Part A: Flow System

Purpose

The aim of this experimental study is to provide better understanding of the hydrodynamic and mixing properties. Though many studies have been reported in bubble column, most of the studies have been carried out in batch bubble columns. Also, the relative ranges of the parameters studied (e.g. $u_G \leq 10.0$ cm/s, $u_L \leq 3.0$-4.0 cm/s) were small. It has been proposed to study the gas holdup as an indicator of the hydrodynamic behavior, and heat dispersion coefficient as an indicator of the mixing behavior. A large number of correlations for both of these properties have been reported in the literature, and have been compiled together by Shah et al. (1981).[1] However, a large scatter in the reported data does not allow a a single correlation. The large scatter is mainly due to the extreme sensitivity of both of these parameters to the material system, and to the trace impurities, which is not well understood.

The ranges of the parameters to be studied have been given in Table 1. It has been proposed to change the viscosity by using water soluble polymer solutions. The reasons for using polymer solutions are: 1) very small quantity of polymer is needed to change the viscosity significantly without changing other physical properties of water, and 2) polymer solutions show non-Newtonian behavior, so the values of holdup and dispersion coefficients can be compared with the Newtonian liquids having the same apparent viscosity.

For changing the surface tension, propanol and higher alcohols have been proposed to use. The advantage of using high alcohols is that very small quantities are needed for changing the surface tension significantly.

TABLE 1
RANGES OF THE PARAMETERS

Parameter	Range
Superficial gas velocity, cm/s	1.0-30.0
Superficial liquid velocity, cm/s	0.0-15.0
Viscosity, cp	1.0-20.0
Surface tension, dynes/cm	45.0-70.0

Experimental Setup

The schematic diagram of the experimental setup is shown in Figure 1. The experiments have been carried out in a 15.2 cm diameter x 305.0 cm height, vertical, cocurrent bubble column. The column has four major sections:

1) Conical bottom section for the gas inlet and distribution

2) 30.0 cm tall calming section packed with Raschig rings for mixing of gas and slurry

3) Main test section below the heater

4) Heating coil at the top

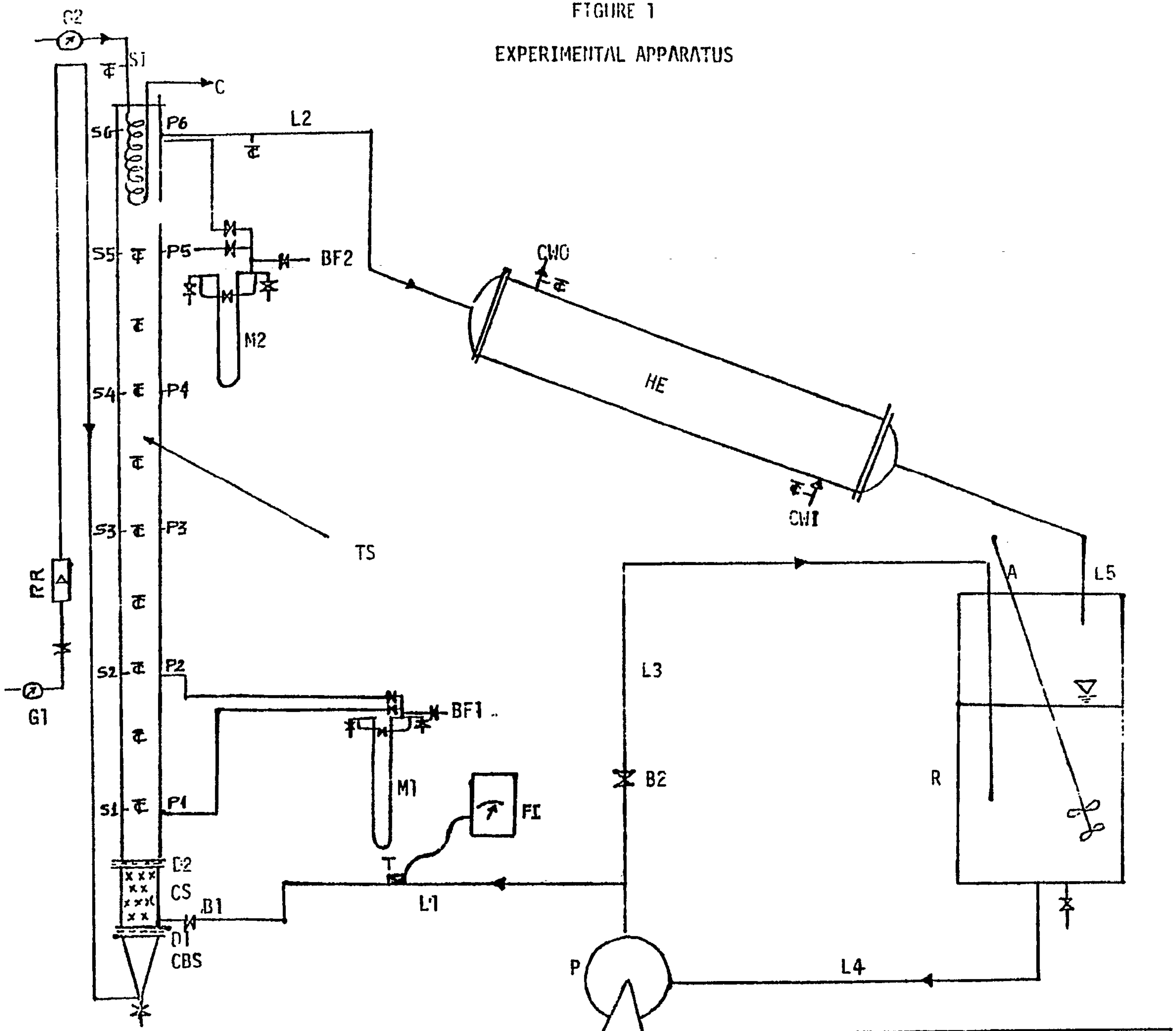
Two distributor plates, one between test section and calming section and the other between calming section and conical bottom section, are used to ensure uniform flow at the bottom of the test section. Four pressure taps have been used to measure the pressure along the length of the column. To ensure that all the connecting lines are filled with water, a backflushing system is used.

For heat tracer experiments, eleven iron-constantan thermocouples, located 30.0 cm apart from each other along the length of the column are used. All thermocouples are connected to a single digital readout device. A shell and tube heat exchanger is located in the outlet line of the column to cool the heated liquid to the desired inlet temperature during the steady state heat tracer experiments. A steam heated coil is used to provide about 74 kilowatt heat into the flowing liquid system.

Gas and liquid flow rates are measured by a rotameter and an ultrasonic device respectively. To ensure that the gas pressure is kept constant, a pressure regulator is attached before the rotameter. All the experiments are carried out in a continuous and steady state manner. Column is insulated with fiberglass insulation material to prevent heat losses during the experiments with heat input.

FIGURE 1

EXPERIMENTAL APPARATUS



DEFINITIONS FOR FIGURE 1

A	Agitator
B1, B2	Ball Valves
BF1, BF2	Backflushing System
C	Condensate
CBS	Conical Bottom Section
CS	Calming Section
CWI, CWO	Cooling Water Inlet and Outlet
D1, D2	Distributor Plates
G1, G2	Pressure Gauges
HE	Shell and Tube Heat Exchanger 1" OD SS tubes on the tube (slurry side) Heat transfer area 25 ft^2 14" OD, 6 ft long Black iron shell side (cooling water)
L1-L5	2" OD, Schedule 80, PVC pipes
M1, M2	Manometers
P	Galigher Horizontal Centrifugal Pump
P1-P6	Pressure Taps
R	Reservoir (550 liter, plastic)
RR	Gas Rotameter
SI	Steam Inlet
S1-S6	Sampling Taps
TS	Main Test Section
T, FI	Transducer and Flow Indicator (ultrasonic)
℄	Thermocouple Holes

Analysis of Raw Data

The mamometric readings are converted to absolute pressures by a simple hydrostatic head technique. Pressures are observed to be linear with respect to height. This proves that the frictional pressure drop is negligible and there is no local variation of the holdup. The final form of the equation can be written as

$$\varepsilon_G = \frac{HH|_{V_G=0} - HH}{HH|_{V_G=0}} \tag{1}$$

where HH is the hydrostatic head, at any height and $HH|_{V_G=0}$ is the hydrostatic head at zero gas velocity.

The measured temperatures along the length of the column are correlated with the help of axial dispersion model. The assumptions made during this analysis are listed somewhere else.[2] The final equation can be written as,

$$-A \frac{dT^2}{dZ^2} + B \frac{dT}{dZ} = 0 \tag{2}$$

where

$A = D_L \rho_L C_{pL} \varepsilon_L$

$B = \rho_L V_L C_{pL}$

Different boundary conditions have been tried, with approximately the same results. Final boundary conditions are,

$$\begin{aligned} @\ Z &= Zc,\ T = T_C \\ @\ Z &= Z_H,\ T = T_H \end{aligned} \tag{3}$$

The analytical solution results in the following relationship,

$$\frac{T-T_C}{T_H-T_C} = \frac{\exp\left[\frac{V_L}{D_L \varepsilon_L} (Z-Z_c)\right]-1}{\exp\left[\frac{V_L}{D_L \varepsilon_L} (Z_H-Z_c)\right]-1} \tag{4}$$

The value of D_L is optimized from the given data, with the help of computer.

The calculated dispersion coefficient data are found to be independent of the heat input to the system.

Results and Discussion

So far four different systems have been studied, whose physical properties are shown in Table 2. In Tables 3 to 6, the gas holdup values obtained in this study are compared with those obtained from the correlations of Akita and Yoshida (1973),[3] and Hikita et al. (1980).[4] In Tables 7 to 10, the values of heat dispersion coefficients obtained in this study are tabulated, and compared with those obtained from the correlations of Deckwer et al. (1974),[5] Baird and Rice (1975),[6] Joshi (1980),[7] and Field and Davidson (1980).[8]

Effect of Viscosity: Effect of viscosity has been studied with the help of water soluble CMC polymer (carboxy methyl cellulose) solutions. Two different concentrations are prepared and their consistency index is calculated with the help of Brookfield viscometer. It is observed that the consistency index was close to 1, and the apparent viscosity did not change significantly with shear rate. The gas holdup is plotted against superficial gas velocity for 50 ppm CMC solution (Fig. 2). As can be seen, the

TABLE 2

PHYSICAL PROPERTIES OF THE LIQUIDS

System	Viscosity kg·m/sec	Density kg/m^3	Surface Tension Nt/m
50 ppm CMC	0.002	1000.0	0.0695
1000 ppm CMC	0.0076	1000.1	0.068
0.5% propanol	0.001	1000.0	0.0641
1.0% propanol	0.001	1000.0	0.0579

holdup for zero liquid velocity is significantly different from the ones for other liquid velocities. For non-zero liquid velocities, the gas holdup is independent of liquid velocity. Figure 3 compares the data for 50 ppm, with those obtained from Akita and Yoshida (1973)(3) and Hikita et al. (1980)(4) correlations. The experimental values are consistently higher than both of these correlations. This is in agreement with the observations made by Nishikawa et al. (1977).(9) The data for 1000 ppm CMC solution are compared with those of air-water and 50 ppm CMC solution in Figure 4. Both the CMC solutions show higher values of gas holdup than air-water. It is believed that, CMC solutions show maximum with respect to the gas holdup as a function of apparent viscosity. Though more data are needed to reach the conclusion, Bucholtz et al. (1978)(10) observed similar maximum in Newtonian (glycerol) medium near the viscosity of 2 cp.

For 50 ppm CMC solution, the heat dispersion coefficient as a function of gas velocity is plotted in Figure 5. Considerable scattering is observed, probably due to the temperature averaging technique which is employed in measuring the temperatures. The dispersion coefficients for CMC solutions are compared with air-water values (Figure 6), surprisingly it is found that the values are higher than the air-water data. This is believed to be due to the effect of irregular bubble shape and stream formation which are observed by Shumpe and Deckwer (1980)[11] in the CMC solutions.

Effect of Surface Tension: Effect of surface tension is studied by using two different concentrations of propanol. The results for both the gas holdup and the dispersion coefficients are surprising. The gas holdup for 0.5% propanol, as a function of gas velocity is plotted in Figure 7. The liquid velocity has clear effect on the holdup values, though the effect becomes insignificant at higher liquid velocities. When the experimental values of gas holdup for 1.0% propanol are compared with Akita and Yoshida (1973) and Hikita et al. (1980) correlations, it is found that the experimental values are considerably higher than air-water data (Figure 8) and those predicted by the correlations. This can be explained on the basis of drift flux theory. When drift flux is plotted as a function of gas holdup (Figure 9) all the data are found to fall below the bubbly regime line (Equation of that line is drift flux (m/s) = .18 ε_G m/s). When the same experiments are carried out in 30 cm diameter bubble column, it is observed that very tiny bubbles are formed with uniform distribution. Also the system showed some foaming characteristics.

When the dispersion coefficients are plotted as a function of superficial gas velocity, for 1.0% propanol solution, negligible (almost zero) values of dispersion coefficients are observed at low gas velocities (< 5.0 cm/s) but as the gas velocity is increased further, tremendous increase in dispersion coefficient with significant scattering is noted (Figure 10). When the overall value of dispersion coefficient (product of dispersion coefficient and liquid holdup) is plotted as a function of gas velocity (Figure 11) two distinct regions are observed.

This can be qualitatively explained on the basis that, at low gas velocity, due to the dynamic surface tension effect (C_3H_7-chain is attached

TABLE 3: Gas Holdup for 50 ppm CMC Solution

P1	P2	P3	P4	PAV	EG	VSL(M/S)	VG(M/S)	EGA	EGH
	PSI							(AKITA/YOSHIDA)	(HIKITA ET AL)
3.80472	2.93742	0.79298	-0.07402	1.86528	0.10504	0.00000	0.01001	0.02704	0.04127
3.53600	2.66870	0.84673	-0.02027	1.75779	0.17945	0.00000	0.02634	0.06157	0.07193
3.39268	2.52538	0.86464	-0.00236	1.69508	0.21665	0.00000	0.05146	0.10121	0.10568
3.24936	2.38206	0.84673	-0.02027	1.61447	0.24559	0.00000	0.08560	0.14067	0.14139
3.10604	2.23874	0.82881	-0.03819	1.53385	0.27452	0.00000	0.12885	0.17762	0.17852
2.96272	2.09542	0.82881	-0.03819	1.46219	0.30759	0.00000	0.18126	0.21133	0.21681
2.81940	1.95210	0.82881	-0.03819	1.39053	0.34066	0.00000	0.24299	0.24189	0.25604
3.42851	2.79410	0.90047	0.44552	1.89215	0.31172	0.03374	0.27132	0.25368	0.27588
3.46434	2.77619	0.90047	0.37386	1.87871	0.28692	0.03374	0.23862	0.23997	0.25587
3.48225	2.79410	0.82881	0.30220	1.85184	0.26625	0.03374	0.17981	0.21052	0.21650
3.57183	2.90159	0.86464	0.12305	1.86528	0.20425	0.03374	0.12714	0.17635	0.17836
3.60766	2.90159	0.84673	0.21262	1.89215	0.21665	0.03374	0.08488	0.13996	0.14118
3.64349	2.86576	0.79298	0.15888	1.86528	0.19598	0.03374	0.05158	0.10137	0.10548
3.60766	2.86576	0.79298	0.08722	1.83840	0.18772	0.03374	0.02652	0.06190	0.07180
3.94804	3.13449	0.82881	0.08722	1.99964	0.10918	0.03374	0.00998	0.02695	0.04122
4.12719	3.33155	0.97213	0.17679	2.15192	0.08851	0.05451	0.00982	0.02658	0.04123
3.94804	3.22406	1.07962	0.37386	2.15640	0.17531	0.05451	0.02568	0.06034	0.07184
3.87638	3.15240	1.06171	0.39177	2.12057	0.19598	0.05451	0.05020	0.09948	0.10553
3.91221	3.15240	1.13337	0.49926	2.17431	0.21252	0.05451	0.08273	0.13779	0.14118
3.96596	3.22406	1.22294	0.58884	2.25045	0.22078	0.05451	0.12342	0.17354	0.17820
3.91221	3.15240	1.27669	0.89339	2.30867	0.30346	0.05451	0.17210	0.20607	0.21643
3.94804	3.22406	1.38418	0.82173	2.34450	0.27865	0.05451	0.22887	0.23555	0.25571
3.94804	3.31364	1.42001	0.91131	2.39825	0.29932	0.05451	0.25973	0.24900	0.27560
4.34217	3.51070	1.13337	0.35594	2.33555	0.08024	0.07943	0.00972	0.02632	0.04117
4.10928	3.31364	1.22294	0.51718	2.29076	0.17118	0.07943	0.02545	0.05991	0.07179
4.16302	3.42113	1.33043	0.66050	2.39377	0.19185	0.07943	0.04927	0.09820	0.10537
4.30634	3.56445	1.50958	0.73216	2.52813	0.17531	0.07943	0.08084	0.13586	0.14083
4.34217	3.60028	1.59916	0.98297	2.63114	0.22492	0.07943	0.12022	0.17107	0.17772
4.37800	3.68985	1.70665	1.090[illegible]6	2.71624	0.[illegible]4145	0.07943	0.16736	0.20[illegible]	0.21577
4.37800	3.76151	1.849[illegible]	1.26961	2.81[illegible]7	[illegible]	0.07943	0.22199	0.23[illegible]4	0.25467
4.46758	3.77943	1.88580	1.32335	2.86404	0.27452	0.07943	0.25218	0.24585	0.27440
4.25260	3.43904	0.99005	0.21262	2.22358	0.06784	0.12896	0.00975	0.02640	0.04124
4.57507	3.79734	1.65290	0.89339	2.72968	0.15051	0.12896	0.02475	0.05859	0.07152
4.80796	4.10190	1.93954	1.25169	3.02527	0.17945	0.12896	0.04738	0.09556	0.10470
5.11252	4.42437	2.35159	1.66374	3.38805	0.20425	0.12896	0.07674	0.13155	0.13944
5.27375	4.58560	2.53074	1.86080	3.56272	0.21252	0.12896	0.11380	0.16596	0.17567
5.34541	4.35271	2.72780	2.07578	3.62543	0.24559	0.12896	0.15867	0.19792	0.21327
5.66788	4.97973	3.06819	2.41617	4.03299	0.24972	0.12896	0.20669	0.22487	0.25051
5.73954	5.10514	3.15776	2.57740	4.14496	0.27039	0.12896	0.23392	0.23786	0.26962

TABLE 4: Gas Holdup for 1000 ppm CMC Solution

P1	P2	P3	P4	PAV	EG	VSL(M/S)	VG(M/S)	EGA	EGH
	PSI							(AKITA/YOSHIDA)	(HIKITA ET AL)
3.91221	3.04491	0.82881	-0.03819	1.93694	0.08851	0.00000	0.00982	0.02171	0.03859
3.73306	2.86576	0.82881	-0.03819	1.84736	0.12984	0.00000	0.02582	0.05061	0.06726
3.58974	2.72244	0.82881	-0.03819	1.77570	0.16291	0.00000	0.05047	0.08525	0.09884
3.46434	2.59704	0.82881	-0.03819	1.71300	0.19185	0.00000	0.08384	0.12085	0.13225
3.32102	2.45372	0.82881	-0.03819	1.64134	0.22492	0.00000	0.12613	0.15509	0.16702
3.21353	2.34623	0.82881	-0.03819	1.58759	0.24972	0.00000	0.17723	0.18691	0.20288
3.10604	2.23874	0.82881	-0.03819	1.53385	0.27452	0.00000	0.23732	0.21616	0.23967
3.01646	2.14916	0.82881	-0.03819	1.48906	0.29519	0.00000	0.27107	0.22996	0.25834
3.94804	3.15240	0.81090	0.05139	1.99068	0.10091	0.02567	0.01043	0.02293	0.03837
3.82264	3.00908	0.77507	0.05139	1.91454	0.12984	0.02567	0.02744	0.05321	0.06689
3.71515	2.97325	0.79298	0.12305	1.90111	0.17118	0.02567	0.05307	0.08842	0.09824
3.60766	2.86576	0.75715	0.14096	1.84288	0.20012	0.02567	0.08851	0.12512	0.13150
3.57183	2.82993	0.79298	0.21262	1.85184	0.22492	0.02567	0.13180	0.15904	0.16602
3.41059	2.68661	0.70341	0.19471	1.74883	0.25799	0.02567	0.18715	0.19224	0.20183
3.33893	2.68661	0.72132	0.26637	1.75331	0.29106	0.02567	0.25019	0.22161	0.23851
3.32102	2.63287	0.79298	0.28428	1.75779	0.29932	0.02567	0.28498	0.23522	0.25716
4.10928	3.27781	0.91839	0.14096	2.11161	0.08438	0.04682	0.01016	0.02239	0.03832
4.01970	3.24198	0.99005	0.26637	2.12952	0.13398	0.04682	0.02665	0.05194	0.06677
4.01970	3.20615	1.07962	0.35594	2.16535	0.15465	0.04682	0.05168	0.08674	0.09808
3.94804	3.20615	1.06171	0.40969	2.15640	0.18358	0.04682	0.08555	0.12243	0.13124
3.94804	3.22406	1.16920	0.55301	2.22358	0.21665	0.04682	0.12739	0.15598	0.16567
3.94804	3.22406	1.24086	0.62467	2.25941	0.23318	0.04682	0.17810	0.18738	0.20122
3.94804	3.25989	1.31252	0.73216	2.31315	0.25799	0.04682	0.23668	0.21588	0.23766
3.94804	3.29572	1.40209	0.82173	2.36690	0.27865	0.04682	0.26852	0.22897	0.25611
4.28843	3.47487	1.15128	0.33803	2.31315	0.08851	0.07654	0.01003	0.02214	0.03826
4.25260	3.49279	1.20503	0.48135	2.35794	0.12984	0.07654	0.02618	0.05119	0.06666
4.25260	3.51070	1.27669	0.57092	2.40273	0.15051	0.07654	0.05081	0.08567	0.09790
4.32426	3.58236	1.45584	0.76799	2.53261	0.17945	0.07654	0.08335	0.12039	0.13084
4.37800	3.63611	1.56333	0.96505	2.63562	0.21252	0.07654	0.12397	0.15355	0.16507
4.41383	3.72568	1.54541	1.05463	2.68489	0.22492	0.00024	0.00307	0.00057	0.23732
4.46758	3.77943	1.72456	1.19795	2.79238	0.24559	0.07654	0.22954	0.21274	0.23655
4.46758	3.81526	1.88580	1.30544	2.86852	0.27039	0.07654	0.26033	0.22574	0.25481
4.25260	3.43904	1.04379	0.17679	2.22806	0.05957	0.09812	0.01011	0.02228	0.03829
4.48549	3.70777	1.36626	0.60675	2.54157	0.10504	0.09812	0.02598	0.05087	0.06655
4.55715	3.77943	1.59916	0.83965	2.69385	0.14225	0.09812	0.05012	0.08483	0.09763
4.82588	4.04815	1.77831	1.16212	2.95361	0.15465	0.09812	0.08164	0.11878	0.13023
4.89754	4.17356	2.04703	1.37710	3.12381	0.18772	0.09812	0.12102	0.15142	0.16412
4.86171	4.24522	2.17244	1.53833	3.20442	0.23318	0.09812	0.17113	0.18351	0.19931
5.36333	4.60352	2.56657	1.98621	3.62991	0.22078	0.09812	0.22111	0.20893	0.23395

TABLE 5: Gas Holdup for 0.5% Propanol

P1	P2	P3	P4	PAV	EG	VBL(M/S)	VG(M/S)	EGA	EGH
	PSI							(AKITA/YOSHIDA)	(HIKITA ET AL)
3,75098	3,06283	0,84673	-0,02027	1,91006	0,12984	0,00000	0,00992	0,02995	0,04335
2,92689	2,16708	0,84673	-0,02027	1,48010	0,31999	0,00000	0,02664	0,06840	0,07551
2,56859	1,80878	0,84673	-0,02027	1,30095	0,40266	0,00000	0,03858	0,09013	0,09279
2,03114	1,28924	0,84673	-0,02027	1,03671	0,52667	0,00000	0,05333	0,11268	0,11032
1,47577	0,76971	0,84673	-0,02027	0,76798	0,65481	0,00000	0,07091	0,13518	0,12766
0,92041	0,21434	0,84673	-0,02027	0,49030	0,78295	0,00000	0,09150	0,15729	0,14387
4,09136	3,29572	0,95422	0,21262	2,13848	0,10504	0,06261	0,00996	0,03004	0,04317
3,76889	3,02700	1,00796	0,37386	2,04443	0,21665	0,06261	0,02613	0,06738	0,07529
3,41059	2,79410	1,04379	0,48135	1,93246	0,32412	0,06261	0,05114	0,10958	0,11069
3,21353	2,61495	1,07962	0,60675	1,87871	0,39853	0,06261	0,08483	0,15054	0,14815
3,23144	2,61495	1,25877	0,75007	1,96381	0,42746	0,06261	0,12631	0,18756	0,18708
3,24936	2,70453	1,25877	0,89339	2,02651	0,45640	0,06261	0,17641	0,22120	0,22718
3,30310	2,74036	1,34835	1,01880	2,10265	0,47293	0,06261	0,23431	0,25115	0,26833
3,26727	2,75827	1,42001	1,09046	2,13400	0,49774	0,06261	0,26638	0,26499	0,28924
4,37800	3,51070	1,24086	0,44552	2,39377	0,09264	0,09473	0,00983	0,02969	0,04309
4,12719	3,38530	1,31252	0,62467	2,36242	0,19185	0,09473	0,02572	0,06655	0,07511
4,07345	3,33155	1,52750	0,91131	2,46095	0,27039	0,09473	0,04970	0,10750	0,11028
4,05553	3,36738	1,70665	1,16212	2,57292	0,33239	0,09473	0,08169	0,14724	0,14739
4,05553	3,40321	1,86788	1,37710	2,67593	0,38199	0,09473	0,12167	0,18393	0,18595
4,10928	3,60028	2,02912	1,62791	2,84164	0,42746	0,09473	0,16869	0,21658	0,22550
4,18094	3,67194	2,13661	1,75331	2,93570	0,43986	0,09473	0,22372	0,24620	0,26616
4,23468	3,70777	2,24410	1,86080	3,01184	0,45227	0,09473	0,25362	0,25968	0,28669
4,10928	3,25989	0,93630	0,14096	2,11161	0,08438	0,13183	0,00998	0,03011	0,04318
4,37800	3,61819	1,45584	0,60675	2,51470	0,12984	0,13183	0,02548	0,06607	0,07501
4,46758	3,76151	1,84997	1,21586	2,82373	0,24972	0,13183	0,04867	0,10598	0,10986
4,52132	3,83317	2,40533	1,23378	2,99840	0,24145	0,13183	0,07974	0,14515	0,14668
4,62881	3,99441	2,31576	1,78914	3,18203	0,34479	0,13183	0,11817	0,18111	0,18481
4,93337	4,35271	2,65614	2,20119	3,53585	0,36959	0,13183	0,16216	0,21254	0,22342
5,07669	4,44228	2,88904	2,34451	3,68813	0,36959	0,13183	0,21449	0,24171	0,26339
4,41383	3,52862	1,24086	0,48135	2,41616	0,09264	0,15326	0,00976	0,02951	0,04310
4,66464	3,79734	1,74248	0,98297	2,79686	0,15051	0,15326	0,02497	0,06503	0,07482
4,91545	4,17356	2,19035	1,53833	3,20442	0,22078	0,15326	0,04751	0,10425	0,10936
5,04086	4,35271	2,47699	1,96829	3,45971	0,29106	0,15326	0,07758	0,14278	0,14578
5,20209	4,51394	2,83529	2,29076	3,71052	0,32826	0,15326	0,11458	0,17816	0,18344
5,57831	4,92599	3,28317	2,77447	4,14048	0,35306	0,15326	0,15664	0,20900	0,22137
5,86495	5,28429	3,67730	3,24026	4,51670	0,39440	0,15326	0,20462	0,23672	0,25998

END USER: KELKAR [114105,225451] JOB: FOR06 SEQ: 29434 FINISHED: 10-APR-81 20:14 PAGES: 2 SYSTEM: 8 END

TABLE 6: Gas Holdup for 1.0% Propanol

P1	P2	P3	P4	PAV	EG	VSL(M/S)	VG(M/S)	EGA	EGH
	PSI							(AKITA/YOSHIDA)	(HIKITA ET AL)
3.73306	3.33155	0.84673	-0.02027	1.97277	0.13398	0.00000	0.00986	0.03011	0.04412
3.32102	2.59704	0.84673	-0.02027	1.68613	0.22905	0.00000	0.01706	0.04830	0.05999
2.81940	2.02376	0.84673	-0.02027	1.41740	0.34479	0.00000	0.02669	0.06915	0.07686
2.26403	1.54005	0.84673	-0.02027	1.15763	0.47293	0.00000	0.03886	0.09140	0.09431
1.00998	0.17851	0.84673	-0.02027	0.50374	0.76229	0.00000	0.05515	0.11614	0.10965
4.10928	3.33155	0.99005	0.23054	2.16535	0.10504	0.06274	0.00997	0.03041	0.04392
3.71515	2.99117	0.99005	0.33803	2.00860	0.22078	0.06274	0.02626	0.06829	0.07661
3.28519	2.63287	0.95422	0.40969	1.82049	0.33652	0.06274	0.05159	0.11112	0.11267
3.21353	2.57912	1.07962	0.62467	1.87423	0.40266	0.06274	0.08487	0.15167	0.15077
3.12395	2.54329	1.09754	0.73216	1.87423	0.44813	0.06274	0.12712	0.18939	0.19042
3.12395	2.54329	1.18711	0.85756	1.92798	0.47707	0.06274	0.17875	0.22384	0.23114
3.14187	2.61495	1.31252	0.98297	2.01308	0.50187	0.06274	0.23577	0.25314	0.27317
3.37476	2.82993	1.50958	1.23378	2.23701	0.50600	0.06274	0.26488	0.26571	0.29412
4.37800	3.36738	1.24086	0.44552	2.35794	0.09264	0.09626	0.00987	0.03013	0.04385
4.12719	3.38530	1.31252	0.62467	2.36242	0.19185	0.09626	0.02577	0.06731	0.07642
4.01970	3.31364	1.52750	0.91131	2.44304	0.28279	0.09626	0.04988	0.10865	0.11221
4.01970	3.36738	1.68873	1.19795	2.56844	0.34893	0.09626	0.08020	0.14670	0.15045
4.09136	3.42113	1.50958	1.44876	2.61771	0.39026	0.09626	0.12211	0.18547	0.18932
4.12719	3.51070	2.06495	1.64582	2.83717	0.42746	0.09626	0.16879	0.21791	0.22944
4.12719	3.60028	2.19035	1.87872	2.94913	0.48120	0.09626	0.22383	0.24756	0.27072
4.23468	3.65402	2.27993	1.96829	3.03423	0.47707	0.09626	0.25358	0.26099	0.29157
4.05553	3.25989	0.90047	0.08722	2.07578	0.08438	0.12974	0.01004	0.03059	0.04394
4.27051	3.51070	1.42001	0.73216	2.48334	0.18358	0.12974	0.02561	0.06696	0.07633
4.44966	3.70777	1.83205	1.21586	2.80134	0.25385	0.12974	0.04888	0.10718	0.11178
4.62881	3.92275	2.20827	1.64582	3.10141	0.31172	0.12974	0.07948	0.14592	0.14900
4.75422	4.08398	2.40533	1.91455	3.28952	0.34479	0.12974	0.11776	0.18196	0.18770
4.82588	4.20939	2.58448	2.12953	3.43732	0.37786	0.12974	0.16356	0.21467	0.22756
5.13043	4.13773	2.94278	2.45200	3.66574	0.38199	0.12974	0.21544	0.24349	0.26796
4.41383	3.60028	1.20503	0.40969	2.40721	0.07611	0.16136	0.00982	0.02999	0.04384
4.64673	3.92275	1.76039	1.05463	2.84612	0.17118	0.16136	0.02500	0.06572	0.07605
4.82588	4.33479	2.35159	1.66374	3.29400	0.27039	0.16136	0.04740	0.10497	0.11109
5.39916	4.71101	2.69197	2.25493	3.76427	0.27452	0.16136	0.07640	0.14253	0.14760
5.68580	5.01556	3.19359	2.64906	4.13600	0.29932	0.16136	0.11212	0.17727	0.18531
5.88286	5.15888	3.48023	2.93570	4.36442	0.31999	0.16136	0.15515	0.20928	0.22427
5.97244	5.33803	3.73104	3.22234	4.56596	0.36546	0.16136	0.20478	0.23810	0.26409

TABLE 7: Dispersion Coefficient for 50 ppm CMC Solution

VG M/S	VL M/S	DL CM**2/S EXPTL	DLD CM**2/S DECKWER	DLB CM**2/S BAIRD-RICE	DLJ CM**2/S JOSHI	DLF CM**2/S FIELD-DAVIDSON	DVS M	UT M/S	US M/S
0.01000	0.03370	188.30000	108.40216	118.64088	176.00294	177.20016	0.00780	0.24004	0.21280
0.02600	0.03370	309.20000	148.58642	167.00499	202.40680	184.44380	0.00695	0.24274	0.19081
0.05100	0.03370	342.40000	185.58210	219.52160	84.62515	175.44409	0.00641	0.24462	0.18978
0.08400	0.03370	292.70000	218.80139	263.32807	219.27373	270.05061	0.00604	0.24600	0.18487
0.12600	0.03370	276.50000	250.12678	305.57913	297.59562	346.37635	0.00575	0.24711	0.18923
0.17900	0.03370	520.80000	280.85323	343.22186	334.75797	395.26907	0.00551	0.24806	0.17317
0.23700	0.03370	449.80000	308.10934	378.15893	379.21012	445.32196	0.00533	0.24882	0.16872
0.27000	0.03370	449.30000	321.65326	394.95226	397.17546	467.62994	0.00525	0.24917	0.16309
0.01000	0.05450	221.40000	108.40216	115.63819	163.26413	154.41648	0.00780	0.24004	0.21974
0.02600	0.05450	188.20000	148.58642	157.42180	211.64159	190.23679	0.00695	0.24274	0.19447
0.05000	0.05450	266.90000	184.37330	210.10044	135.84975	138.83512	0.00643	0.24456	0.18974
0.08200	0.05450	334.70000	217.06834	255.35058	214.10533	255.67392	0.00606	0.24593	0.18616
0.12300	0.05450	369.50000	248.14561	297.53860	288.72449	330.01957	0.00577	0.24704	0.18459
0.17100	0.05450	434.50000	276.64743	329.85553	312.66442	369.55336	0.00555	0.24794	0.16405
0.22700	0.05450	405.30000	303.75711	368.44201	376.76917	431.76794	0.00536	0.24871	0.17051
0.25800	0.05450	444.30000	316.86366	384.74707	394.99026	453.82443	0.00528	0.24905	0.16591
0.01000	0.07940	291.40000	108.40216	110.33405	166.85073	147.13956	0.00780	0.24004	0.22263
0.02500	0.07940	187.20000	146.67568	138.91940	234.04603	208.81491	0.00698	0.24263	0.19552
0.04900	0.07940	324.10000	183.14819	198.92768	178.08382	14.04011	0.00644	0.24451	0.19080
0.08000	0.07940	339.80000	215.30673	251.10294	241.56693	261.16174	0.00607	0.24586	0.19697
0.11900	0.07940	378.60000	245.45304	287.44086	281.40369	312.03793	0.00579	0.24695	0.18347
0.16600	0.07940	349.90000	273.95144	325.56493	336.00088	371.31993	0.00557	0.24786	0.17947
0.22000	0.07940	486.60000	300.63352	358.46868	373.06488	416.50127	0.00538	0.24862	0.16952
0.25000	0.07940	436.00000	313.58705	376.29338	397.81367	442.92053	0.00530	0.24897	0.16975
0.02500	0.12900	99.20000	146.67568	114.64265	254.95100	213.94988	0.00698	0.24263	0.20193
0.04800	0.12900	516.40000	181.90621	179.08371	224.64098	152.24782	0.00646	0.24445	0.19441
0.07600	0.12900	358.00000	211.69295	224.50872	139.32859	183.99164	0.00611	0.24572	0.18816
0.11300	0.12900	196.20000	241.29804	270.77357	279.27651	285.38756	0.00583	0.24681	0.18682
0.15700	0.12900	312.00000	268.95821	306.19389	326.67219	339.46646	0.00560	0.24771	0.17835
0.20400	0.12900	400.50000	293.23505	341.45793	379.10586	394.70174	0.00543	0.24842	0.17785
0.23100	0.12900	444.30000	305.51312	356.00705	394.57589	414.12266	0.00535	0.24875	0.17269

TABLE 8: Dispersion Coefficient for 1000 ppm CMC Solution

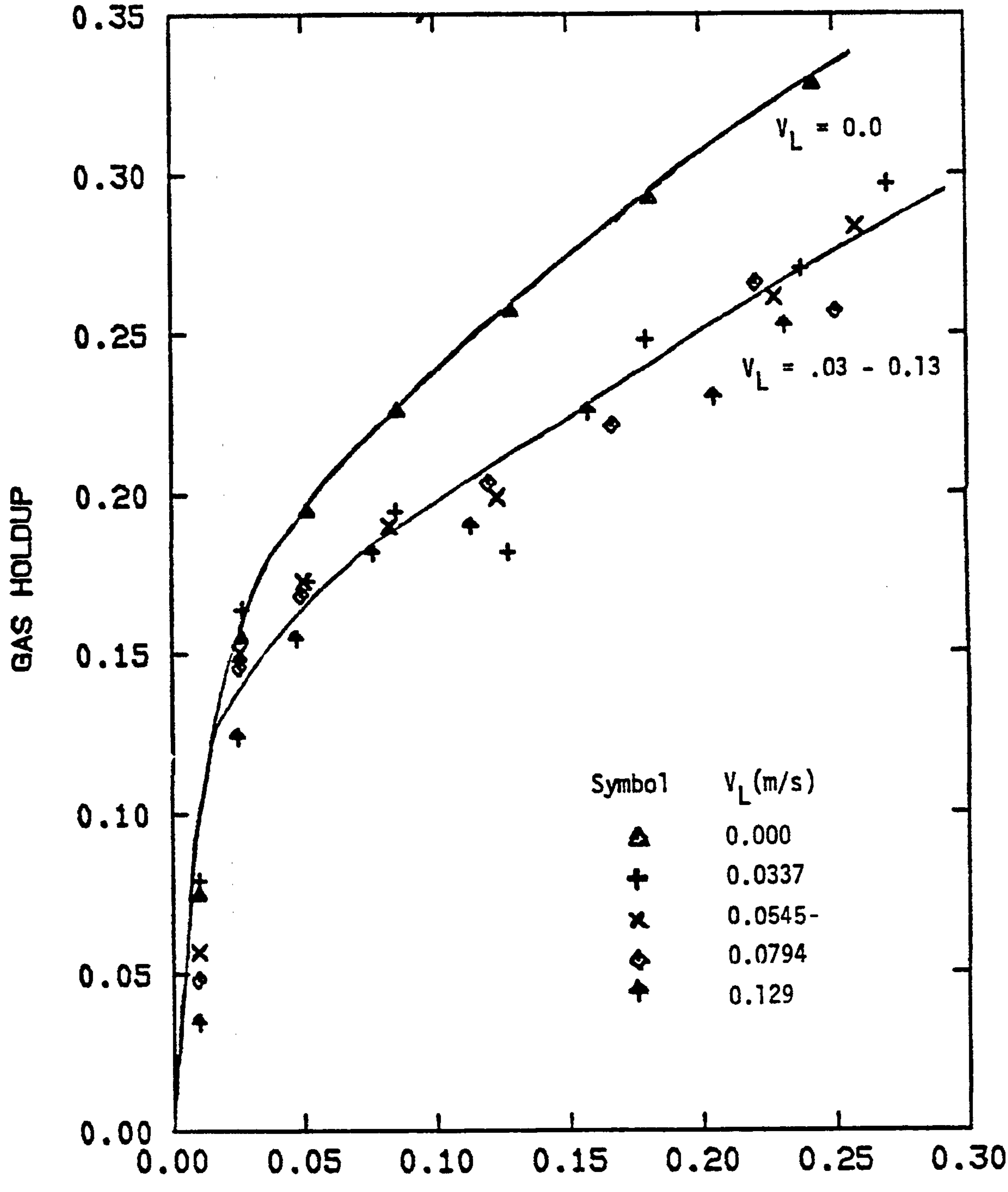
VG M/S	VL M/S	DL CM**2/S EXPTL	DLD CM**2/S DECKWER	DLB CM**2/S BAIRD-RICE	DLJ CM**2/S JOSHI	DLF CM**2/S FIELD-DAVIDSON	DVS M	UT M/S	US M/S
0.01000	0.02570	166.80000	108.40216	127.27788	130.37698	129.83075	0.01074	0.25606	0.23714
0.02700	0.02570	282.00000	150.44853	181.11384	105.53948	137.89704	0.00953	0.25894	0.22922
0.08800	0.02570	349.80000	222.18626	271.60128	245.37365	292.01771	0.00827	0.26229	0.20799
0.13100	0.02570	275.30000	253.35965	311.22178	297.68145	351.69530	0.00789	0.26340	0.20083
0.18600	0.02570	390.30000	284.43117	330.42283	344.18165	406.67620	0.00756	0.26437	0.19143
0.24900	0.02570	481.20000	313.17256	386.67421	386.24043	456.46574	0.00730	0.26516	0.18281
0.28400	0.02570	500.00000	327.06417	404.39334	408.04874	481.21278	0.00719	0.26552	0.18079
0.01000	0.04680	180.60000	108.40216	125.86806	88.71986	64.33490	0.01074	0.25606	0.24337
0.02600	0.04680	218.50000	148.58642	172.94677	101.14319	84.31275	0.00958	0.25883	0.22779
0.05100	0.04680	236.40000	185.58210	221.57895	191.79147	216.95077	0.00883	0.26076	0.22186
0.08500	0.04680	296.60000	219.65756	265.00611	252.06084	285.85987	0.00831	0.26220	0.21315
0.12700	0.04680	296.30000	250.78014	304.25391	299.63889	342.33166	0.00792	0.26331	0.20340
0.17700	0.04680	336.70000	279.81377	341.69266	348.12992	397.25364	0.00761	0.26423	0.19886
0.23500	0.04680	382.80000	307.24888	376.48740	388.92774	445.15505	0.00735	0.26501	0.19189
0.26700	0.04680	432.60000	320.46945	392.87604	406.27125	466.60211	0.00724	0.26535	0.18628
0.01000	0.07650	166.30000	108.40216	118.08302	137.19565	113.80864	0.01074	0.25606	0.24198
0.02600	0.07650	254.70000	148.58642	165.84714	133.88986	67.25161	0.00958	0.25883	0.22912
0.05000	0.07650	299.40000	184.37330	214.37080	193.84436	204.48464	0.00885	0.26070	0.22345
0.08300	0.07650	255.20000	217.93837	257.43122	255.03222	274.10427	0.00833	0.26213	0.21467
0.12300	0.07650	362.50000	248.14561	295.34229	300.65311	328.67502	0.00795	0.26323	0.20452
0.17200	0.07650	373.50000	277.18026	333.82567	352.82340	386.75286	0.00763	0.26415	0.20140
0.22800	0.07650	469.70000	304.19804	368.52188	394.51480	435.15868	0.00738	0.26492	0.19570
0.25800	0.07650	403.40000	316.86366	383.59523	409.01130	454.08298	0.00727	0.26526	0.18858
0.01000	0.09800	219.50000	108.40216	118.97991	105.11366	59.16400	0.01074	0.25606	0.24546
0.02600	0.09800	218.50000	148.58642	168.92484	160.08652	146.36027	0.00958	0.25883	0.23832
0.05000	0.09800	234.90000	184.37330	211.74948	206.89343	205.43122	0.00885	0.26070	0.22642
0.08100	0.09800	268.50000	216.19118	254.84485	274.13988	279.57534	0.00836	0.26206	0.22297
0.12000	0.09800	300.40000	246.13180	291.82834	314.98299	329.50542	0.00797	0.26316	0.21269
0.17000	0.09800	343.40000	276.11249	327.74363	351.35894	375.96271	0.00765	0.26412	0.19878
0.21900	0.09300	361.70000	300.18188	362.06752	401.10321	429.04773	0.00742	0.26481	0.20308

TABLE 9 - Dispersion Coefficients for 0.5% Propanol

VG M/S	VL M/S	DL CM**2/S EXPTL	DLD CM**2/S DECKWER	DLB CM**2/S BAIRD-RICE	DLJ CM**2/S JOSHI	DLF CM**2/S FIELD-DAVIDSON	DVS M	UT M/S	US M/S
0.00997	0.06270	0.00000	108.29473	85.83543	215.89632	208.08777	0.00610	0.22666	0.19485
0.02626	0.06270	0.00000	149.07512	126.97524	263.86476	242.34858	0.00543	0.22926	0.16648
0.05180	0.06270	161.00000	186.53775	168.82289	289.88679	242.42034	0.00500	0.23107	0.14325
0.08530	0.06270	316.80000	219.91310	218.05038	278.56413	174.01049	0.00471	0.23239	0.13239
0.12700	0.06270	499.00000	250.78014	263.76809	235.13573	215.45202	0.00449	0.23344	0.12564
0.17800	0.06270	544.70000	280.33448	307.63964	169.89305	315.27903	0.00432	0.23432	0.12151
0.23700	0.06270	700.00000	308.10934	347.24016	286.64773	384.37288	0.00417	0.23506	0.11796
0.26600	0.06270	696.00000	320.07286	364.93758	322.49627	412.89243	0.00411	0.23536	0.11748
0.00987	0.09670	0.00000	107.93507	22.22828	230.89580	210.52531	0.00611	0.22663	0.19828
0.02580	0.09670	0.00000	148.20826	88.04824	277.17593	248.32936	0.00544	0.22922	0.17351
0.05000	0.09670	0.00000	184.37330	141.91582	298.32281	251.56658	0.00503	0.23098	0.15387
0.08220	0.09630	108.40000	217.24291	194.67824	293.27255	212.09693	0.00473	0.23229	0.14178
0.12300	0.09630	376.20000	248.14561	245.60081	252.77274	164.32545	0.00451	0.23335	0.13514
0.16900	0.09630	462.60000	275.57545	287.60128	78.28613	279.69989	0.00434	0.23418	0.13025
0.22500	0.09630	687.90000	302.87131	319.81562	235.38071	337.77976	0.00420	0.23492	0.12120
0.25500	0.09630	554.00000	315.64301	342.77417	300.36182	378.06787	0.00413	0.23525	0.12200
0.01000	0.13000	0.00000	108.40216	77.47131	245.29552	211.70369	0.00610	0.22667	0.20095
0.02560	0.13000	0.00000	147.82814	96.48128	300.53845	262.33636	0.00545	0.22920	0.17551
0.05000	0.13000	0.00000	184.37330	111.51803	312.24234	259.73051	0.00503	0.23098	0.16013
0.08000	0.12900	458.90000	215.30673	173.14039	308.62082	232.33152	0.00475	0.23222	0.14878
0.11800	0.12970	410.10000	244.77044	228.84352	270.47890	54.96502	0.00453	0.23324	0.14310
0.16400	0.12970	515.00000	272.8578[illegible]	[illegible]84026	159.76904	255.2571[illegible]	0.00436	0.23410	0.13766
0.21700	0.12970	695.00000	299.27444	320.65955	302.54536	347.41786	0.00421	0.23483	0.13739
[illegible]0982	0.16190	[illegible].00000	107.75432	93.89221	[illegible]	211.66491	0.00600	[illegible]	0.20221
[illegible]2500	0.16100	[illegible].00000	[illegible]46.67568	125.6523[illegible]	[illegible]	268.48527	0.00537	0.22794	0.17787
0.04740	0.16100	[illegible].00000	1[illegible]1.15268	143.16466	355.99361	300.22206	0.00497	0.22963	0.15571
0.07690	0.16140	279.6000	212.51697	155.86201	318.45203	239.45908	0.00477	0.23212	0.15632
0.11200	0.16140	464.2000	240.59127	218.35849	274.48458	105.52407	0.00456	0.23311	0.15196
0.15600	0.16140	497.60000	268.39167	268.23188	190.09623	253.82862	0.00438	0.23397	0.14832
0.20600	0.16140	558.70000	294.18065	301.06581	277.02343	313.87693	0.00424	0.23469	0.14032

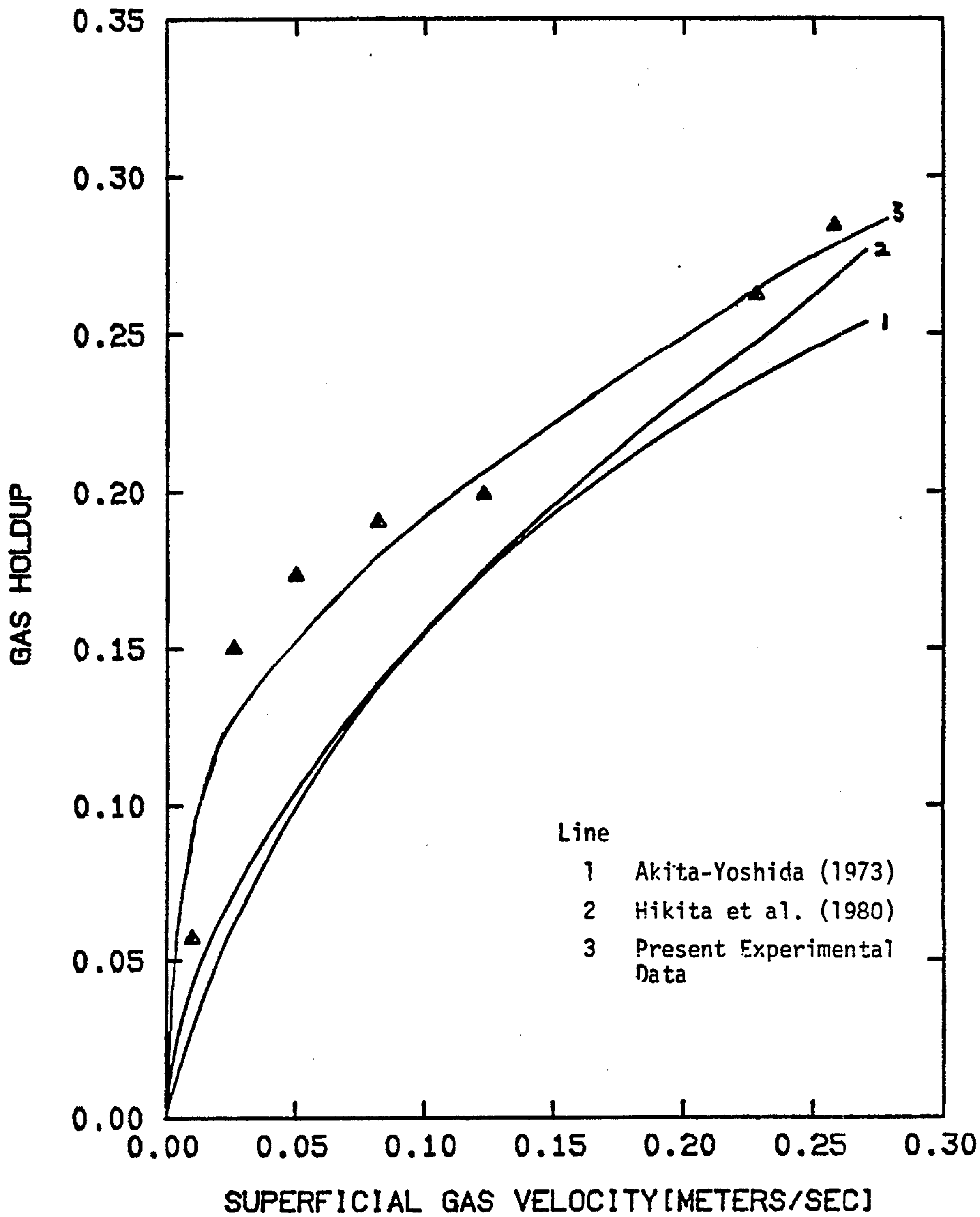
TABLE 10 - Dispersion Coefficients for 1.0 Propanol

VG M/S	VL M/S	DL CM**2/S EXPTL	DLD CM**2/S DECKWER	DLB CM**2/S BAIRD-RICE	DLJ CM**2/S JOSHI	DLF CM**2/S FIELD-DAVIDSON	DVS M	UT M/S	US M/S
0.00997	0.06270	0.00000	108.29473	85.83543	215.89632	208.08777	0.00610	0.22666	0.19485
0.02626	0.06270	0.00000	149.07512	126.97524	263.86476	242.34858	0.00543	0.22926	0.16648
0.05180	0.06270	161.00000	186.53775	168.82289	289.88679	242.42034	0.00500	0.23107	0.14325
0.08530	0.06270	316.80000	219.91310	218.05038	278.56413	174.01049	0.00471	0.23239	0.13239
0.12700	0.06270	499.00000	250.78014	263.76809	235.13573	215.45202	0.00449	0.23344	0.12564
0.17800	0.06270	544.70000	280.33448	307.63964	169.89305	315.27903	0.00432	0.23432	0.12151
0.23700	0.06270	700.00000	308.10934	347.24016	286.64773	384.37288	0.00417	0.23506	0.11796
0.26600	0.06270	696.00000	320.07286	364.93758	322.49627	412.89243	0.00411	0.23536	0.11748
0.00987	0.09670	0.00000	107.93507	22.22828	230.89580	210.52531	0.00611	0.22663	0.19828
0.02580	0.09670	0.00000	148.20826	88.04824	277.17593	248.32936	0.00544	0.22922	0.17351
0.05000	0.09670	0.00000	184.37330	141.91582	298.32281	251.56658	0.00503	0.23098	0.15387
0.08220	0.09630	108.40000	217.24291	194.67824	293.27255	212.09693	0.00473	0.23229	0.14178
0.12300	0.09630	376.20000	248.14561	245.60081	252.77274	164.32545	0.00451	0.23335	0.13514
0.16900	0.09630	462.60000	275.57545	287.60128	78.28613	279.69989	0.00434	0.23418	0.13025
0.22500	0.09630	687.90000	302.87131	319.81562	235.38071	337.77976	0.00420	0.23492	0.12120
0.25500	0.09630	554.00000	315.64301	342.77417	300.36182	378.06787	0.00413	0.23525	0.12200
0.01000	0.13000	0.00000	108.40216	77.47131	245.29552	211.70369	0.00610	0.22667	0.20095
0.02560	0.13000	0.00000	147.82814	96.48128	300.53845	262.33636	0.00545	0.22920	0.17551
0.05000	0.13000	0.00000	184.37330	111.51803	312.24234	259.73051	0.00503	0.23098	0.16013
0.08000	0.12900	458.90000	215.30673	173.14039	308.62082	232.33152	0.00475	0.23222	0.14878
0.11800	0.12970	410.10000	244.77044	228.84352	270.47890	54.96502	0.00453	0.23324	0.14310
0.16400	0.12970	515.00000	272.85781	273.84026	159.76904	255.25719	0.00436	0.23410	0.13766
0.21700	0.12970	695.00000	299.27444	320.65955	302.54536	347.41786	0.00421	0.23483	0.13739
0.00982	0.16100	0.00000	107.75432	93.89221	257.93710	211.66491	0.00600	0.22544	0.20221
0.02500	0.16100	0.00000	146.67568	125.65239	316.63187	268.48527	0.00537	0.22794	0.17787
0.04740	0.16100	0.00000	181.15268	143.16466	355.99361	300.22206	0.00497	0.22963	0.15571
0.07690	0.16140	279.60000	212.51697	155.86201	318.45203	239.45908	0.00477	0.23212	0.15632
0.11200	0.16140	464.20000	240.59127	218.35849	274.48458	105.52407	0.00456	0.23311	0.15196
0.15600	0.16140	497.60000	268.39167	268.23188	190.09623	253.82862	0.00438	0.23397	0.14832
0.20600	0.16140	558.70000	294.18065	301.06581	277.02343	313.87693	0.00424	0.23469	0.14032



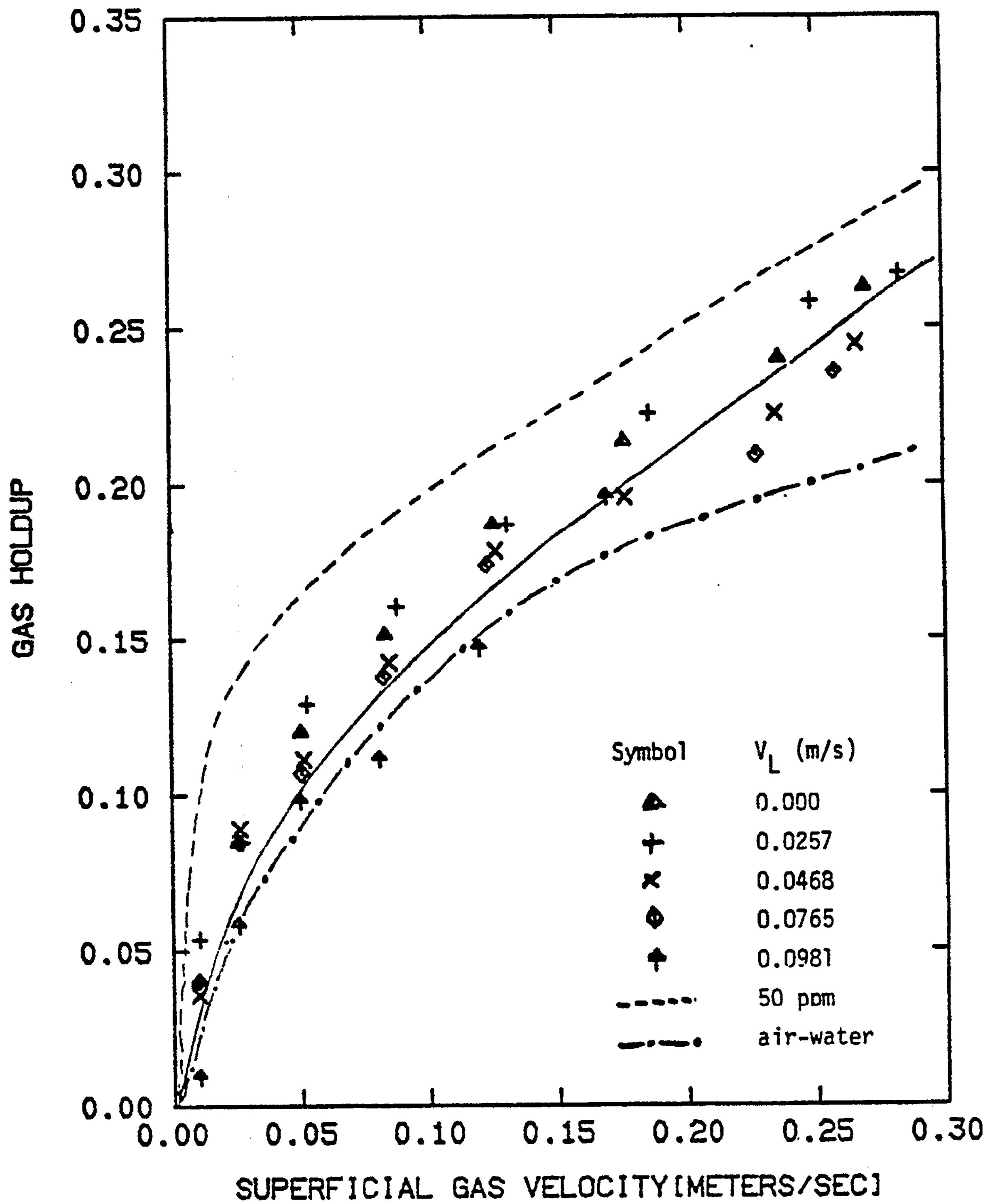
GAS HOLDUP VS SUPERFICIAL GAS VELOCITY[50 PPM CMC GUM]

FIGURE 2



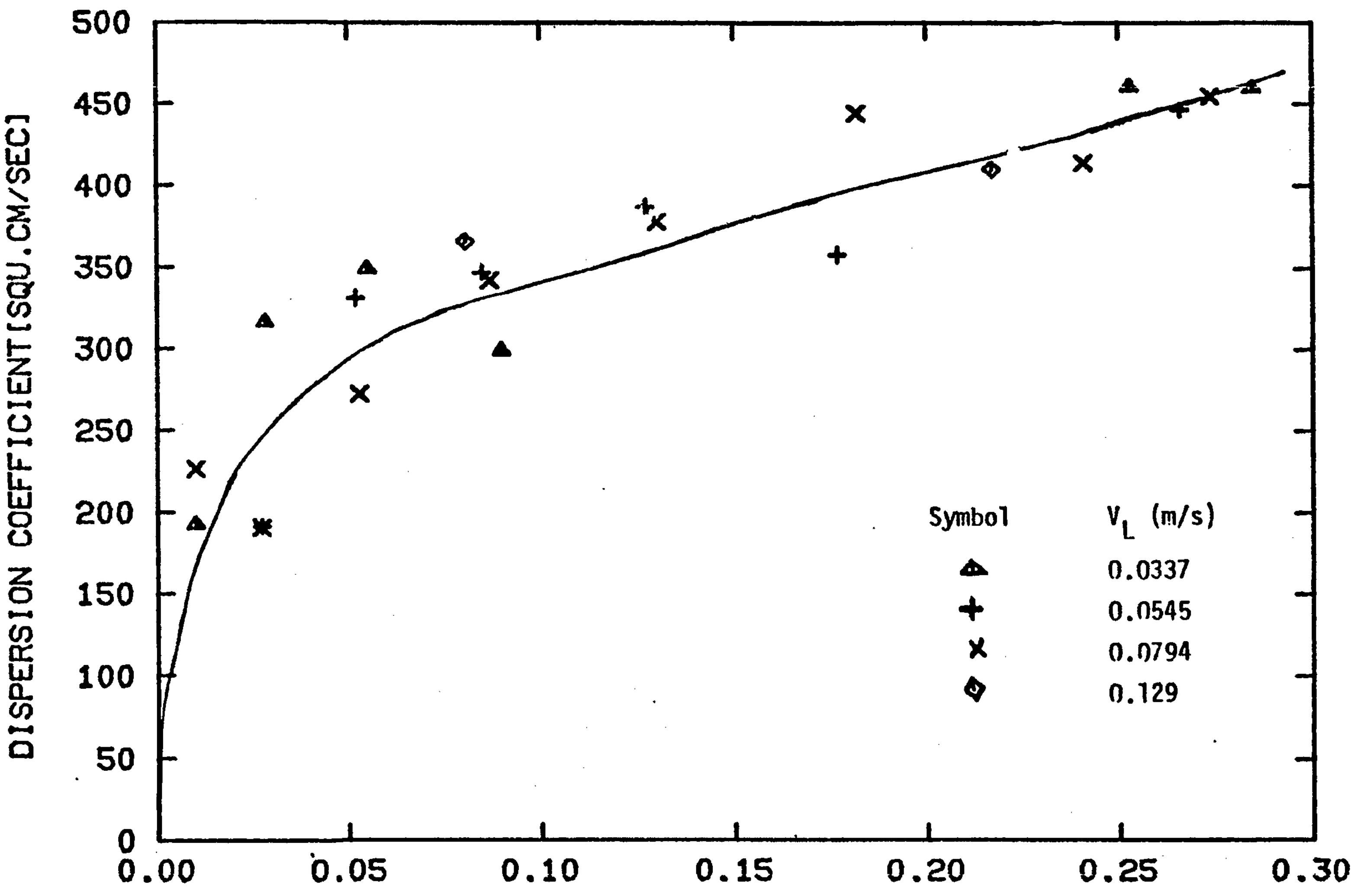
GAS HOLDUP VS SUPERFICIAL GAS VELOCITY[COMPARISON WITH LITERATURE]

FIGURE 3



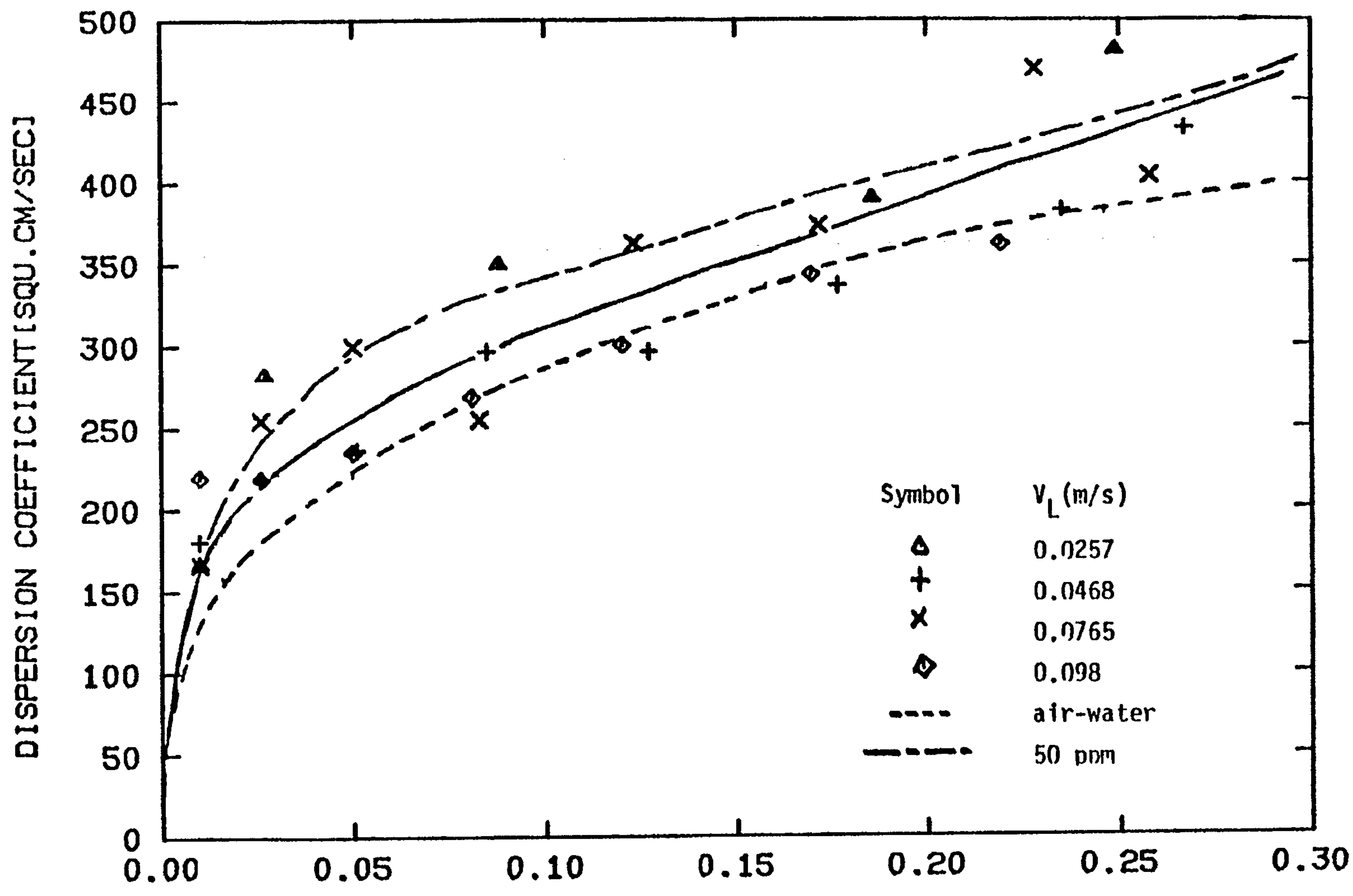
GAS HOLDUP VS SUPERFICIAL GAS VELOCITY[1000 PPM CMC GUM]

FIGURE 4



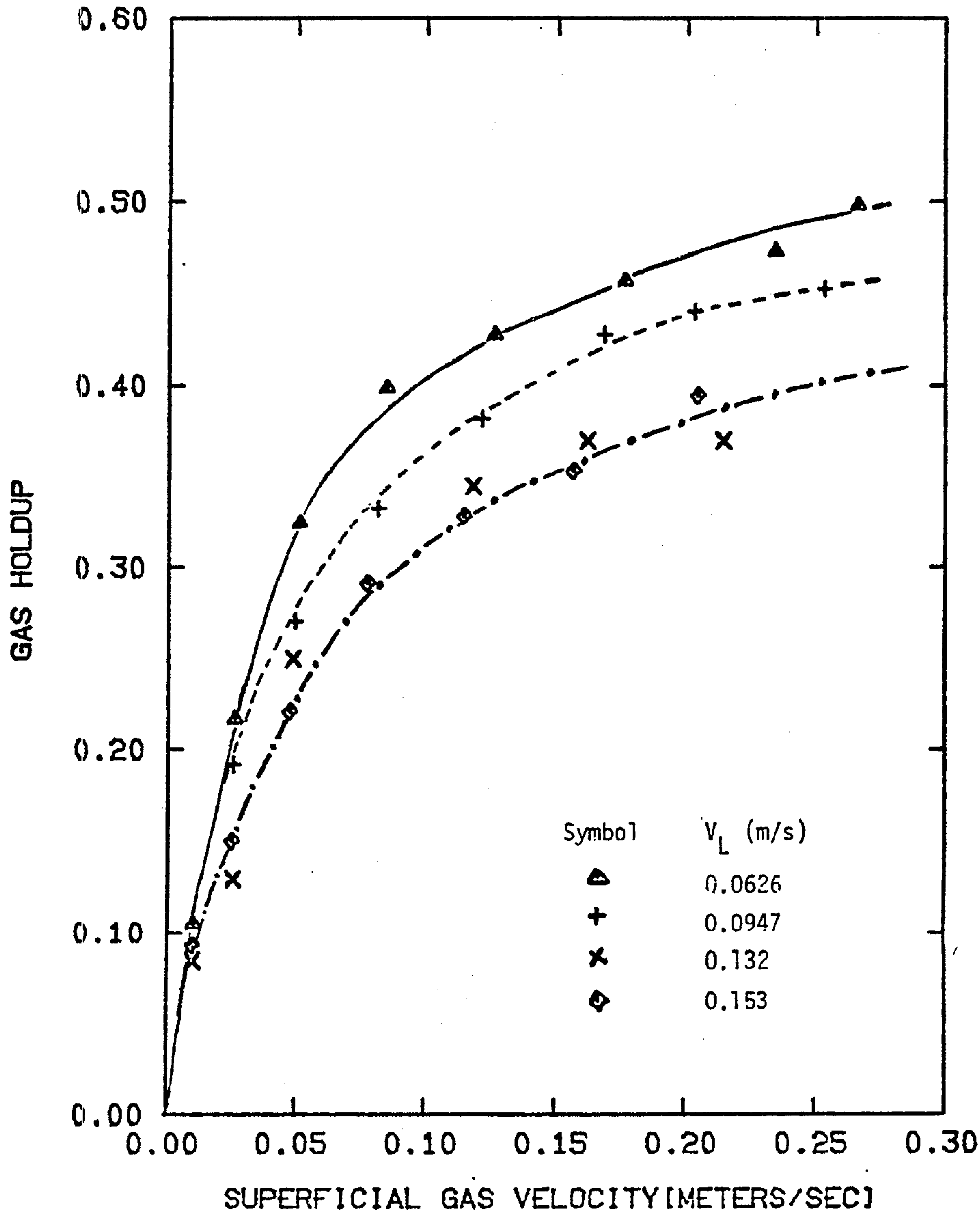
DISPERSION COEFFICIENT VS SUPERFICIAL GAS VELOCITY[50 PPM CMC GUM]

FIGURE 5



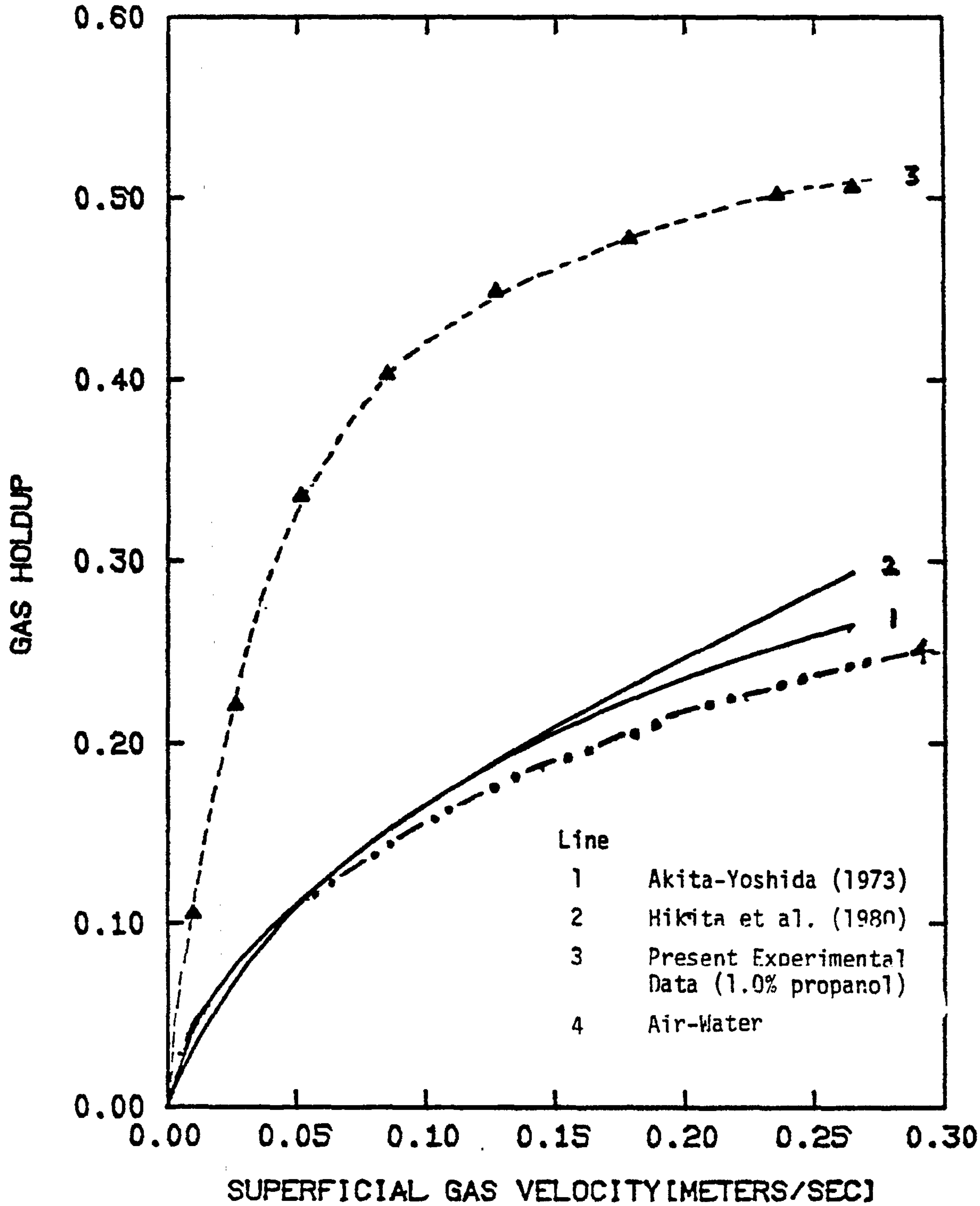
DISPERSION COEFFICIENT VS SUPERFICIAL GAS VELOCITY[1000 PPM CMC GUM]

FIGURE 6



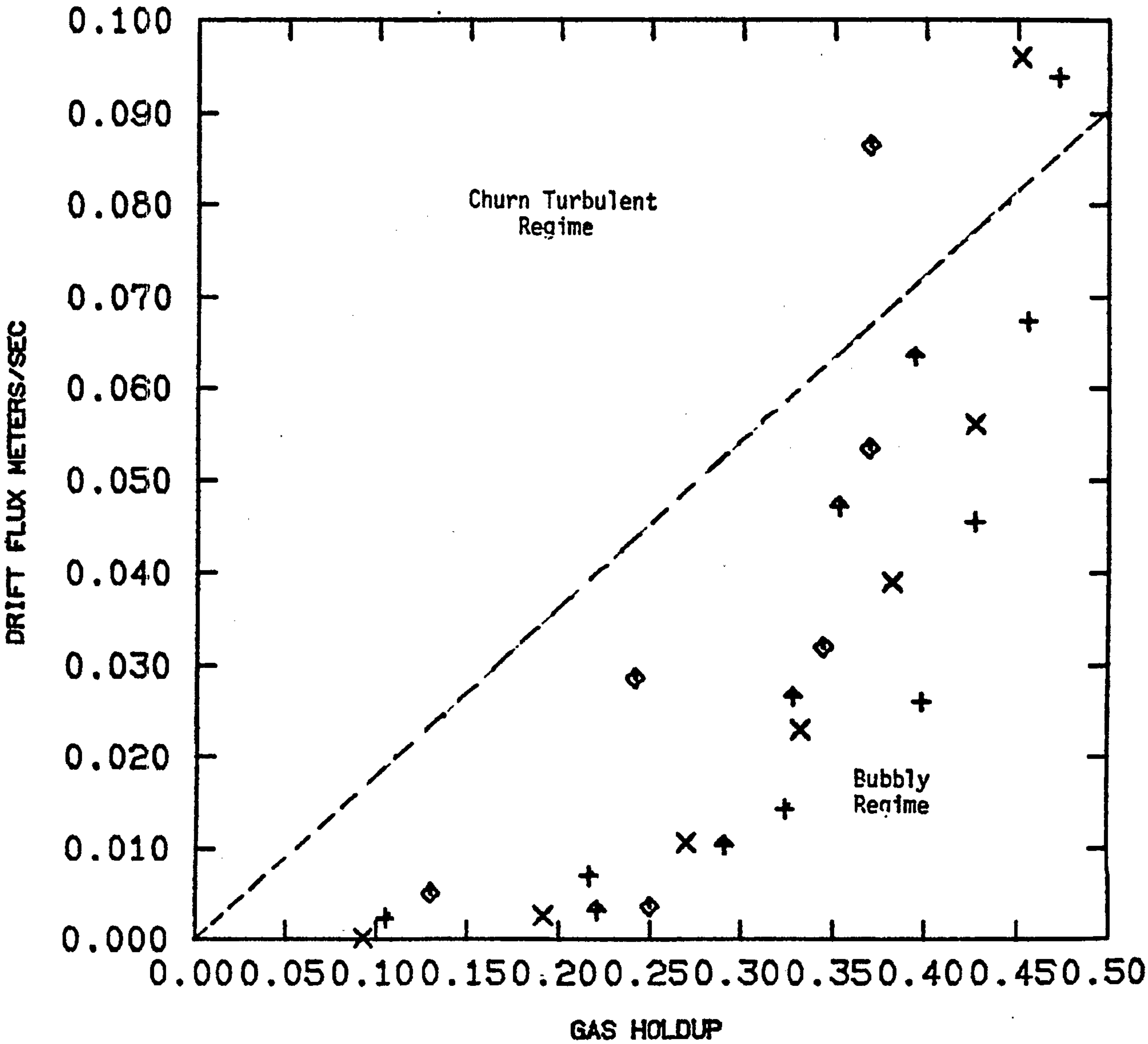
GAS HOLDUP VS SUPERFICIAL GAS VELOCITY[0.5% PROPANOL]

FIGURE 7



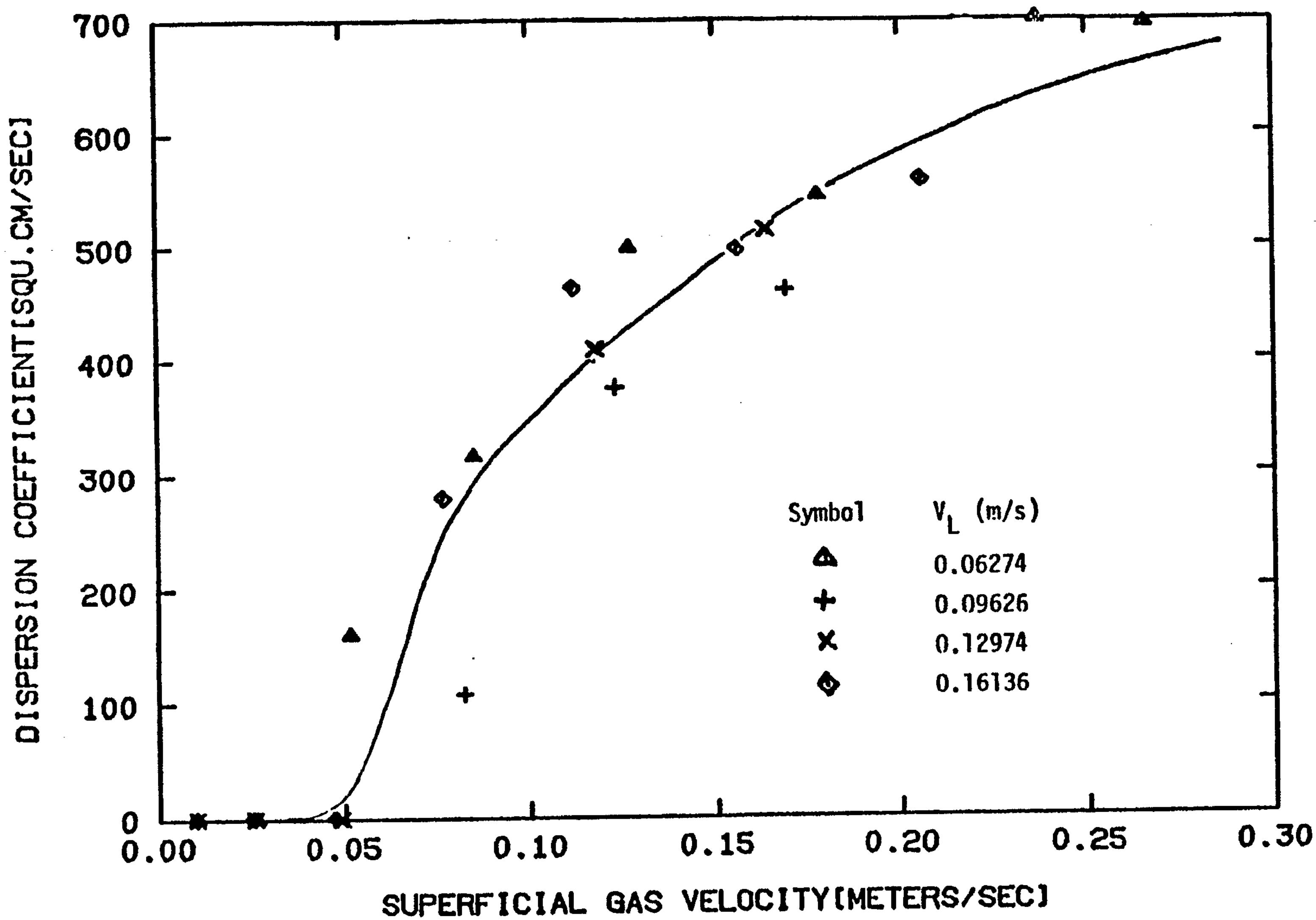
GAS HOLDUP VS SUPERFICIAL GAS VELOCITY [COMPARISON WITH LITERATURE]

FIGURE 8



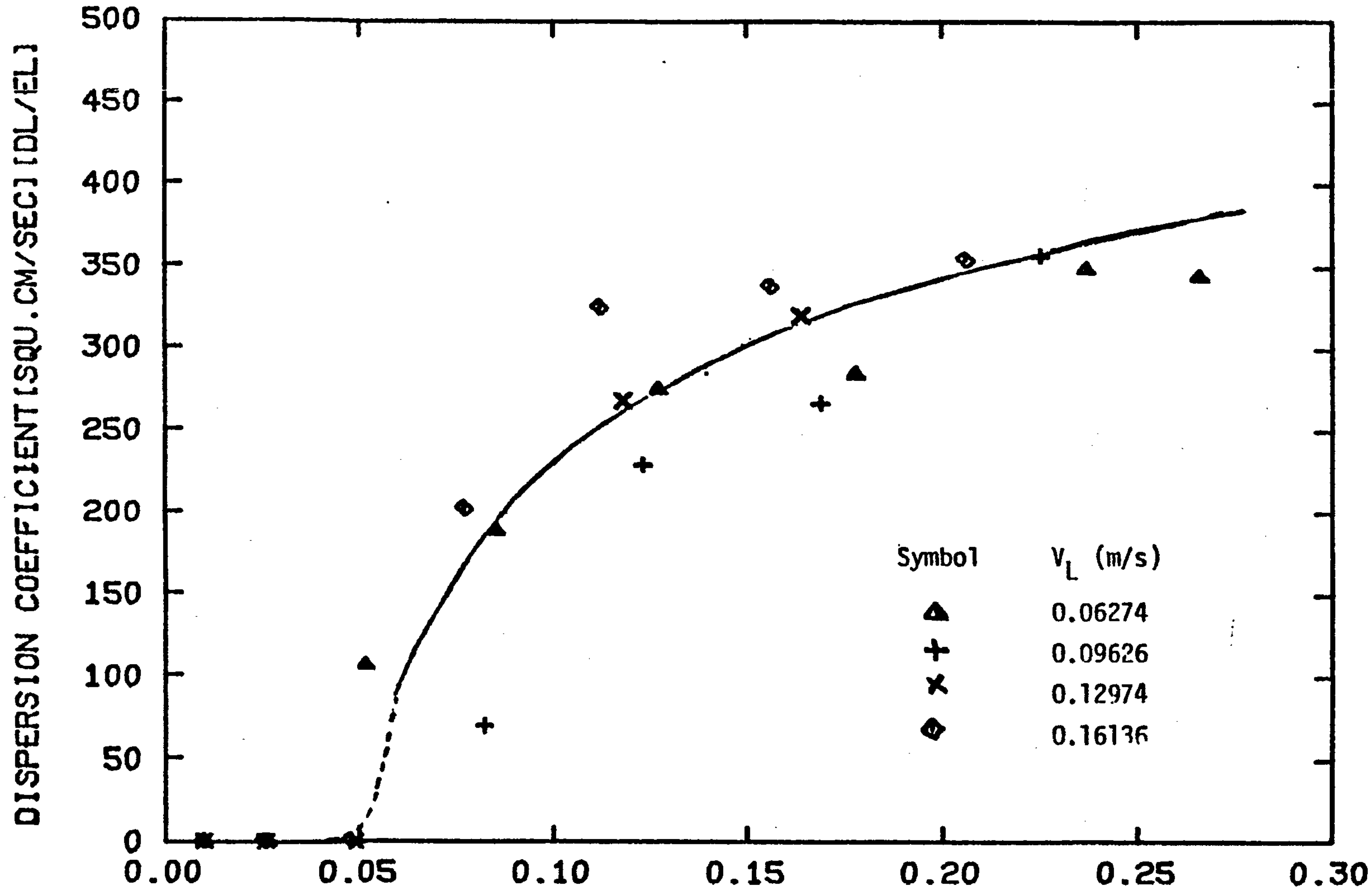
DRIFT FLUX VS GAS HOLDUP[0.5% PROPANOL]

FIGURE 9



DISPERSION COEFFICIENT VS SUPERFICIAL GAS VELOCITY[1.0% PROPANOL]

FIGURE 10



DISPERSION COEFFICIENT VS SUPERFICIAL GAS VELOCITY[1.0% PROPANOL]

FIGURE 11

to air bubble while -OH molecules are attracted towards water) the air bubble carries significant amounts of liquid with it. Therefore, the whole medium behaves as a pseudo-homogeneous single phase system, but as the gas velocity is further increased, the liquid which is being carried by bubbles becomes unstable, and the medium no longer remains homogeneous, and liquid is no longer being carried out throughout the length of the column, and the recirculation starts. Similar observations are noted when the experiments are carried out in 30 cm diameter column. Further studies are needed to prove this qualitative explanation.

Part B: Batch Bubble Column

Purpose

The main emphasis of the proposed study in this part is to understand the hydrodynamics and mass transfer occurring in nonaqueous systems in batch bubble columns. Most of the studies reported in the literature are carried out for air-water systems. It is planned to study the gas holdup, volumetric mass transfer coefficient and interfacial area in a batch bubble column. Disengagement techniques coupled with a photographic method for bubble size determination and sulfite oxidation method for interfacial area determination will be used to get the contribution of large and small bubbles to the actual interacial area or conversion. This will also give the rise velocities and gas holdup for the individual bubble classes. The volumetric mass transfer coefficient will be measured by recording the profile of oxygen physically absorbed in the liquid phase. The critical velocity required to completely suspend the solids will be determined by following the variation in pressure drop along the length of the column. Table 11 gives a list of liquids, solids and ranges of the parameters to be studied in future experiments.

The aqueous solutions of certain polymers have a non-Newtonian rheology and they will be studied in comparsion with Newtonian nonaqueous systems having the same viscosity. Aqueous solutions of alcohols will be used to study the effect of surface tension on the hydrodynamic parameters. Certain alcohol solutions (e.g. propanol) have a tendency to foam and the foaming can actually be observed in this glass bubble column. An attempt will be made to cover as much wide range of viscosities and surface tensions as possible.

TABLE 11

Types of Liquids

non-Newtonian

1. Dilute polymer solutions (CMC)
2. Polyethylene glycol solutions

Newtonian

1. Glycerine in water solutions
2. Sugar solutions
3. n-propanol solutions

Types of Solids

1. Glass beads or crushed glass
2. Coal
3. Alumina
4. Silica
5. Metal beads or powders

Ranges of Parameters

Liquid viscosity:	1-200 cP
Liquid surface tension:	45-72 dynes/cm
Superficial gas velocity:	0-30 cm/sec
Particle size:	5-5000 microns
Solid specific gravity:	1.2-5.0

TABLE 12

wt%	Viscosity (cp)	Surface Tension (dynes/cm)
CMC Solutions		
0.15	14.0	52.3
0.20	20.4	52.3
0.25	31.2	59.2
n-Propanol Solutions		
0.0 (water)	1.0	72.0
0.5	1.0	64.2
1.0	1.0	60.9
1.5	1.0	56.1

Experimental Setup

A schematic diagram of the experimental setup is shown in Figure 12. The glass column used in these experiments is 1.0 ft in diameter and 8.0 ft in height. Pressure taps and sampling ports are located along the length of the column as shown. A diagram of the pressure measurement system is given in Figure 13. By opening and closing the proper valves, the pressure can be read from any of the pressure taps.

Air from the house line is fed through a filter, a pressure regulator, and a rotameter before entering the column. The conical section is two feet in height and is packed with Berl saddles. The cone is separated from the column by a perforated plate with 1.0 mm holes acting as a gas distributor. The conical section serves as a calming section and a uniform gas distribution is obtained. A wide range of air velocities can be achieved by adjusting the air regulator and the valves leading to the rotameter and the conical section.

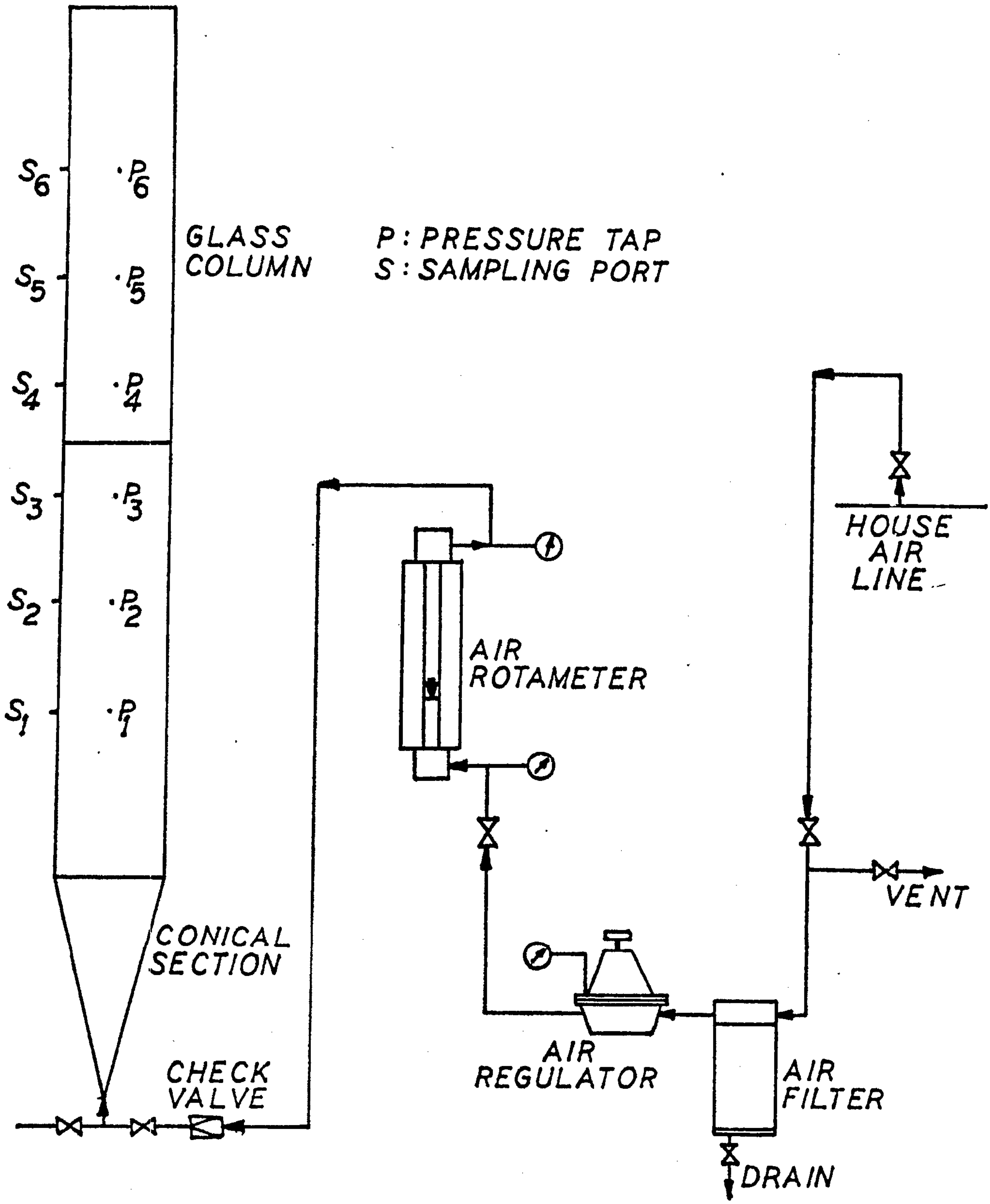


FIGURE 12 - Experimental Setup

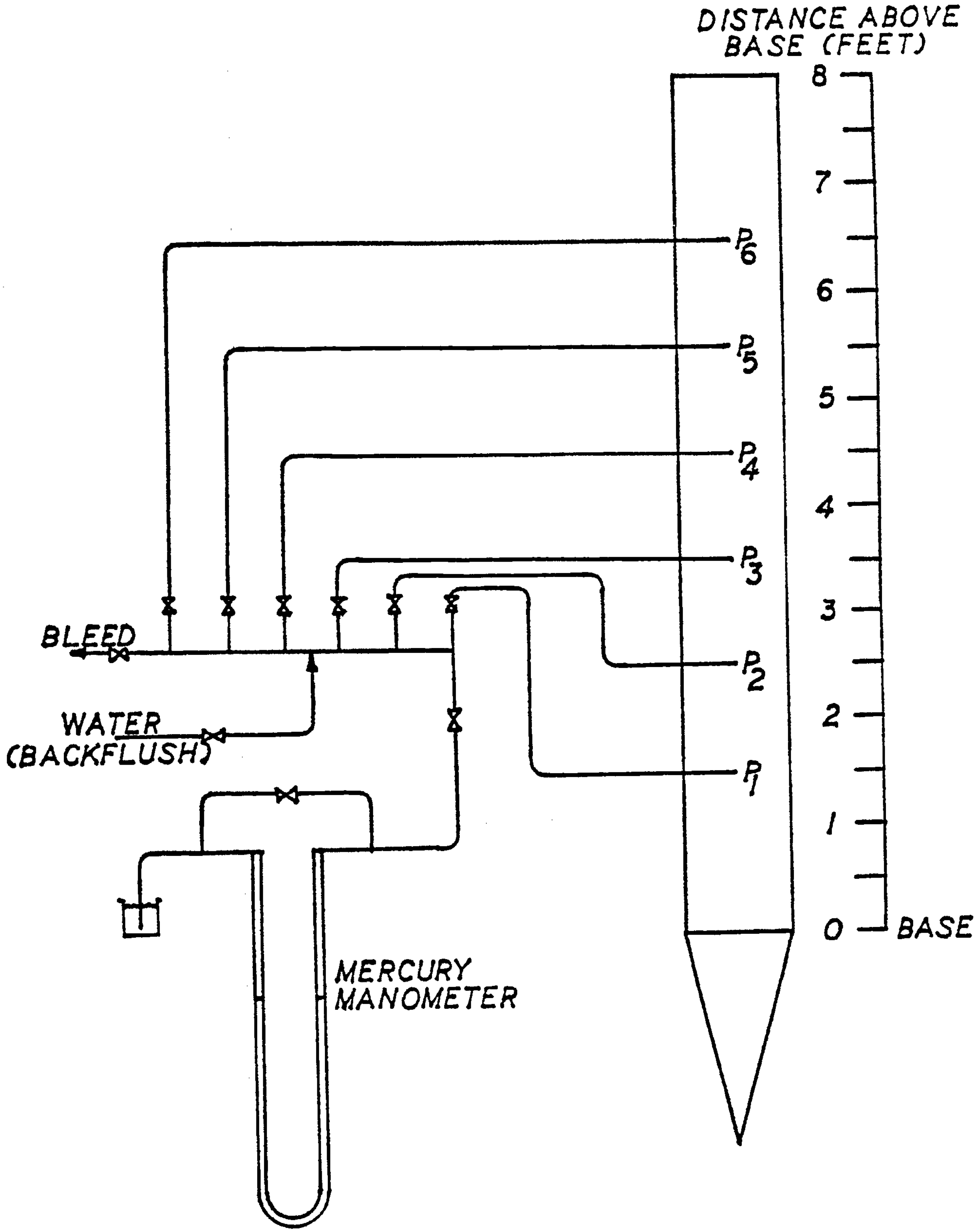


FIGURE 13 - Pressure Measurement System

Procedure

First the column is filled to the desired height with liquids; usually three different initial heights are used for each liquid studied. Next, the air flow is adjusted at the desired value. The pressure is measured from six pressure taps along the length of the column with the help of the pressure measurement system shown in Figure 13. The pressure lines are backflushed to be sure they are filled with water. Then the pressure measurements are repeated for different air flow rates. A sample of each liquid is taken in order to determine its viscosity and surface tension.

The sampling ports will be used to take samples directly from the column. This will be utilized in future work for determining the solid fraction as a function of height in the column.

Results and Discussion of Up to Date Work

This work includes holdup data for aqueous solutions of carboxy methyl cellulose (CMC) and n-propanol. The range of viscosities and surface tension covered in this study is shown in Table 12.

The pressure along the axis of the column is measured manometrically and is coverted to absolute pressure by hydrostatic correction. Pressure varies along the length of the column in a linear fashion and the pressure gradient in the column is measured by fitting a straight line through the pressure readings. The holdup is then calculated by using

$$- \frac{dP}{dX} = \varepsilon_L \rho_L$$

or

$$\varepsilon_g = 1 + \frac{1}{\rho_L} \frac{dP}{dX}$$

This method assumes no local variation of the holdup and negligible frictional drop.

The holdup values are compared with the correlations of Akita and Yoshida,[3] Hikita et al.,[4] and Joshi and Sharma,[12] in the case of n-propanol-water solutions. In the case of aqueous solutions of CMC the gas holdup values are compared with the correlation of Deckwer et al.[13] in addition to the other correlations mentioned. Tables (13-15) and (16-18) include these values tabulated for three CMC concentrations and three propanol concentrations. The air-water data in these tables refer to the correlation of Joshi and Sharma.[12]

The apparent viscosity varies from 14.0 cP to 31.2 cP for the aqueous solutions of CMC gum. Higher gas holdup values are observed at low gas velocities because of the distributor plate design, this effect diminishes at higher gas velocities, and the holdup becomes less than that predicted by Akita and Yoshida,[3] Deckwer et al.[13] and Joshi and Sharma's[12] correlation for air-water. Deckwer et al.[13] have developed a unified correlation for highly viscous CMC solutions. They found no effect of viscosity on gas holdup above an apparent viscosity of 50 cP. The maximum viscosity used here was 31.2 cP and hence a dependence of gas holdup with an increase in apparent viscosity is observed. At higher gas velocities the correlation by Deckwer et al.[13] tends to predict larger gas holdup values. Actually at higher gas velocities the holdup seems to flatten out. In all three CMC solutions the observed bubble size distribution was heterogeneous even at low gas velocities. The bubbly flow regime was never observed in this column which is evident from the fact that there is no flat portion in the graph of bubble rise velocity vs. V_G (Figures 14-16). The gas holdup data at various superficial gas velocities are compared with

SURFACE TENTION= 0.00523 NEWTCN/M
LIQUID VISCOSITY= 0.01400 KG/(M*SEC)

HOLDUP EXPERIMENTAL	HOLDUP AIR-WATER	HOLDUP AKITA &YOSHIDA	HOLDUP DECKWER ET AL.	VG(CM/SEC)	VDRIFT(CM/SEC)	VRISE(CM/SEC)
0.06626	0.02524	0.02192	0.02201	0.79761	0.74476	12.03681
0.07034	0.05390	0.04523	0.04316	1.81251	1.68502	25.76950
0.07862	0.08350	0.06811	0.06537	3.00734	2.77090	38.25016
0.10334	0.10830	0.08667	0.08508	4.14731	3.71873	40.13223
0.11157	0.13064	0.10310	0.10411	5.30517	4.71328	47.55098
0.12388	0.15754	0.12274	0.12916	6.90020	6.04538	55.69910
0.14239	0.18397	0.14207	0.15666	8.73187	7.48853	61.32315
0.16091	0.20282	0.15601	0.17848	10.23702	8.58974	63.61813
0.16089	0.21550	0.16549	0.19441	11.36166	9.53363	70.61581
0.06792	0.02746	0.02378	0.02368	0.87169	0.81249	12.83467
0.09456	0.05915	0.04936	0.04702	2.01241	1.82212	21.28203
0.09663	0.10174	0.08181	0.07974	3.83209	3.46180	39.65825
0.11914	0.14597	0.11431	0.11807	6.18481	5.44798	51.91417
0.15477	0.18729	0.14452	0.16036	8.98421	7.59369	58.04737
0.18978	0.22845	0.17531	0.21188	12.61938	10.22452	66.49607
0.21654	0.27398	0.21130	0.28587	18.18270	14.24542	83.96941
0.21451	0.29496	0.22900	0.32896	21.57833	16.94964	100.59527
0.21651	0.30603	0.23872	0.35483	23.66564	18.54174	109.30396
0.24326	0.31697	0.24865	0.38302	25.97780	19.65851	106.79148
0.05152	0.06273	0.05217	0.04968	2.15205	2.04117	41.77099
0.09262	0.09424	0.07621	0.07375	3.48400	3.16133	37.61808
0.12331	0.15992	0.12448	0.13151	7.05389	6.18408	57.20494
0.14393	0.19299	0.14872	0.16685	9.42938	8.07223	65.51465
0.19528	0.23082	0.17712	0.21522	12.86205	10.35039	65.86574
0.19094	0.27183	0.20954	0.28183	17.86992	14.45781	93.58854
0.20942	0.28206	0.21802	0.30163	19.41279	15.34735	92.69764
0.20740	0.29057	0.22523	0.31935	20.81209	16.49574	100.34935
0.21556	0.30195	0.23511	0.34501	22.86952	17.93977	106.09365
0.24222	0.31468	0.24654	0.37688	25.47130	19.30154	105.15598

TABLE 13 - Holdup and Gas Velocities for 0.15 wt% CMC Solution

SURFACE TENTION= 0.00523 NEWTON/M
LIQUID VISCOSITY= 0.02040 KG/(M*SEC)

HOLDUP EXPERIMENTAL	HOLDUP AIR-WATER	HOLDUP AKITA &YOSHIDA	HOLDUP DECKWER ET AL.	VG(CM/SEC)	VDRIFT(CM/SEC)	VRISE(CM/SEC)
0.05598	0.02[illegible]17	0.02063	0.02196	0.79512	0.75[illegible]41	14.20345
[illegible]05596	[illegible]	0.03790	0.0[illegible]33	.56835	1.46[illegible]9	28.02859
0.07853	0.06874	0.05401	0.05416	2.39095	2.20319	30.44608
0.08605	0.11096	0.08470	0.08727	4.27802	3.90649	49.25961
0.27224	0.12204	0.09261	0.09662	4.84333	3.52478	17.79069
0.11768	0.15298	0.11462	0.12472	6.61249	5.83432	56.18944
0.13822	0.18865	0.14014	0.16188	9.08828	7.83211	65.75291
0.14649	0.20562	0.15248	0.18191	10.47753	8.94265	71.52240
0.15269	0.21616	0.16024	0.19526	11.42216	9.67876	74.81030
0.[illegible]4334	0.02732	0.02234	0.02357	0.86617	0.82930	20.00077
0.07817	0.06413	0.05058	0.05072	2.20615	2.03444	28.23330
0.10481	0.10279	0.07884	0.08058	3.88181	3.47495	37.03627
0.11762	0.14159	0.10652	0.11400	5.92515	5.22887	50.38264
0.13416	0.17463	0.13006	0.14657	8.05073	6.97061	60.00648
0.14650	0.20362	0.15102	0.17945	10.30516	8.79546	70.34303
0.17538	0.23114	0.17144	0.21567	12.89528	10.63377	73.52962
0.17736	0.26159	0.19498	0.26344	16.45719	13.53895	92.79272
0.19797	0.27994	0.20982	0.29740	19.08048	15.30353	96.38497
0.20421	0.28983	0.21010	0.31776	20.68573	16.46158	101.29837
0.22679	0.29746	0.22462	0.33460	22.03043	17.03421	97.14130
0.08222	0.03238	0.02633	0.02734	1.03868	0.95328	12.63335
0.09261	0.07501	0.05864	0.05808	2.64752	2.40233	28.58721
0.11316	0.13649	0.10290	0.10934	5.63216	4.99474	49.77098
0.17469	0.20024	0.14855	0.17537	10.02011	8.26967	57.35840
0.19098	0.23721	0.17604	0.22448	13.54032	10.95433	70.89742
0.20740	0.26943	0.20125	0.27740	17.52717	13.89265	84.51384
0.20339	0.28347	0.21275	0.30448	19.63612	15.64275	96.54714
0.24231	0.30991	0.23556	0.36451	24.45415	18.52924	100.92457
0.24018	0.31930	0.24410	0.38940	26.50622	20.14003	110.36107

TABLE 14 - Holdup and Gas Velocities for 0.20 wt% CMC Solution

SURFACE TENTION= 0.00592 NEWTCN/M
LIQUID VISCOSITY= 0.03120 KG/(M*SEC)

HOLDUP EXPERIMENTAL	HOLDUP AIR-WATER	HOLDUP AKITA &YOSHIDA	HOLDUP DECKWER ET AL.	VG(CM/SEC)	VDRIFT(CM/SEC)	VRISE(CM/SEC)
0.05390	0.02752	0.02078	0.02372	0.87370	0.82660	16.20921
0.06830	0.05319	0.03935	0.04263	1.78565	1.66370	26.14550
0.09097	0.08986	0.06499	0.07030	3.28631	2.98737	36.12667
0.09094	0.11721	0.08376	0.09251	4.59317	4.17544	50.50504
0.11982	0.15528	0.10979	0.12695	6.75663	5.94707	56.39144
0.13007	0.17681	0.12466	0.14889	8.20649	7.13907	63.09247
0.14246	0.18093	0.12753	0.15333	8.50614	7.29432	59.70734
0.13007	0.20925	0.14751	0.18642	10.79515	9.39102	82.99437
0.15681	0.23108	0.16338	0.21559	12.88885	10.86779	82.19572
0.05971	0.02480	0.01878	0.02168	0.78290	0.73615	13.11150
0.07408	0.06428	0.04719	0.05083	2.21303	2.04910	29.87480
0.10895	0.09202	0.06648	0.07199	3.38308	3.01451	31.05309
0.07001	0.11250	0.08054	0.08856	4.35504	4.05016	62.20950
0.08844	0.14049	0.09966	0.11298	5.86153	5.34313	66.27558
0.12595	0.15889	0.11227	0.13049	6.98703	6.10701	55.47456
0.12182	0.17808	0.12554	0.15024	8.29742	7.28666	68.11431
0.13827	0.20064	0.14138	0.17585	10.05314	8.66309	72.70637
0.16095	0.22358	0.15788	0.20516	12.13261	10.17990	75.38257
0.17333	0.24154	0.17117	0.23096	14.01832	11.58853	80.87664
0.15883	0.25730	0.18317	0.25612	15.90251	13.37675	100.12411
0.18149	0.26894	0.19156	0.27487	17.33294	14.18720	95.50391
0.19798	0.27588	0.19782	0.28950	18.46443	14.80888	93.26508
0.06170	0.03131	0.02357	0.02655	1.00218	0.94034	16.24156
0.09261	0.08379	0.06080	0.06559	3.01993	2.74024	32.60783
0.10283	0.13164	0.09361	0.10500	5.36048	4.80924	52.12730
0.12345	0.18266	0.12873	0.15521	8.63362	7.56779	69.93535
0.15407	0.20984	0.14794	0.18716	10.84775	9.17645	70.40854
0.16023	0.22926	0.16204	0.21302	12.70186	10.66667	79.27371
0.17251	0.24700	0.17528	0.23938	14.64379	12.11766	84.88885
0.19096	0.28192	0.20272	0.30136	19.39106	15.68808	101.54355
0.21149	0.30287	0.22034	0.34720	23.04627	18.17226	108.97196
0.23606	0.31440	0.23050	0.37613	25.40940	19.41116	107.63778
0.23195	0.32415	0.23941	0.40312	27.64981	21.23642	119.20560

TABLE 15 - Holdup and Gas Velocities for 0.25% CMC Solution

SURFACE TENTION= 0.0[illegible]561 NEWTON/M
LIQUID VISCOSITY= 0.00100 KG/(M*SEC)

HOLDUP EXPERIMENTAL	HOLDUP AIR-WATER	HOLDUP AKITA &YOSHIDA	HOLDUP DECKWER ET AL.	VG(CM/SEC)	VDRIFT(CM/SEC)	VRISE(CM/SEC)
0.07652	0.00507	0.00690	0.00570	0.15353	0.14178	2.00631
0.11975	0.02564	0.03278	0.02231	0.81070	0.71362	6.76998
0.17528	0.05492	0.06528	0.04390	1.85095	1.52652	10.56015
0.20001	0.07554	0.08605	0.05928	2.66954	2.13560	13.34696
0.22680	0.09809	0.10737	0.07680	3.66048	2.83027	16.13949
0.23906	0.10592	0.11451	0.08313	4.03155	3.06778	16.86431
0.26387	0.11679	0.12424	0.09215	4.57143	3.36518	17.32472
0.12345	0.03660	0.04545	0.03046	1.18490	1.03862	9.59807
0.22176	0.10730	0.11576	0.08426	4.09866	3.18973	18.48214
0.28737	0.14752	0.15082	0.11953	6.27805	4.47394	21.84676
0.33247	0.16734	0.16747	0.13898	7.54575	5.03704	22.69626
0.49819	0.19568	0.19093	0.16997	9.64482	4.83984	19.35960
0.44908	0.20662	0.19996	0.18315	10.56435	5.82007	23.52424
0.30378	0.13096	0.13664	0.10440	5.32318	3.70612	17.52325
0.10359	0.00859	0.01156	0.00884	0.26213	0.23497	2.53047
0.16555	0.03574	0.04447	0.02982	1.15458	0.96344	6.97416
0.24673	0.07199	0.08258	0.05660	2.52298	1.90048	10.22559
0.38027	0.15849	0.16007	0.13010	6.96150	4.31427	18.30684
0.46372	0.18143	0.17917	0.15387	8.54289	4.58139	18.42254
0.51705	0.20251	0.19657	0.17810	10.21075	4.93130	19.74815
0.52321	0.21572	0.20747	0.19470	11.38266	5.42717	21.75554
0.50880	0.22640	0.21631	0.20902	12.41191	6.09674	24.39452
0.55187	0.24679	0.23335	0.23906	14.62003	6.55160	26.49157
0.54569	0.25850	0.24326	0.25814	16.05550	7.29411	29.42215
0.54365	0.27227	0.25510	0.28266	17.93404	8.18423	32.98830
0.55390	0.28242	0.26398	0.30236	19.46999	8.68556	35.15073

TABLE 16 - Holdup and Gas Velocities for 0.5 wt% n-Propanol Solutions

SURFACE TENTION= 0.00639 NEWTON/M
LIQUID VISCOSITY= 0.00100 KG/(M*SEC)

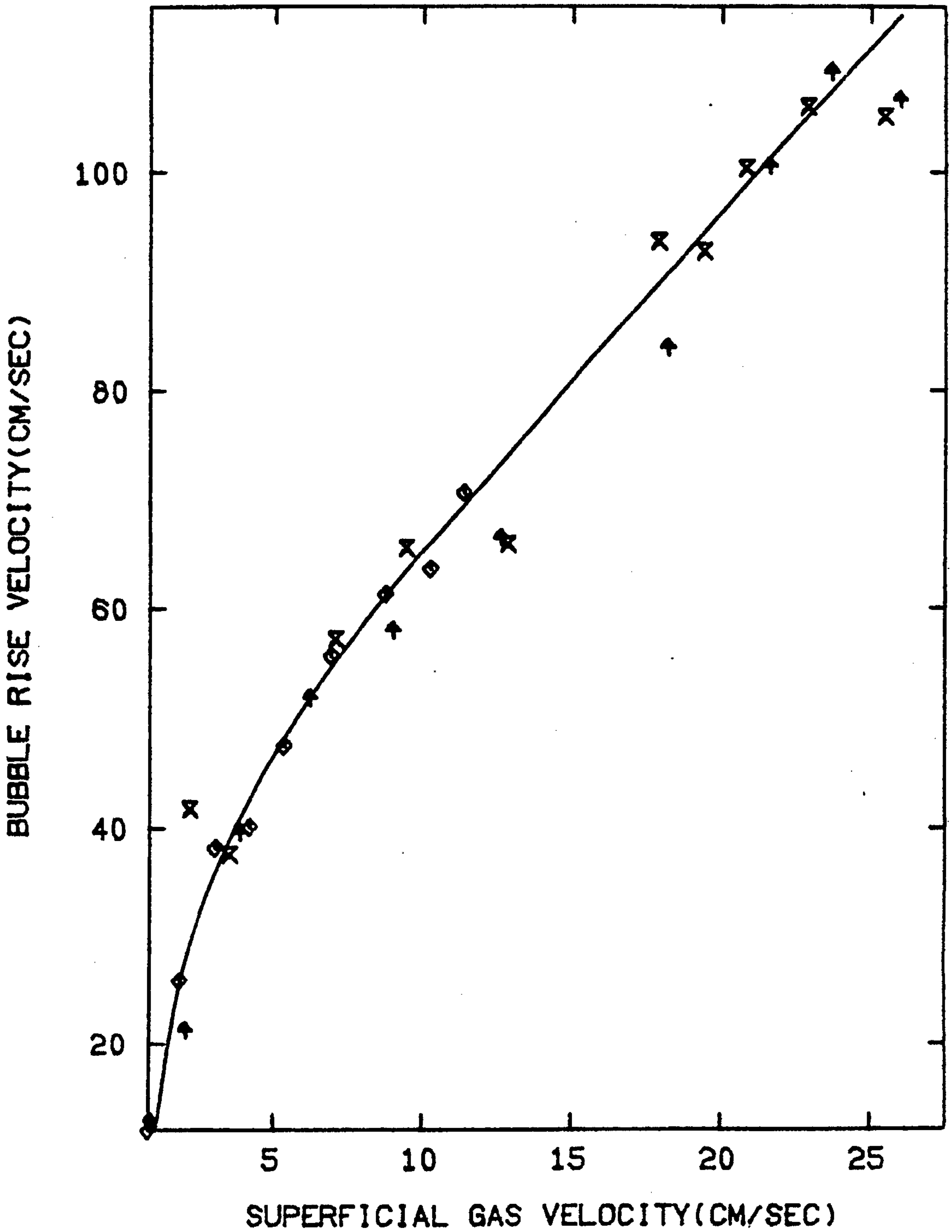
HOLDUP EXPERIMENTAL	HOLDUP AIR-WATER	HOLDUP AKITA &YOSHIDA	HOLDUP DECKWER ET AL.	VG(CM/SEC)	VDRIFT(CM/SEC)	VRISE(CM/SEC)
0.07853	0.00689	0.00923	0.00735	0.20945	-0.19300	2.66708
0.10740	0.02678	0.03382	0.02317	0.84874	0.75759	7.90246
0.16424	0.05235	0.06208	0.04201	1.75407	1.46599	10.68022
0.18564	0.05546	0.06532	0.04430	1.87140	1.52400	10.08094
0.21443	0.06950	0.07951	0.05473	2.42176	1.90247	11.29408
0.25971	0.09169	0.10066	0.07167	3.36457	2.49075	12.95493
0.28454	0.09746	0.10606	0.07630	3.63156	2.59822	12.76275
0.09091	0.00560	0.00754	0.00619	0.16985	0.15441	1.86836
0.10287	0.02631	0.03328	0.02282	0.83327	0.74755	8.10040
0.19303	0.07419	0.08411	0.05826	2.61348	2.10900	13.53922
0.22995	0.09494	0.10374	0.07430	3.51565	2.70724	15.28899
0.26277	0.11879	0.12511	0.09377	4.66946	3.44246	17.77014
0.29355	0.11843	0.12488	0.09354	4.65566	3.28900	15.86000
0.33174	0.12998	0.13494	0.10353	5.26893	3.52104	15.88291
0.37086	0.14602	0.14866	0.11811	6.18776	3.89296	16.68483
0.40385	0.15721	0.15808	0.12884	6.87934	4.10111	17.03437
0.42239	0.16694	0.16619	0.13857	7.51829	4.34267	17.79959
0.42863	0.18307	0.17955	0.15567	8.66485	4.95087	20.21540
0.13457	0.04719	0.05663	0.03823	1.56337	1.35299	11.61759
0.17480	0.07836	0.08814	0.06142	2.78757	2.30030	15.94727
0.28783	0.11558	0.12236	0.09113	4.50966	3.21167	15.66807
0.31863	0.13559	0.13976	0.10852	5.58048	3.80238	17.51408
0.43501	0.16973	0.16851	0.14144	7.70853	4.35524	17.72036
0.46579	0.18714	0.18291	0.16019	8.97273	4.79334	19.26357
0.49448	0.20604	0.19847	0.18243	10.51385	5.31501	21.26262
0.51498	0.21735	0.20778	0.19682	11.53429	5.59436	22.39753
0.51498	0.22995	0.21821	0.21400	12.77300	6.19515	24.80286
0.54162	0.27542	0.25674	0.29861	18.39575	8.43218	33.96410
0.50466	0.29069	0.27022	[illegible]	20.83177	10.31871	41.27842
0.55185	0.30267	0.28197	0.34571	23.00650	10.31029	41.68952
0.54590	0.32018	0.29749	0.39182	26.70777	12.12797	48.92420

TABLE 17 - Holdup and Gas Velocities for 1.0 wt% n-Propanol Solution

SURFACE TENSION= 0.03642 NEWTON/M
LIQUID VISCOSITY= 0.00109 KG/(M*SEC)

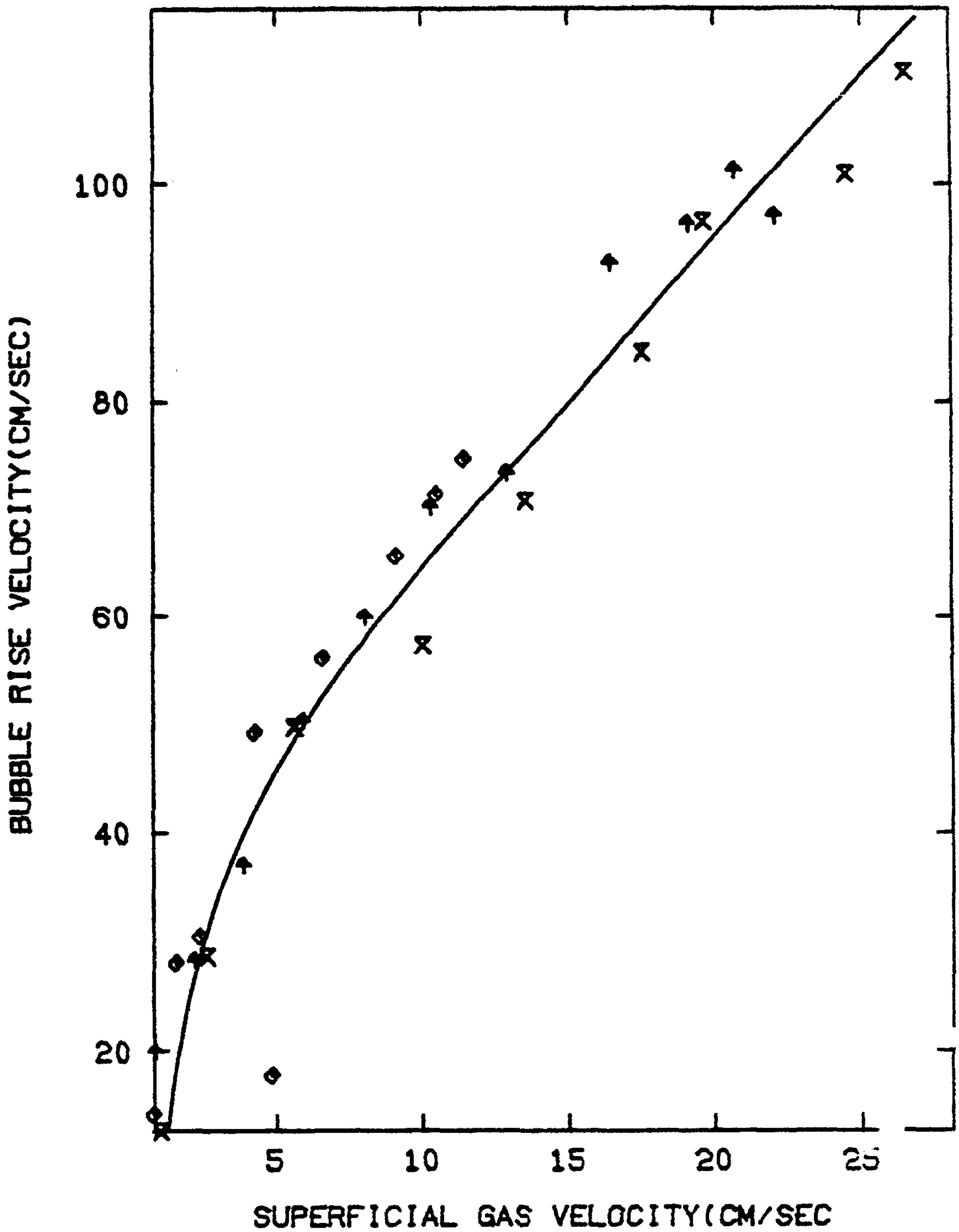
HOLDUP EXPERIMENTAL	HOLDUP AIR-WATER	HOLDUP AKITA &YOSHIDA	HOLDUP DECKWER ET AL.	VG(CM/SEC)	VDRIFT(CM/SEC)	VRISE(CM/SEC)
0.22751	0.05631	0.06586	0.04492	1.90351	1.47044	8.36660
0.33917	0.11894	0.12481	0.09397	4.68175	3.09383	13.80345
0.58493	0.20244	0.19436	0.17802	10.20490	4.23577	17.44643
0.60356	0.23986	0.22579	0.22842	13.83039	5.48296	22.91479
0.49863	0.18234	0.17833	0.15487	8.61046	4.31700	17.26815
0.15422	0.02973	0.03705	0.02537	0.94839	0.80213	6.14968
0.26889	0.08883	0.09763	0.06950	3.24076	2.36935	12.05243
0.36669	0.12282	0.12820	0.09729	4.88422	3.09323	13.31979
0.24020	0.10110	0.10892	0.07922	3.80199	2.88868	15.82813
0.36085	0.14115	0.14397	0.11360	5.90038	3.72404	15.99676
0.41199	0.15955	0.15945	0.13114	7.02981	4.13358	17.06295

TABLE 18 - Holdup and Gas Velocities for 1.5 wt% n-Propanol Solution



VM VS.VG FOR(0.15WT%)CMC-WATER.

FIGURE 14



VM VS.VG FOR(0.20WT%)CMC-WATER.

FIGURE 15

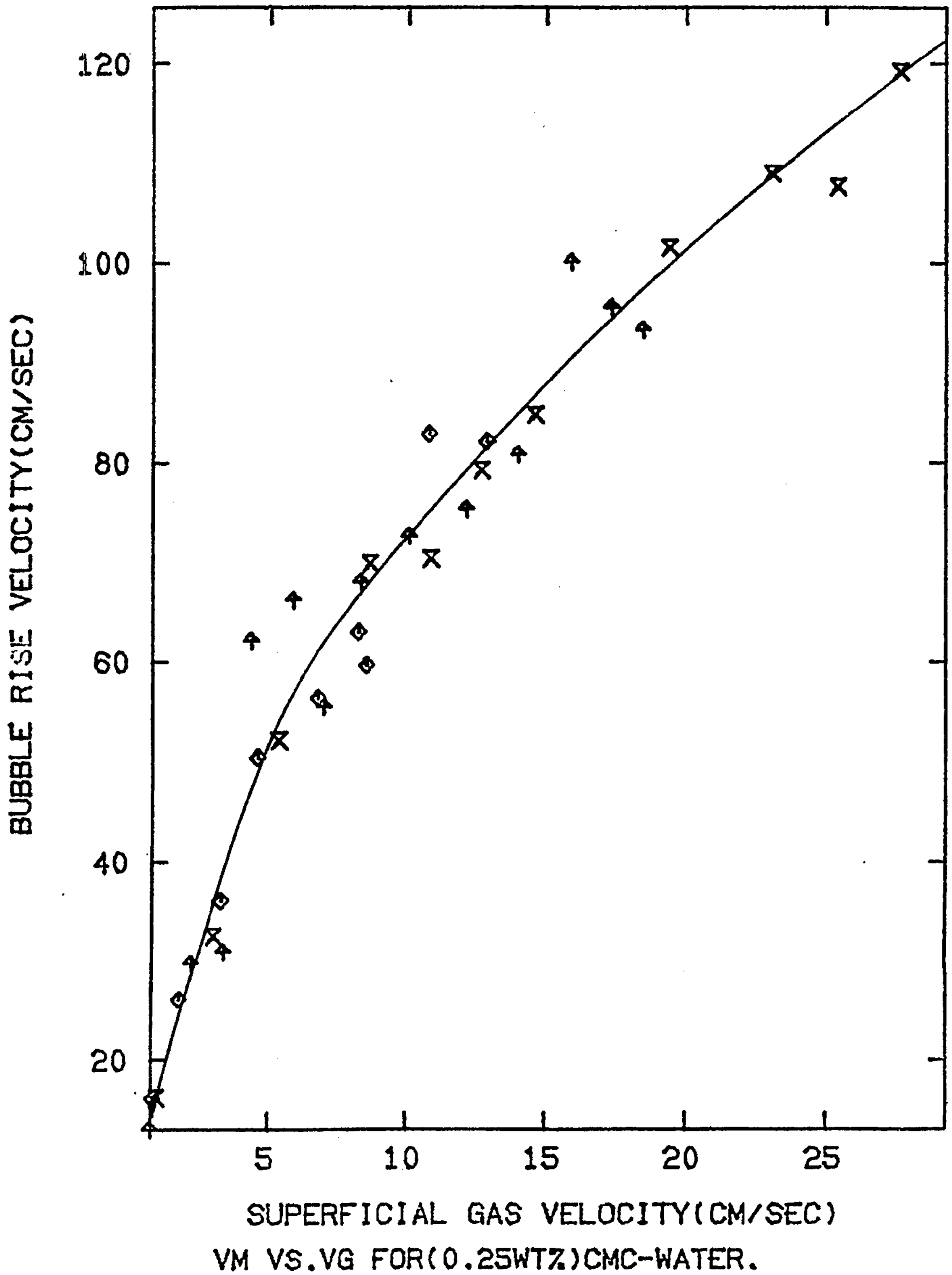
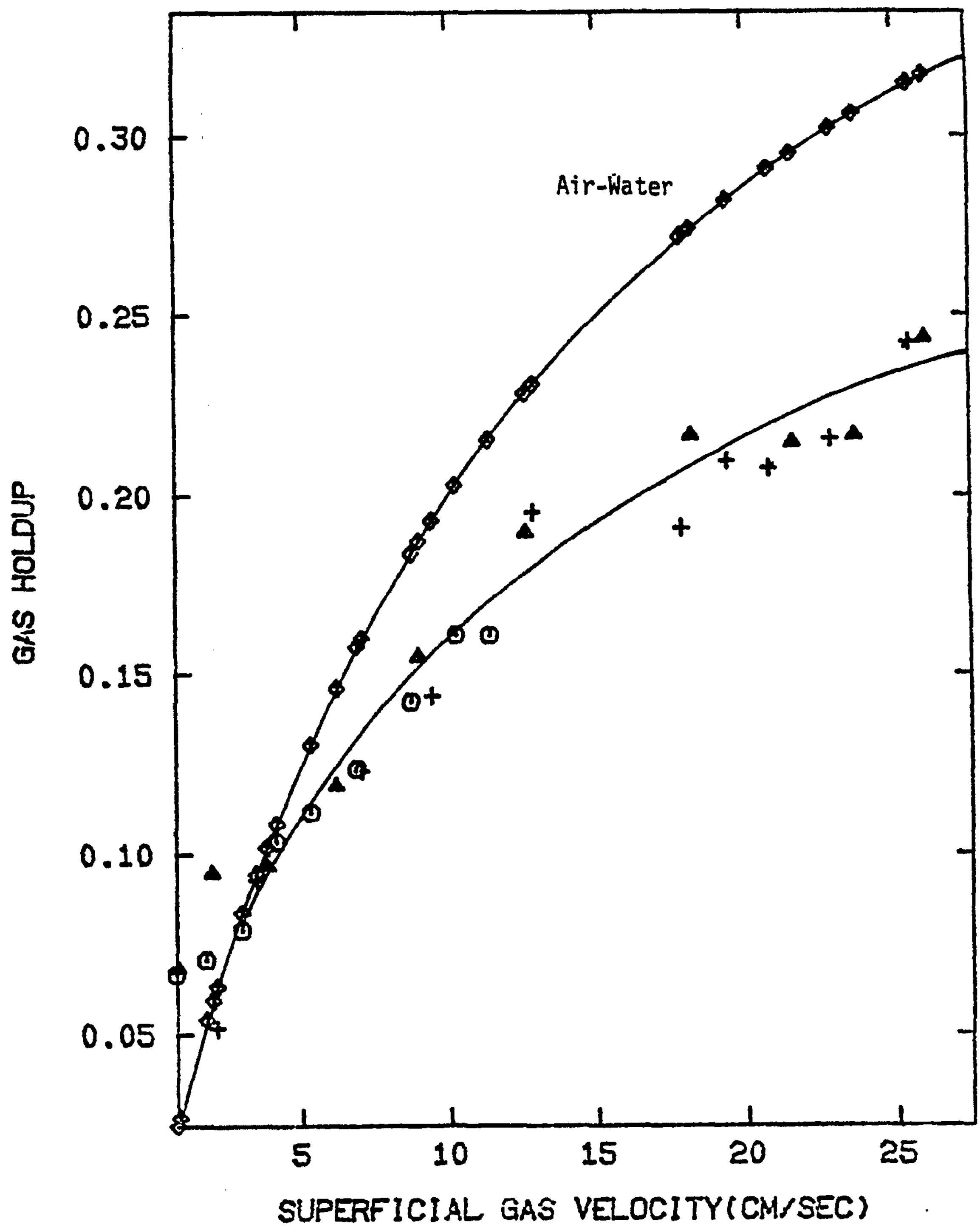

120
100
80
60
40
20
BUBBLE RISE VELOCITY(CM/SEC)
5
10
15
20
25
SUPERFICIAL GAS VELOCITY(CM/SEC)
VM VS.VG FOR(0.25WT%)CMC-WATER.

FIGURE 16



HOLDUP VS. VG FOR(0.15WT%)CMC SOLUTION

FIGURE 17

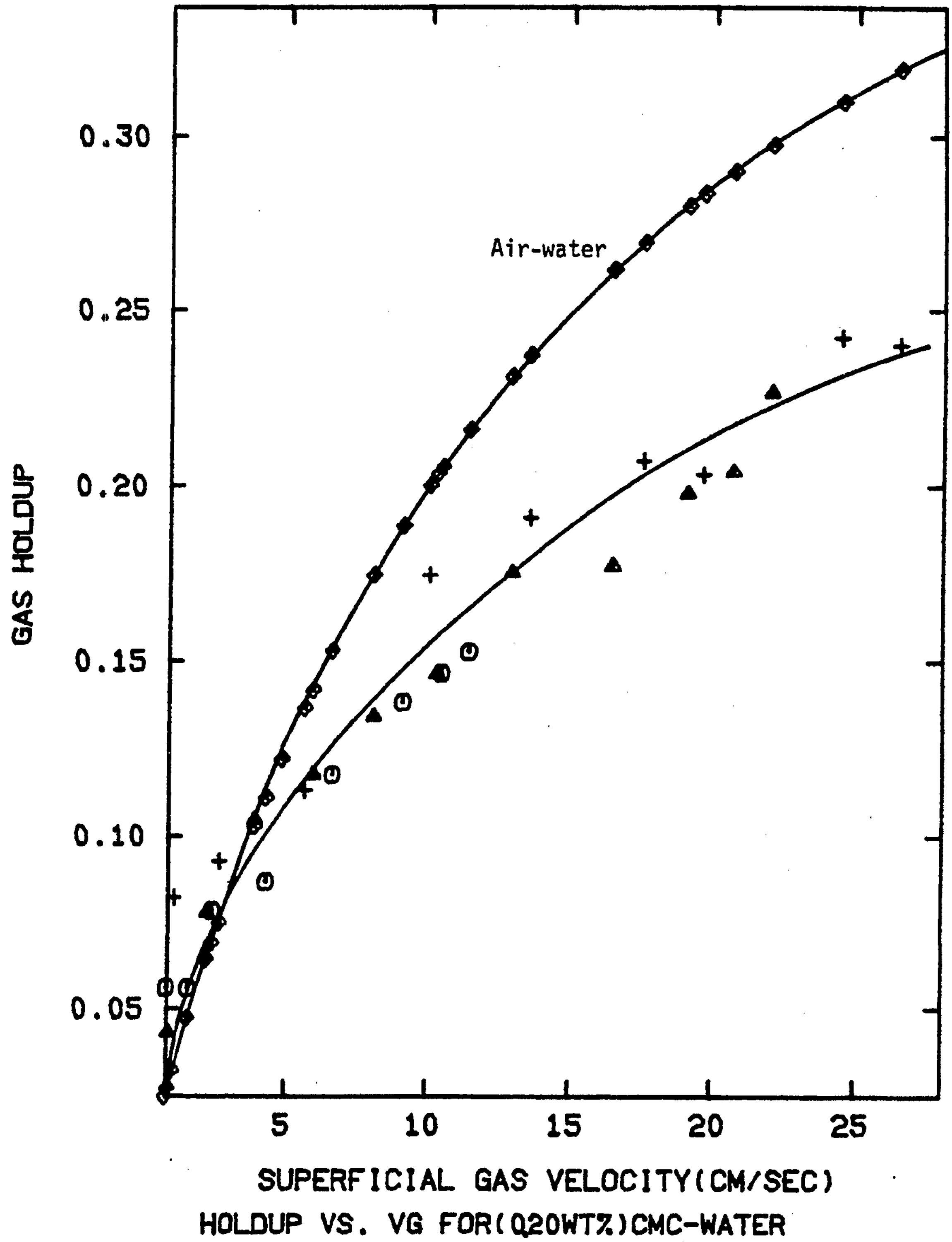
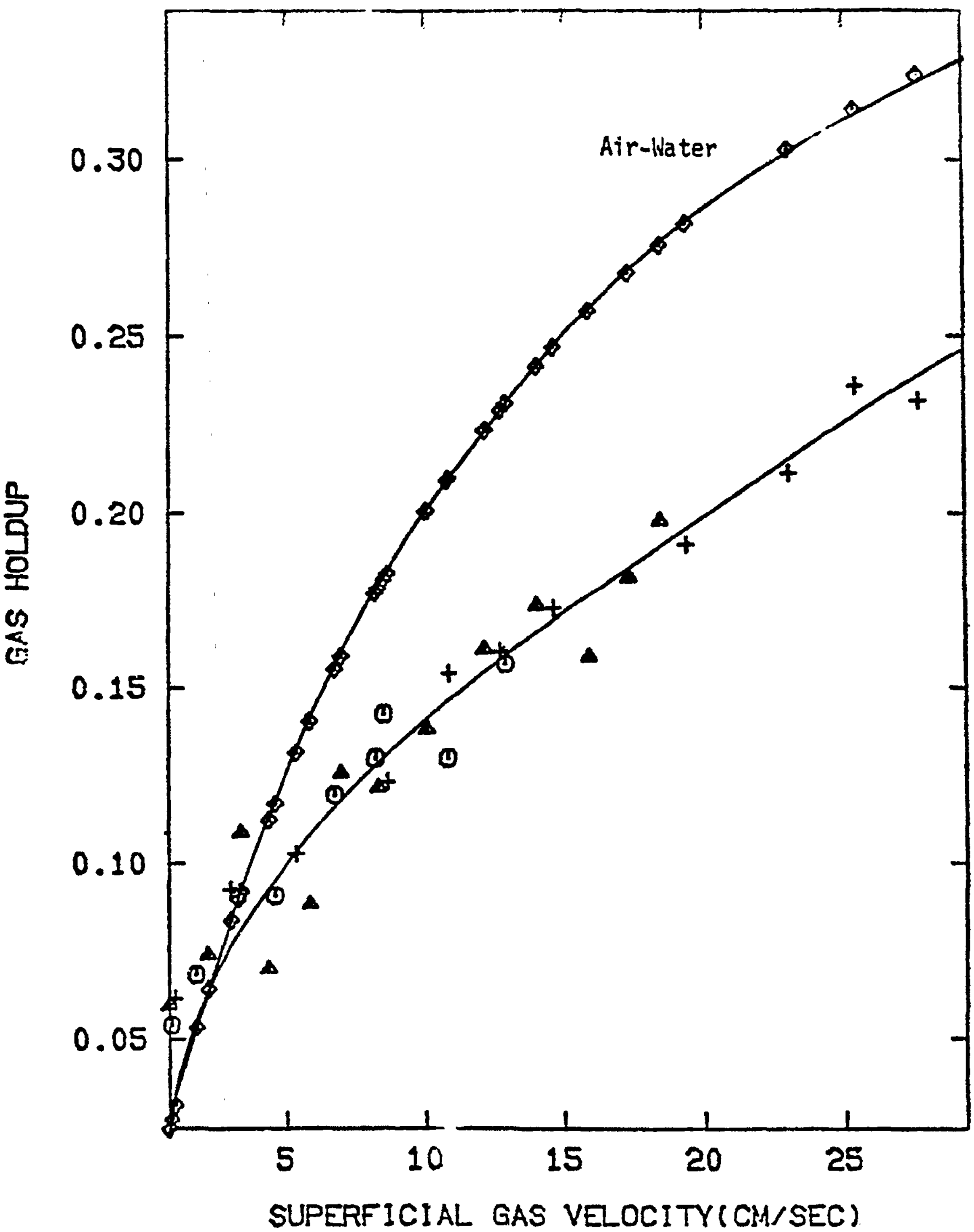
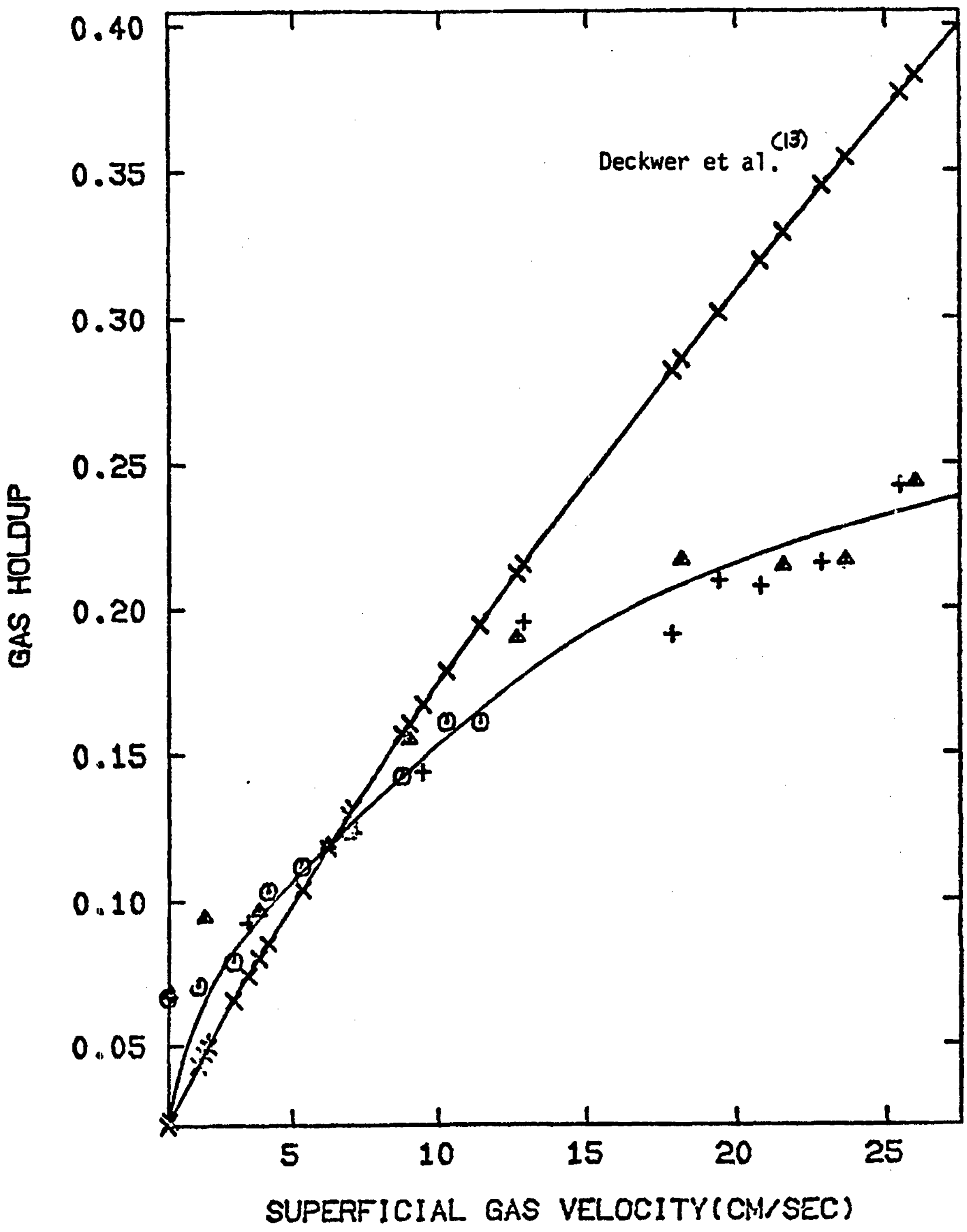

Air-water
0.30
0.25
0.20
0.15
0.10
0.05
GAS HOLDUP
5
10
15
20
25
SUPERFICIAL GAS VELOCITY(CM/SEC)
HOLDUP VS. VG FOR(0.20WT%)CMC-WATER

FIGURE 18



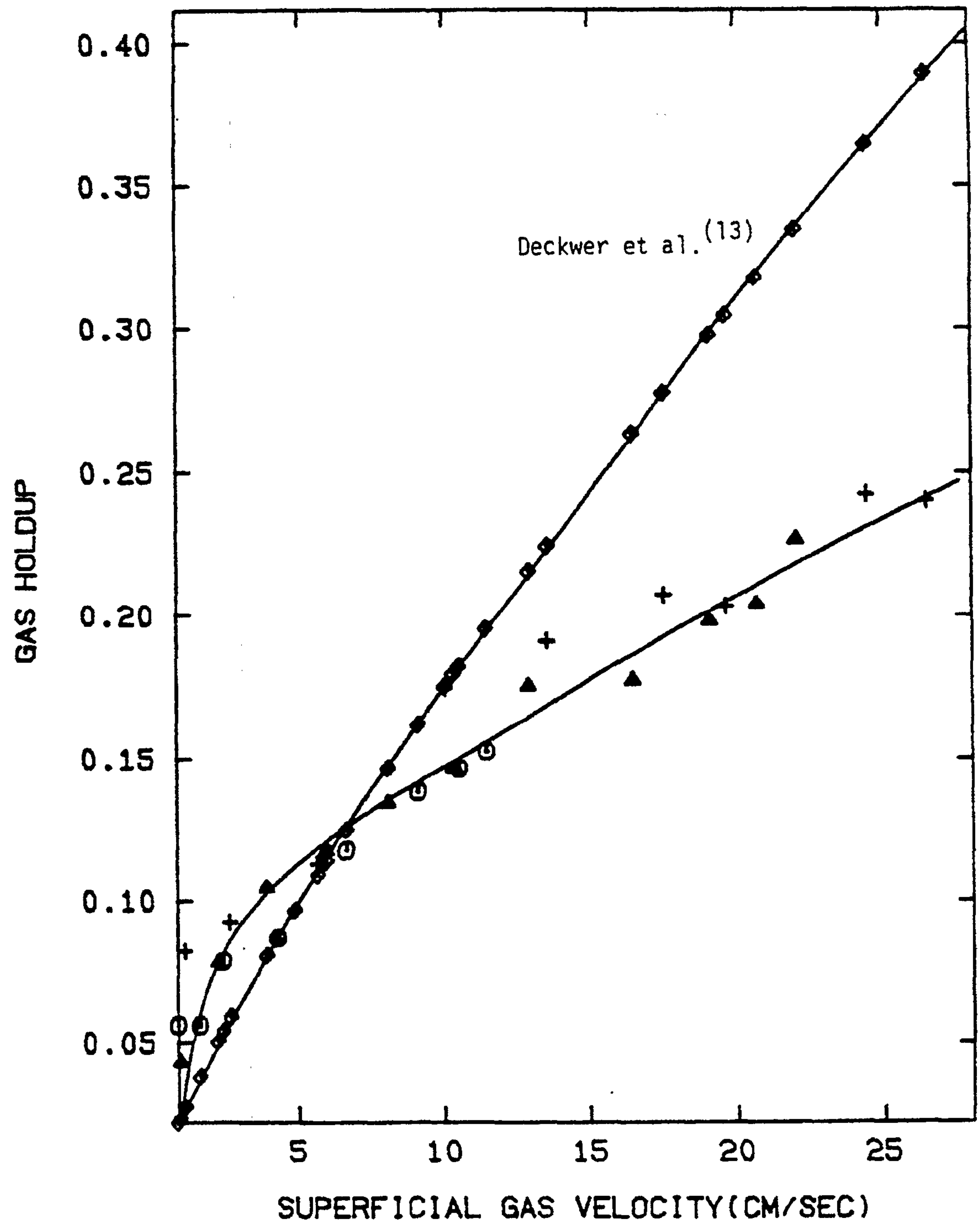
HOLDUP VS. VG FOR(0.25WT%)CMC SOLUTION

FIGURE 19



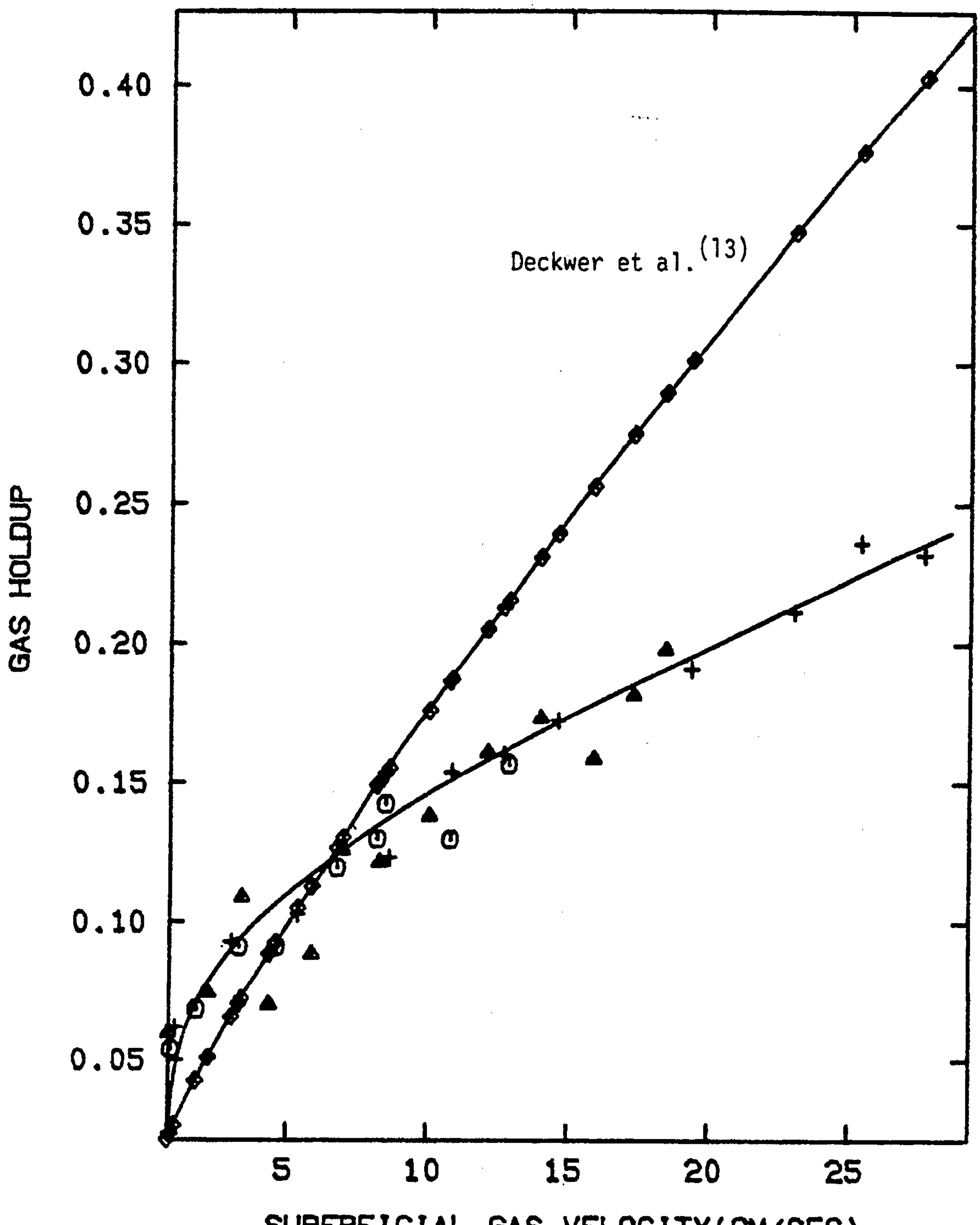
HOLDUP VS. VG FOR(0.15WT%)CMC SOLUTION

FIGURE 20



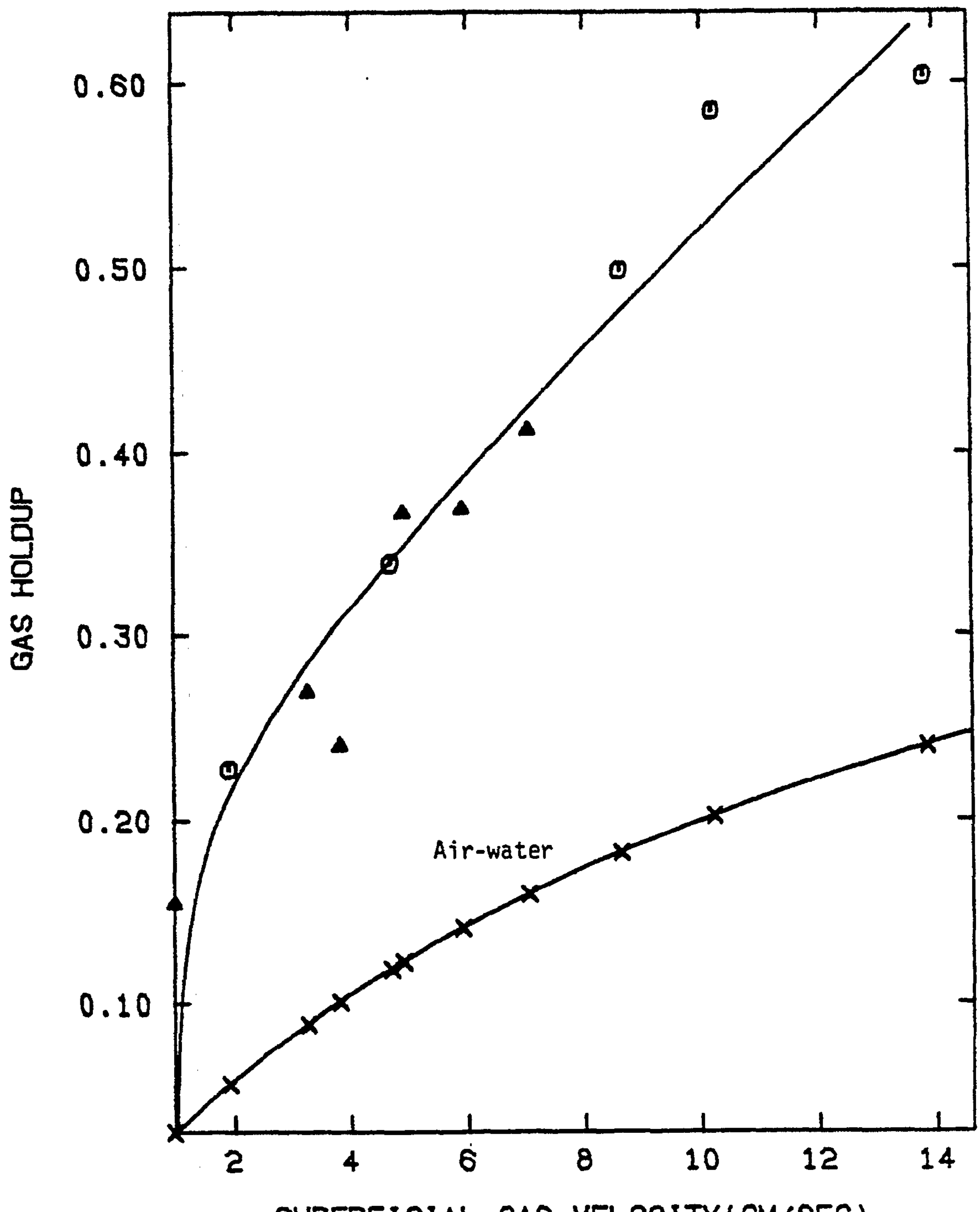
HOLDUP VS. VG FOR(0.20WT%)CMC-WATER

FIGURE 21



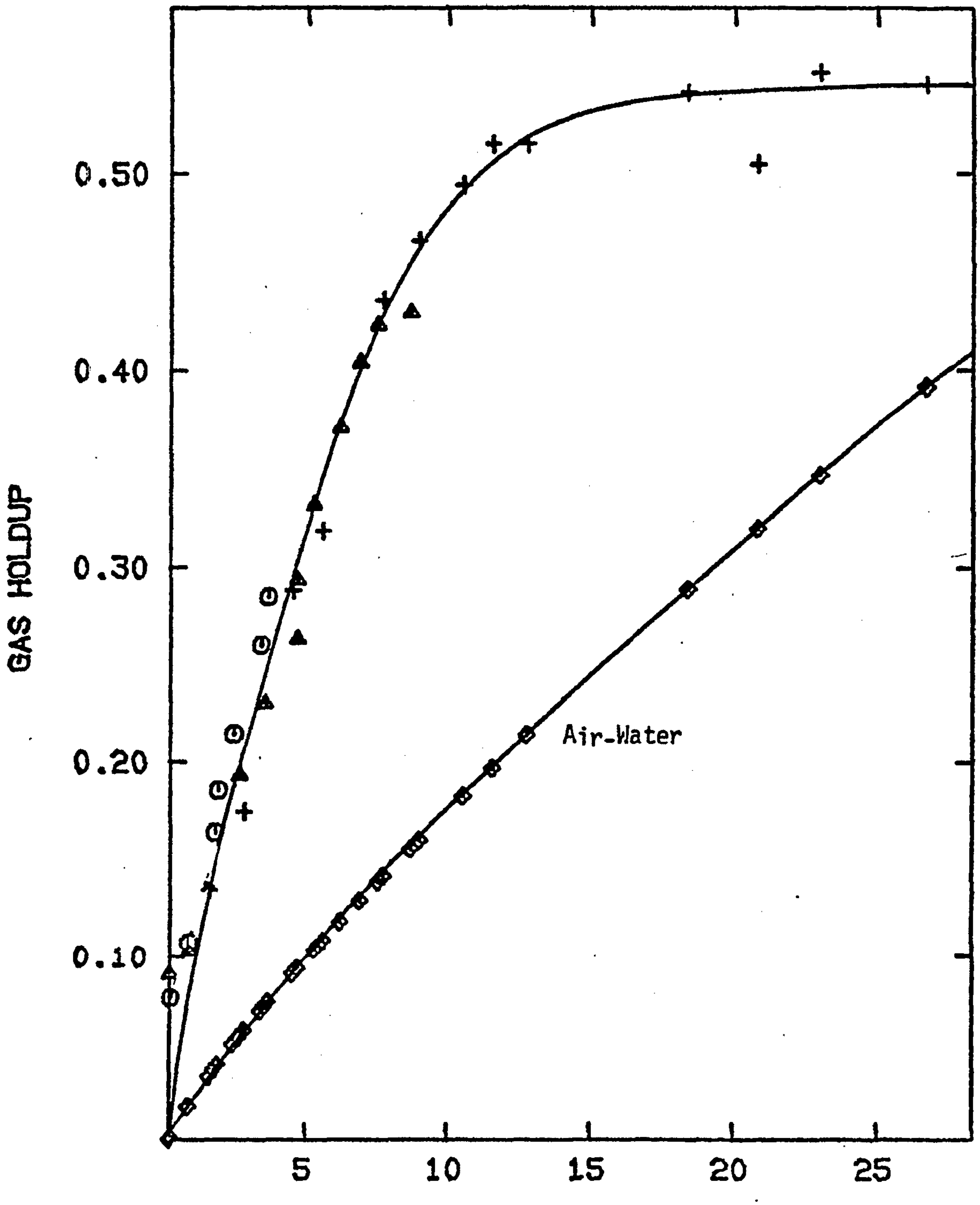
HOLDUP VS. VG FOR(0.25WT%)CMC-WATER

FIGURE 22



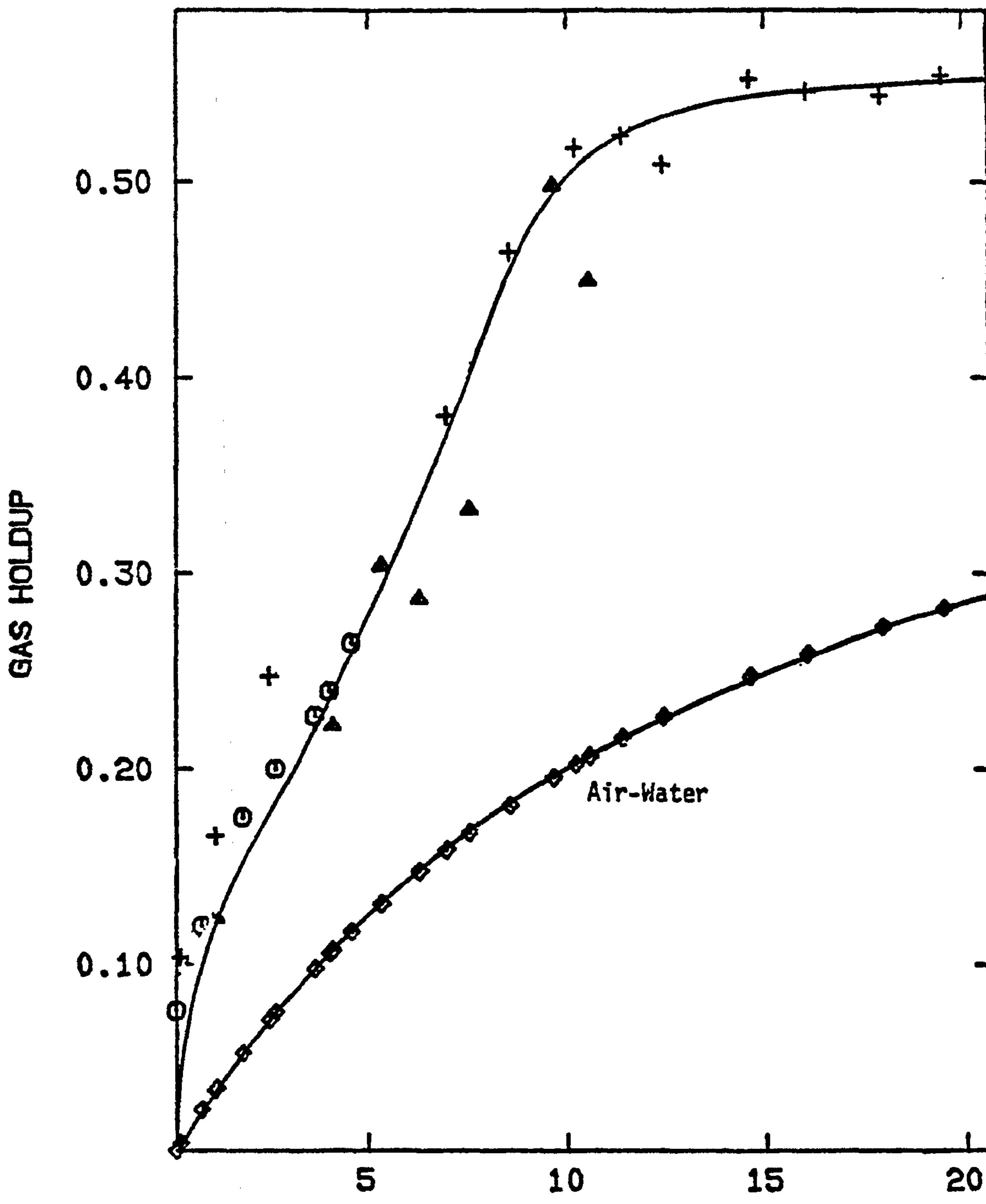
HOLDUP VS. VG FOR(0.5WT%)N-PROPANOL-WATER

FIGURE 23



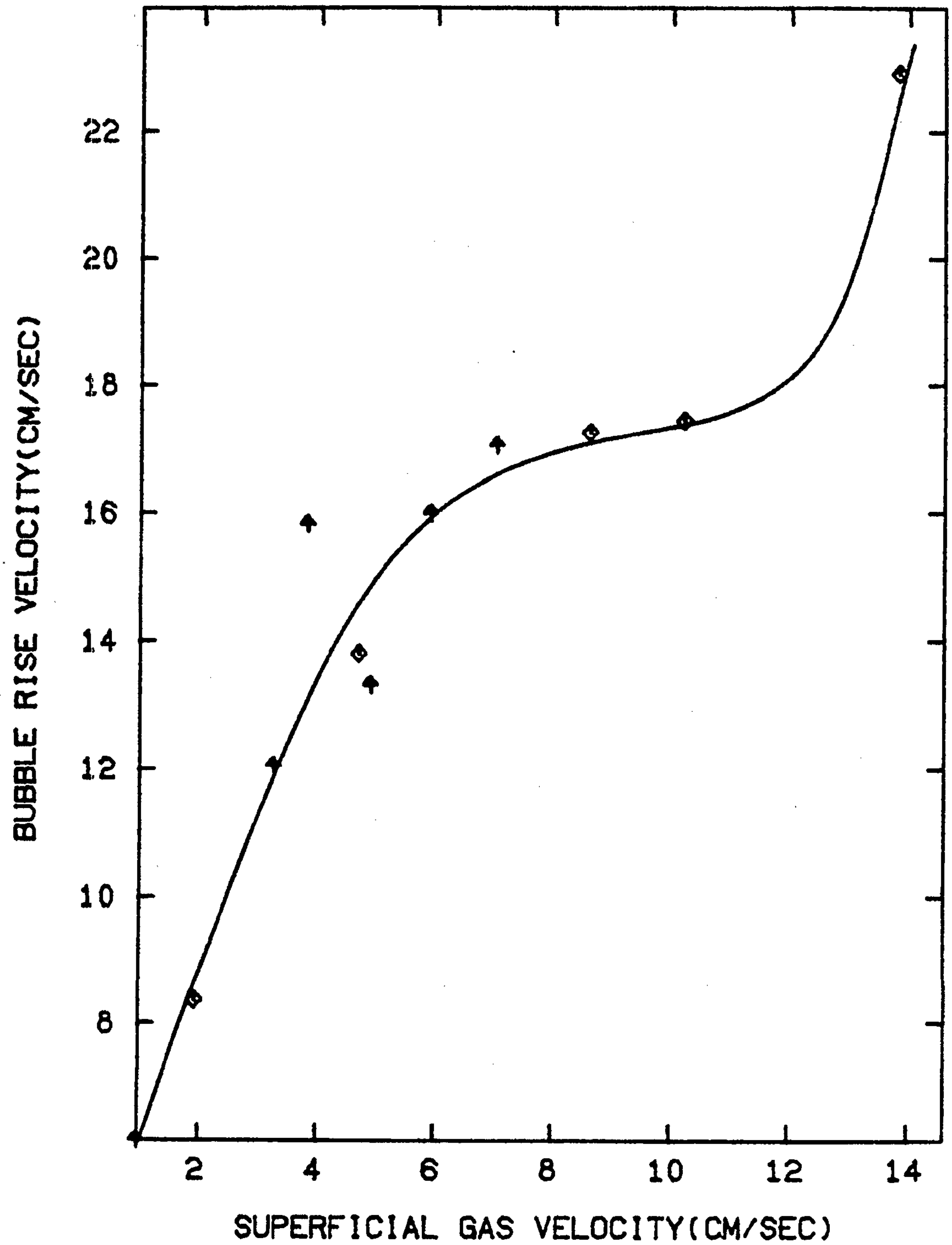
HOLDUP VS. VG FOR(1.0WT%)N-PROPANOL-WATER

FIGURE 24



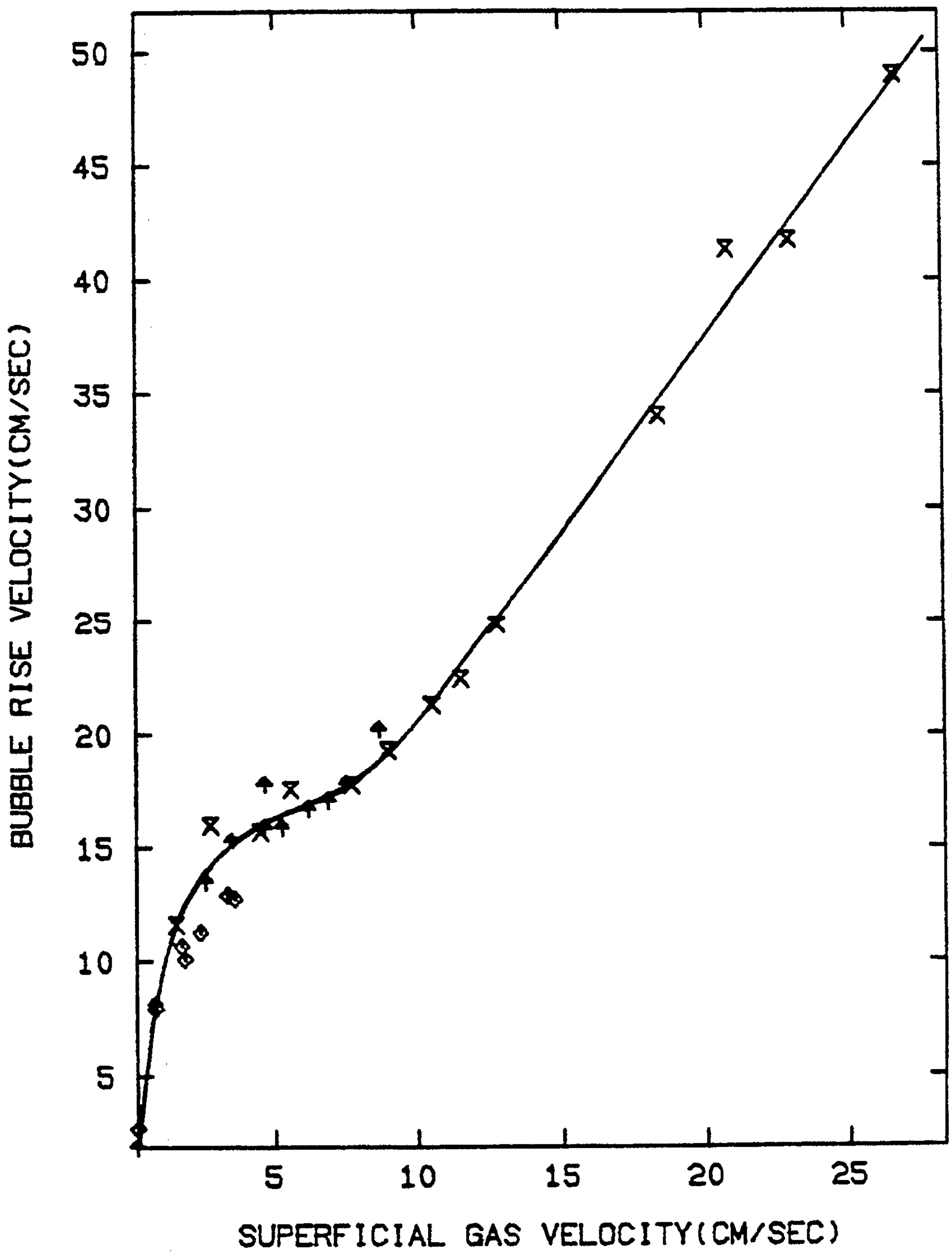
HOLDUP VS. VG FOR(1.5WT%)N-PROPANOL-WATER

FIGURE 25



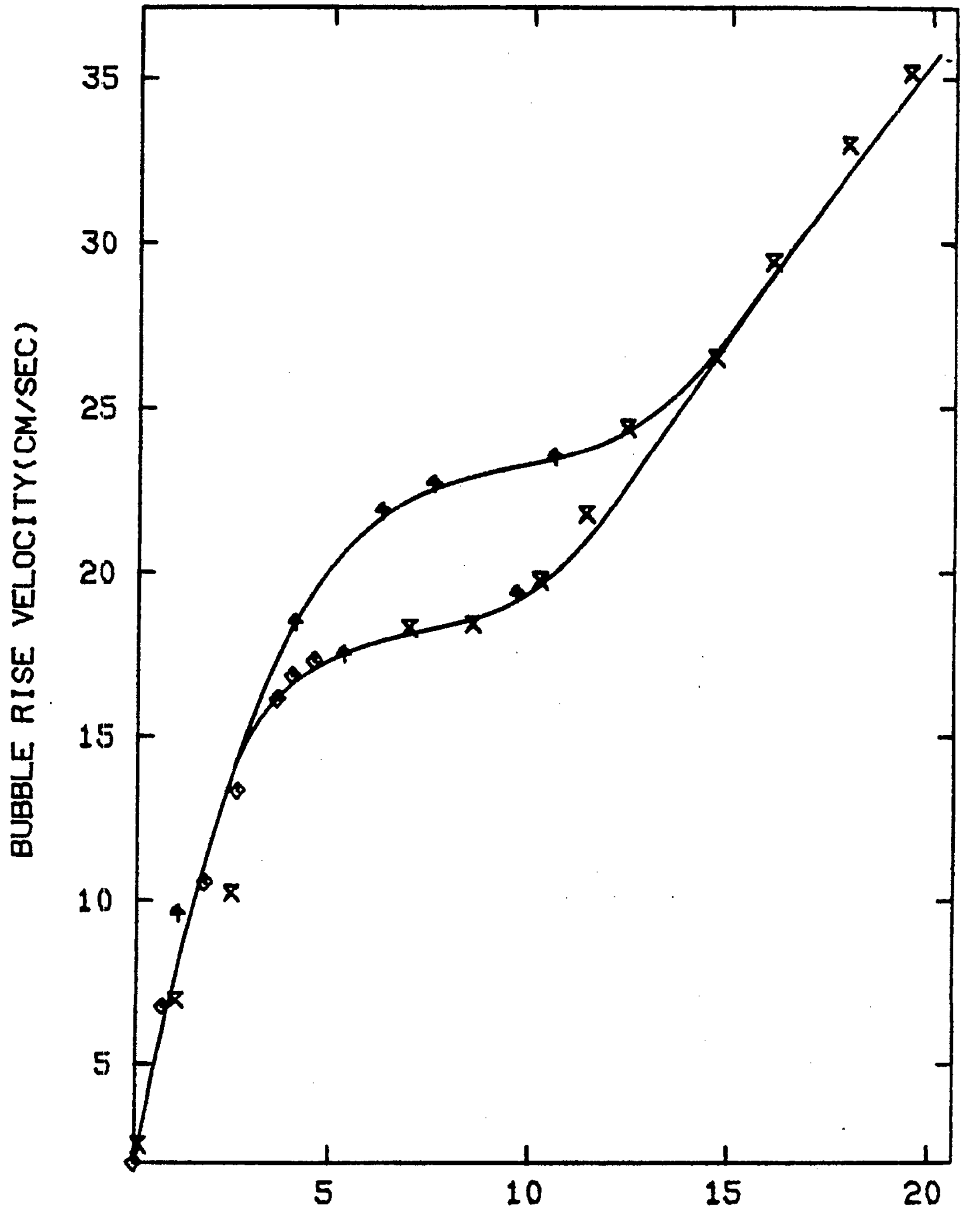
VM VS.VG FOR(0.5WT%)N-PROPANOL-WATER.

FIGURE 26



VM VS.VG FOR(1.0WT%)N-PROPANOL-WATER.

FIGURE 27



VM VS.VG FOR(1.5WT%)N-PROPANOL-WATER.

FIGURE 28

those for air-water system and predicted from the correlation of Deckwer et al.[13] as shown in Figures 17-22.

Aqueous solutions of n-propanol (0.5 wt%, 1.0 wt% and 1.5 wt%) are used to study the effect of surface tension. Surprisingly very high gas holdup values are realized even at low gas velocities compared to those predicted by the correlations of Akita and Yoshita,[3] Hikita et al.[4] and Joshi and Sharma.[12] The gas holdup against the superficial gas velocity is plotted in Figures 23-25. Figures 26-28 represent the plots of bubble rise velocity against the superficial gas velocity for the three concentrations of propanol solutions. From the flat portion of graphs of V_{rise} vs. V_G (Figures 26-28), bubbly flow regime is indicated. The bubble size distribution (visually observed) is very homogeneous and even at high gas velocities no large bubbles are observed. The reason for such high gas holdup values is discussed in Part A. No increase in gas holdup is observed with an increase in propanol concentration. This might be because of the fact that the dynamic surface tension effect discussed in Part A does not vary proportionately with the propanol concentration. Each experiment is carried out using three different initial liquid heights and gas holdup does not change with small changes in hydrostatic head.

Part C: Measurements of Mass Transfer Coefficients in Three Phase Agitated Reactor System under High Pressure, High Temperature Conditions

Many industrial processes like hydrogenation of fatty oils, oxydesulfurization, fermentation, etc. involve three phase, high pressure, high temperature agitated reactors. A knowledge of the values of gas-liquid-solid mass transfer coefficients is important to have an order of magnitude estimates of the transport rates and relative mass transfer resistances. Hence, in this project work, measurements of mass transfer coefficients are being carried out for a three phase agitated reactor system under high pressure, high temperature conditions.

The flow diagram of the apparatus is shown in Figure 29. The basic technique involves batch absorption of the solute gas in initially solute free liquid containing solids. Measurement of total pressure of the gas phase with respect to time, as the absorption proceeds, is used to calculate the mass transfer coefficients. A pressure transducer is used to carry out these measurements with good accuracy.

Procedure

The steps involved in the procedure are as follows:

1. Take requisite amount of liquid in the reactor and add to it predetermined quantity of solids.

2. Degas the liquid by applying vacuum and agitation.

3. Pressurize the reactor to the desired pressure.

4. As soon as the desired pressure reaches, close the inlet valve and start agitation, and measure the total pressure of the gas phase as a function of time.

5. Utilize this knowledge of pressure as a function of time to calculate the volumetric mass transfer coefficient '$k_\ell a$'.

A quick response pressure transducer coupled with a high speed recorder is effectively utilized to measure the gas phase pressure as a function of time.

Method of Calculations

The rate of solute gas uptake is related to the rate of change in the pressure as

$$\frac{dN}{dt} = \frac{V_g}{RT}\frac{dP}{dt}$$

where

N = number of moles of the gas

V_g = volume of the gas phase

P = pressure of the gas phase

t = time

Also,

$$-\frac{dN}{dt} = V_\ell \, k_\ell a \, (C^* - C_b)$$

where

V_ℓ = volume of (liquid + solid) phase

$k_\ell a$ = volumetric mass transfer coefficient

C^* = equilibrium concentration of the solute gas

C_b = bulk concentration of the solute gas

Expressing all the concentrations in terms of pressure using Henry's law and integrating between the limits of initial and final pressure, we get

$$-\frac{P_f}{P_i} \, \ell n \frac{P-P_f}{P_i-P_f} = k_\ell a \, t$$

where P_f and P_i are values of the final and initial pressure and P is the value of pressure at time t. Hence, a plot of $-\frac{P_f}{P_i} \ln \frac{P-P_f}{P_i-P_f}$ versus time will be a straight line and $k_\ell a$ will be the slope of the line.

The linearity of this plot was excellent in all the runs.

Results and Discussion

Initially, to confirm the usefulness and applicability of the technique, data for oxygen-water-glass beads are collected. Tables 19 and 20 summarize the data for this system for various values of pressure and agitator rpm. Table 19 gives the data for oxygen-water (without any solids) system and Table 20 gives the data for oxygen-water-glass beads (2 volume % solids of 75 microns average size) system. The product of mass transfer coefficient 'k_ℓ' and interfacial area per unit volume of liquid + solid phase 'a' is determined. The total volume of liquid + solid in the vessel is kept constant in all experiments. The gas side resistance to mass transfer is assumed to be negligible.

Data from Table 19 is plotted in Figure 30 as '$k_\ell a$' versus total pressure at various values of rpm. The plot indicates that at higher values of rpm '$k_\ell a$' is independent of the total pressure. This is in agreement with the findings of Teramato et al. (1974). However, at lower values of rpm (400), '$k_\ell a$' decreases slightly (10 to 20%) with increase in the pressure and then remained constant. The order of magnitude of '$k_\ell a$' values is in close agreement with the findings of Koetsier et al. (1973), who have reported their data for various ratios of impeller diameter to reactor diameter and rpm.

Data from Table 20 with 2 volume % solids are plotted in Figure 31 for various values of pressure and agitator rpm. It indicates that 2 volume % solids do not have any effect on '$k_\ell a$', and also, in presence of solids, '$k_\ell a$' remains independent of the total pressure for high values of rpm, and for low values of rpm (400) '$k_\ell a$' decreases slightly with increase in the pressure. Joosten, et al. (1977) have found a slight increase in value of '$k_\ell a$' with small volume fraction of solids. However, we did not find any noticeable change (more than 15%) in '$k_\ell a$' by addition of 2 volume % solids. More data are needed at higher volume % of solids to explain in clear cut terms the decrease in '$k_\ell a$' with pressure at lower values of rpm.

Table 21 summarizes the effect of agitator rpm on '$k_{\ell}a$' at constant value of total pressure. As expected, '$k_{\ell}a$' increases slightly initially and then significantly with increase in the rpm. The power input to the agitator per unit volume of liquid + solid is measured by using a power meter. Plots of agitator rpm or power input per unit volume for the two cases of no solids and 2 volume % solids are shown in Figure 32. As shown in Figure 33 the log-log plot of '$k_{\ell}a$' versus power/volume is linear as reported by Joosten et al. (1977). However the slopes of the two plots are not the same because of gas sparging and different stirrer geometry involved in the work of Joosten et al.

Currently, the experiments are being carried out for higher concentrations of solids. After that, major consideration will be given to obtain the data at high pressure and high temperature in the presence of the solids and liquids with varying properties.

Future Plan of Work

The process variables which will be studied are as follows:

1. Total pressure - 0 to 1500 psig
2. Temperature - 20 to 200^{o}C
3. Power input or agitator rpm - 400, 600, 800, 1000
4. Solids concentration - 0 to 40 volume %
5. Solids particle size - 75 to 500 microns
6. Solid properties - certain solids like Keisulguhr increase viscosity of liquid simulating the effect of certain mineral matters in coal liquefaction. Also, certain solids like active carbon which have a highly porous structure increase the mass transfer rates. Effect of such solids on '$k_{\ell}a$' will be studied.

7. Liquid properties - various liquids like CMC solutions, glycol etc. will be studied to see the effect of liquid properties like density, viscosity, surface tension etc.

8. Geometric parameters like ratio of impeller diameter to reactor diameter, baffled and unbaffled vessel etc. will be studied.

TABLE 19

DATA FOR OXYGEN-WATER-GLASS BEADS SYSTEM

Volume % of Solids = 0.0

Average Temperature = 23°C

RPM	Initial Pressure (psig)	Average Pressure (psig)	$k_{\ell}a$ (sec^{-1})
400	190	183.9	0.12
	380	359.3	0.117
	585	558.3	0.103
	790	750.5	0.101
600	185	175.8	0.121
	375	355.2	0.117
	595	564.7	0.115
	785	745.8	0.115
800	200	189.1	0.161
	390	365.5	0.152
	585	551.4	0.156
	790	742.6	0.154
1000	200	190.5	0.22
	380	363	0.224
	600	557.3	0.218
	790	738.9	0.221
	1000	947.2	0.218

TABLE 20

SOLIDS - GLASS BEADS OF AVERAGE 75 MICRON SIZE

Volume % of Solids = 2.0

Average Temperature = 23^{o}C

RPM	Initial Pressure (psig)	Average Pressure (psig)	$k_{\ell}a$ (sec^{-1})
	195	186.8	0.12
400	385	366.6	0.117
	600	572.5	0.103
	195	186.5	0.116
600	385	364.2	0.116
	595	565	0.113
	195	185.1	0.16
800	385	362.1	0.158
	595	561.6	0.156
	200	188.2	0.23
1000	370	348.8	0.22
	595	561.5	0.216

TABLE 21

EFFECT OF AGITATOR RPM OR POWER/VOLUME ON '$k_\ell a$'

Average Pressure = 590 psig
Average Temperature = 23°C

RPM	Power/Volume kw/m^3	$k_\ell a$ (sec^{-1}) Without Solids	$k_\ell a$ (sec^{-1}) With 2 Vol. % Solids
400	0.4	0.103	0.103
600	0.8	0.115	0.113
800	2.1	0.156	0.156
1000	4.0	0.218	0.216

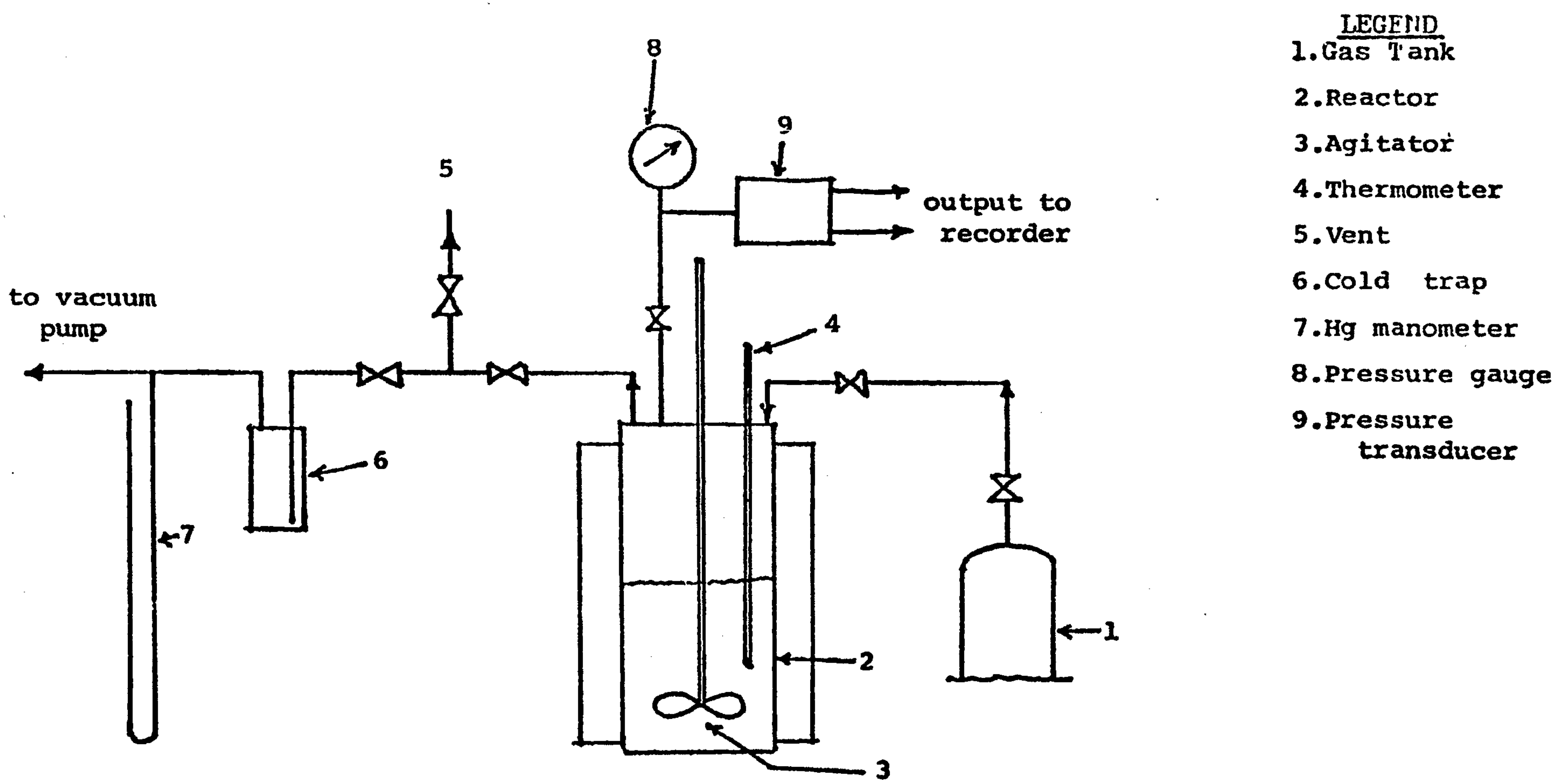


FIGURE 29: SCHEMATIC FLOW DIAGRAM OF THE APPARATUS FOR MEASUREMENT OF MASS TRANSFER COEFFICIENTS

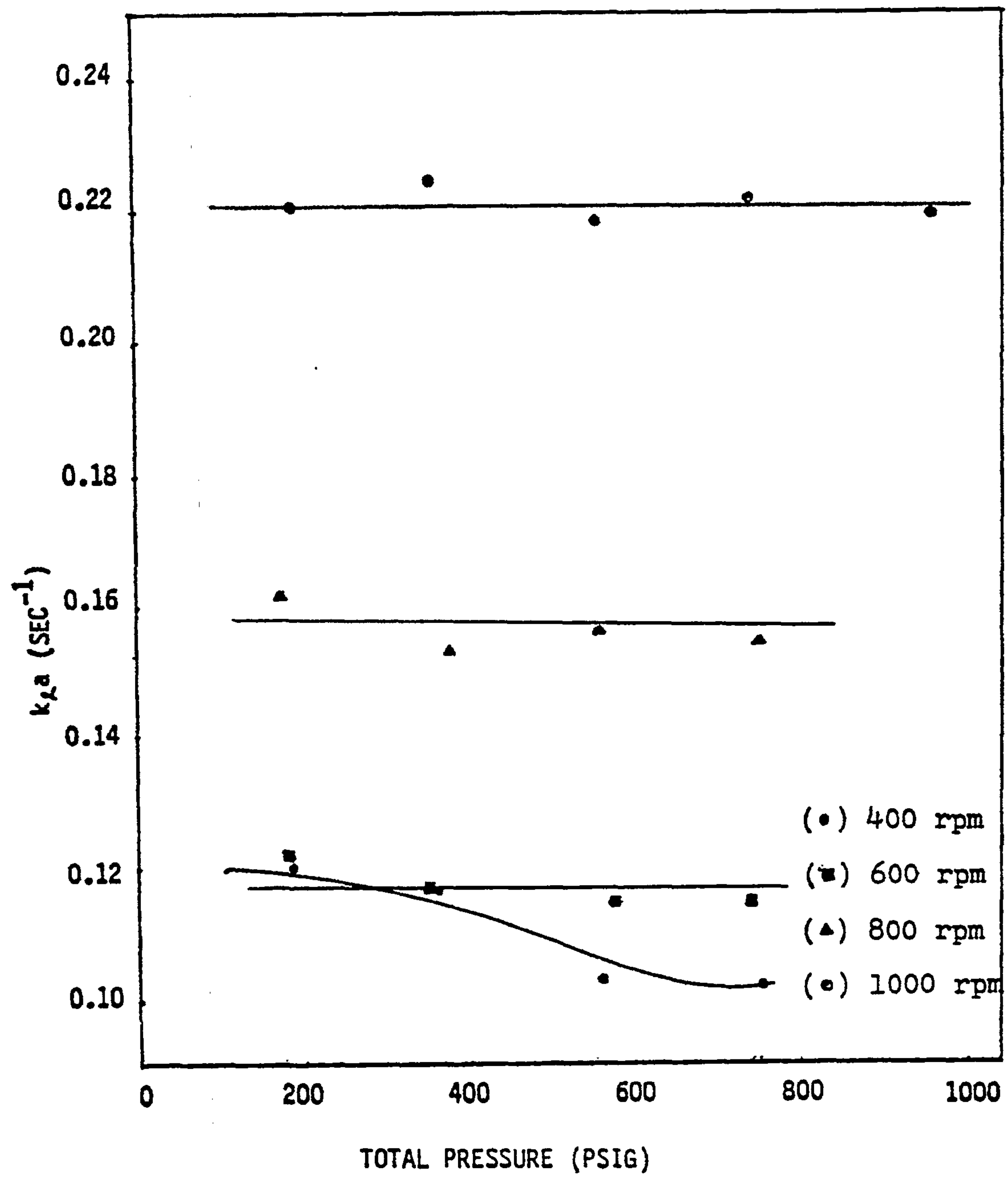


FIGURE 30 - EFFECT OF TOTAL PRESSURE ON '$k_\ell a$' FOR VARIOUS VALUES OF AGITATOR R.P.M.
(0 VOL. % SOLIDS)

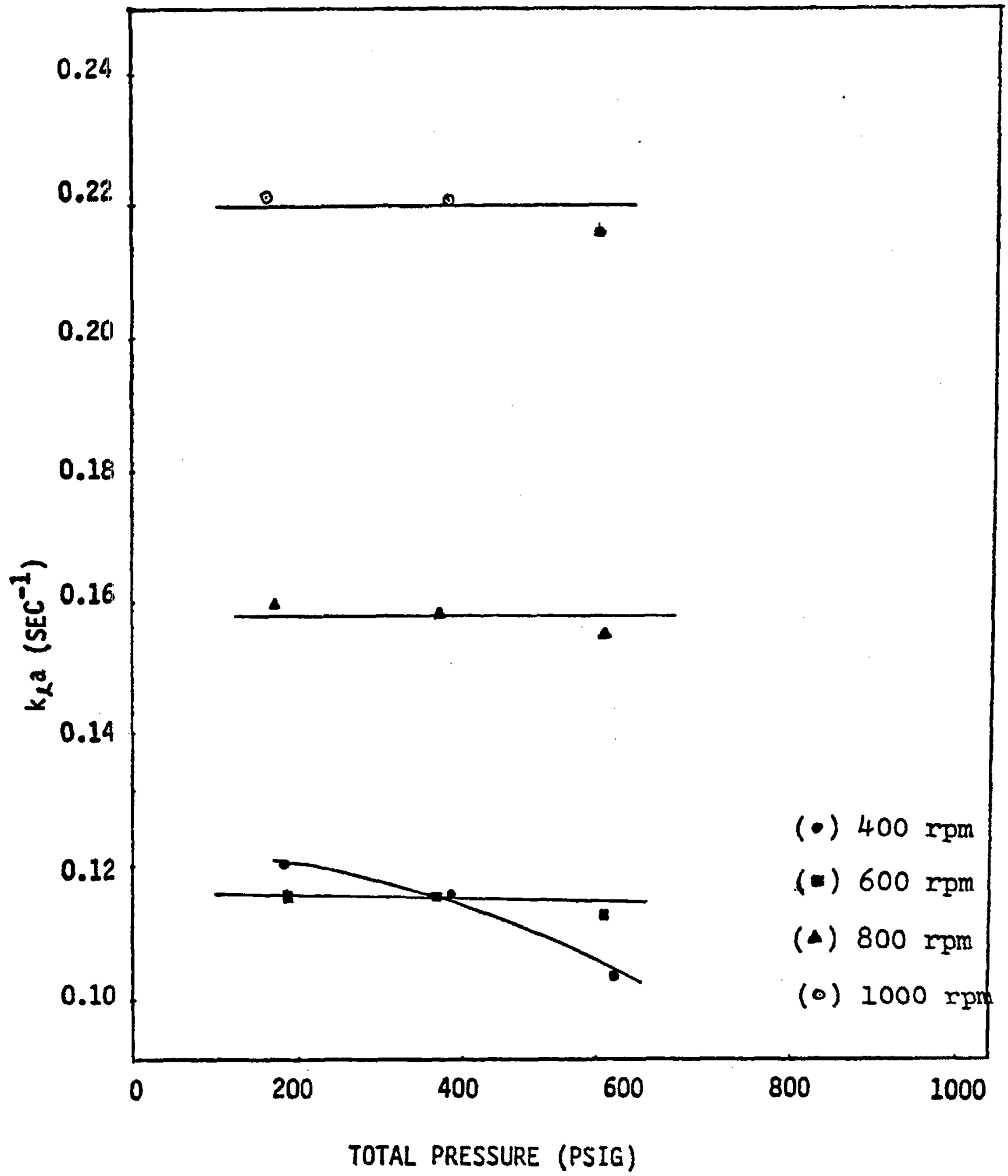


FIGURE 31 - EFFECT OF TOTAL PRESSURE ON '$k_\ell a$' FOR VARIOUS VALUES OF AGITATOR R.P.M.

(2 VOL. % SOLIDS)

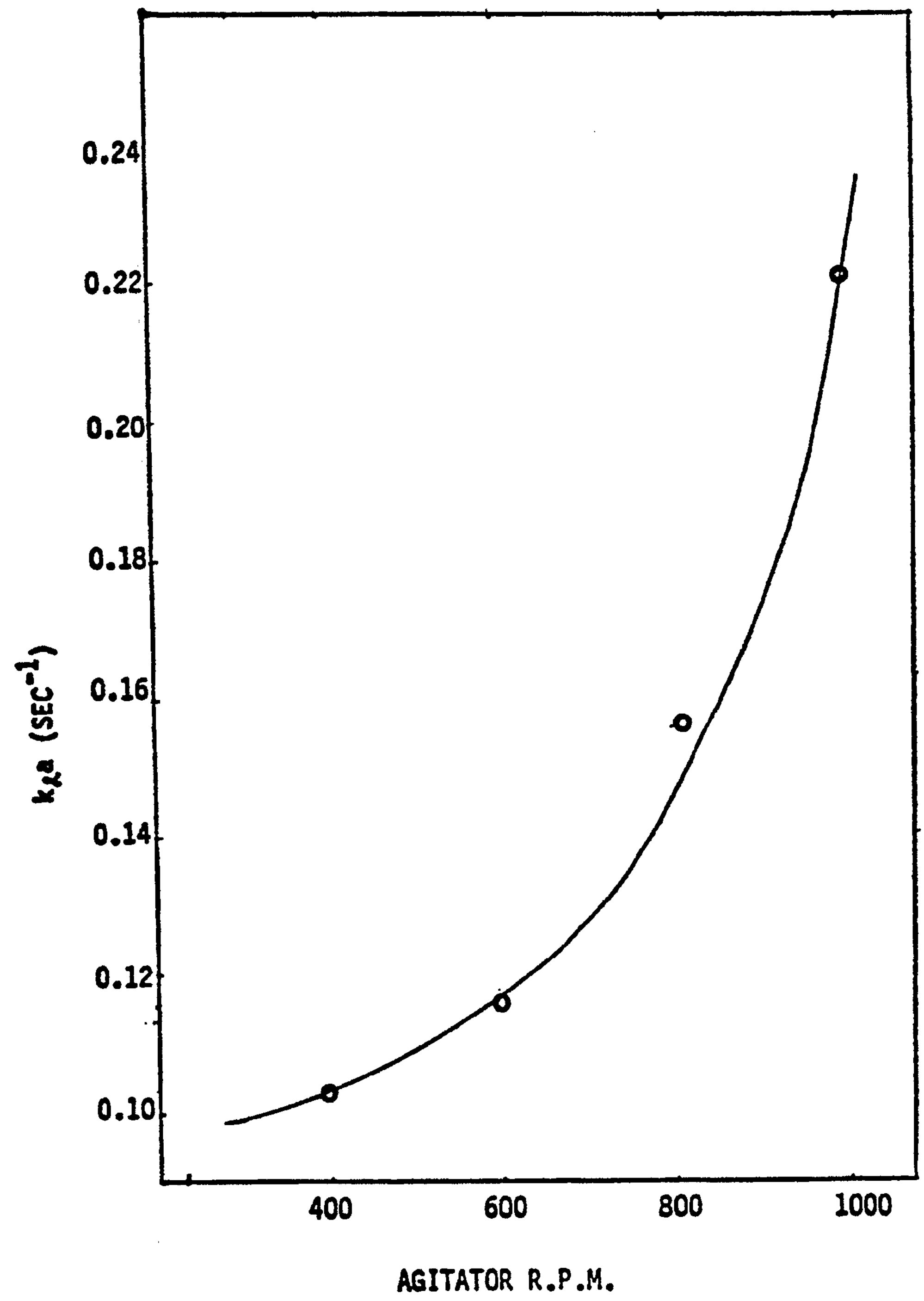


FIGURE 32 - EFFECT OF AGITATOR R.P.M. ON '$k_\ell a$'
(0 AND 2 VOL. % SOLIDS)

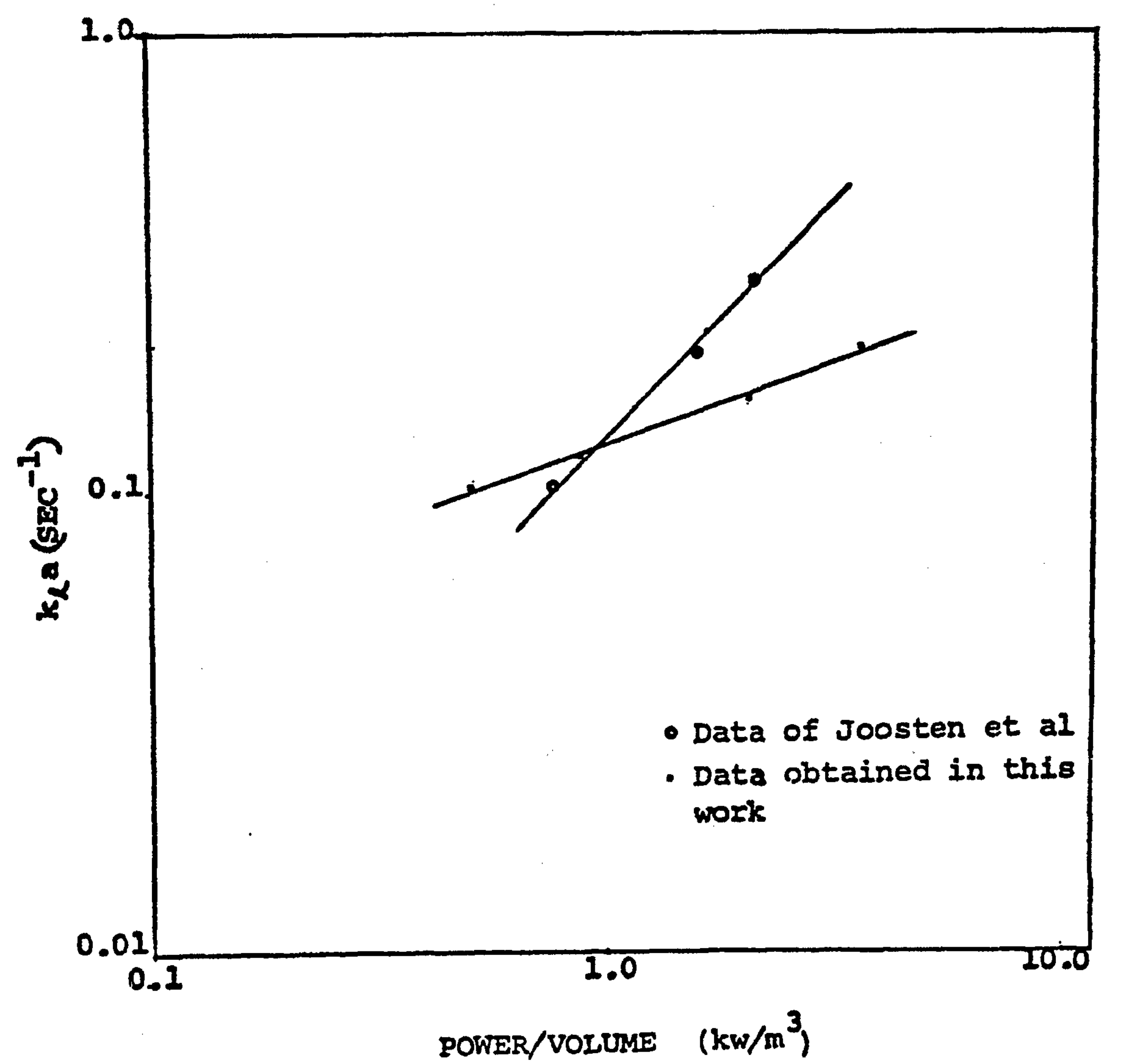


FIGURE 33 - LOGARITHMIC PLOT OF $k_l a$ VERSUS POWER/VOLUME

Nomenclature

C_b	bulk concentration of the solute gas
C^*	equilibrium concentration of the solute gas
C_{pL}	specific heat of liquid phase
D_L	dispersion coefficient of liquid phase
HH	hydrostatic head
$k_{\ell}a$	volumetric mass transfer coefficient
N	number of moles of the gas
P	hydrostatic pressure, pressure of the gas phae (in part C)
t	time
T_c	temperature at Z_c
T_H	temperature at Z_H
V_g	volume of the gas phase
V_G	superficial gas velocity
V_{ℓ}	volume of (liquid + solid) phase
V_L	superficial liquid velocity
X	vertical distance
Z_c	distance from the bottom to the first thermocouple
Z_H	distance from the bottom to the last thermocouple
ε_G	gas holdup
ε_L	liquid holdup
ρ_L	density of the liquid medium

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