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Study of Multiphase Flow Useful to Understanding Scaleup of Coal Liquefaction Reactors

Technical Progress Resport
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Harold N. Knickle

Department of Chemical Engineering
University of Rhode Island
Kingston, R.I. 02881
401-792-2678 or 2655

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MULTIPHASE FLOW
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I. Highlights

This report details completion of a series of experiments with their analysis using non- Newtonian liquids in the large (13 inch) bubble column. Air and aqueous carbony methyl cellulose (CMC) were used as the working fluids. The CMC concentration was changed to simulate different non-Newtonian conditions. All the solutions can be fit with a power law model to represent the non Newtonian behavior.

The flow pattern, bubble size, and gas holdup were all studied under these conditions. Details of a procedure for CMC solution makeup are given in this report.

Experimental observations indicate that the transition from the bubble to the bubble-slug flow pattern shifts to lower gas superficial velocities as the CMC concentration increases.

The diameter of the smaller bubbles in the bubble-slug pattern tended to be independent of interfacial gas velocity.

Foam accumulation occurred at high gas velocities resulting in gas holdup values higher than might be expected in an operating bubble column. The effect of isopropyl alcohol in the liquid solution on gas holdup was large because of enhanced foam development. Increasing concentration of CMC caused a reduction in gas holdup. Correlations for holdup developed for these experiments were consistent with the small amount of data found in the literature.

II. OBJECTIVES AND SIGNIFICANCE

There are three major objectives for this proposed study. These objectives are basic to the understanding needed to develop a rationale for scale up in bubble columns. This understanding is the key to improving our scientific and technical knowledge of the fundamental process involved in complex two and three phase flows.

These objectives are:

1. to properly characterize two phase flow patterns in the region of interest that direct coal liquefaction reactors will be operated.
2. to characterize for viscous liquids, Newtonian and non-Newtonian, the flow pattern boundaries in the operating region of direct coal liquefaction reactors. The characterization would include both empirical and theoretical models.
3. to develop empirical expressions and models for the gas holdup in the flow regimes of interest. This objective would focus on non-Newtonian liquids that follow some elementary models for constitutive behavior.

The significance to the fossil energy program includes:

1. Flow pattern prediction will aid in the design and scaleup of coal liquefaction reactors.

EXPERIMENTAL

Equipment:

The bubble column used in this study consisted of a 0.33 meter inside diameter acrylic column that stands 5.38 meters high. Air was supplied by a ten horsepower compressor and was filtered and regulated prior to its introduction to the bottom of the column. Two rotameters were utilized to measure a large variety of air flow. Temperature and pressure of the air were also measured to correct the velocities to the column conditions. Liquid was introduced to the column at a point just above the distributor plate and was supplied by a one horsepower pump. Liquid velocities were measured using a bypass rotameter arrangement (Figure 1) calibrated for each fluid. Liquid was stored in and recirculated through a 170 gallon tank. Another tank was used for solution makeup. The air-liquid mixture leaving the column was separated by overflowing into a trough, the air being released to the atmosphere and the liquid draining back into the 170 gallon tank.

Holdup Measurement:

Two methods were employed to measure gas holdup. Static pressure drop was used to measure local axial holdup at intervals along the column. A manometer containing carbon tetra chloride was used to measure the static pressure. This method measures the bulk density of the two phase mixture by means of an energy balance around the manometer and the section of the column being measured. The bulk density of te two phase mixture is related to the gas holdup as follows:

$$E_G = 1 - \rho_m/\rho_W$$

This equation ignores the density of the gas which may be neglected under the test conditions.

The other method used to measure gas holdup was by measuring bed expansion. In this method the height of the two phase mixture was measured then the air and liquid flows were stopped simultaneously, the liquid height in the column was then measured after all the air had escaped. Holdup by this method can then be determined as follows:

$$E_G = (h_1 - h_2)/(h_T - h_1)$$

Flow Pattern Determination:

Flow patterns and transition regions between patterns were determined through visual observation. Photographic methods were utilized to enhance observations. The bubble to bubble slug transition region was also determined by observing the holdup versus gas velocity data. In using this method the maximum and minimum holdup on the holdup versus velocity curve using a porous plate distributor indicated the boundaries of the transition zones.

Non-Newtonian Fluids:

Eight different non-Newtonian fluids were studied (see Table 1). These included four carboxymethyl cellulose (CMC) solutions and four CMC and isopropyl alcohol (IPA) solutions. CMC was chosen for its pseudoplasatic behavior, its popularity for use in researching non-Newtonian fluids, its stability under shear and its non-hazardous nature, (8).

The rheology of CMC solutions is pseudoplastic and can be characterized using the power model, i.e.:

$$\mu = k(\dot{\gamma})^{n-1}$$

Solutions Containing IPA were utilized to provide a variation in surface tension.

Flow curves and power law coefficients were determined using a Haake RV-12 viscometer. Surface tension was measured using a Dougnoy-ring tensiometer.

Gas Distribution

Two gas distributors were utilized in this study; a polyethylene porous plate and a sieve plate. The porous plate was one quarter inch thick and 12 inches in diameter with an average pore size of 70 microns. The sieve plate was a one eighth inch acrylic plate with one eighth inch holes on a one half inch triangular pitch.

Fluid Velocities

Gas velocities were varied for each run between 0.003 and 0.012M/S. This range of gas velocities were studied to provide measurements well into the bubble-slug flow pattern (see figure 2). The number of velocities studied within this range varied between eight and ten depending on the fluid.

Three liquid velocities were studied for each fluid; 0, 0.005 and 0.012M/S. For each fluid and distributor plate runs were repeated for each of these liquid velocities.

Bubble Sizes:

Bubble sizes were determined for each fluid and distributor plate as a function of gas velocity. Still picture photography was utilized to measure bubble sizes. A transparent millimeter scale was included in all photographs to facilitate measurement of bubble diameters.

Sauter average bubble diameters were determined for each photography. The sauter average was calculated from:

$$d_{SB} = \frac{\sum n_i d_B^3}{\sum n_i d_B^2}$$

Experimental Errors:

Experimental errors occurred in the overall gas holdup measurements in CMC/IPA solutiaons at low to moderate gas velocities and in all solutions at high gas velocities. In the CMC/IPA solutions, foam accumulation in the column and the lack of a well defined liquid-foam interface resulted in gas holdup measurements greatly exceeding the average axial holdup by as much as 50%.

Due to the viscous nature of the fluids tested, errors in manometric measurements were minimal and were estimated to average plus or minus 0.2 inches. The resulting error in the gas holdup averaged less than four percent.

Other sources of error included, measurement of chemical quantities for solution makeup, viscosity measurements and rotameter variations. Of these only the viscosity measurement errors were considered important. Low viscosity fluids that had shear stress measurements less than ten percent of full scale at the highest shear rates had error that exceeded ten percent

Experimental Procedure

Gas holdup experiments were conducted at three different liquid velocities and then two types of distributor plates. Table 2 lists the solute concentrations and liquid velocities for each distributor plate and experimental run.

The procedure used in these experiments was as follows:

1. The column was filled with liquid.
2. The gas shutoff valve was actuated and the velocity was adjusted to one of the predetermined meter calibrations.
3. The differential pressure between the top two pressure taps on the column were monitored.
4. The gas velocity was monitored and adjusted as needed.
5. The liquid velocity was monitored and adjusted as needed.
6. When the pressure differential at the top of the column became constant, usually after five minutes but as long as twenty, the gas meter reading, gas temperature and pressure were recorded.
7. The differential pressure between all of the pressure taps, beginning at the top of the column. Each time the manometer valves were switched the new differential pressure was monitored until a new equilibrium condition was established.
8. Finally the height of the two-phase mixture in the column was measured if the liquid velocity was zero. If the liquid velocity was not zero the bed height was considered the top of the column. The electric shutoff valves were then actuated, first the liquid then the gas. The height of the liquid was then measured after the gas had left the bed.
10. Observations were made during each run concerning bubble sizes and flow patterns. These observations were recorded on the respective runs data sheets.

Solution Makeup

Two types of solutions were utilized in the experiments; IPA and CMC solutions and CMC solutions without IPA. Only one concentration of IPA (eight percent by weight) was used in solutions that contained IPA. The solutions, their concentrations and physical properties are detailed in Table 2.

The solution makeup procedure was as follows:

1. The small tank was filled to three quarters with deionized water and the large tank was filled to one hundred gallons with deionized water.
2. CMC was added to the small tank by slowly shaking the CMC in the proximity of the agitator. The agitator speed was adjusted as CMC was added to maintain a high circulation rate.
3. If IPA was used, it was added to the one hundred gallons of water in the large tank.
4. When the CMC in the small tank had dissolved, usually after two hours or when the solution became clear, it was pumped into the large tank. The solution in the large tank was then pumped back into the small tank several times to rinse the small tank.
5. Finally, the small tank was rinsed with deionized water several times, pumping the rinse water into the large tank. The large tank was then filled to the one hundred seventy gallon mark.

Photographic Procedure

Photographs were taken on all runs where the liquid velocity was 0.012 m/s. Photographs were taken at the column wall 0.3 meters above the distributor plate.

DISCUSSION AND RESULTS

Flow Patterns:

The bubble to bubble-slug flow transition was observed for all of the fluids studied. This transition varied with both CMC and IPA concentrations. Transitions were only observed visually. However, in some CMC-IPA solutions the change was so subtle, the point where bubble slug flow began could not be pinpointed. This was the case with two of the CMC-IPA solutions, 0.25% CMC and 0.5% CMC. In these solutions a gradual appearance of substancially larger bubbles (20mm as opposed to 1-5mm) with increasing gas velocity occurred. But the point which the flow pattern changed was not obvious. But the point which the flow pattern changed was not obvious. The IPA solution with 0.75%wt CMC showed a well defined transition from bubble to bubble-slug while the IPA solution showed a dependence on height in the column. Coalescence began at the top of the column and moved downward with increased gas velocity. The behavior above and below the transition point in the column was easy to distinguish. The two phase mixture at the top was highly turbulent and very large bubbles occurred with a short frequency. The mixture at the bottom of the column displayed a lot of backmixing but not the violent action observed at the top and no very large bubbles were observed in the bottom.

A Phenomenon that hampered observation of flow pattern transition in the IPA solutions was the occurrence of foam in the column. In the bubble flow pattern foaming was extensive and with no liquid flow the foam was observed to overflow the column for as long as twenty minutes. Once the transition point was past, the foam broke down however. At increased liquid velocities foam was less of a problem as it was continuously discharged from the column. At higher CMC concentrations (0.75 and 1.0%) foam was also hindered some what. The 1.0% solution showed only a pronounced zone at the top of the column at low gas velocities below the transition. The 0.75% solution showed more foam however, it was considerably less than that observed at lower concentrations.

Analysis of the gas holdup data revealed flow pattern transitions at for the most part the same gas velocities as the visual observations. For both CMC solutions with and without IPA a general trend was observed in the transition gas velocity and CMC concentration. For both types of solutions this trend followed;

$$V_t = A-B(\text{CMC Conc})$$

Errors arising in the determination of these transitions at the location of peak gas holdup were not well defined in most of the gas holdup data. These errors were estimated by considering the distance between adjacent data point as the range in which the peak may lie.

Gas holdup was measured as a function of height in the column and gas velocity. In general gas holdup was higher with the porous plate than with the sieve plate. The most predominent difference was observed in the bubble flow pattern. In the bubble-slug flow pattern the differences were small.

The effect of CMC concentration on gas holdup with the sieve plate was predictable in solutions of CMC and water alone, holdup decreased with increased CMC concentration. Gas holdup for CMC solutions with IPA was unpredictable the 0.5% solutions gave higher holdup values than all of the others including the 0.25% solution. The 0.25% and 0.75% had almost identical holdup curves for the zero liquid flow case.

Gas holdup data with the porous plate revealed the two flow patterns in which the column was operated, bubble flow and bubble-slug flow. Gas holdup in the bubble flow pattern increased faster with gas velocity than in the bubble-slug pattern. See Figures 3 and 4.

The effect of IPA on gas holdup was pronounced. Gas holdup was observed to exceed 50 percent at peaks in several solutions; 0.0%, 0.25%, and 0.5% CMC. These excessive gas holdups were possibly due to foam accumulation in the column. Foam was observed in the bubble column with all of the IPA solutions. The lower concentrations of CMC resulted in higher foam production.

The effect of CMC concentration of gas holdup was to retard it. Gas holdup increased in the bubble flow pattern with increased CMC concentration. The gas velocity at maximum gas holdup in the bubble flow pattern decreased with increased CMC concentration. In the bubble-slug flow pattern the differences were substancially less however, between various CMC solutions.

The effect of liquid velocity on gas holdup was to decrease it in the bubble flow pattern, (figures 5, and 6). There was a negligible effect on holdup in the bubble-slug flow pattern. IPA solutions showed little change in the bubble flow pattern however, peak holdup was reduced with increased liquid velocity; probably due to the expulsion of foam from the column.

Correlation of Results:

Flow pattern transitions for both CMC solutions and IPA and CMC solutions were found to be inversely related to CMC concentration and thus related to apparent viscosity. Since the shear rate in the bubble flow pattern and in the bubble to bubble-slug transition had never been determined, Nishikawa (30) determined shear rates for heterogeneous flow, a pseudo apparent viscosity was used. This pseudo apparent viscosity was defined as:

$$\mu_{app^1} = KV_{Gs}^{n-1} \qquad (1)$$

The transition gas velocity for acqueous CMC solutions was found to fit:

$$V_{GS} = 0.0023\mu_{app}^{1-0.69} \qquad (2)$$

The transition superficial gas velocity could then be determined by inserting equation 1 into 2 and rearranging:

$$LnV_G = -\frac{0.69LnK + 6.075}{0.69n + 0.31} \qquad (3)$$

The transition gas velocity for CMC and IPA solutions were fitted similarly this resulted in:

$$V_{GS}(t) = 0.188\,\mu_{app}^{-0.326} \qquad (4)$$

and

$$LnV_G(T) = -\frac{0.326LnK + 1.671}{0.306n + 0.694} \qquad (5)$$

The calculated and observed transition gas velocities were plotted in figure 7.

Equations 3 and 5 indicate that the transition from bubble to bubble-slug flow is dependent on the rheological properties of the liquid. Prior studies (5,6,39) for newtonian liquids indicated the transition to be independent of viscosity.

Gas holdup data for both aqueous CMC solutions and CMC and IPA solutions were fitted to equations of the form:

$$E_G = \frac{\alpha}{B + K} V_{GS}^{(c-n)\gamma} \qquad (7)$$

For aqueous CMC solutions holdup data in the bubble flow patterns for the porous plate distributor were correlated. The resulting equation was;

$$E_G = \frac{0.0694}{0.0583 + K} V_{GS}^{2.8(n-0.761)} \qquad (6)$$

The standard deviation of the differences for this equation was 0.015.

This correlation is limited to the bubble flow pattern. The maximum gas velocity in this flow pattern can be determined using equation 3.

Gas holdup data for CMC solutions with the sieve plate distributor were fitted to:

$$E_G = \frac{0.10}{0.135 + K} V_{GS}^{0.773(1.682-n)} \qquad (7)$$

The standard deviation from this curve was found to be 0.011 (Figure 8).

There is no apparent physical explanation to the form of these equations in that the addition of a constant to k makes no physical sense. Further apparent viscosity or shear stress can not be extracted from k and the velocity term in either equation. The form of the gas velocity terms however does have physical implications. The sign on the flow index "n" is positive for the bubble flow pattern and negative for the bubble slug. This indicates a different set of forces or a different balance of forces acting on the bubbles in both patterns. In the bubble flow pattern gas holdup is proportional to $Vgs^{2.8n}$, this indicates that holdup increases with shear stress. It is possible that increased shear stress retards bubble vibrations and oscillations thus reducing interactions with other bubbles, this combined with decreased bubble rise velocities would result in increased gas holdup up to the point where bubbles are bunched too close together and begin to interact anyway. This phenomenon was noted by Schumpe and Deckwer (35) and attributed to reduced bubble rise velocities.

Gas holdup data for IPA solutions could not be correlated to any models similar to the ones used for aqueous CMC solutions. This lack of fit may have been due to the complex nature of these solutions. It was apparent in figures 5 and 6 that there were competing effects from the CMC and IPA in solution. Gas holdup was maximized in the 0.5% CMC solution and minimized in the one percent CMC solution. This would suggest that CMC and IPA interact at the interface in some way.

Bubble Sizes:

Bubble diameters were measured for each fluid and gas distributor. The resulting sauter mean bubble diameters varied between 0.0008 and 0.02M. Bubble diameters did not appear to correlate with gas velocity except that they tended to stay constant. No relation was sought however, due to the excessive scatter in the data; figures 9 and 10.

This scatter was most likely due to the small sample of data obtained for large diameter bubbles. The appearence of ocassional large bubbles in photographs caused the large spikes in figures 9 and 10. This was again the result of too small a sample and a disproportionate number of small bubbles near the column wall.

Comparison of Results with Literature:

Flow Pattern:

Schumpe and Deckwer did not discuss flow pattern transitions and the effect of CMC concentration or rheological properties on the flow pattern transitions. They did however provide a flow map whose coordinates are gas velocity and apparent viscosity. This flow map indicated a decrease in the bubble to bubble-slug flow pattern transition with increased apparent viscosity. This agreed with the present study.

The gas velocities at peak gas holdup in the bubble flow pattern reported by Schumpe and Deckwer were plotted with the data from this study as both CMC concentrations and the gas velocity predicted by equation (3), in Figures 11 and 12. Schumpe and Deckwer's data exhibited behavior that varied from the present study in figure 11, their velocity vs. concentration data appeared to fall on a curve while data from this study fell closer to a straight line. This was probably due to differences in rheological properties of the solutions used and the use of a different gas distributor; Schumpe and Deckwer used a sintered plate with an average pore diameter of 150mm. In figure 12 Schumpe and Deckwer's data was plotted against gas velocities predicted with equation 3 and their viscosity data. This plot showed a closer relationship between the two sets of data, Schumpe nd Deckwer's values were however higher than predicted for the most part. This was possibly due to the different gas distributors.

Gas Holdup:

The correlation developed for gas holdup in the bubble flow pattern, equation 6 was plotted for a 1.0% CMC solution with Schumpe and Deckwer's correlation for gas holdup in the bubble flow pattern for solution concentration greater than 0.8%, see figure 13. Gas holdup in the bubble flow pattern was found to be higher in this study than reported by Schumpe and Deckwer. This was probably again due to difference in the gas distributors. Insertion of "k" and "n" for Schumpe and Deckwer solutions into equation 6, predicted generally higher holdup than that observed by Schump and Deckwer, see Figure 12.

Equation 7 was compared with Schumpe and Deckwer's correlation for holdup using a sieve plate and Godbole etals correlation for gas holdup, also with a sieve plate, see figure 14. All three curves showed good agreement upto a gas velocity of 0.04m/s. At velocities above 0.04m/s the curves diverged, Schumpe and Deckwer's increased faster and Godbole etals increased slower than equation 6. Godbole etals curve was much closer to equation 6.

CONCLIUSIONS AND RECOMMENDATIONS

Conclusions:

Based on the results of this study a number of conclusions may be drawn about the effect of non-newtonian liquids on two phase flow parameters:

1. Rheological properties can effect gas holdup in bubble columns. The way in which these properties affect gas holdup depends on the flow pattern the column is operating in. In the bubble flow pattern gas holdup increases with viscosity at a particular gas velocity. In the bubble-slug or hetergeneous flow pattern gas holdup generally decreases with viscosity.
2. Liquid velocity effects gas holdup in the bubble flow pattern. Increasing the liquid velocity reduces the gas holdup at any particular gas velocity. This effect is accentuated by increased viscosity.
3. The bubble to bubble-slug transition is dependent on viscosity. The transition gas velocity decreases with increasing gas viscosity. There is no effect of liquid velocity on this transition however in the range studied.
4. The effect of alcohol on two-phase flow parameters was extreme. Holdup in the bubble flow pattern was very high, often greater than 0.5 at peaks. The bubble to bubble-slug transition occurred at higher gas velocities than in aqueous CMC solutions. There also appeared to be competing effects between alcohol and CMC concentrations.

Recommendations:

There is a need for further investigation of two-phase flow with non-newtonian liquids. A more extensive variety of liquid properties need to be studied to separate rheological properties from other physical chemical properties such as ionic strength, surface activity.

Shear rates need to be determined in the bubble flow pattern to help understand the effect of viscosity on gas holdup. Shear rates are only known for heterogeneous flow at gas velocities above 0.04m/s.

Fast and reliable methods for determining interfacial area and bubble size distributions need to be developed. Photographic techniques are tedious, photographs are often difficult to interpret and interpretations are often dependent on the individual. Chemical methods for determination of interfacial area provide good average values however, to axial and radial dependencies local methods are required.

REFERENCES

1. Akita K. and Yoshida F., "Gas Holdup and Volumetric Mass Transfer Coefficients in Bubble Columns", Ind. Eng. Chem. Process Des. Dev., Vol. 12, No. 1, 1973, pp. 76-80.
2. Akita K. and Yoshida F., "Bubble Size, Interfacial Area and Liquid Phase Mass Transfer Coefficient in Bubble Columns", Ind. Eng. Chem. Processes Des. Dev., Vol. 13 No. 1, 1974, pp. 84-91.
3. Astarita, G. and Apuzzo, G., "Motion of Gas Bubbles in Non-Newtonian Liquids", A.I.Ch.E. Journal Vol. 11, No. 5, 1965.
4. Bailey, J.E. and Ollis, D.F., "Biochemical Engineering Fundamentals", McGraw Hill N.Y. 1977.
5. Buchholz, H., Buchholz, R., Lucke, J. and Schugerl, K., "Bubble Swarm Behavior and Gas Absorption in Non-Newtonian Fluids in Sparged Columns", Chem. Eng. Sci., Vol. 33, 1978 pp. 1061-1070.
6. Buchholz R., Franz K. and Schugerl K., "Comprehensive Study of the Gas Holdup and Bubble Size Distribution in Highly Viscous Liquids", Chem. Eng. Commun., Vol. 5, 1980, pp. 165-202.
7. Danckwerts, P.V., "Gas-Liquid Reactions",
8. Davidson, R.L., "Handbook of Water Soluble Gums and Resins", McGraw Hill, 1980.
9. Deckwer, W.D. et al, "Hydrodynamic Properties of the Fischer tropsch Slurry Process", Ind. Eng. Chem. Process Des. Dev. 1980, 19, Pg. 699-708.
10. Deckwer, W.D. etal "Oxygen Transfer into Aerated CMC Solution in a Bubble Column" Biotechnology and Bioengineering", Vol. XXIV, Pg. 461-481 1982.
11. Eissa S.H. andSchugerl K., "Holdup and Backmixing Investigations in Cocurrent and Counter Current Bubble Columns", Chem. Eng. Sci., Vol. 30, 1975, pp. 1251-1256.
12. Fernandes, R.C. etal., "A Hydrodynamic Model or Gas-Liquid Slug Flow in Vertical Tubes",
13. Florez, M.R., "Rheology of Exxon Donar Solvent (EDS) p]rocess Coal Liquefaction Streams", AIChE Fall, Annual Meeting, New Orleans, LA Nov. 8th-12th, 1981.
14. Govier and Aziz, "The Flow of Complex Mixtures in Pipes", Krieger, 1977.
15. Godbole, M.F., Honath and Shah, Y.T., "Holdup Structure in Highly Viscous Newtonian and Non-Newtonian Liquids in Bubble Columns", Chem. Eng. Commun., Vol. 16, 1982, pp. 119-134.

16. Hatate Y., Louh, C.J., Wen C.Y., "A Mathematical Model for Coal Liquefaction in the Solvent Refined Coal Process", AIChE Symposium Series, 1981.

17. Harmathy, T.Z., "Velocity of Large Drops and Bubbles in Media of Infinite Restricted Extent," AIChE J., Vol. 6, 1960, pg. 281.

18. Hewitt, G.E., "Measurement of Two Phase Flow Parameters," 1978, Academic Press.

19. Hikita, H. and Kikukawa, H., Chem. Eng. J., 8, 191, 1974.

20. Joshi, J.B. and Sharma, M.M., "A Circulation Cell Model for Bubble Columns," Inst. Chem. Eng. Trans., Vol. 57, 1979, pp. 244-251.

21. Kamat, A.B. and Knickle, H.N., "Gas Holdup and Flow Pattern Studies in a Bubble Column," submitted to Ind. Eng. Chem. Proc. Des. and Dev., Jan. 1982.

22. Kelkar, B.G., Godbole, S.P., Honath, M.F., Shah, Y.T., Carr, N.L., and Deckwer, W.D., "Effect of Addition of Alcohols on Gas Holdup and Backmixing in Bubble Columns," AIChE Journal, Vol. 29, No. 3, 1983, pp. 361-368.

23. Kirpekar, A.L. and Knickle, H.N., "A Proposed Flow Map for Use in the Design of Coal Liquefaction bubble Column Reactors," Orlando AIChE Meeting, 1982.

24. Landau, J., Boyle, J., Gomaa, H.G. and Taweel, A.M., "Comparison of Methods for Measuring Interfacial Areas in Gas Liquid Dispersions," Canadian J. Chem. Eng., Vol. 55, Feb. 1977, pp. 3-18.

25. Mahalingam, R. and Vall, M.A., "Momentum Transfer in Two-Phase Flow of Gas-Pseudoplastic Liquid Mixtures," Ind. Eng. Chem. Fund., Vol. 11, No. 4, 1972, pg. 470.

26. Mikkilineni, S., "The Effect of Gas Distributor on Holdup and Flow Pattern in a Bubble Column," Masters of Science Thesis, U.R.I., 1983.

27. Miksis, M.J., et al., "Rising Bubbles," J. Fluid Mech., Vol. 123, 1982, pp. 31-44.

28. Miller, D.N., "Gas Holdup and Pressure Drop in Bubble Column Reactors," Ind. Eng. Chem. Process Des. Dev., Vol. 19 1980 pp. 371-377.

29. Nakanoh, M. and Yoshida, F., "Gas Absorption by Newtonian and Non-Newtonian Liquids in a Bubble Column," Ind. Eng. Chem. Process Des. Dev., Vol. 19, 1980, pp. 190-195.

30. Nishikawa, et al., "Heat Transfer in Aerated Tower Filled with Non-Newtonian Liquid," Ind. Eng. Chem Process Des. Dev., Vol. 16, No. 1, 1977.

31. Pal, S.S., Mitra, A.K. and Roy, A.N., "Pressure Drop and Holdup in Vertical Two-Phase Cocurrent Flow with Improved Gas-Liquid Mixing," Ind. Eng. Chem. Process Des. Dev. Vol. 19, 1980, pp. 67-75.

32. Perez, J.F. and Sandall, O.C., "Diffusivity Measurements for Gasses in Power Law Non-Newtonian Liquids," A.I.ChE. Journal, Vol. 19, No. 5, 1979, pp. 1073-1075.

33. Probstein, R.F. and Hicks, R.E., "Synthetic Fuels," McGraw Hill, N.Y. 1982.

34. Sato, Y. nd Sekoguchi, K., "Liquid Velocity Distribution in Two-Phase bubble Flow," J. Multi Phase Flow, Vol. , 1975, pp. 44-251.

35. Schumpe, A. and Deckwer, W.D., "Gas Holdups, Specific Interfacial Areas, and Mass Transfer Coefficients of Aerated Carboxymethyl Cellulose Solutions in a Bubble Column." Ind. Eng. Chem. Process Des. Dev., Vol. 21, 1982, p. 706.

36. Schumpe, A. and Deckwer, W.D., "Comparison of the Photographic and the Sulfite Oxidation Method for Interfacial Area Determination in Bubble Columns," Chem. Eng. Commun., Vol. 17, 1982, pp. 13-324.

37. Skelland, "Non-Newtonian Flow and Heat Transfer," 1967, John Wiley and Sons, N.Y.

38. Slattery and Bird, "Non-Newtonian Flow Past a Sphere," Chem. Eng. Sci. Vol. 16, No. 3 and 4, 1961.

39. Taitel, Y., et al., "Modelling Flow Pattern Transitions for Steady Upward Gas-Liquid Flow in Vertical Tubes," A.I.ChE. Journal, Vol. 26, No. 3, 1980, pp. 345-354.

40. Thursgood, et al., "The Rheological Characteristics of Coal Liquefaction Preheater Slurries," AIChE Journal, Vol. 28, No. 1, January, 1982.

41. Towell, G.D. et al., "Mixing and Mass Transfer in Large Diameter Bubble Columns."

42. Vasalos, I.A. et al., "Modelling the Fluid Dynamics of the H-Coal Reactor," Presented at the Annual A.I.ChE. Meeting.

43. Vasalos, I.A. et al., "Experimental Techniques for Studying the Fluid Dynamics of the H-Coal Process," A.I.ChE. Transactions 1980.

44. Vermeer, D.J. nd Krisha, K., "Hydrodynamics and Mass Transfer in Bubble Columns Operating in the Churn Turbulent Regime," Ind. Eng. Chem. Process Des. Dev. Vol. 20, 1981, pp. 475-482.

45. Walter, J.F. and Blanch, H.W., "Liquid Circulation Patterns and Their Effect on Gas Holdup and Axial Mixing in Bubble Columns," Chem. Eng. Commun., Vol. 19, 1983, p. 243.

Table 1 Liquid Physical Properties

CMC Conc. (wt. %)	IPA Conc. (wt. %)	Specific Gravity	Surface Tension (Dynes/CM)	Power Law Parameters K	N
0.0	0.0	1.0	72	0.01	1.0
0.25	0.0	1.0	72	0.012	0.97
0.5	0.0	1.0	72	0.015	0.95
0.75	0.0	1.0	72	0.025	0.91
1.0	0.0	1.0	72	0.04	0.88
0.0	8.0	0.986	45	0.009	1.0
0.25	8.0	0.986	45	0.018	0.958
0.5	8.0	0.986	45	0.034	0.918
0.75	8.0	0.986	45	0.06	0.878
1.0	8.0	0.986	45	0.095	0.833

TABLE 2 EXPERIMENTAL RUNS USING AQUEOUS CMC SOLUTION

POROUS PLATE				SIEVE PLATE			
RUN#	CMC CONC. (wt. %)	IPA CONC. (wt. %)	LIQUID VEL. (M/S)	RUN#	CMC CONC. (wt. %)	IPA CONC. (wt. %)	LIQUID (M/S)
2	0.0	0.0	0.0	1	0.0	0.0	0.0
3	0.5	8.0	0.0	6	0.5	8.0	0.0
4	0.5	8.0	0.005	7	0.5	8.0	0.00
5	0.5	8.0	0.012	8	0.5	8.0	0.0
12	0.25	8.0	0.0	9	0.25	8.0	0.0
13	0.25	8.0	0.012	10	0.25	8.0	0.00
14	0.25	8.0	0.005	11	0.25	8.0	0.01
18	1.0	8.0	0.0	15	1.0	8.0	0.0
19	1.0	8.0	0.005	16	1.0	8.0	0.00
20	1.0	8.0	0.012	17	1.0	8.0	0.01
21	0.75	8.0	0.0	23	0.75	8.0	0.01
22	0.75	8.0	0.005	24	0.75	8.0	0.0
29	0.25	0.0	0.0	25	0.75	8.0	0.00
30	0.25	0.0	0.005	26	0.25	0.0	0.0
31	0.25	0.0	0.012	27	0.25	0.0	0.00
32	0.5	0.0	0.0	28	0.25	0.0	0.01
33	0.5	0.0	0.005	35	0.5	0.0	0.0
34	0.5	0.0	0.012	36	0.5	0.0	0.00
41	0.75	0.0	0.0	37	0.5	0.0	0.01
42	0.75	0.0	0.005	38	0.75	0.0	0.0
43	0.75	0.0	0.012	39	0.75	0.0	0.00
44	1.0	0.0	0.0	40	0.75	0.0	0.01
45	1.0	0.0	0.005	47	1.0	0.0	0.0
46	1.0	0.0	0.012	48	1.0	0.0	0.00
50	0.75	0.0	0.0	49	1.0	0.0	0.01
51	0.75	0.0	0.005	53	0.0	8.0	0.0
52	0.75	0.0	0.012	54	0.0	8.0	0.00
56	0.0	8.0	0.0	55	0.0	8.0	0.01
57	0.0	8.0	0.005				
58	0.0	8.0	0.012				

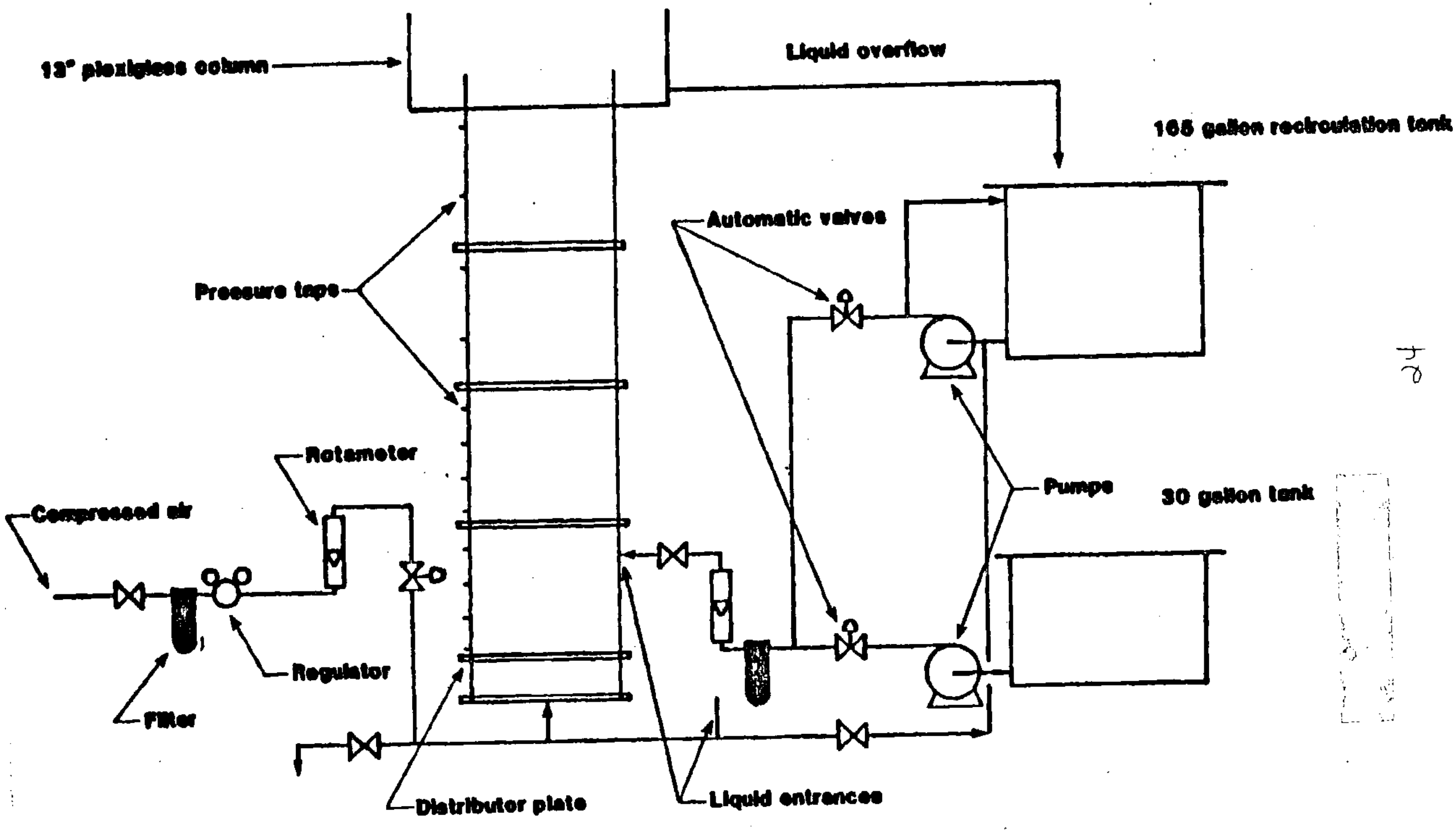

Figure 1 Bubble Column Schematic

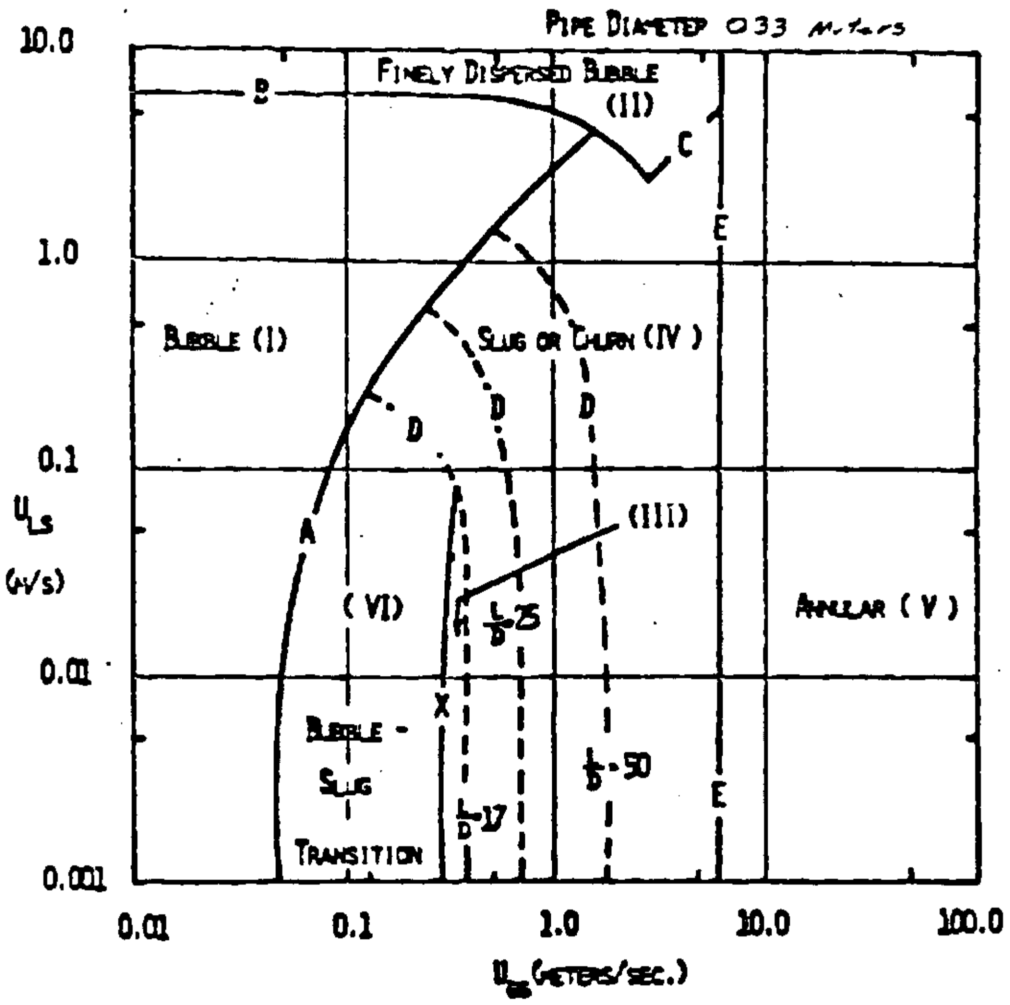

Figure 2 Flow Map for the Air-Water System

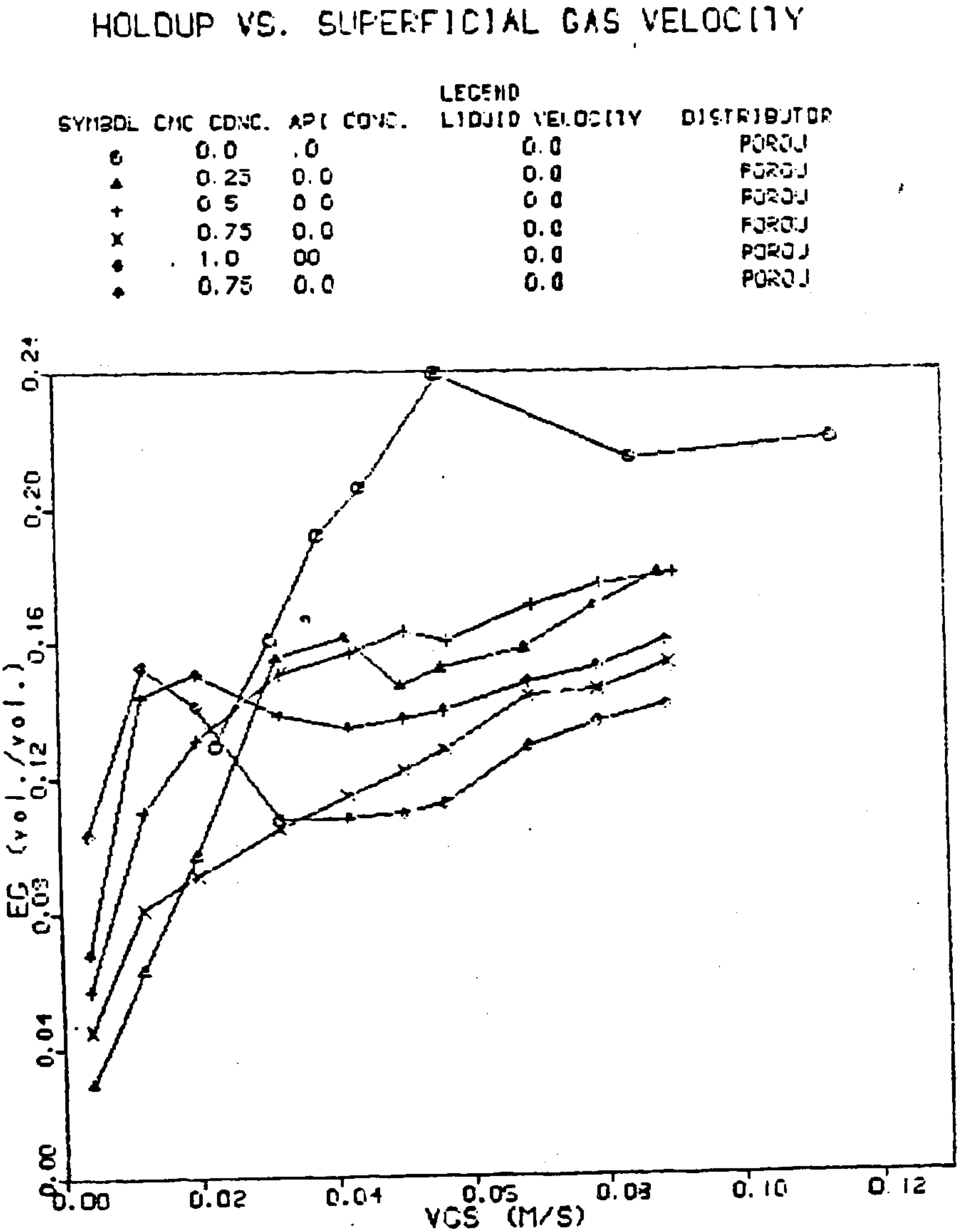

Figure 3 Effect of Porous Plate on Gas Holdup -CMC Solutions

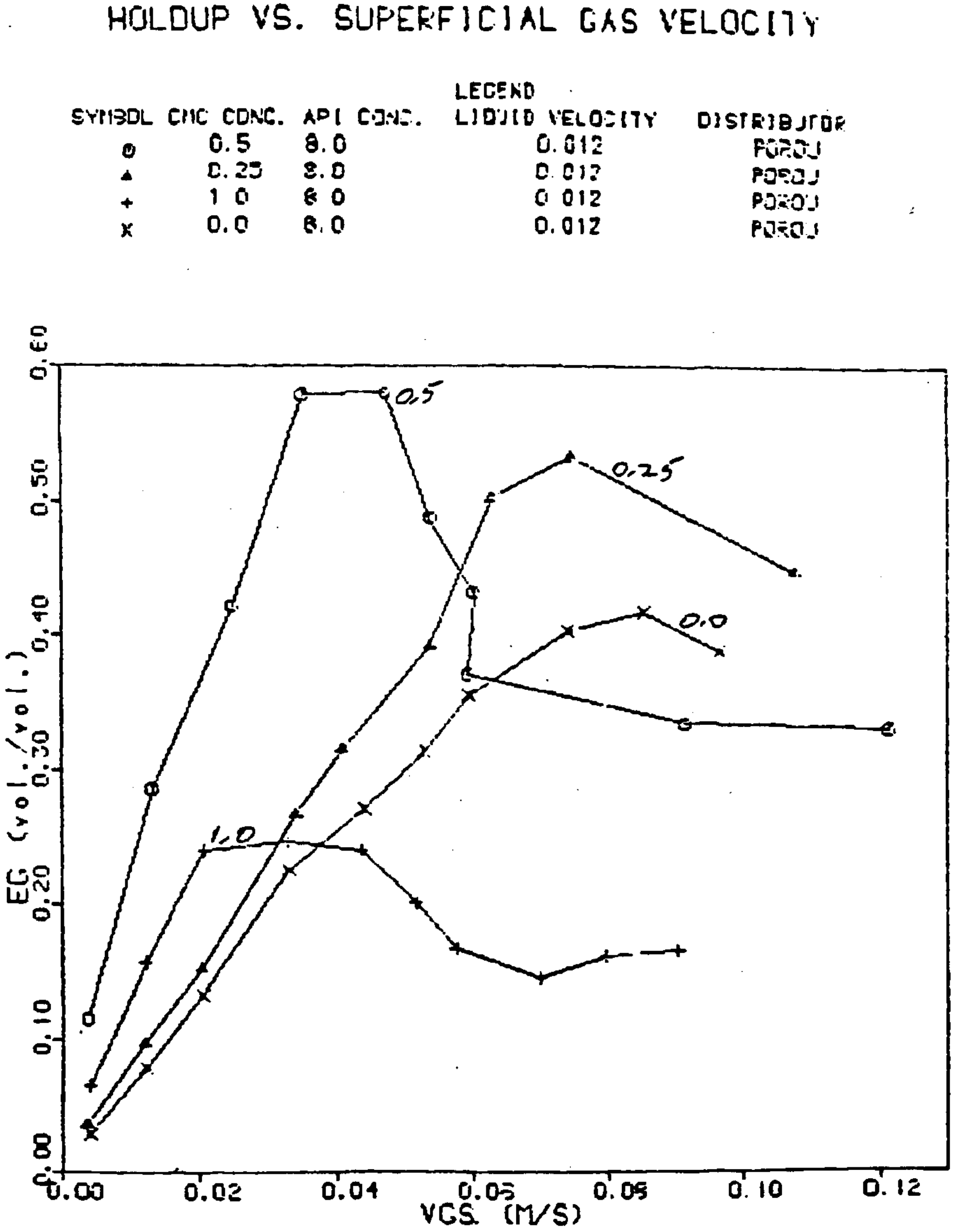

Figure 4 Effect of Porous Plate on Gas Holdup —CMC and IPA Solutions

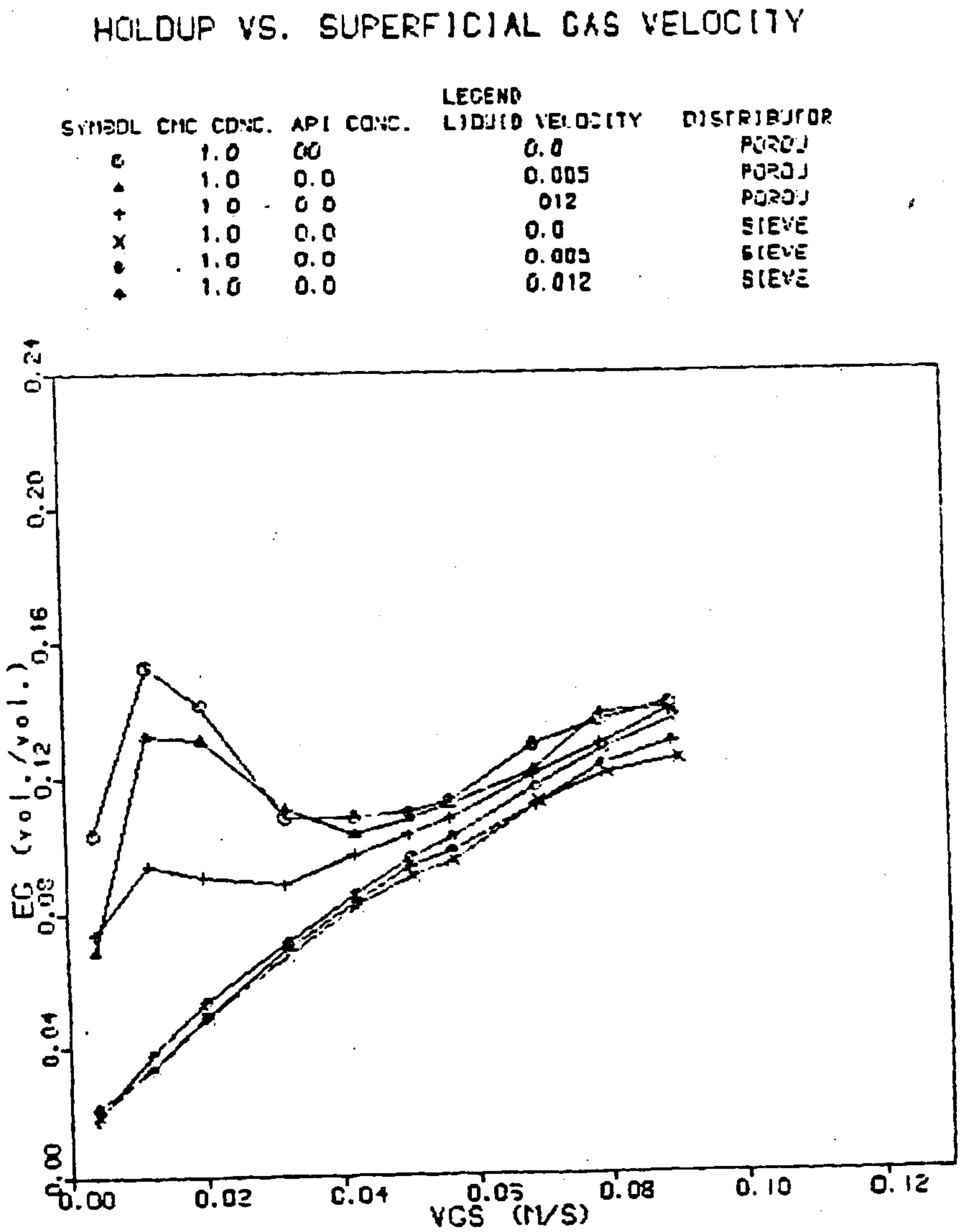

Figure 5 **Effect of Liquid Velocity on Gas Holdup; 1.0% CMC**

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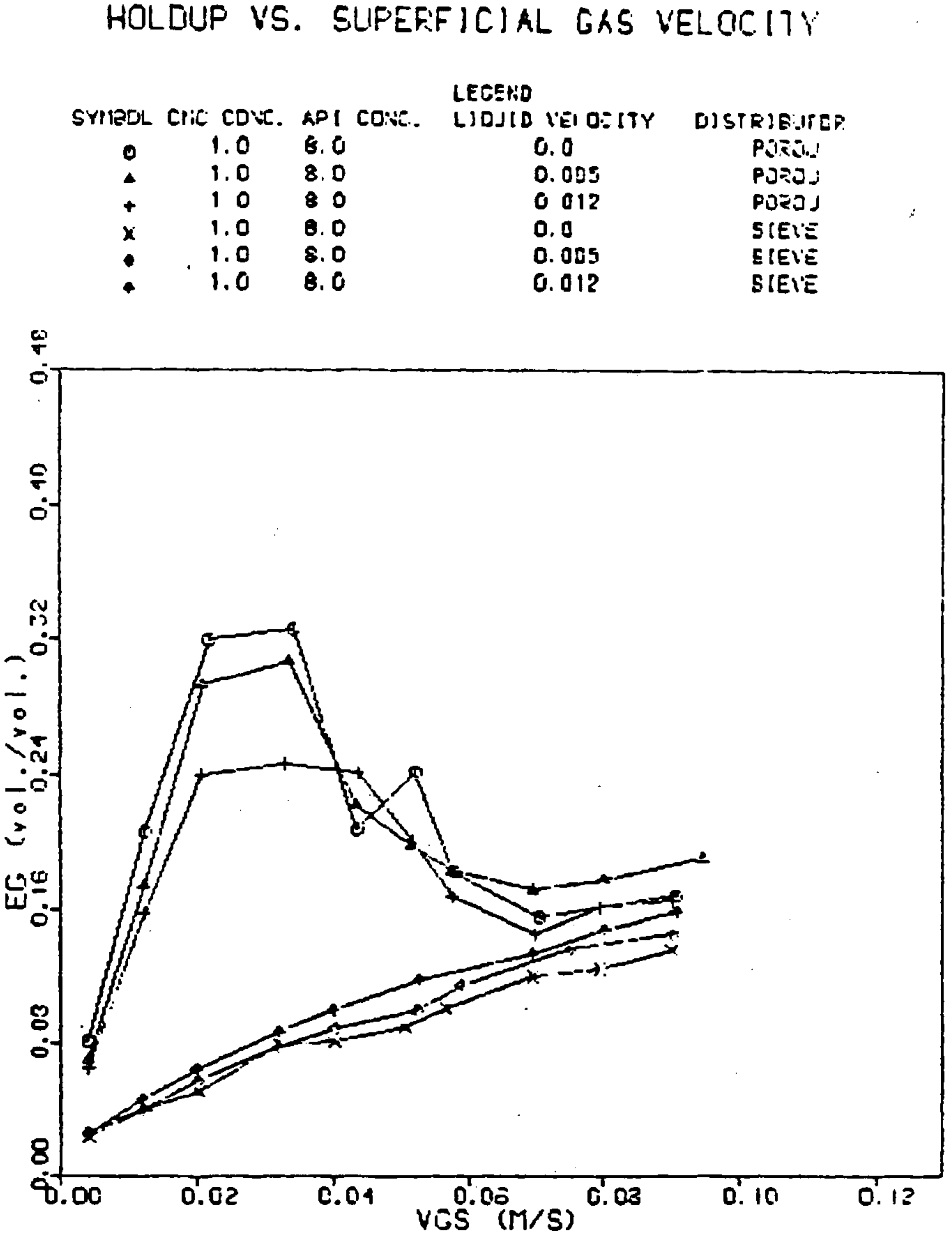


Figure 6 **Effect of Liquid Velocity on Gas Holdup; 1.0% CMC, 8.0% IPA**

CALCULATED VS. OBSERVED HOLDUP

Model

$$E_G = \frac{0.0694}{0.0583+K} V_{GS}^{(n-0.761)2.8}$$

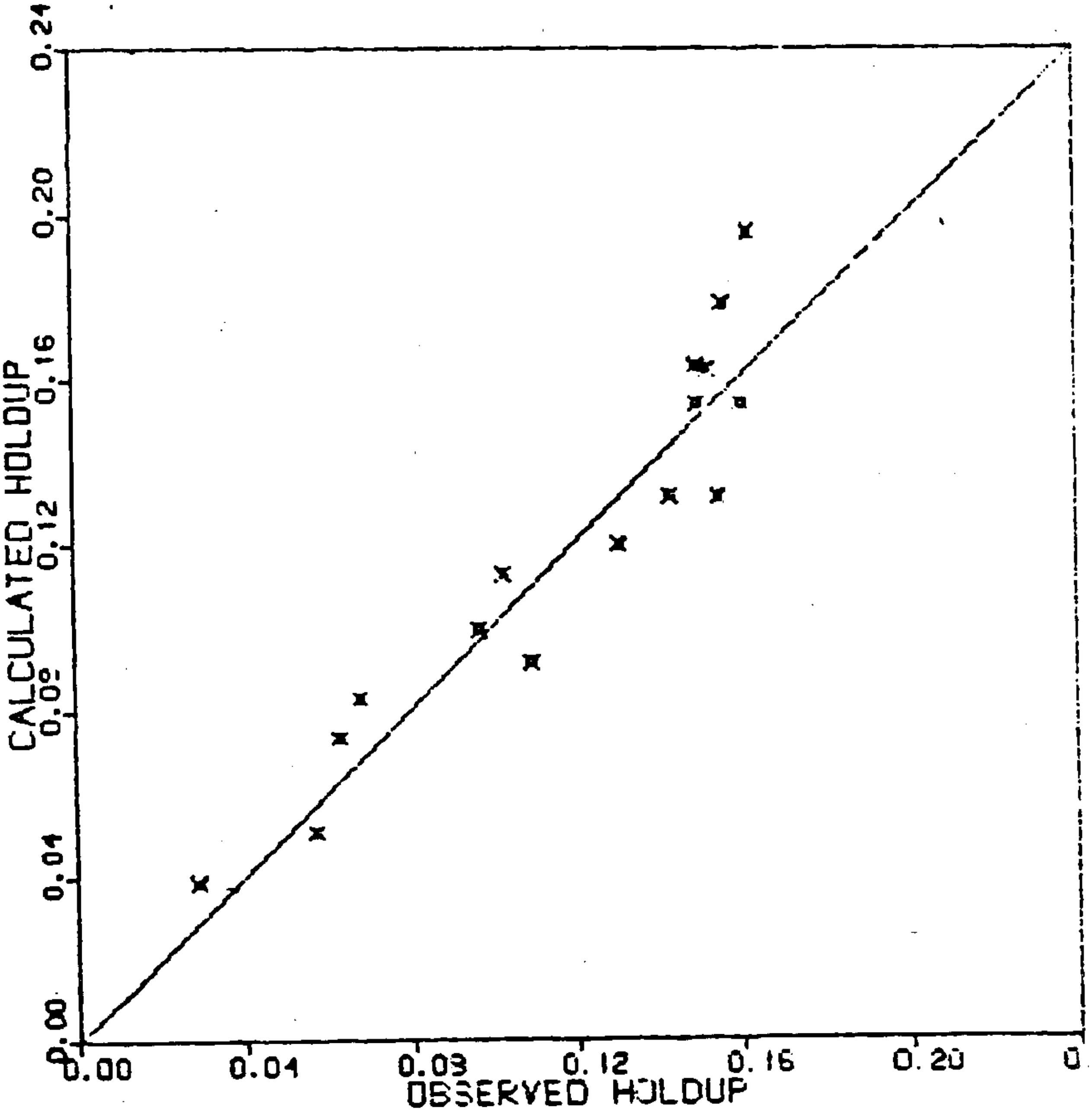
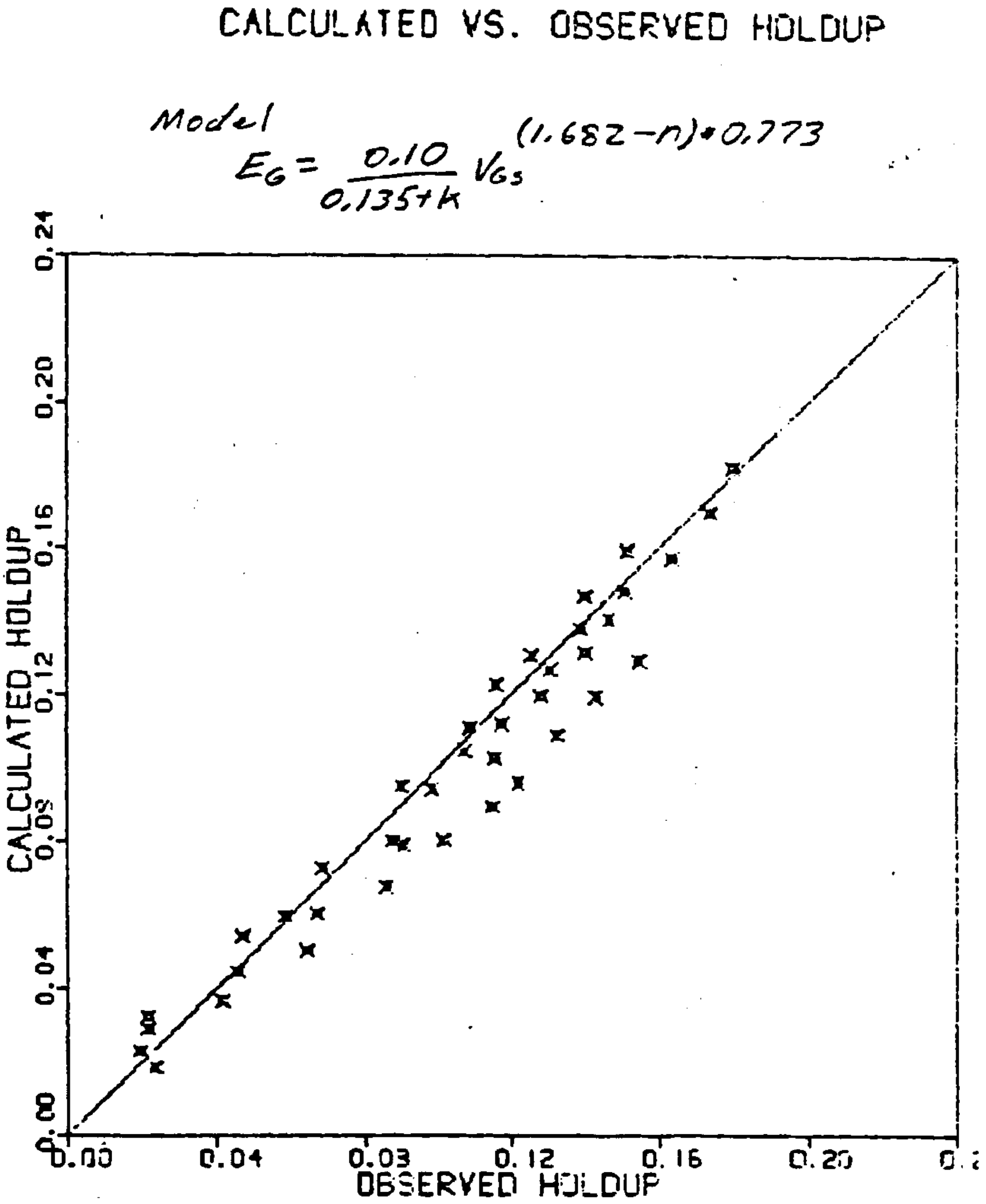


Figure 7 Parity Plot for Equation



Model

$$E_G = \frac{0.10}{0.135+k} V_{Gs}^{(1.682-n)\cdot 0.773}$$

Figure 8 **Parity Plot for Equation**

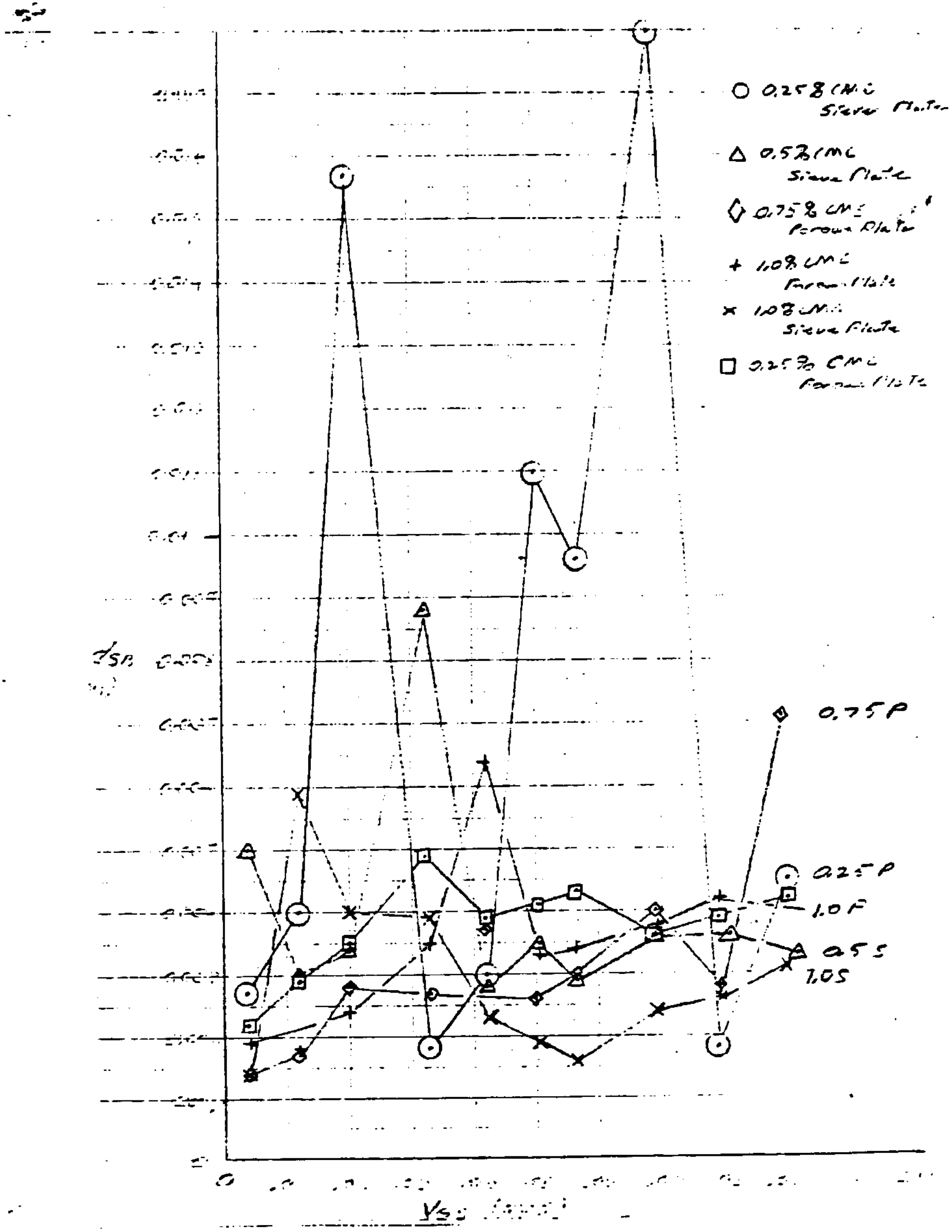


Figure 9 Variation of Bubble Sizes With Gas Velocity -CMC Solutions

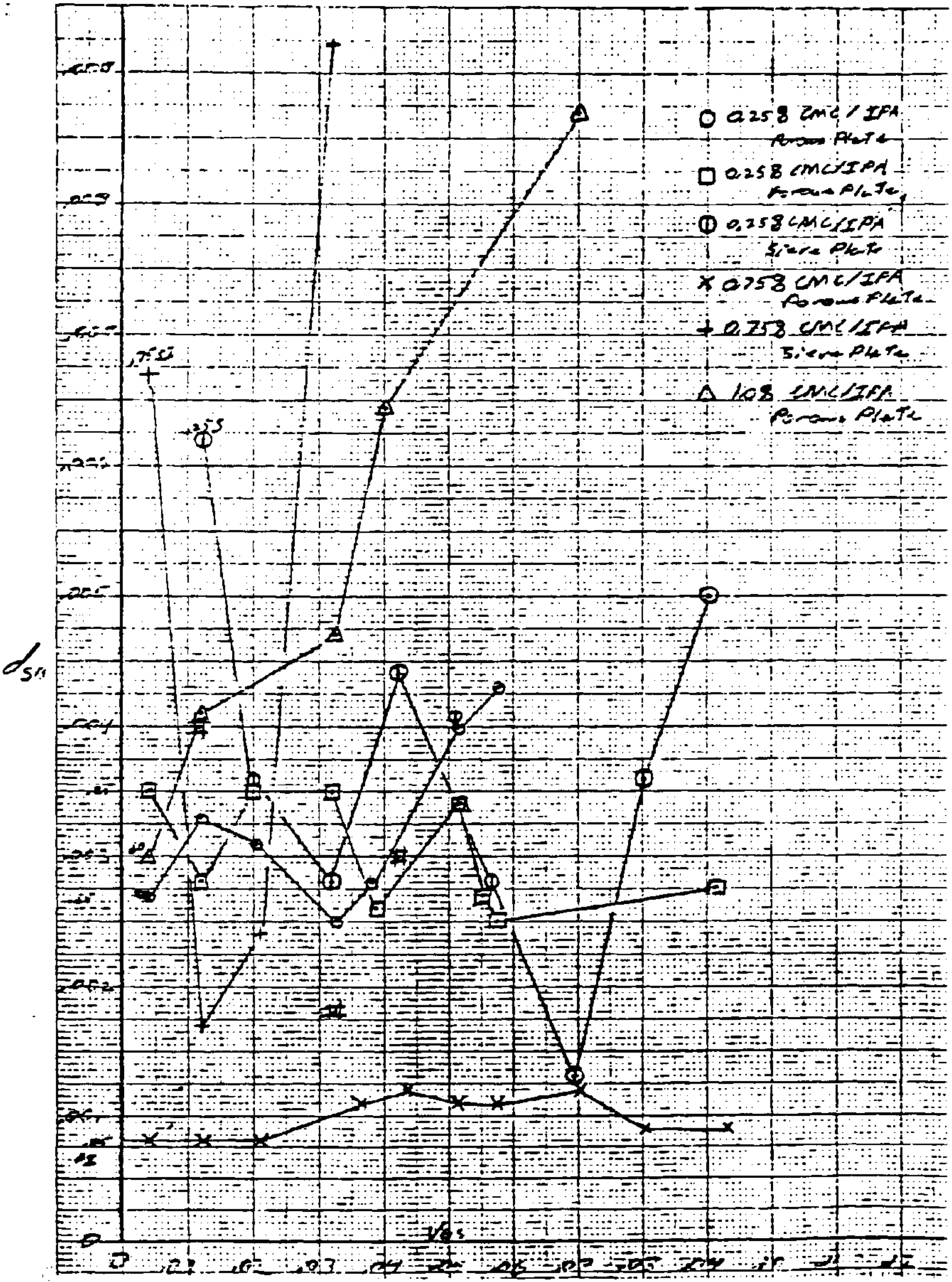


Figure 10 Variation of Bubble Sizes with Gas Velocity
-CMC and IPA Solutions

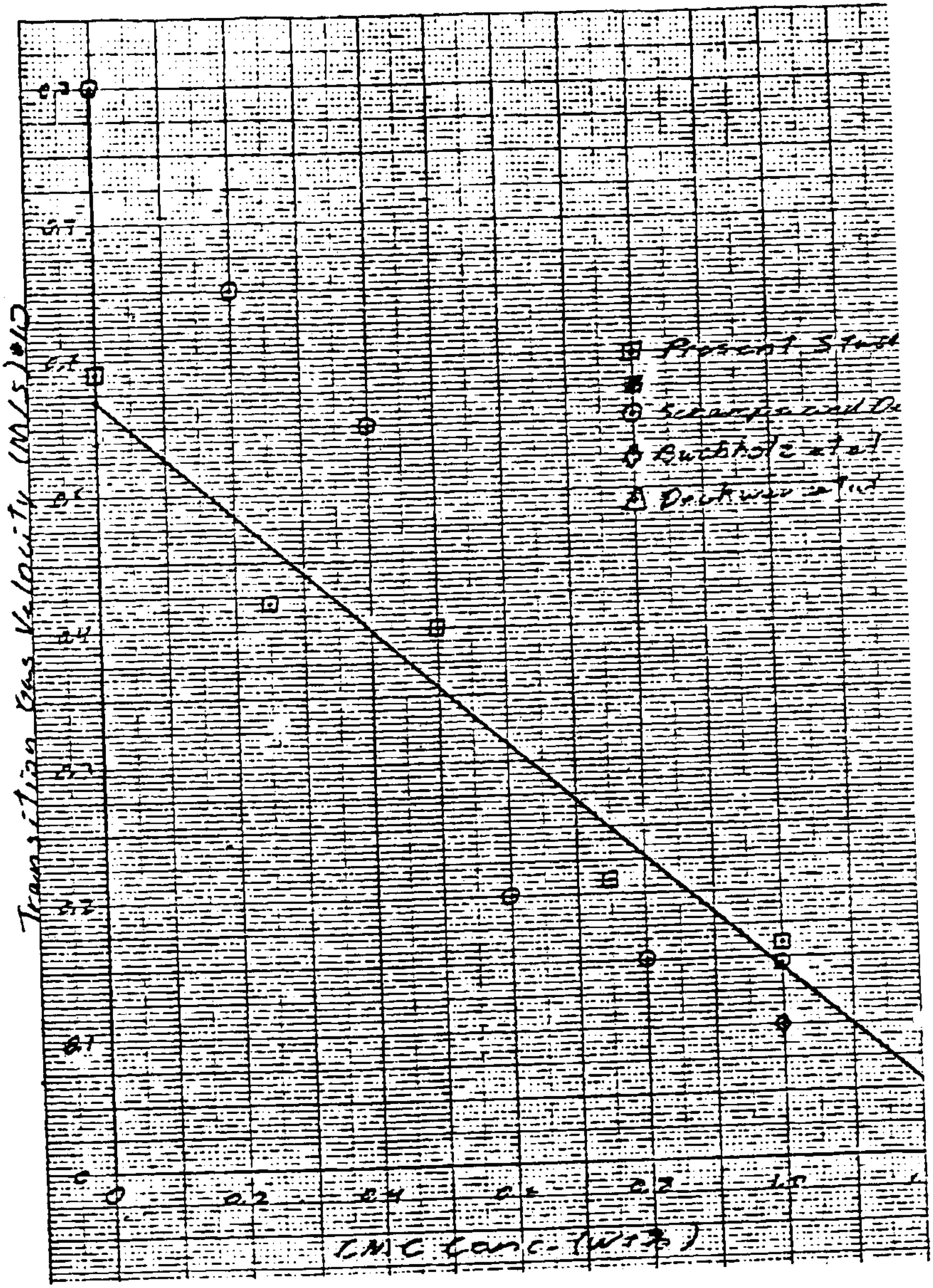


Figure 11 Comparison of Transition Gas Velocities

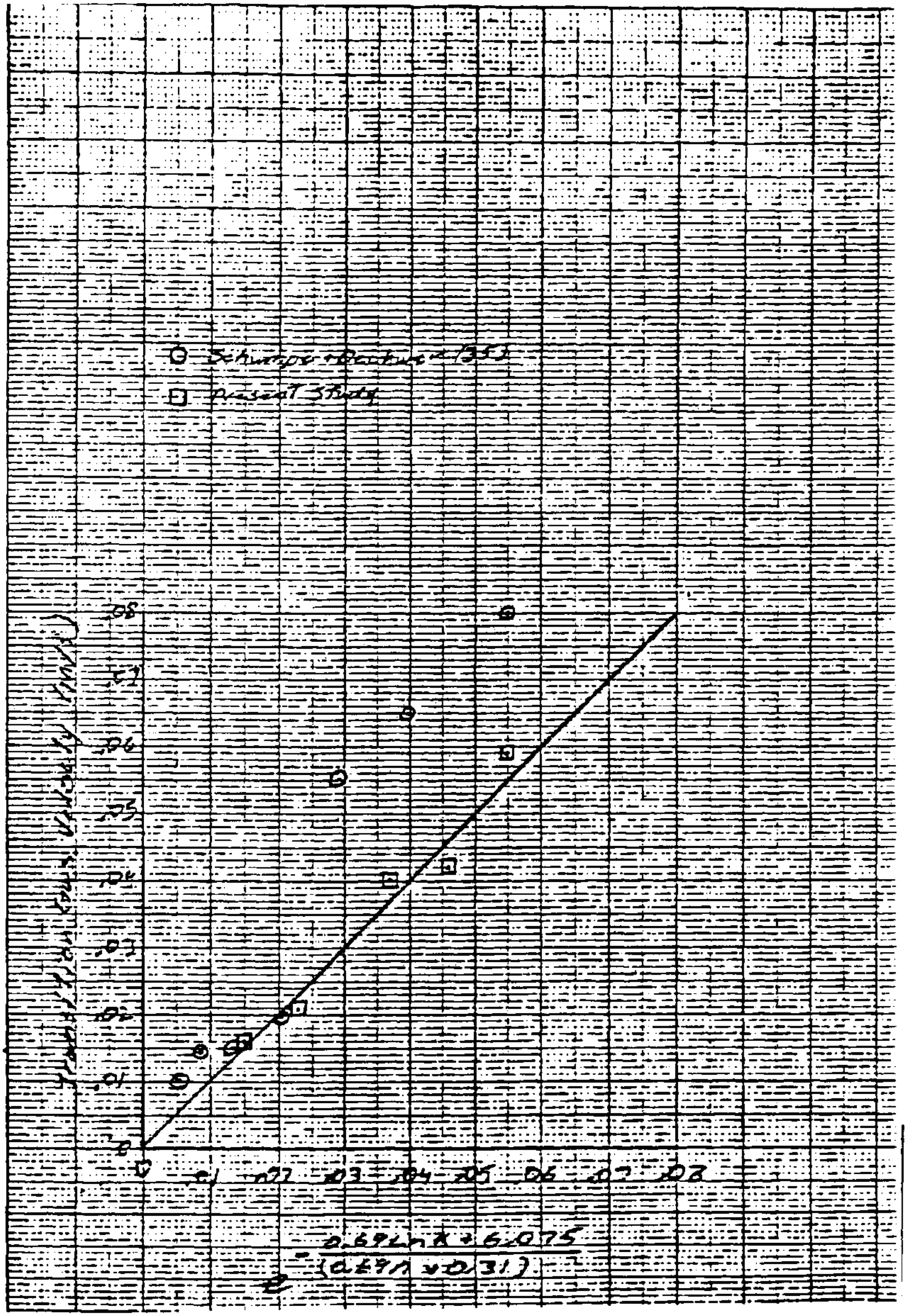


Figure 12 Comparison of Equation 4-3 with Literatur

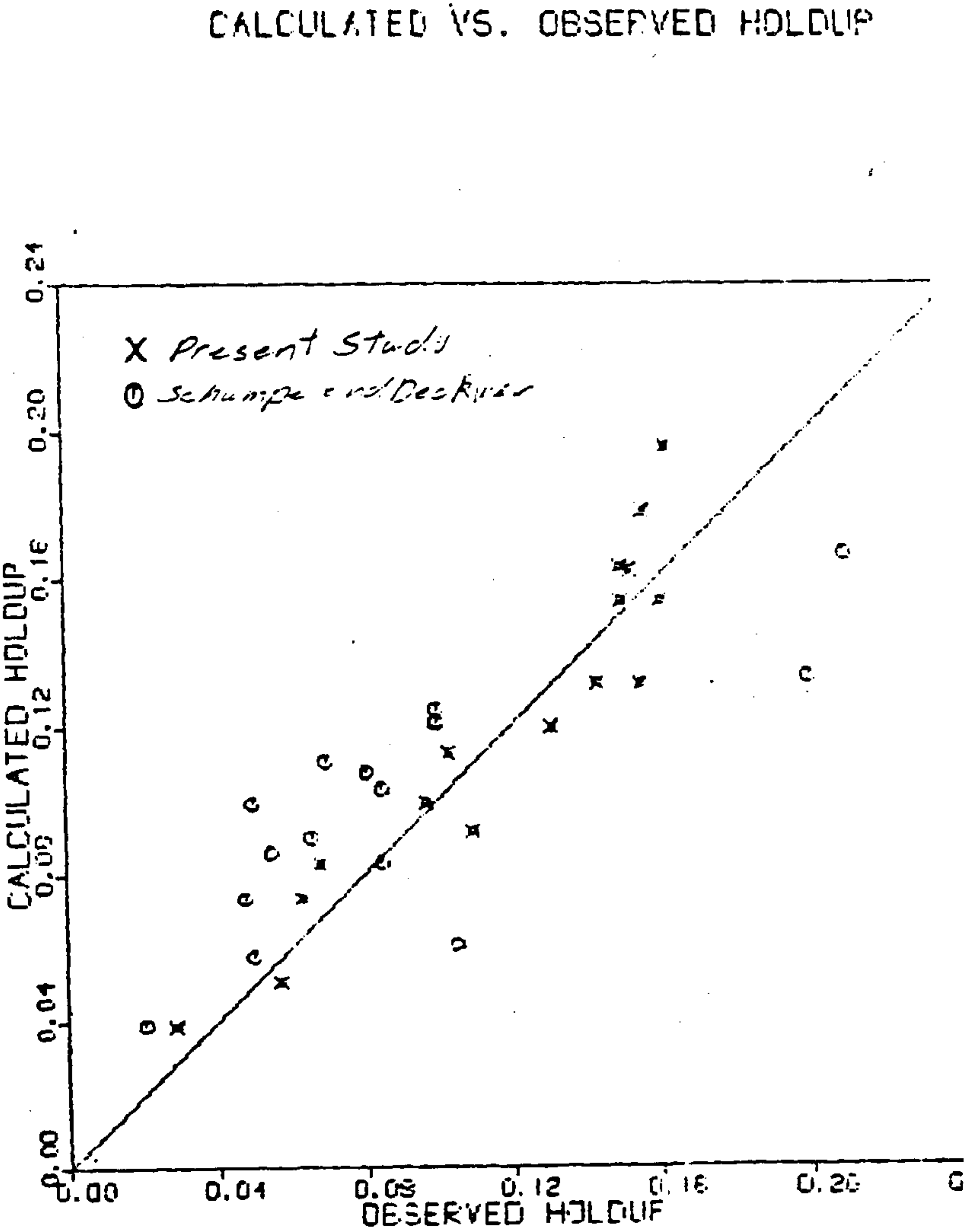


Figure 13 **Comparison of Equation 4-6 with Literatur**

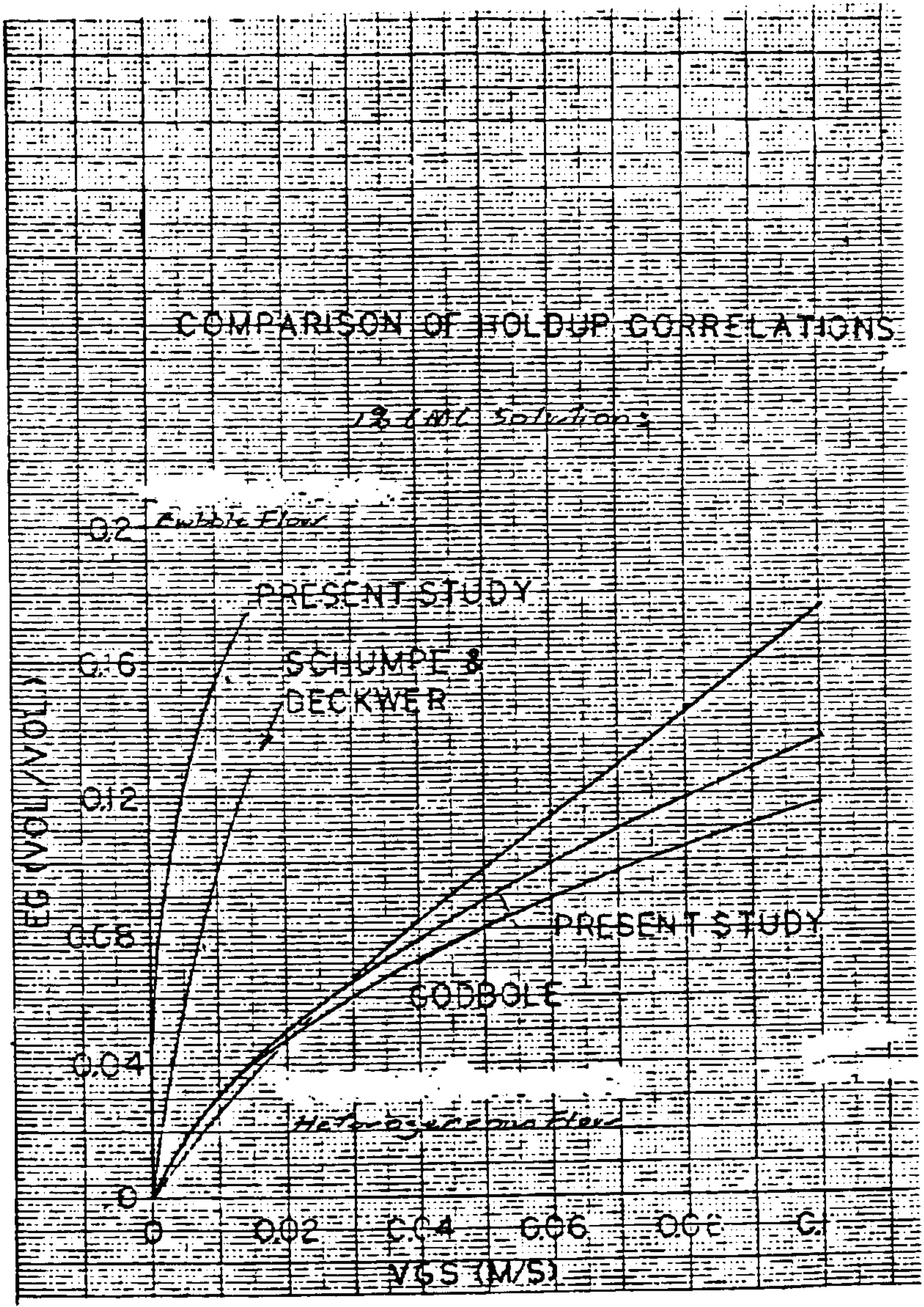


Figure 14 Comparison of Gas Holdup Correlations with Literature