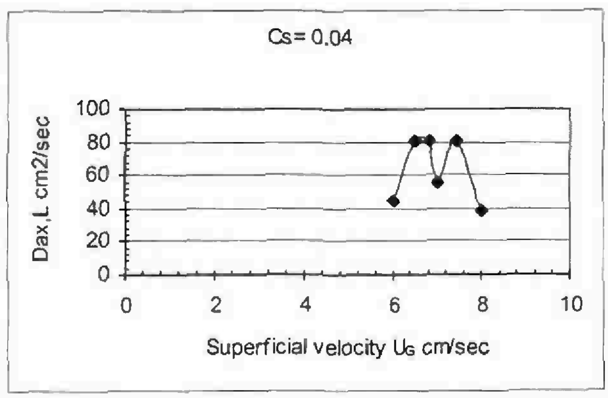
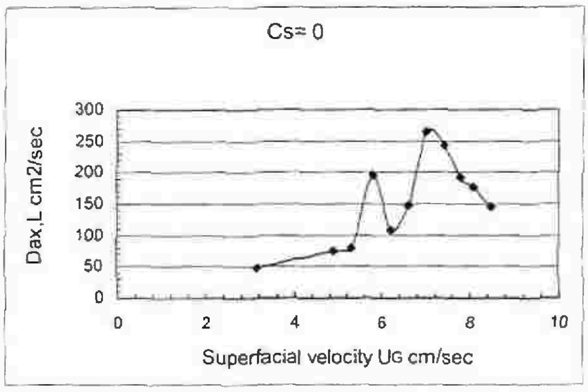
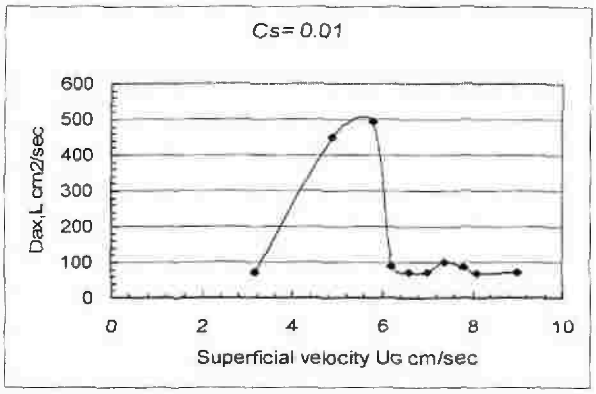


(e)

Figure (5-12): Effect of Solid Concentration on the Dispersion Coefficient in Slurry Bubble Column Containing 35 Cooling Tubes



(a)



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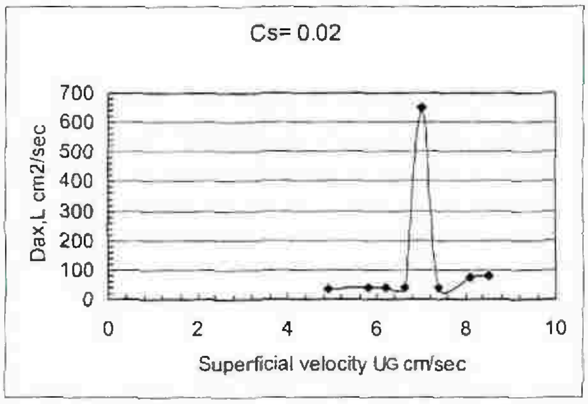

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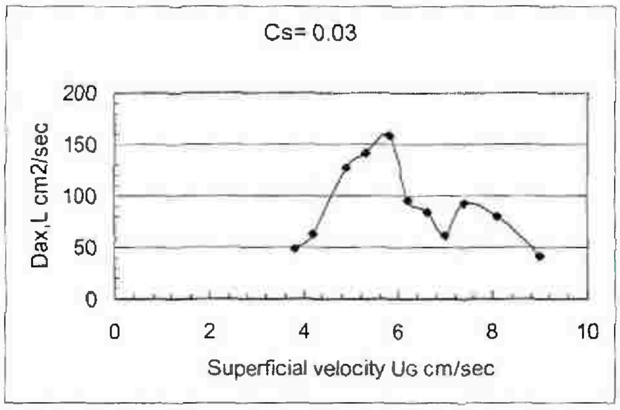

(d)

Figure (5-13): Effect of Solid Concentration on the Dispersion Coefficient in Slurry Bubble Columns Containing 57 Cooling Tubes