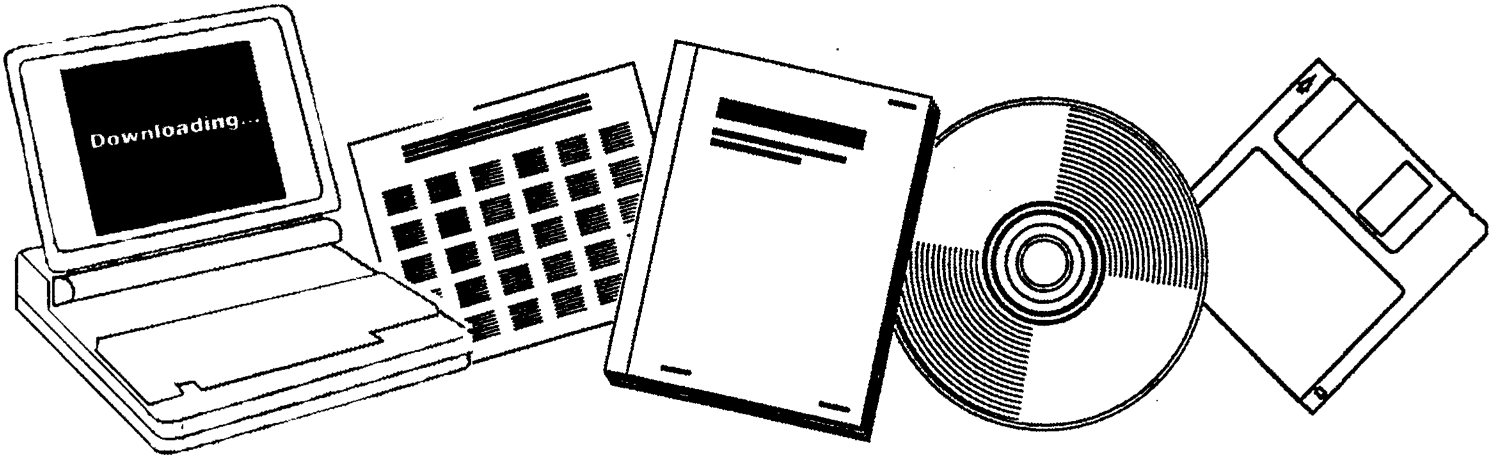
GAS/SLURRY FLOW IN COAL-LIQUEFACTION PROCESSES (FLUID DYNAMICS IN 3-PHASE FLOW COLUMN)

AIR PRODUCTS AND CHEMICALS, INC.
ALLENTOWN, PA

MAY 1980



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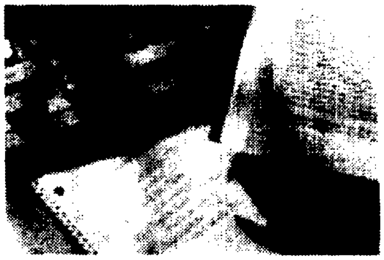

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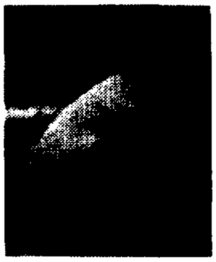

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GAS/SLURRY FLOW IN COAL LIQUEFACTION PROCESSES
(FLUID DYNAMICS IN 3-PHASE FLOW COLUMN)

Quarterly Technical Progress Report
for Period 1 January 1980-31 March 1980

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May 1980

Prepared for the United States Department of Energy

Under Contract No. DE-AC01-79ET14801

SUMMARY

This is the second quarterly report under Contract Number DE-AC01-79ET14801 titled "Gas/Slurry Flow in Coal Liquefaction Processes". This work covers the period 1 January 1980 to 31 March 1980. This work is a continuation of studies initiated by Air Products and Chemicals, Inc. on the fluid dynamics of 3-phase flow to support the design of the 6000 T/D dissolver for the SRC-I demonstration plant which began in July 1978. DOE supported these 3-phase flow studies under the Bridging Task program from 1 July 1979 to 30 September 1979 at the start of the current contract. A background of information developed at Air Products prior to DOE support was included in the first quarterly report.

The 6000 T/D SRC-I demonstration plant will employ verticle tubular reactors feeding slurry and gas concurrently upward through these vessels. In the SRC-I design this reactor is essentially an empty vessel with only a distributor plate located near the inlet. Because the commercial plant represents a considerable scale-up over either Wilsonville or Ft. Lewis, this program is addressing the need for additional data on behavior of three phase systems in large vessels. Parameters being investigated in this program are being studied at conditions that relate directly to the projected demonstration plant operating conditions.

Liquid backmixing in a gas/liquid/solid system was studied in a 12-inch diameter column with three different sand particle sizes, namely, 60/80 mesh, 100 mesh minus, and 140 mesh minus. The gas and liquid superficial velocities were studied over a range from 0.0-0.33 ft/sec and 0.01-0.07 ft/sec, respectively, which were chosen to cover the flow conditions designed for the SRC-I demonstration plant. The solid concentration inside the column varied from 2 lbs/ft^3 to 20 lbs/ft^3, which relates to experience of solid accumulation in the pilot plant dissolver at Wilsonville. The study of the larger particles will cover the case of possible particle agglomeration in the demonstration unit.

The results show that the liquid axial dispersion coefficient was independent of liquid velocity regardless of the presence of solids, the solids concentration and their particle size. Increasing gas velocity, however, increased the liquid dispersion coefficient in all conditions. All the results clearly

indicated a decrease in liquid dispersion coefficient as well as liquid backmixing in the presence of solid particles. Effective slurry viscosity was used to rationalize this dispersion coefficient reduction. A correlation by Hikita and Kikukawa includes the effect of liquid viscosity on the axial dispersion coefficient. The predicted axial dispersion coefficients from this correlation agree reasonably well with our experimental values for the air/water system. This correlation predicted that the range of effective slurry viscosity values that would give the same axial dispersion coefficients as found for the air/water/sand system would be from 10 cps to 50 cps. The viscosity of water/sand slurry will be measured to compare with these values. More quantitative conclusions will be made after obtaining viscosity data of water/sand slurries. Furthermore, particle size and solid concentration showed no effect on the liquid dispersion coefficient.

Solid dispersion experiments were conducted during this quarter in both the 5-inch and 12-inch diameter columns. Two different modes of operations, batch and continuous, were used. The variables studied in the batch experiments were: gas velocity (0.05-0.43 ft/sec), types of solid particles (glass beads and sand), particle size (60/70, 60/80, 140/170, and 140 mesh minus), and reactor solid concentration (6 lbs/ft^3 to 29 lb/ft^3). Apparently the solid dispersion coefficient was independent of gas velocity but increased with increasing column diameter. These results are based upon the assumption that effective particle settling velocity was not affected by gas turbulence. Attention is now focused on determining the solid dispersion coefficient independently. The variables studied in the continuous mode of operation were: gas velocity (0.10-0.43 ft/sec), liquid velocity (0.02-0.05 ft/ sec), particle size (40/60 mesh, 60/80 mesh, and 140 mesh minus sand), and feed solid concentration (4.8 lb/ft^3). Again these parameters chosen for the solid dispersion study were generated from the design conditions for the SRC-I demonstration plant. The variations in feed concentration of the large particles (40/60 mesh and 60/80 mesh) prohibited meaningful interpretation of the data at this point. The results with the fine particles indicated very little change in axial solids distribution profile with a four-fold increase in gas velocity. However, increasing liquid velocity at a constant gas input rate reduced solids accumulation. Dispersion of large particles will be discussed in the next quarterly report.

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1.0 OBJECTIVE

The overall objective of this project is to study the solids accumulation and suspension of various gas/liquid/solid systems in cold-flow tubular columns aimed at providing data for the coal dissolver design in the SRC-I demonstration plant.

The specific objectives are:

1. To check whether the existing experimental apparatus using a two-phase system (air/water mixture) is adequate.
2. To study the effects of slurry and gas velocities, solid particle size and concentrations, and liquid viscosity and surface tension on the performance of a cold-flow tubular column.
3. To develop an effective slurry withdrawal technique from the bottom of a tubular column as a means to control the solid concentration in the column.
4. To study the performance of cold-flow tubular column with an improved distributor and in the absence of a distributor.
5. To explore the use of multiple distributors in a tubular column.

2.0 INTRODUCTION

A major element of the coal dissolution section of any liquefaction plant is the dissolver. Although a considerable amount of liquefaction will occur in the preheater, a major amount of necessary chemical change will occur in the dissolver, namely sulfur removal, oil and distillate formation and solvent rehydrogenation.

Vertical tubular reactors are employed in all of the major processes currently under consideration for commercial liquefaction of coal. In all of these processes, SRC, EDS and H-Coal, slurry and gas are concurrently fed upward through these vessels. In the EDS and SRC processes, the reactors are essentially empty vessels, whereas for the H-Coal process a bed of ebullating catalyst is maintained in the reactor. The major differences between the EDS, SRC-I and SRC-II processes in dissolver operation are the composition of the feed streams and reactants within the dissolver. Other hardware differences such as distributor plates, draft tubes or recycle loops can also cause differences in the behavior of slurries in these vessels. A requirement necessary to any design that will be technically feasible and cost effective is an understanding of the physical behavior of three phase systems in tubular columns.

All of the major processes under development require understanding of backmixed three phase systems. Each process employs at least a portion of its dissolver volume in a backmixed mode. As the design of the 6000 T/D SRC-I plant progresses, the increased vessel size (and other considerations) may dictate the use of reactors in series, which would decrease the overall backmixed characteristic of the commercial plant.

The SRC-I demonstration plant dissolver will represent a considerable scale-up over the Wilsonville and Ft. Lewis dissolver. To intelligently make good design decisions, more information is needed on the flow properties of three phase systems in large vessels. More important from the standpoint of slurry behavior is the difference in gas and liquid superficial velocities. This difference can have considerable impact on the process because the gas and liquid superficial velocities have a strong effect on (a) gas void volume, (b) actual solids concentration in the dissolver and (c) the relative degree of backmixing. As velocity through the dissolver increases, the tendency for solids to remain behind diminishes causing a decrease in the actual concentration of ash particles in the reactor. Those particles that do remain will tend to be larger in size. Since considerable evidence points to a definite catalytic effect of the reactor solids, these larger particles will have decreased surface areas exposed and will likely have diminished catalytic activity. Knowing the particle sizes that can accumulate under commercial flow conditions will give us some indication of size of dissolver solids that should be examined for catalytic activity.

Considerable work on the behavior of gas/liquid mixtures flowing through vertical columns has been reported in the literature. Information on three phase (gas/liquid/solid) systems is far less extensive. Detailed background information was presented in the first quarterly report (1). Under this contract, work is being conducted in a 5-inch diameter by 5-foot tall Plexiglass column and a 12-inch diameter by 25-foot tall glass column which are located at the contractor's site. The physical dimensions, auxiliary equipment, and some of the experimental techniques employed in this study were extensively discussed in the first quarterly report. This report contains experimental results from runs conducted during this reporting period (1 January-31 March 1980).

3.0 TECHNICAL PROGRESS

3.1 Task 2 - Two and Three Phase Flow in Vertical Columns

The objectives of this task are:

- to study gas holdup and liquid dispersion in two and three phase systems.
- to study gas/liquid mass transfer
- to study solid dispersion

All of the experimental work during this quarter was related to this task. Gas holdup and liquid dispersion results from two and three phase systems were reported in the last quarterly report. Additional liquid dispersion runs were conducted in this quarter. Several experiments were conducted to study solid dispersion. Due to time restrictions, mass transfer experiments were not completed in this quarter. They will be presented in the next report.

4.0 EXPERIMENTAL SECTION

4.1 Cold Flow Model Equipment

Both the 5-inch diameter and 12-inch diameter columns used in these cold-flow studies, were described in detail in the first quarterly report (1). During this reporting period, two 300 gallon per minute Sandpiper air-operated diaphragm pumps were installed to recycle the feed slurry in order to suspend large sand particles inside the feed tanks. Conical bottoms were also fabricated for these slurry feed tanks to avoid solid settling around the edges.

4.2 Experimental Procedures

4.2.1 Liquid Dispersion

Liquid phase dispersion in an air/water/sand system was investigated in a 12-inch diameter column with solids of varying sizes (60/80 mesh, -100 mesh, -140 mesh), using a tracer detection method. Sodium chloride was used as the tracer and a conductivity probe mounted at the exit line of the column monitored the ion conductivity of the solution continuously. Detailed experimental procedures were described in the previous quarterly report (1).

4.2.2 Solids Dispersion

Solid dispersion experiments were conducted in both 5-inch and 12-inch diameter columns using two different modes of operations, namely batch and continuous. In the batch operation, gas was bubbled through the column which was filled with liquid and a known weight of solid particles. During a 30 minute bubbling period at each gas velocity steady state conditions were established. Then slurry samples were withdrawn from sampling ports at various heights of the columns and measured for solids concentration. In continuous operation, water/sand slurry flowed continuously through the column. Samples were withdrawn from all ports at periodic intervals over 4-6 hours until a steady state condition was achieved. Two different types of continuous experiments were conducted using the 5 inch column. In the first method, water/sand slurry of known concentration was fed to the column in a once-through basis. This method, however, required a minimum of two feed tanks in series and an enormous amount of effort and material to keep up with the once-through operation. The second method involved recycling the column exit stream back to the feed tank. In this method, a slurry of known concentration was prepared in a feed tank and the exit from the 5-inch diameter column is returned to the feed tank thereby creating a closed loop. In the case of the 12-inch diameter column, two feed tanks were used and the exit from the column is returned to the first tank, which in turn is fed to the second tank in series. The advantages of this method are: a) less sand material required per experiment, b) less labor needed to prepare a fresh batch of slurry every ten minutes, and c) less possibility of human error in preparing multiple batches in a short time frame. However, the solids accumulation measured from the recycle mode would be slightly different than that from the once-through operation because the particle size distribution of the feed material would be different. In the recycle mode, the larger particles of the feed initially prepared in the tank will be depleted as they were retained in the column, leading to a slightly higher estimate of solid accumulation based on the steady state feed concentration and size distribution. This difference decreased with decreasing particle size range in the feed, however. Therefore, using a narrow size range could reduce the error caused by the recycle mode operation. One set of operating conditions was duplicated in both methods to check the experimental reproducibility and sample relationship to each other. This will be discussed in a later part of this report.

5.0 RESULTS AND DISCUSSION

5.1 Liquid Dispersion in Gas/Liquid/Solid System

Liquid dispersion experiments were performed in the 12-inch diameter column for gas/liquid/solid systems. Table I lists the ranges of variables studied during this reporting period. The fits of all the experimental tracer curves with the theoretical curves from the axial dispersion model are displayed in the appendix (A). In these curves, the circles represent the experimental tracer curve while the solid line represents the theoretical curve obtained from the axial dispersion model. Detailed description of the procedure can be found in the previous quarterly report (1).

Table I

Liquid Dispersion - Experimental Conditions

Liquid Velocity	-	0.01 - 0.07 ft/sec
Gas Velocity	-	0.0-0.327 ft/sec
Particle Size	-	60/80 Mesh, 100 Mesh Minus, 140 Mesh Minus
Concentration	-	2.00-20.0 lbs/ft^3

The dispersion numbers and the axial dispersion coefficients for all the experiments conducted in this quarter are listed in Table II. Except for Run XIX-1, all the other experiments were conducted by placing a known amount of sand in the column at the beginning of the experiment. The average solids concentration in the column was determined by taking an average of the solids concentration at the beginning and at the end of the experiments. For very fine particles (140 mesh minus and 100 mesh minus) large amounts of the sand were carried out of the column by the liquid which resulted in an enormous difference in solid concentration between the beginning and the end of the run (Runs XVI-1 and XVI-2). Therefore, averaging extreme concentration values was not justified for the very fine particles. Hence, the axial dispersion coefficients for Runs XVI-1 and XVI-2 are presented as a range rather than a single number. Since the Run XIX-1 was carried out by pumping a continuous slurry (with a known solids concentration) into the column we were able to a) determine the liquid axial dispersion coefficient in the presence of fine particles at an uniform concentration of solids and b) compare the effect of varying solids concentration and uniform solids concentration on liquid axial dispersion coefficients.

Axial liquid dispersion coefficients were reported in the last quarterly report for air/water system and air/water/sand system using 20/30 mesh particles. Results from these experiments will be included in the following discussion to show the overall effects of liquid velocity, gas velocity, solid concentration, and particle size.

Table II

Data from Liquid Dispersion Experiments

Batch Operation

Run Number	Liquid Velocity ft/sec	Gas Velocity ft/sec	Particle Size Mesh	Solids Concentration lbs/cu ft	Dispersion Number[a]	Axial Dispersion Coefficient ft^2/sec
XVI-1	0.016	0.080	-140	2.06 to 19.33	0.9	0.33 to 0.38
XVI-2	0.043	0.327	100	4.88 to 9.47	0.5	0.53 to 0.55
XVII-1	0.017	0.327	60/80	5.0	1.00	0.43
XVII-2	0.031	0.327	60/80	5.0	0.5	0.38
XVII-3	0.049	0.0	60/80	5.0	Very Low	Very Low
XVII-4	0.035	0.327	60/80	5.0	0.5	0.44
XVII-5	0.055	0.05	60/80	5.0	0.22	0.30
XVII-6	0.069	0.097	60/80	5.0	0.20	0.35
XVII-7	0.050	0.327	60/80	5.0	0.33	0.42
XVII-8	0.057	0.194	60/80	5.0	0.27	0.38
XVII-9	0.054	0.327	60/80	5.0	0.35	0.48
XVIII-1	0.045	0.050	60/80	20.0	0.20	0.23
XVIII-2	0.050	0.194	60/80	20.0	0.27	0.34
XVIII-3	0.041	0.327	60/80	20.0	0.43	0.45
XVIII-4	0.018	0.327	60/80	20.0	1.0	0.46
XIX-1(1)	0.049	0.327	-140	5.0	0.35	0.43

(1) Continuous operation

[a] Dispersion number is the inverse of Peclet Number.

5.1.1 Effect of Liquid Velocity

In general, liquid velocity had no effect on axial liquid dispersion coefficient as illustrated in Table III. When no solids were present, a five-fold increase of liquid velocity from 0.009 to 0.049 ft/sec resulted in no change in the value of the axial liquid dispersion coefficient. Similar lack of dependence on liquid velocity was observed in the presence of solid particles although scatter in the data increased in the presence of solids. The most severe fluctuation occurred at high concentration (20 lb/ft^3) of the large sand particles (20/30 mesh). The occurrence of the extreme deviations at 0.013 ft/sec and 0.030 ft/sec liquid velocities were not clearly understood. These deviations did not show a trend with liquid velocity. In any event, the results showed consistently that liquid dispersion coefficient was not affected by liquid velocity at the following conditions, namely no solids, 20/30 mesh sand at 5 and 20 lb/ft^3, and 60/80 mesh sand at 5 and 20 lb/ft^3.

5.1.2 Effect of Gas Velocity

Increasing gas velocity increased the liquid backmixing as well as the liquid dispersion coefficient. Table IV shows the effect of gas velocity on liquid dispersion coefficient for the air/water/sand system using 60/80 mesh particles. The liquid axial dispersion coefficient increased with gas velocity at both low and high concentrations of solid particles which agrees with earlier results (last quarterly report) in the air/water system and air/water/sand system using 20/30 mesh particles.

Table III

Effect of Liquid Velocity on Axial Liquid Dispersion Coefficient

Gas Velocity = 0.327 ft/sec

Liquid Velocity, ft/sec	Axial Liquid Dispersion Coefficient, ft^2/sec				
	No Solids	20/30 Mesh		60/80 Mesh	
		C_S = 5.0 lbs/ft^3	C_S = 20.0 lbs/ft^3	C_S = 5.0 lbs/ft^3	C_S = 20.0 lbs/ft^3
0.009	0.61	0.51			
0.013			0.20		
0.018				0.43	0.46
0.026			0.38		
0.030		0.48	0.50	0.38	
0.035				0.44	
0.040		0.47	0.36		0.45
0.049	0.62		0.38	0.42	
0.053		0.47		0.48	
0.059		0.48			

C_S - Concentration of solids

Table IV

Effect of Gas Velocity on Axial Liquid Dispersion Coefficients

Liquid Velocity = 0.045-0.069 ft/sec

Particle Size = 60/80 Mesh

Gas Velocity ft/sec	Axial Liquid Dispersion Coefficients C_S = 5.0 lbs/ft^3	C_S = 20.0 lbs/ft^3
0.05	0.30	0.23
0.097	0.35	--
0.194	0.38	0.34
0.327	0.43	0.45

5.1.3 Effect of Solid Concentration and Particle Size

The presence of solid particles decreased the axial liquid dispersion coefficient. Table V presents the effect of particle size and solids concentration on axial liquid dispersion coefficient as a function of gas velocity. For the runs with 100 mesh minus and 140 mesh minus particles (last two columns of Table V), a range of the dispersion coefficient is presented due to the wide differences between the solids concentration at the beginning and the end of each experiment. In the case of the run using 140 mesh particles, the solids concentration in the column varied from 19.33 lbs/ft^3 at the beginning of the run to 2.06 lbs/ft^3 at the end of the run. In the case of 100 mesh minus particles the solids concentration varied from 9.47 to 4.88 lbs/ft^3. Axial dispersion coefficients identified with a star in this table are averages of values taken at several liquid velocities. Since it had been established that superficial liquid velocity has no effect on axial liquid dispersion, using the average values is a better way to even out the slight scattering of the data.

Table V
Effect of Solids on Axial Dispersion Coefficients

Gas Velocity ft/sec	Axial Dispersion Coefficients, ft^2/sec							
	No Solids	C_S = 5.0 lbs/ft^3			C_S = 20 lbs/ft^3		C_S = 19.33 to 2.06 lbs/ft^3	C_S = 9.47 to 4.88 lbs/ft^3
		20/30 Mesh	60/80 Mesh	140 Mesh Minus	20/30 Mesh	60/80 Mesh	140 Mesh Minus	100 Mesh Minus
0.05	0.40*	0.30	0.30		0.30	0.23		
0.08							0.33-0.38	
0.097	0.48*	0.34	0.35		0.30			
0.194	0.50*	0.36	0.38		0.37	0.34		
0.327	0.61*	0.48*	0.43*	0.43	0.36*	0.45*		0.53-0.55

* Average values from several experiments.

The results summarized in Table V clearly indicate that the presence of solids reduces the axial liquid dispersion coefficient. At a solid concentration of 5 lb/ft^3, a slight increase in dispersion coefficient was observed with decreasing particle size at all gas velocities except at the very high value of 0.327 ft/sec which showed a reverse effect. However, complete reverse results were observed at 20 lb/ft^3 solid concentration, that is, a slight decrease in dispersion coefficient with increasing particle size except at the very high gas velocity. This inconsistency at different solid loadings was indicative that the measured slight difference was probably derived from experimental fluctuation. Therefore, the results suggested that the particle size has no effect on the liquid dispersion coefficient. Similar degree of fluctuation was observed when the effect of solid concentration at fixed particle size was considered. The results tend to suggest that changes in solid concentration has practically no effect on liquid dispersion coefficient. The insignificant difference between the two values measured with 140 mesh sand particles at widely varying solid concentration lends further support to the above conclusion.

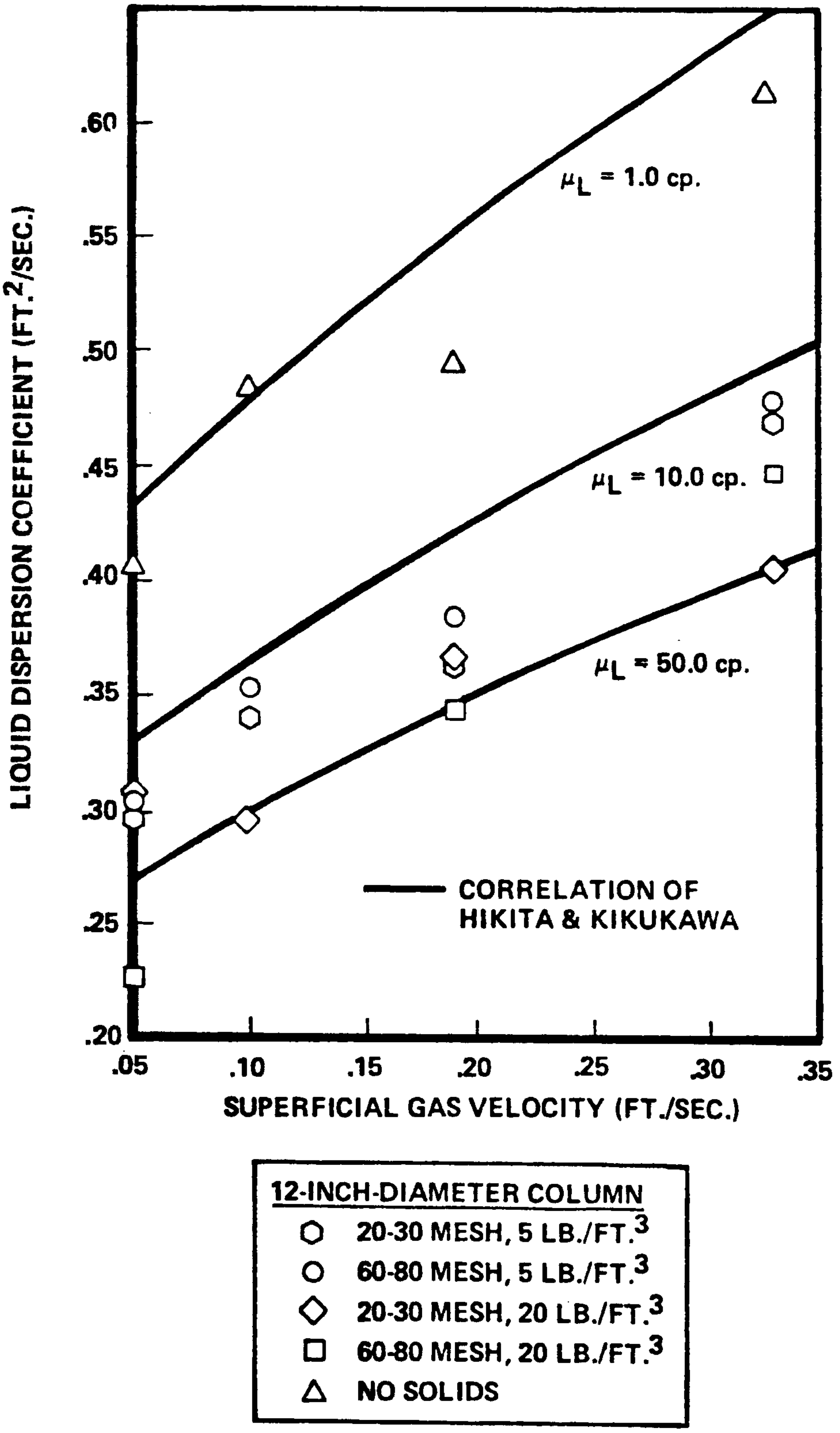
5.1.4 Correlation of Data

Clearly the presence of sand particles, large or small, reduces the liquid dispersion coefficient. This reduction could perhaps be ascribed to the effective properties of the water/sand slurry. Only a few studies (2-5) have been made regarding the effect of liquid properties on liquid axial dispersion coefficients. Unfortunately, no general agreement among these investigators was found. Aoyama, et al(2) and Akita(3) showed that liquid dispersion coefficient was independent of liquid properties. Cova(4) showed that density was the only liquid property that significantly influenced the dispersion coefficient which increased with increasing liquid density. However, the degree of dependence on liquid density decreased with increasing column diameter; its dependence was reduced to an insignificant level in going from a very small diameter column to a 2-inch diameter column. On the other hand, Hikita and Kikukawa(5) showed that liquid dispersion coefficient decreased with increasing liquid viscosity.

It is generally agreed that liquid viscosity increases in the presence of solids. If this is true, then our liquid dispersion coefficient results in the presence of solids qualitatively agreed with the findings of Hikita and Kikukawa. Although the viscosity of water/sand slurry is not known, the viscosity values which were calculated from the correlation of Hikita and Kikukawa bracketing our dispersion coefficient data are shown in Figure (1). Apparently, effective viscosity values of 10 cp and 50 cp bracket our dispersion data. Although 50 cp seems to be high for a water/sand slurry, until slurry viscosity data are available, little can be said quantitatively at this stage. Also included in this figure is the comparison of the prediction from the same correlation in the absence of solids. This fair comparison suggests the general application of this correlation. Furthermore, the viscosity effect is consistent with previous work(6) on gas holdup performed earlier by Air Products. The previous results from a 5-inch diameter column showed a slight reduction in gas holdup in the presence of solid particles. This reduction was ascribed to an increase of slurry viscosity. Neither particle size nor solid concentration could affect the gas holdup. These results were consistent with the independence of liquid dispersion coefficient on particle size and solid concentration. The viscosity of water/sand slurry at different solid concentrations will be measured and will be used to test the validity of the correlation of Hikita and Kikukawa. Depending on the degree of success with this correlation, an in-house correlation may be needed. Further development on this subject will be discussed in the next quarterly report.

FIGURE 1

EFFECT OF SOLIDS
ON AXIAL LIQUID DISPERSION COEFFICIENTS



5.2 Solid Dispersion

5.2.1 Batch Experiments

Table VI presents a list of all the batch experiments conducted in this quarter. Glass beads were purchased in a narrow range and were used to distinguish any differences between particles having narrow and wide ranges. Note that the sand used in the 5-inch diameter column had a narrower range (60/70 mesh) than the one used in the 12-inch diameter column (60/80 mesh). Since the 12-inch diameter column requires much larger quantities of sand, it was not practical to sift that volume of sand in the 60/70 mesh range. In all experiments samples were collected from two different radial positions in the column, one near the wall and the other at the center.

Earlier experiments conducted at Air Products to determine the radial distribution, have shown that an average of these two measurements can approximate the average over five radial positions. Appendix (B) presents all the batch experimental data obtained during this reporting period. In some experiments, it was not possible to withdraw any samples from the lowest sample port because solids settled at low gas velocities. Complete and partial suspension of solids are illustrated schematically in Figure (2). The validity of the sample withdrawn from tap A shown in Figure (2a) is questionable and will not be included in data analysis.

In addition, glass beads were smooth and spherical whereas the sand has irregular shape. Comparison of the results derived from these two types of particle will provide insights to the effect of shape factor.

5.2.1.1 Theoretical Background

In a batch operation (with no liquid flowing), at any cross section of the column, the mass balance of solid particles at steady state conditions results in the following expression:

Table VI

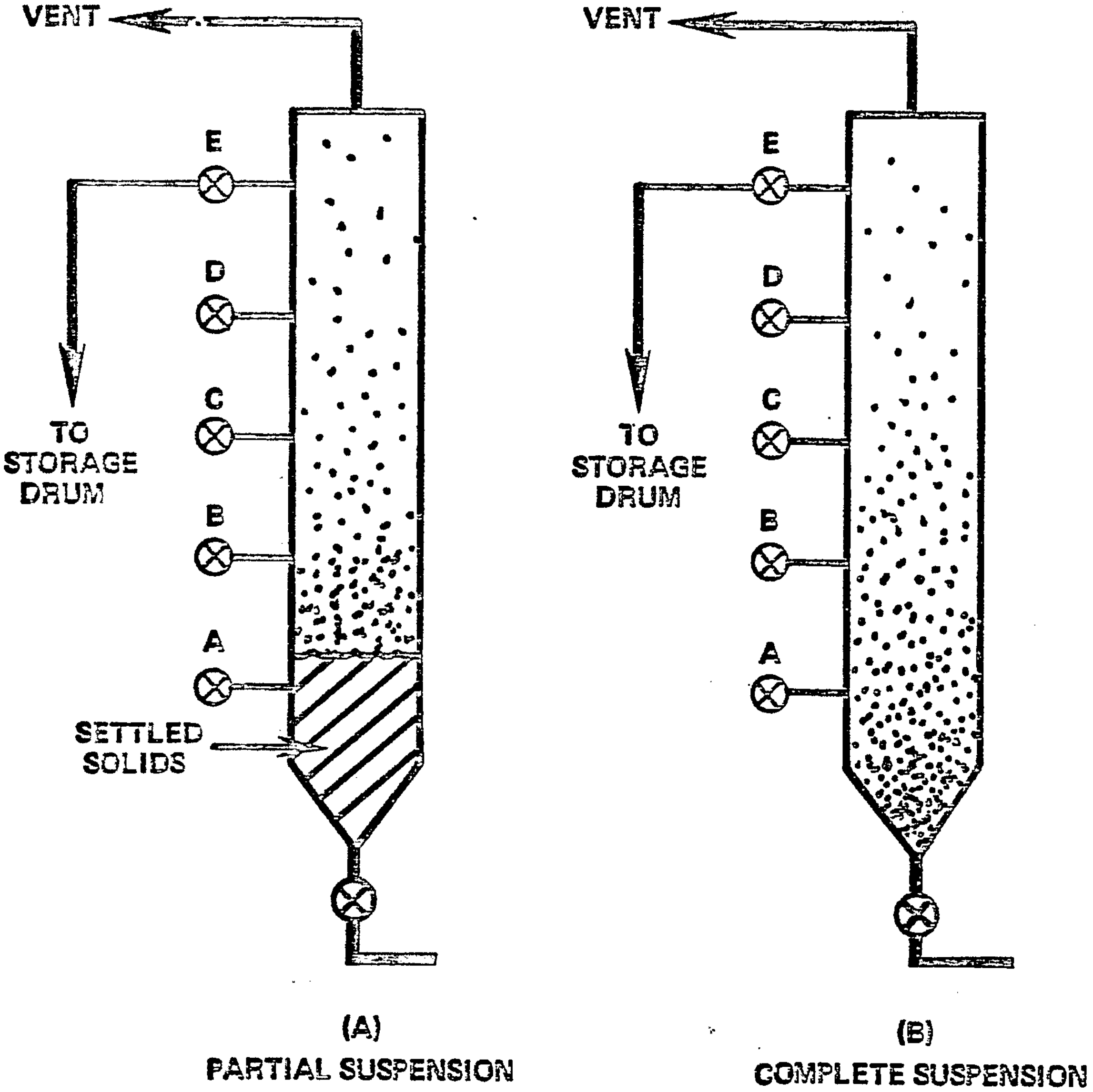
List of Batch Experiments

Liquid Phase - Water

Table Number	Column Used Diameter, inches	Type of Solid Particles	Particle Size Mesh	Solid Concentration lbs/ft^3	Range of Gas Velocities, ft/sec
B-1	5	Glass Beads	60/70	7.4	0.05 - 0.43
B-2	5	Glass Beads	60/70	28.2	0.05 - 0.43
B-3	5	Glass Beads	140/170	7.6	0.05 - 0.33
B-4	5	Glass Beads	140/170	28.6	0.05 - 0.33
B-5	5	Sand	60/70	7.6	0.05 - 0.43
B-6	5	Sand	60/70	29.4	0.05 - 0.43
B-7	5	Silica	-140	7.6	0.05 - 0.43
B-8	5	Silica	-140	29.4	0.05 - 0.43
B-9	12	Sand	60/80	6.2	0.05 - 0.37
B-10	12	Sand	60/80	25.2	0.05 - 0.37
B-11	12	Silica	-140 Mesh	6.2	0.05 - 0.43
B-12	12	Silica	-140 Mesh	25.2	0.05 - 0.43

FIGURE 2

SCHEMATIC DRAWINGS FOR PARTIAL AND FULL SOLID SUSPENSION.



$$V_p C_s + E_{zp} \frac{dC_s}{dL} = 0 \tag{1}$$

where V_p = Settling velocity of solid particles, ft/sec
C_s = Concentration of solid particles in liquid, lbs/ft^3
E_{zp} = Dispersion coefficient of solid particles, ft^2/sec
L = Distance from the bottom of the column, ft

Equation (1) can be rewritten to

$$\frac{d \ln C_s}{dL} = - V_p/E_{zp} \tag{2}$$

Therefore, a plot of ($\ln C_s$) vs (L) should yield a straight line provided that both V_p and E_{zp} are not functions of either solid concentration or column level. Figures (3) through (14) show semi-logarithmic plots of C_s vs L as a function of gas velocities for all the experiments conducted in this quarter. These figures indicate that reasonable straight lines are obtained for both larger and smaller particles above a certain gas velocity. This is not surprising since all the particles will be suspended only above a critical gas velocity and Equation (1) will hold true only for suspended particles.

5.2.1.2 Fine Particles (140/170 mesh glass beads and 140 mesh minus sand)

The results of the fine glass beads are summarized in Figures (3) and (4) at two different average concentrations. The distribution of solid concentration was independent of gas velocity above 0.10 ft/sec which implies that the solid dispersion coefficient is also independent of gas velocity. However, if the effective V_p in Equation (1) varies with gas velocity, the solid dispersion coefficient will be proportionally dependent on gas velocity. When silica was used in the 5-inch diameter column, the scatter

FIGURE 3

SOLIDS CONCENTRATION vs COLUMN HEIGHT
FOR THE 5" COLUMN USING 140/170 MESH GLASS BEADS
AT LOW CONCENTRATION

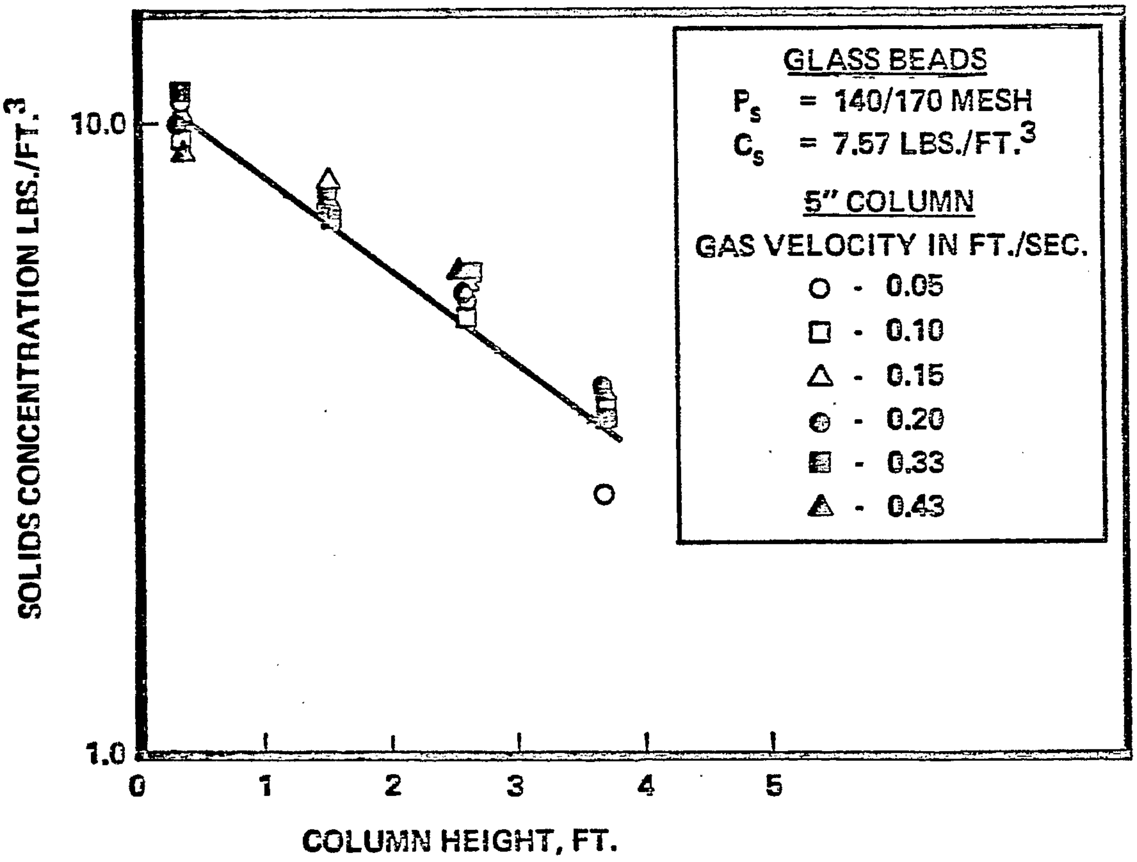
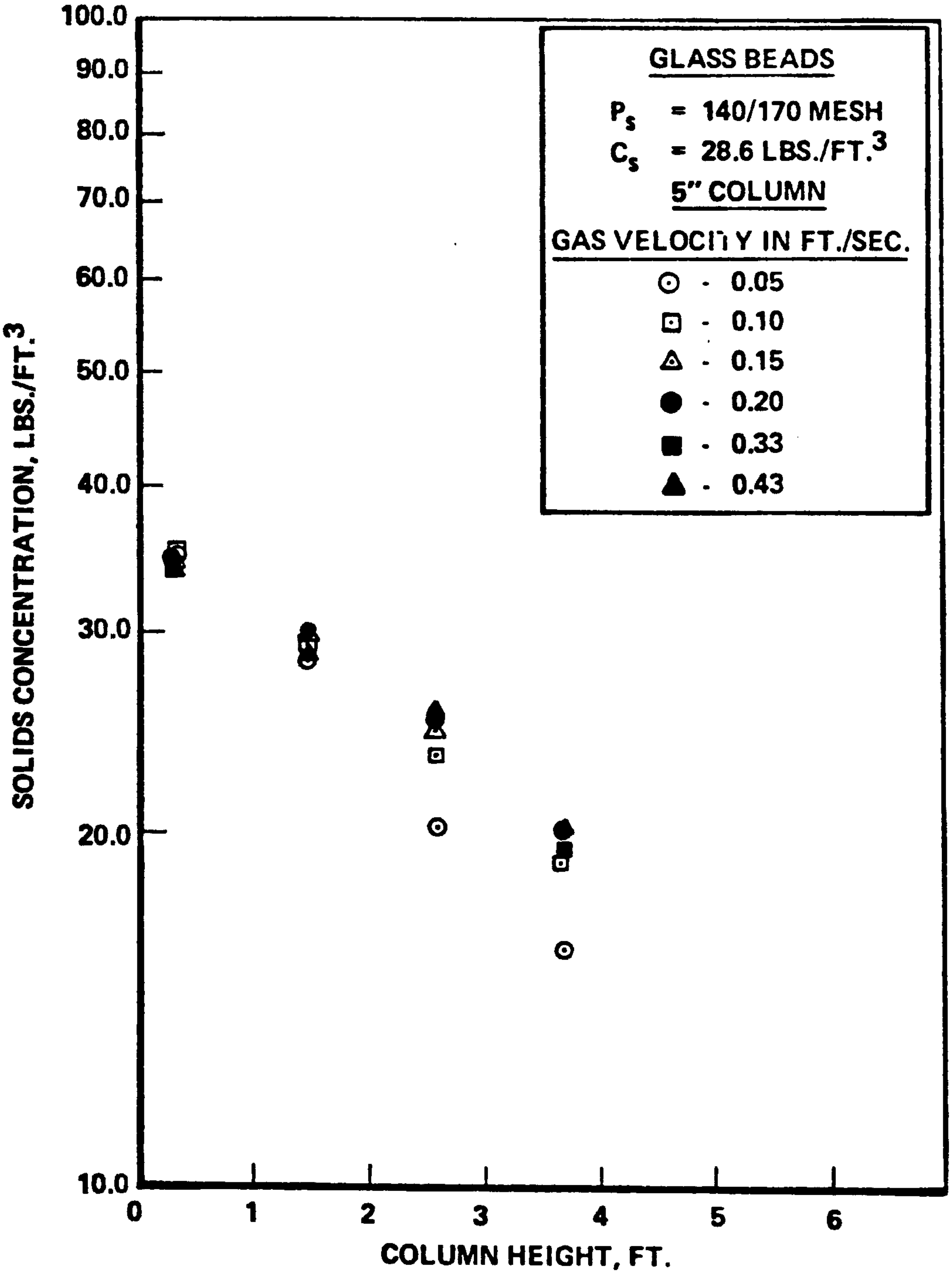


FIGURE 4

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 5" COLUMN USING 140/170 MESH GLASS BEADS AT HIGH CONCENTRATION



in the data increased, as shown in Figures (5) and (6). The scatter in the data can be attributed to the wide range of particle size distribution present in -140 mesh silica particles. However, the results suggest a very uniform solid distribution which means a very well mixed solid phase. Within the scattered band, if there is any dependence of solid dispersion coefficient in the four-fold increase in gas velocity, it will be very small. Increasing the column diameter from 5 inches to 12 inches did not change the general behavior of the -140 mesh sand particles. At both concentrations studied, as shown in Figures (7) and (8), the solids concentration as a function of the height of the column reaches a steady value at a gas velocity of 0.15 ft/sec. Increasing the gas velocity further results in little or no changes in solid concentration. The uniform distribution also reflects a well-mixed solid phase in the 12-inch diameter column.

The V_p/E_{zp} values measured from the slopes of the straight line plots shown in Figures (3) through (8) are summarized in Table VII. Within experimental accuracy, the V_p/E_{zp} values are independent of gas velocity as discussed earlier. Comparison of the results showed that the glass beads had consistently higher V_p/E_{zp} values than sand for both concentrations; the V_p/E_{zp} value for sand is about 10-15% of that for glass beads. This difference can be attributed to both a higher settling velocity and lower dispersion coefficient for glass beads because the average particle size for the 140/170 mesh glass beads was at least a factor of two larger than that for the 140 mesh minus sand. Based upon Stokes' Law, the V_p for glass beads would be at least a factor of four higher than the sand. Therefore, the V_p/E_{zp} values for sand is expected to be less than 25% of the value for glass beads for constant E_{zp}. But if the dispersion coefficient (E_{zp}) varies any with particle size, it is logical to expect an increase with decreasing particle size. This will further widen the difference of V_p/E_{zp} between 140/170 mesh glass beads and 140 mesh minus sand, approaching the value observed experimentally.

FIGURE 5

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 5" COLUMN USING –140 MESH SAND AT LOW CONCENTRATION

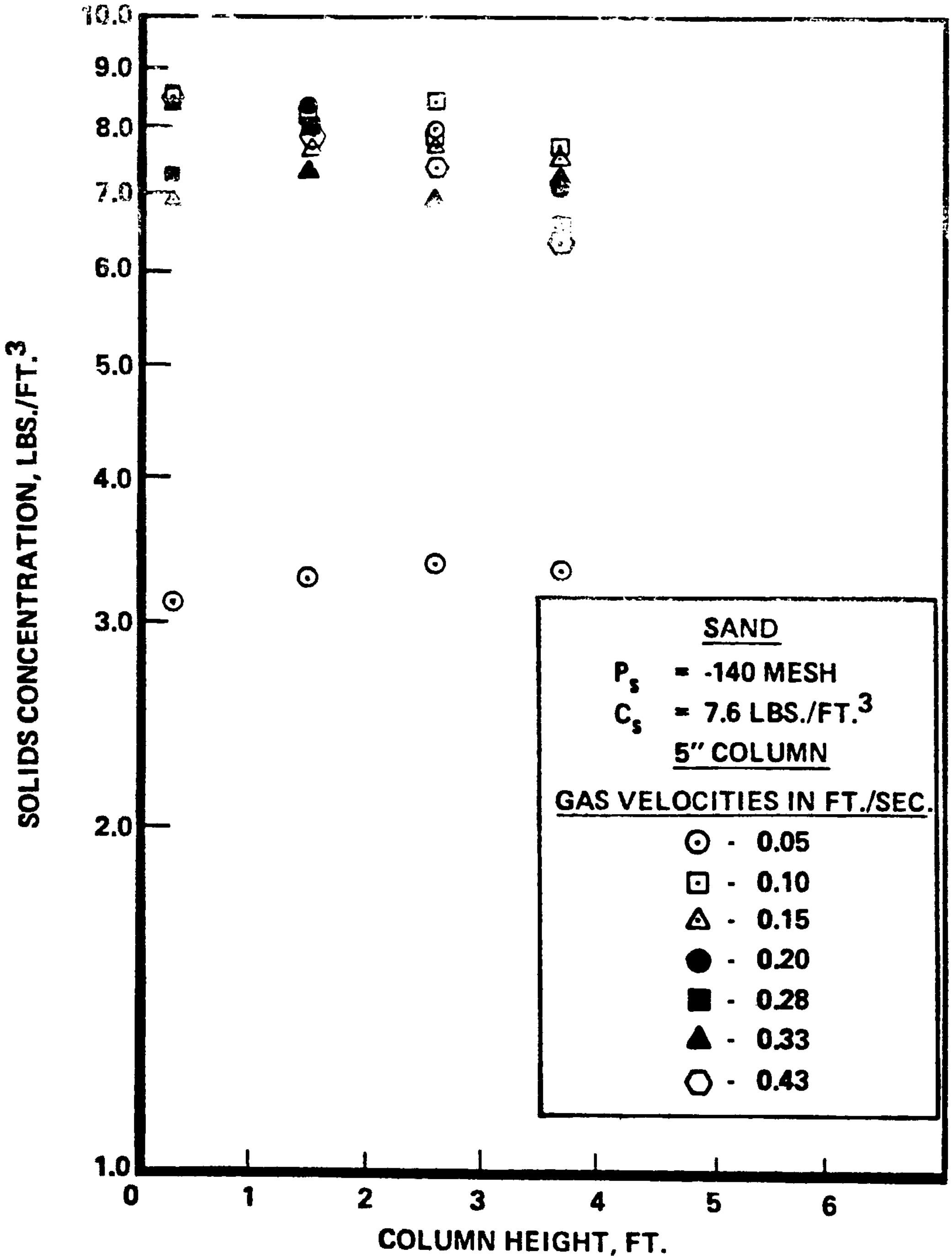


FIGURE 6

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 5" COLUMN USING -140 MESH SAND AT HIGH CONCENTRATION

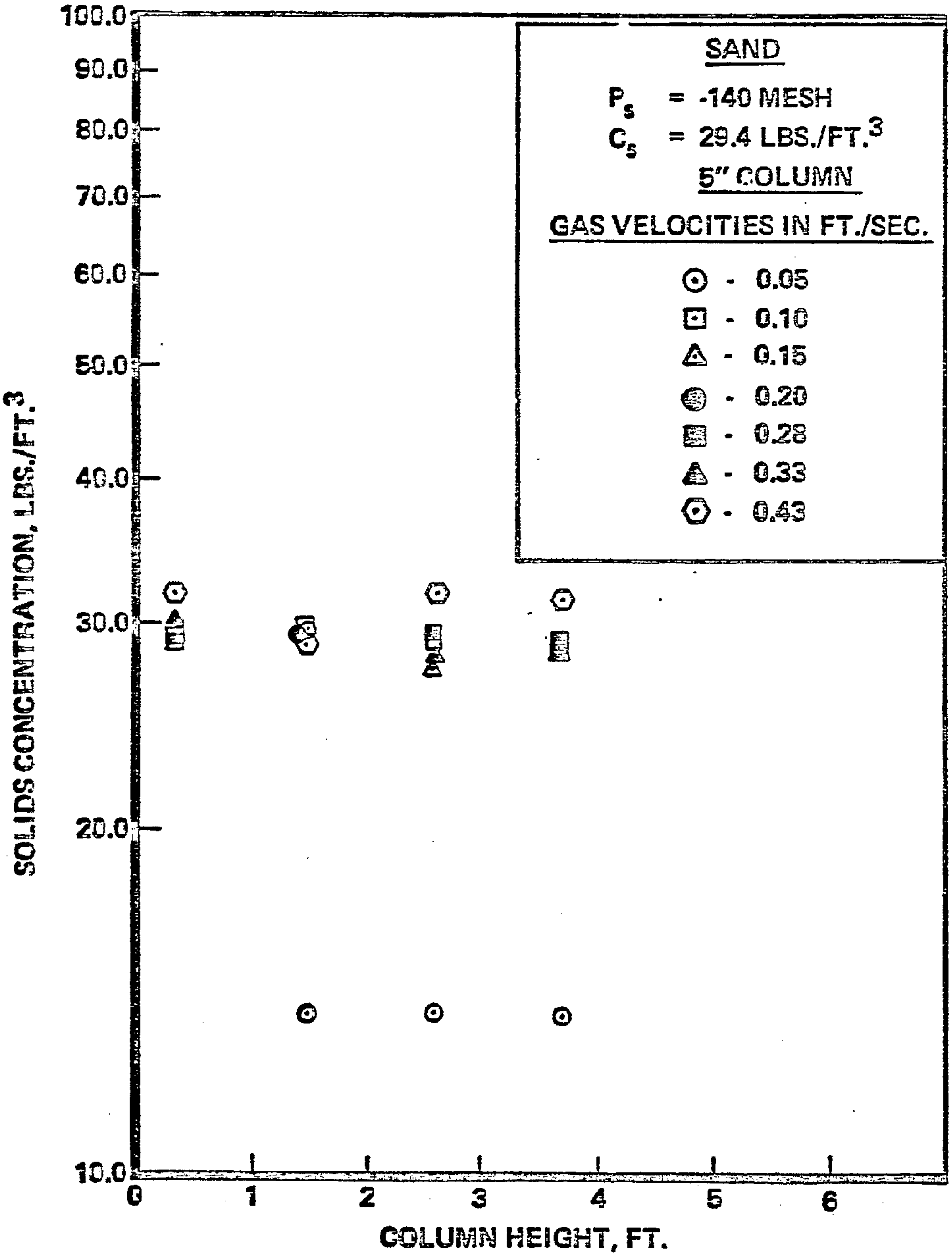


FIGURE 7

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 12" COLUMN USING -140 MESH SAND AT LOW CONCENTRATION

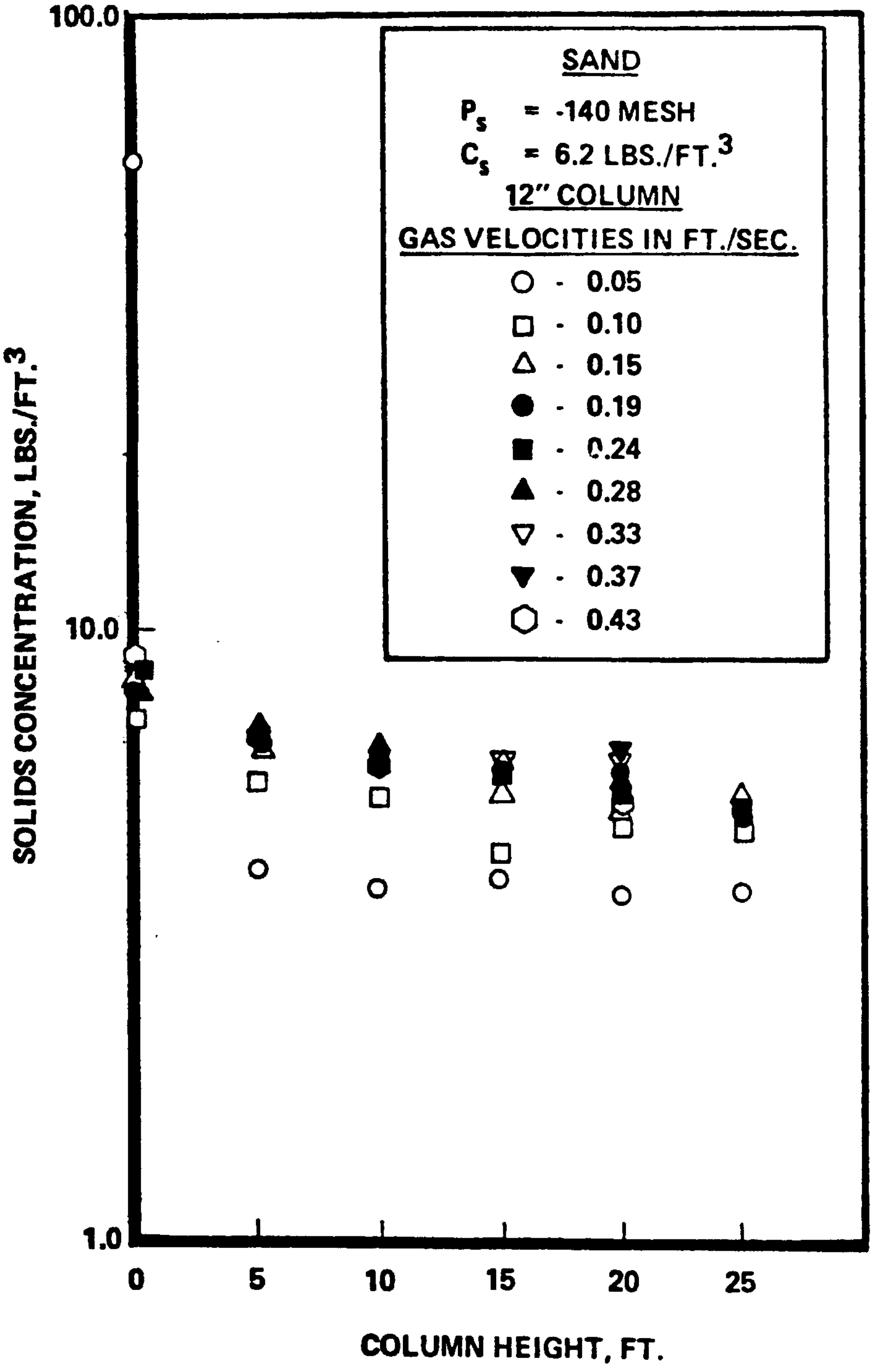


FIGURE 8

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 12" COLUMN USING -140 MESH SAND AT HIGH CONCENTRATION

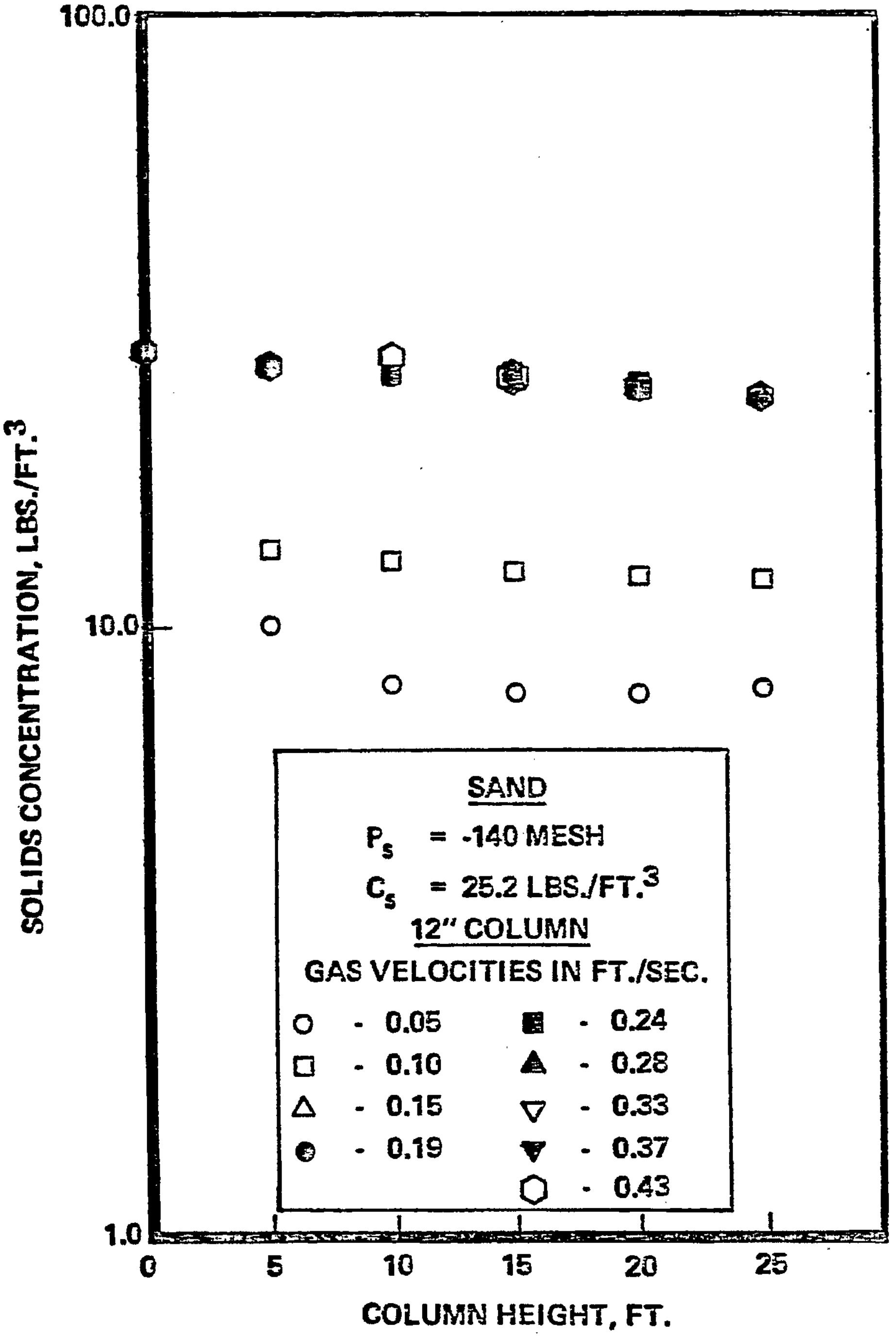


Table VII

Summary of V_p/E_{zp} for Fine Particles as a Functions of Gas Velocity

Particle Size = 140/170 Mesh for Glass Beads Experiments

Particle Size = -140 Mesh for Sand Experiments

Gas Velocity ft/sec	V_p/E_{zp}					
	C_s = 7.5 lbs/ft^3			C_s = 28.6 lbs/ft^3		
	5" Column		12" Column	5" Column		12" Column
	Glass Beads	Sand	Sand	Glass Beads	Sand	Sand
0.10	0.307	0.029	0.016		0.013	
0.15	0.312		0.018	0.156	0.014	0.006
0.20	0.292	0.047	0.017	0.157	0.016	0.005
0.24			0.019			0.007
0.28			0.016			0.005
0.30		0.034				
0.33	0.33	0.043	0.017	0.162	0.019	0.006
0.37			0.015			0.006
0.43	0.275	0.073	0.021	0.148		0.006

Effects of column diameter and solid concentration on V_p/E_{zp} are quite obvious as shown in Table VII. V_p/E_{zp} decreased with both increasing column diameter and solid concentration. The dependence on column diameter is not surprising because the degree of liquid backmixing and liquid dispersion coefficient increased with increasing column diameter, hence solid dispersion coefficient will be expected to increase if there is any column diameter effect. The observed decrease in V_p/E_{zp} value with increasing column diameter directly reflects an increase of E_{zp} which is in qualitative agreement with the above expectation. The reason for the dependence on solid concentration is not so clear, however. It is speculated that perhaps there is a hindrance effect on the particle settling velocity by the neighbor particles. This will qualitatively explain the decrease of V_p/E_{zp} with increasing solid loading. Separating the V_p and E_{zp} values is absolutely necessary to study these two parameters individually. Techniques have been investigated and will be discussed in a later section.

5.2.1.3 Large Particles (60/70 mesh glass beads; 60/70 and 60/80 mesh sand)

Large particles behaved quite differently from the fines. Significant gradients in the solid concentration were measured for both sand and glass beads. Complete suspension of these large particles could not be achieved at low gas velocities. As illustrated in Figure (2), sampling from the bottom port is extremely difficult and the reliability of this sample is questionable. Hence, data from the lowest sampling port were excluded from the analysis unless specified.

The V_p/E_{zp} values for these large particles shown in Figures (9) to (14) at different solid concentration and column diameter were summarized as a function of gas velocity shown in Table VIII. The V_p/E_{zp} values for the glass beads decreased with increasing

FIGURE 9

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 5" COLUMN USING 60/70 MESH GLASS BEADS AT LOW CONCENTRATION

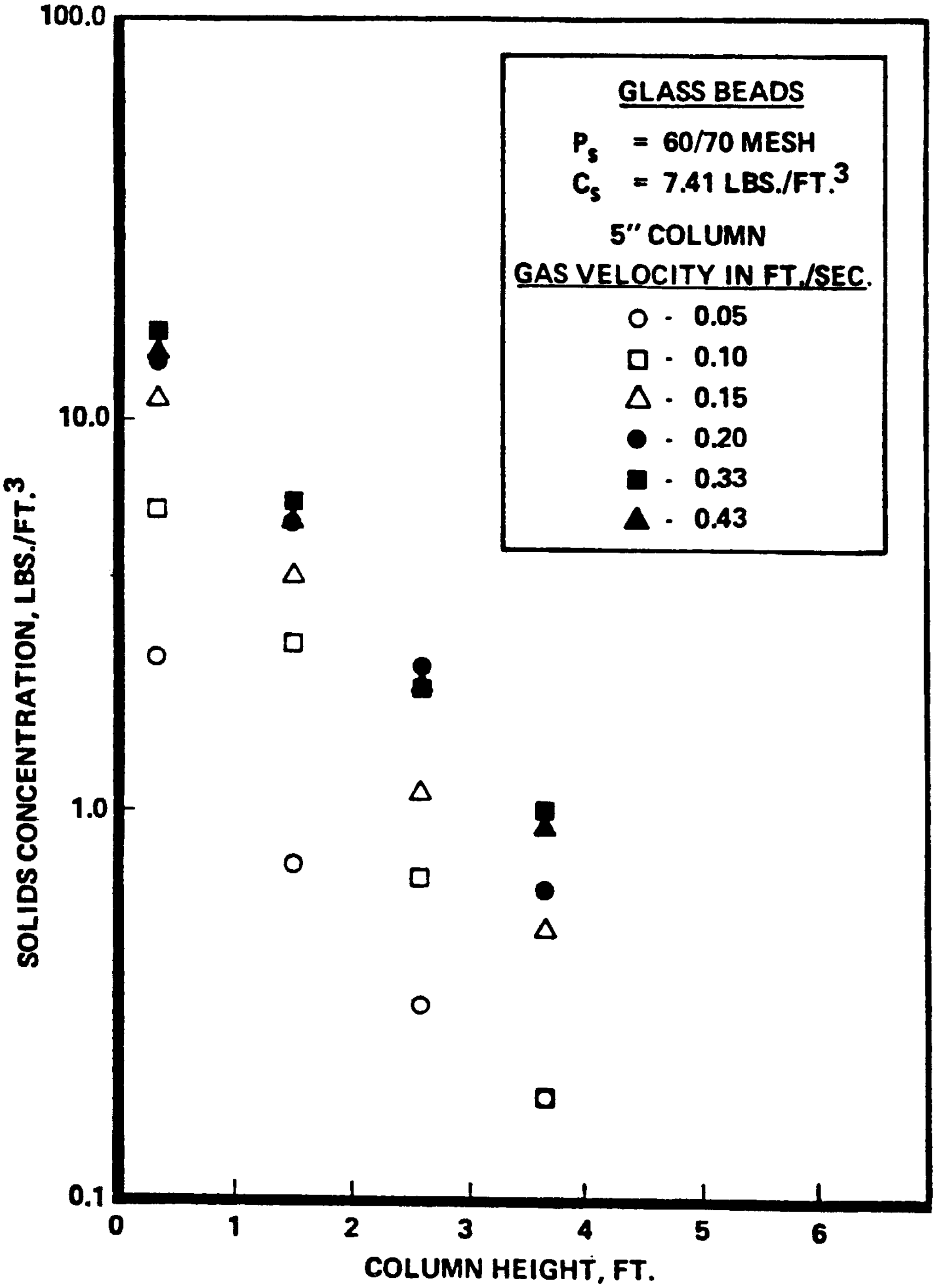


FIGURE 10

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 5" COLUMN USING 60/70 MESH GLASS BEADS AT HIGH CONCENTRATION

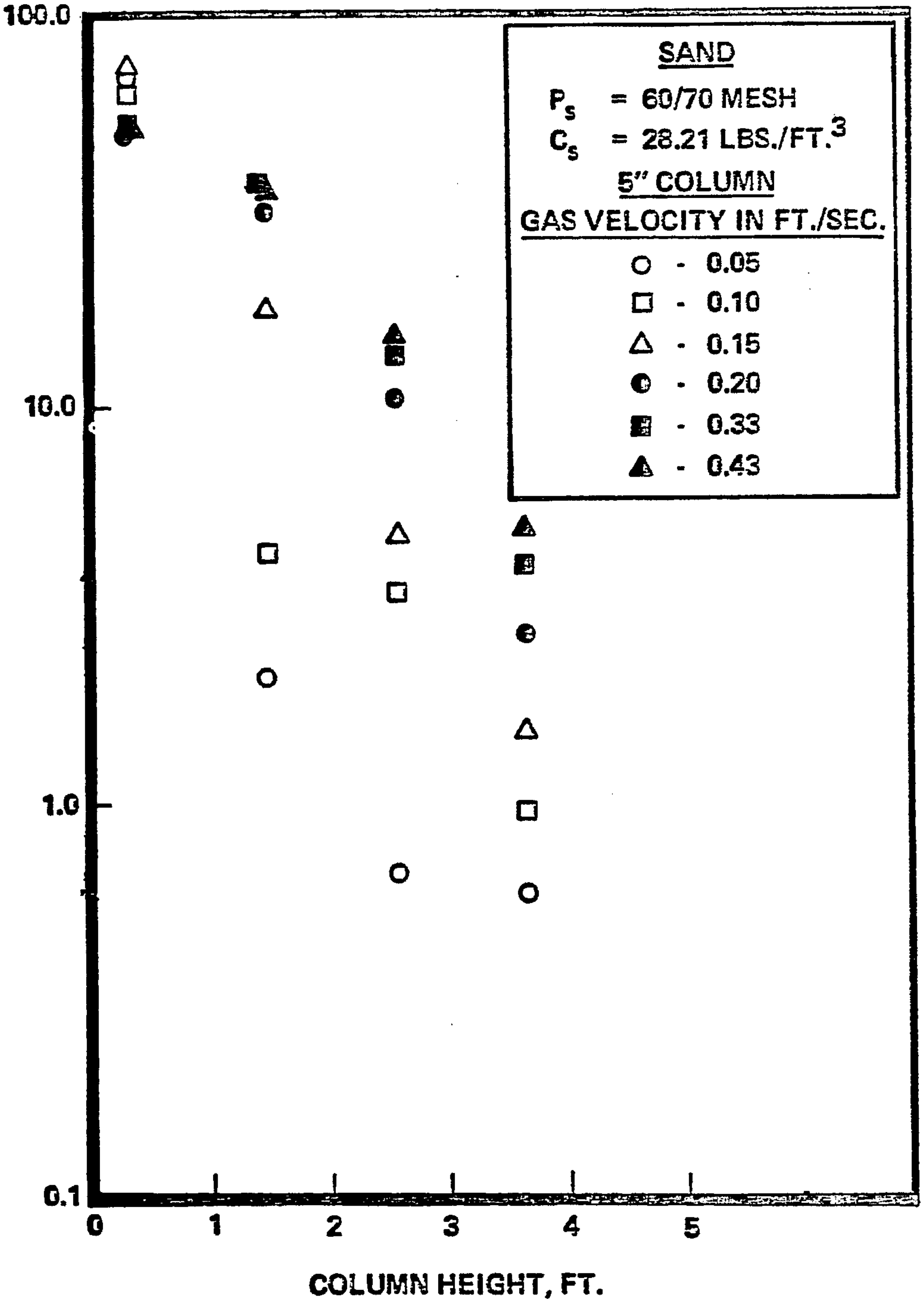


FIGURE 11

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 5" COLUMN USING 60/70 MESH SAND AT LOW CONCENTRATION

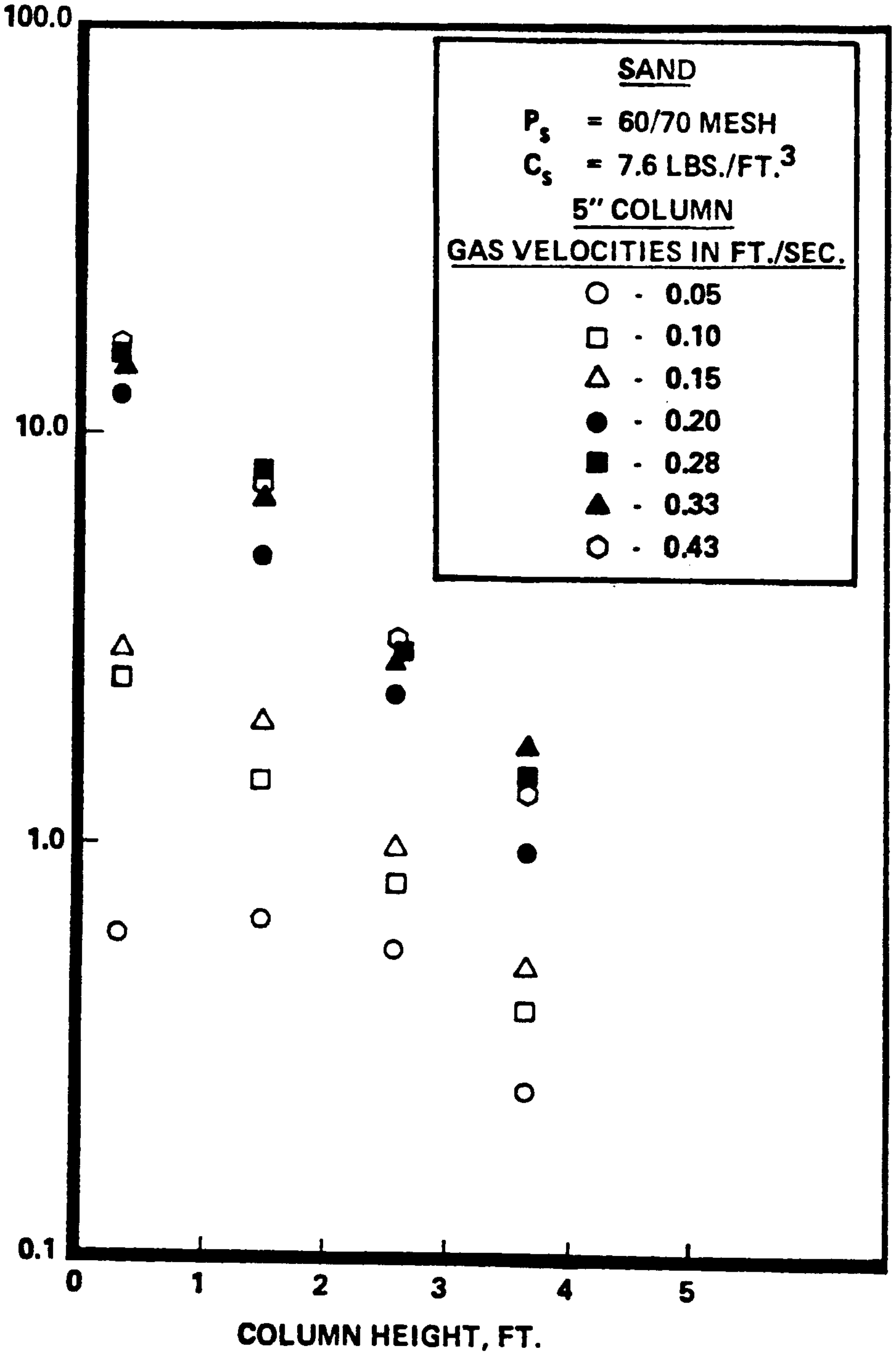


FIGURE 12

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 5" COLUMN USING 60/70 MESH SAND AT HIGH CONCENTRATION

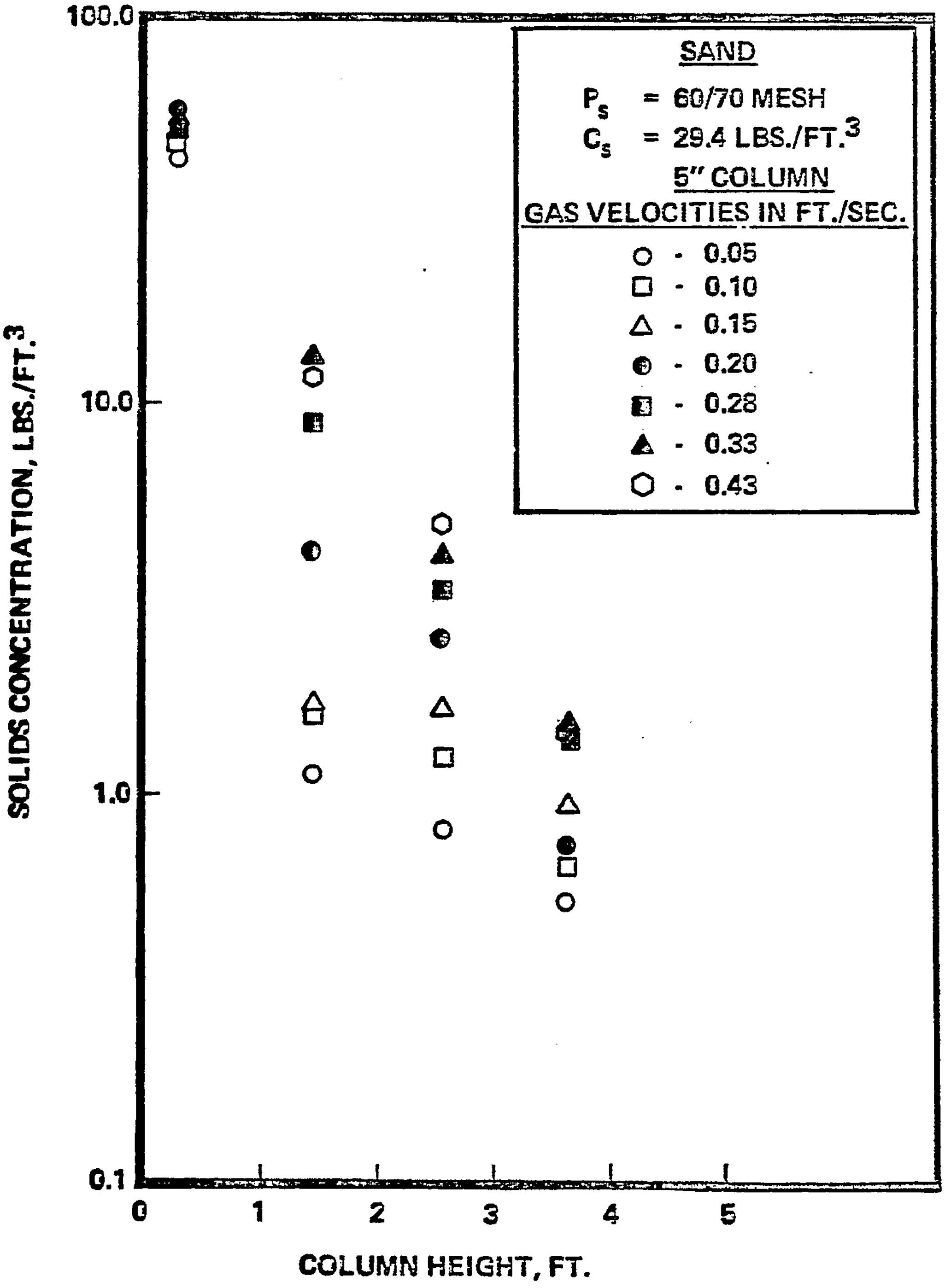


FIGURE 13

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 12" COLUMN USING 60/80 MESH SAND AT LOW CONCENTRATION

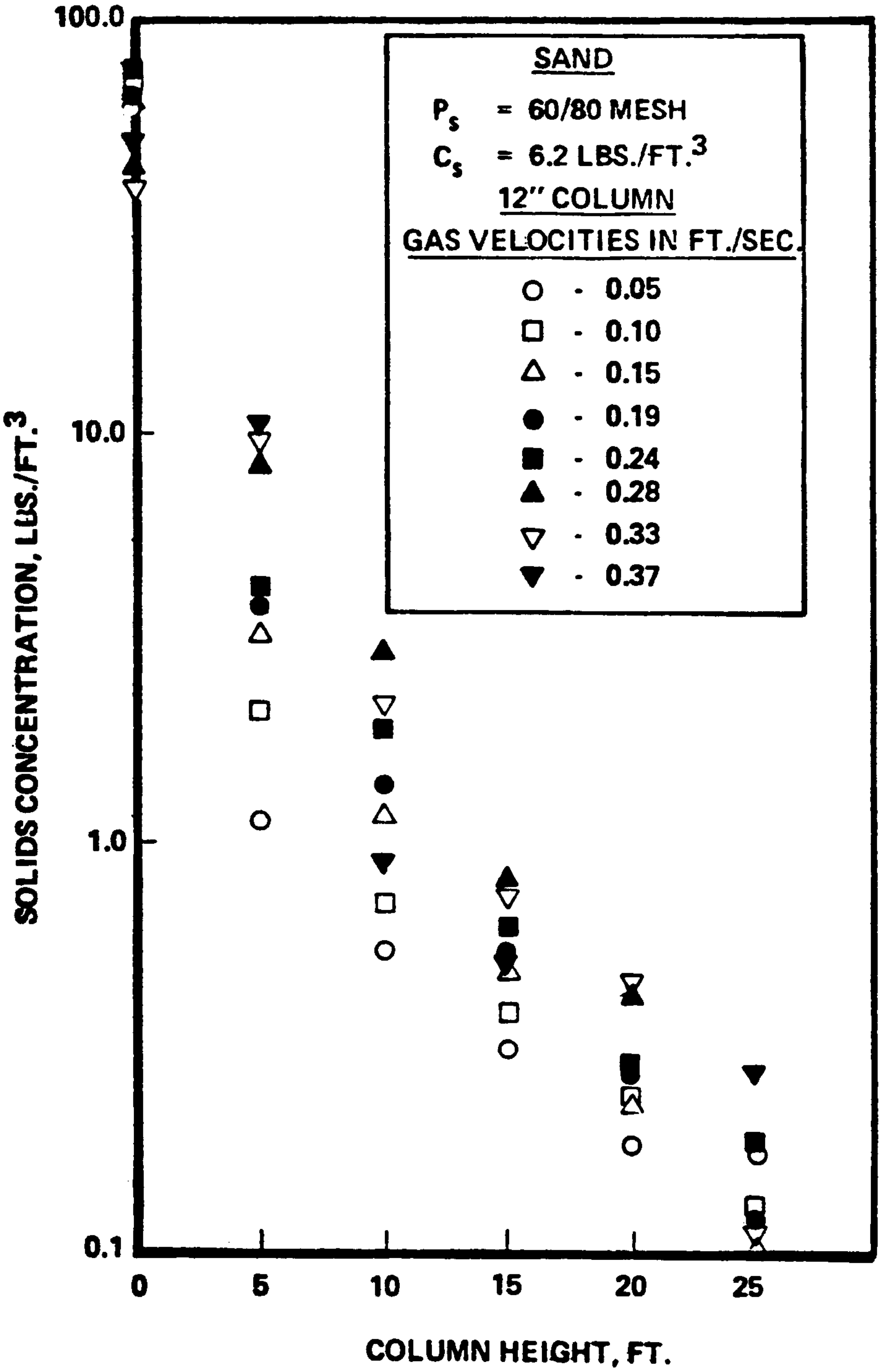


FIGURE 14

SOLIDS CONCENTRATION vs COLUMN HEIGHT FOR THE 12" COLUMN USING 60/80 MESH SAND AT HIGH CONCENTRATION

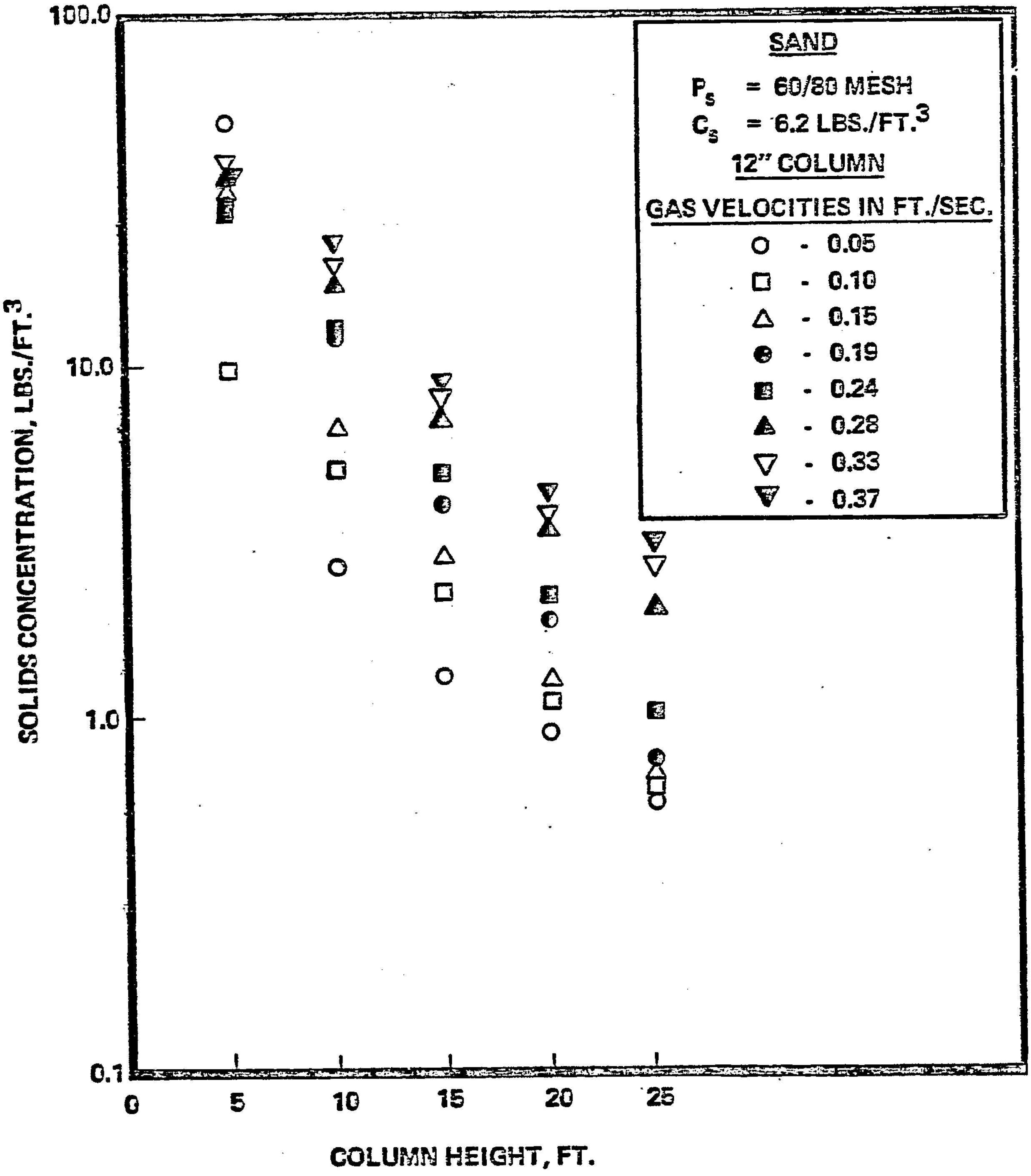


Table VIII

Summary of V_p/E_{zp} for Large Particles as a Function of Gas Velocity

Particle Size = 60/70 Mesh for 5" Column Experiments

Particle Size = 60/80 Mesh for 12" Column Experiments

Gas Velocity ft/sec	V_p/E_{zp}					
	C_s = 7.5 lbs/ft^3			C_s = 28.6 lbs/ft^3		
	5" Column		12" Column	5" Column		12" Column
	Glass Beads	Sand	Sand	Glass Beads	Sand	Sand
0.10						
0.15	0.959		0.174	1.117		
0.20	0.916	0.757	0.175	1.115	0.789	0.193
0.24			0.181			0.179
0.28			0.205			0.152
0.30		0.740			0.828	
0.33	0.864	0.662	0.204	0.982	0.979	0.154
0.37						0.145
0.43	0.846	0.729		0.940	0.946	

gas velocity at both concentrations. For the 60/70 mesh glass beads, the solid dispersion coefficient increased with gas velocities as illustrated by the decrease in the slopes with increasing gas velocities shown in Figure (9) and (10). However, the V_p/E_{zp} values for sand particles behaved dissimilarly. In most of these experiments, complete suspension was achieved only at higher gas velocities (Tables B1 through B12 present the gas velocity at which complete suspension was achieved for each experiment). The critical gas velocity, which is defined as the velocity above which all particles are in complete suspension, for the 60/80 mesh particles in water was determined to be between 0.193 and 0.217 ft/sec. The results shown in Table VIII indicated that above the critical gas velocity, all the V_p/E_{zp} values showed no systematic change with gas velocity. With the limited amount of data available, the V_p/E_{zp} values seemed to be independent of gas velocity which is consistent with the behavior observed with the fine particles.

Increasing the column diameter resulted in a decrease in V_p/E_{zp} values. This means an increase in solid dispersion coefficient with increasing column diameter, and is consistent with the observation using fine particles. Furthermore, the results also indicated that the V_p/E_{zp} values for the sand particles and glass beads are very close. A small difference in V_p/E_{zp} value was observed at low concentration although same size ranges of particles, namely 60/70 mesh, were used in these experiments for both glass beads and sand particles. This slight difference in V_p/E_{zp} values for sand and glass beads possibly reflected some intrinsic difference in the distribution of these particles within the 60/70 mesh range and effect of particle shape.

5.2.1.4 Determining Solid Dispersion Coefficients

The settling velocities should be known in order to calculate the solid dispersion coefficients directly from these results. Terminal velocity of a free falling particle in a stagnant medium can be estimated. However, since the particles used in these experiments have a wide size range, estimating an average particle size and determining the settling velocity are difficult. At this point, several different ways are being explored to determine the solid dispersion coefficients from this data. One of them is to determine the settling velocities directly from experimental measurements. Efforts are being made to conduct some experiments. Another way is to combine the results from batch experiments with continuous experiments in order to independently calculate the value of E_{zp}. We are currently developing some computer programs and results are awaited from all the continuous experiments.

5.2.2 Continuous Experiments

The distribution of solids along the column was determined in experiments with slurry and gas flowing through the column. Table IX lists the experiments that were conducted in this quarter. As pointed out earlier, two different types of continuous experiments were carried out. One involved a once through operation of the slurry which required making fresh batches of slurry. In the other method, the slurry is recycled so that a closed loop operation is employed. Three different particle sizes were used in this quarter. With the large particles feed concentration varied quite a lot (40/60 and 60/80 mesh). This was due to the inability of the existing equipment to maintain a homogeneous feed concentration for these large particles. Modifications are being made to the equipment to obtain uniform suspension of the large particles. With the fine particles, (-140 mesh) it was possible to maintain a uniform suspension. Hence only the results of the fines will be discussed.

One of the objectives of this part of the project is to study the effect of liquid and gas velocities on distribution of solids in the 12" diameter column. Because once-through operation would consume tremendous quantities of sand the 12-inch diameter column was operated only in the recycle mode. Experiments were also conducted to compare the results from these two modes of operation in the 5-inch diameter column; the results are shown in Figure (15). Although the feed concentrations were slightly different for the two experiments, the normalized concentrations (concentration at any height divided by

Table IX
List of Continuous Experiments

Column Diameter	Particle Size	Liquid Velocity	Gas Velocity	Solids Concentration	Type
5	40/60	0.05	0.400	4.8 lbs/ft^3	I
5	60/80	0.05	0.400	4.8 lbs/ft^3	I
5	-140 Mesh	0.05	0.327	4.8 lbs/ft^3	I
5	-140 Mesh	0.05	0.327	4.8 lbs/ft^3	II
12	-140 Mesh	0.05	0.100	4.8 lbs/ft^3	II
12	-140 Mesh	0.05	0.194	4.8 lbs/ft^3	II
12	-140 Mesh	0.02	0.327	4.8 lbs/ft^3	II
12	-140 Mesh	0.05	0.327	4.8 lbs/ft^3	II
12	-140 Mesh	0.05	0.43	4.8 lbs/ft^3	II
12	-140 Mesh	0.04	0.327	4.8 lbs/ft^3	II

Type I - Experiment in which fresh batches of slurry were prepared and fed to the column (once through operation).

Type II - Experiment in which slurry was recycled (closed loop operation).

FIGURE 15

COMPARISON OF CONTINUOUS FEEDING AND RECYCLE RUNS

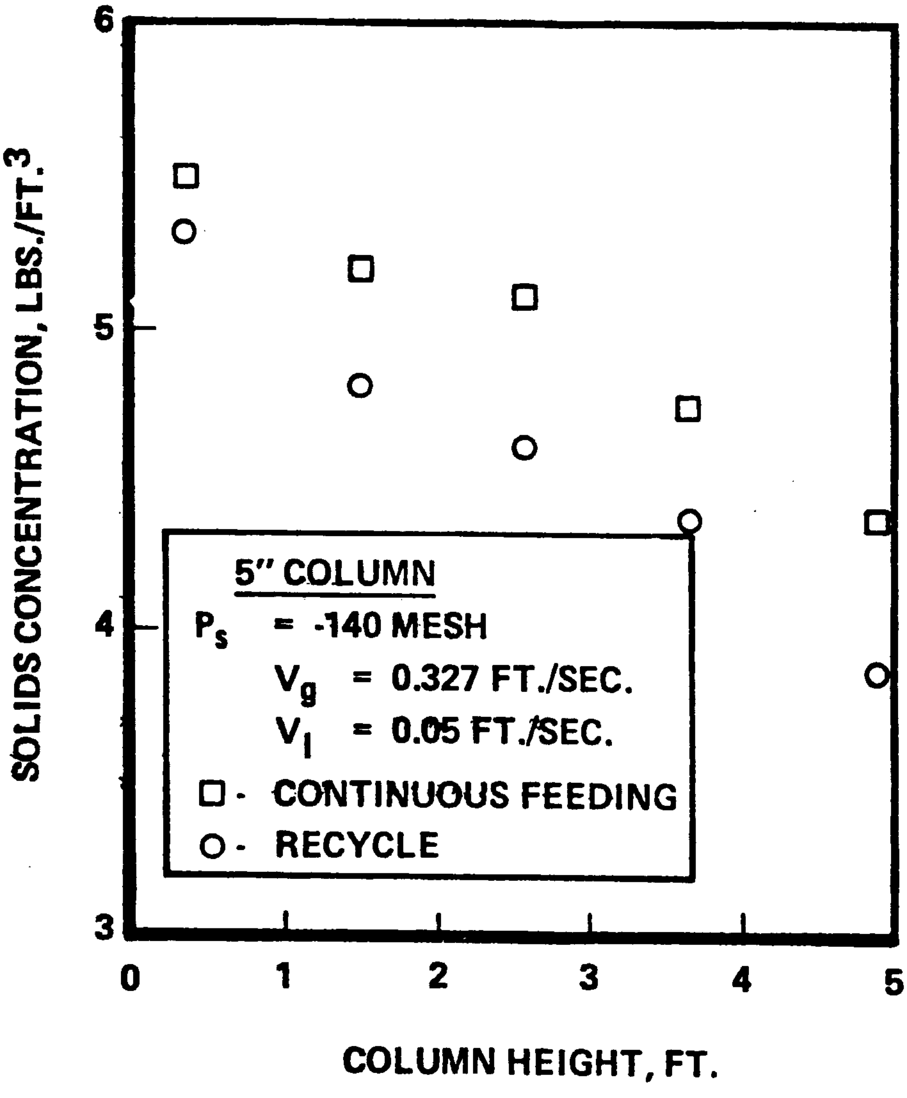
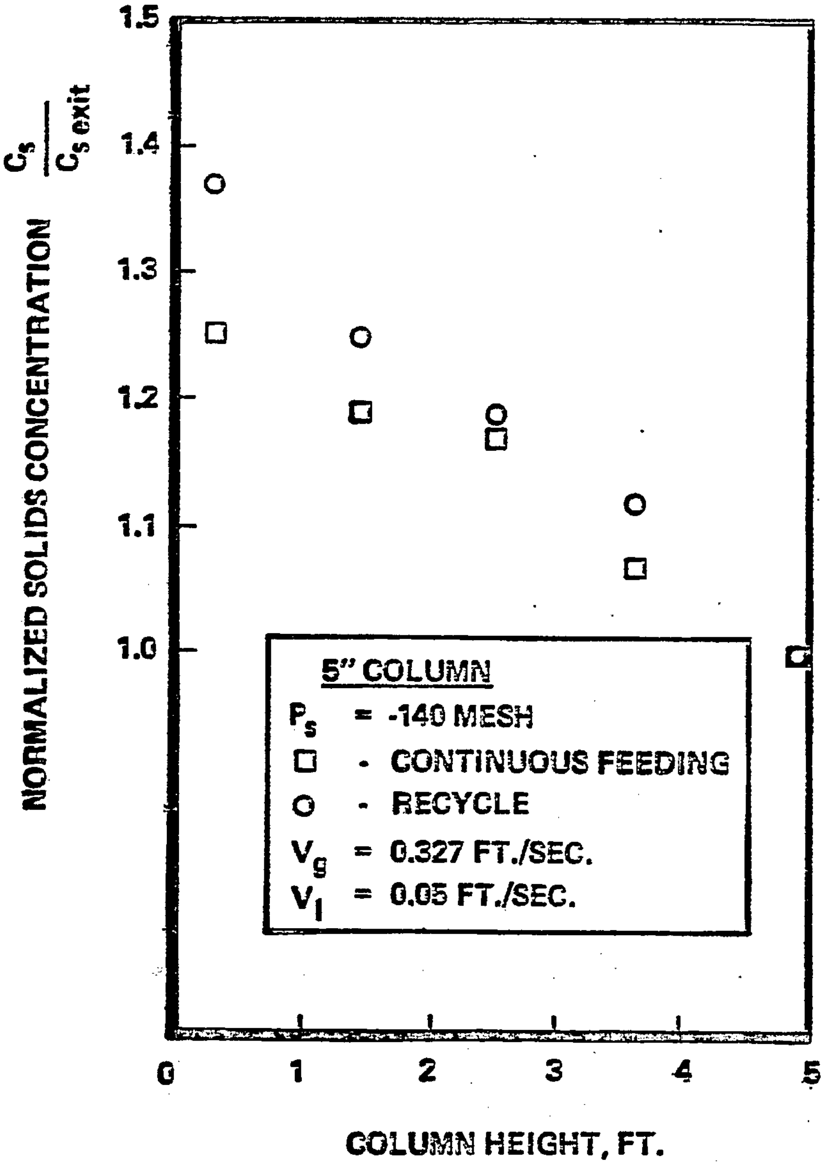


FIGURE 16

COMPARISON OF CONTINUOUS FEEDING AND RECYCLE RUNS USING NORMALIZED SOLIDS CONCENTRATION



feed concentration) as shown in Figure (16) as a function of column height reveal that the two methods are compatible with each other as the column height increases. The differences at the lowest point in the column is due to the wide particle size range used, as explained in the experimental section of this report. Total amounts of retained solids were calculated by integrating the concentration profile and compared to the amount measured by draining the column at the end of the experiment. The less than ten percent difference lends support to the validity of the sampling technique.

Figures (17) and (18) summarize the effects of gas and liquid velocities on the solid concentration distribution in the 12-inch diameter column. Detailed discussion of these results will be presented in the next quarterly report after results from 60/80 mesh experiments become available. In any event, Figure (17) shows that at a constant liquid velocity of 0.05 ft/sec, increasing the gas velocity from 0.1 to 0.43 ft/sec results in very little changes in solids distribution across the length of the column. These results confirm earlier results from batch experiments that for these fine (-140 mesh) particles, changes in gas velocity does not affect the distribution of solids.

A definite effect of liquid velocity on the solids distribution was observed in the 12-inch diameter column as shown in Figure (18). In this figure, the y axis represents normalized solids concentration (solids concentration at a point in the column divided by the exit concentration). These results indicate that increasing liquid velocity results in a decrease in solids accumulation in the column. Results from runs using 60/80 mesh particles will be discussed in the next quarterly report.

6.0 FUTURE WORK

Solid distribution results for 60/80 mesh particles will be analyzed and presented in the next quarter. Experiments to study gas/liquid mass transfer will be conducted. Task 3 will start in the next quarter. The distibutor plate will be removed from the 12-inch diameter column

FIGURE 17

EFFECT OF GAS VELOCITY ON SOLIDS DISTRIBUTION

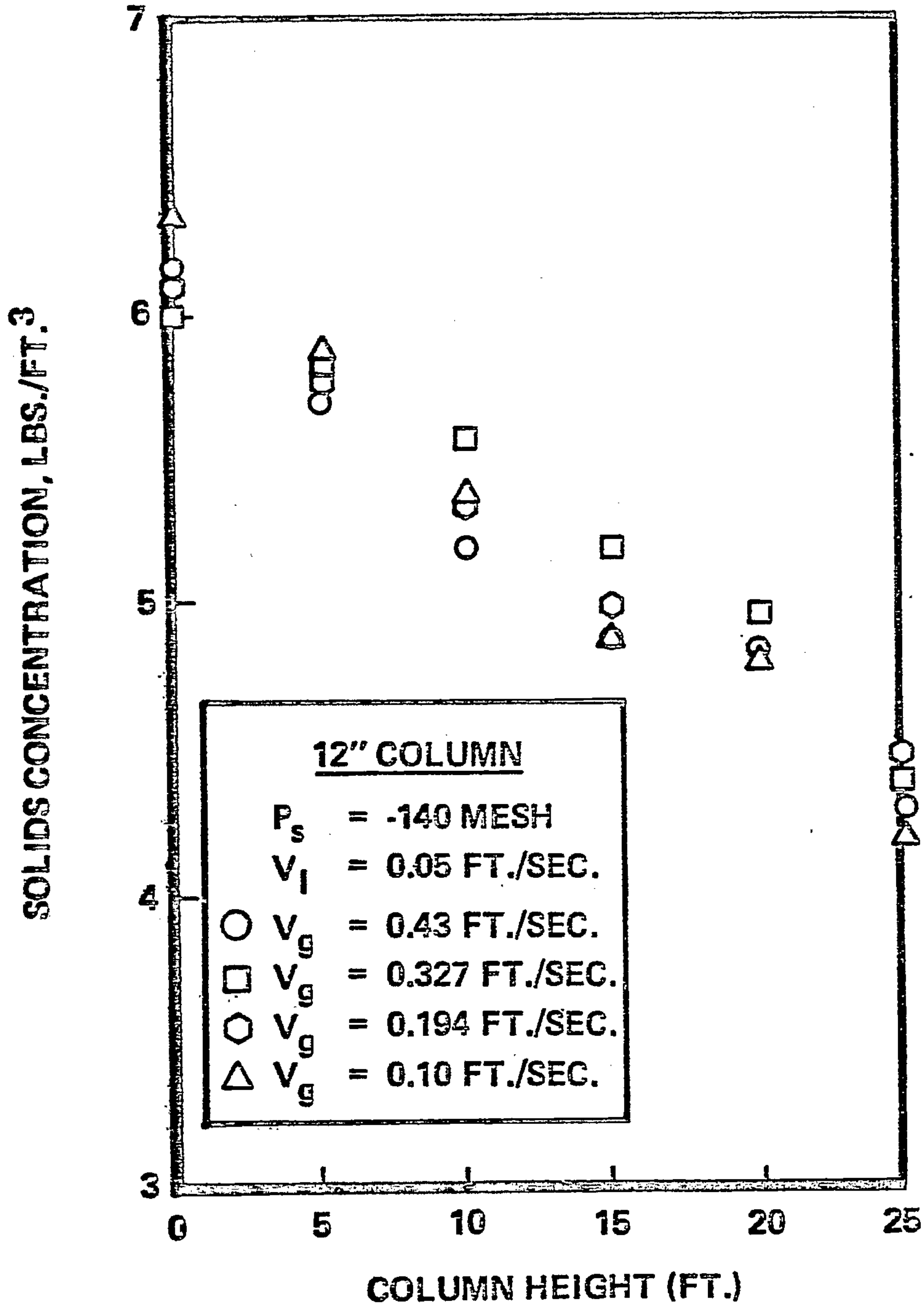
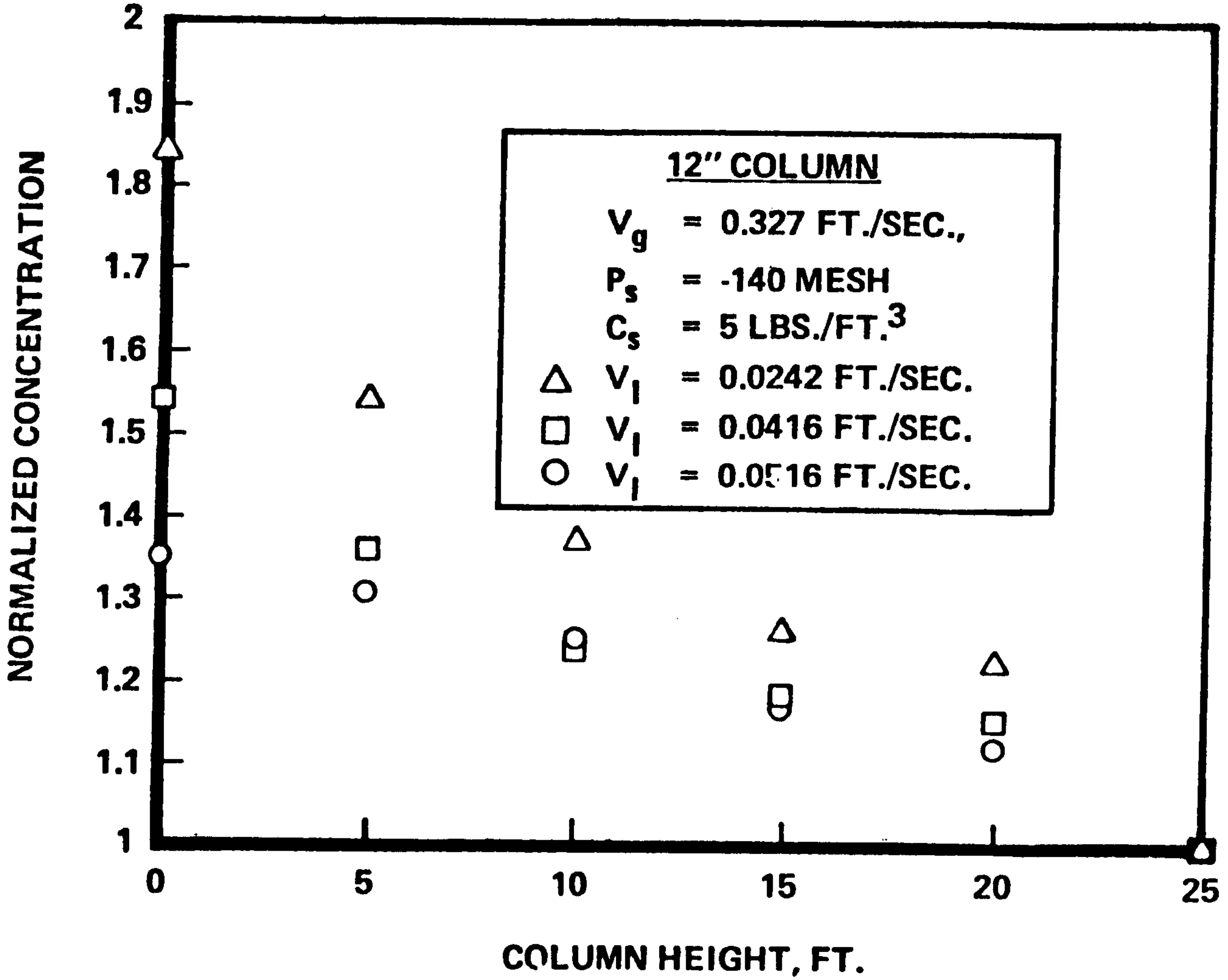


FIGURE 18

EFFECT OF LIQUID VELOCITY ON SOLID CONC.



to study gas holdup and liquid dispersion at the absence of distributor plate. A new distributor will be designed and fabricated. This new distributor will be installed in the column and experiments will be conducted to study the effect of distributor plate on holdup, liquid dispersion, and solids dispersion.

7.0 REFERENCES

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2. Aoyama, Y., Ogushi, K., Korde, K., and Kubota, H., J. Chem. Eng., Japan, Vol. 1, No. 2 (1968) 158.

3. Akita, K., PhD. Thesis, Kyoto University (1973).

4. Cova, D. R., I&EC Process Design and Development, Vol. 13, No. 3 (1974) 292.

5. Hikita, H. and Kikukawa H., Chem. Eng. Journal, Vol. 8 (1974) 191.

6. Ying, D. H., Givens, E. N., and Weimer, R. F., to be published in I&EC Process Design and Development (1980).

Appendix (A)

Experimental Tracer Data

(Figures A-1 through A-16)

FIGURE A-1

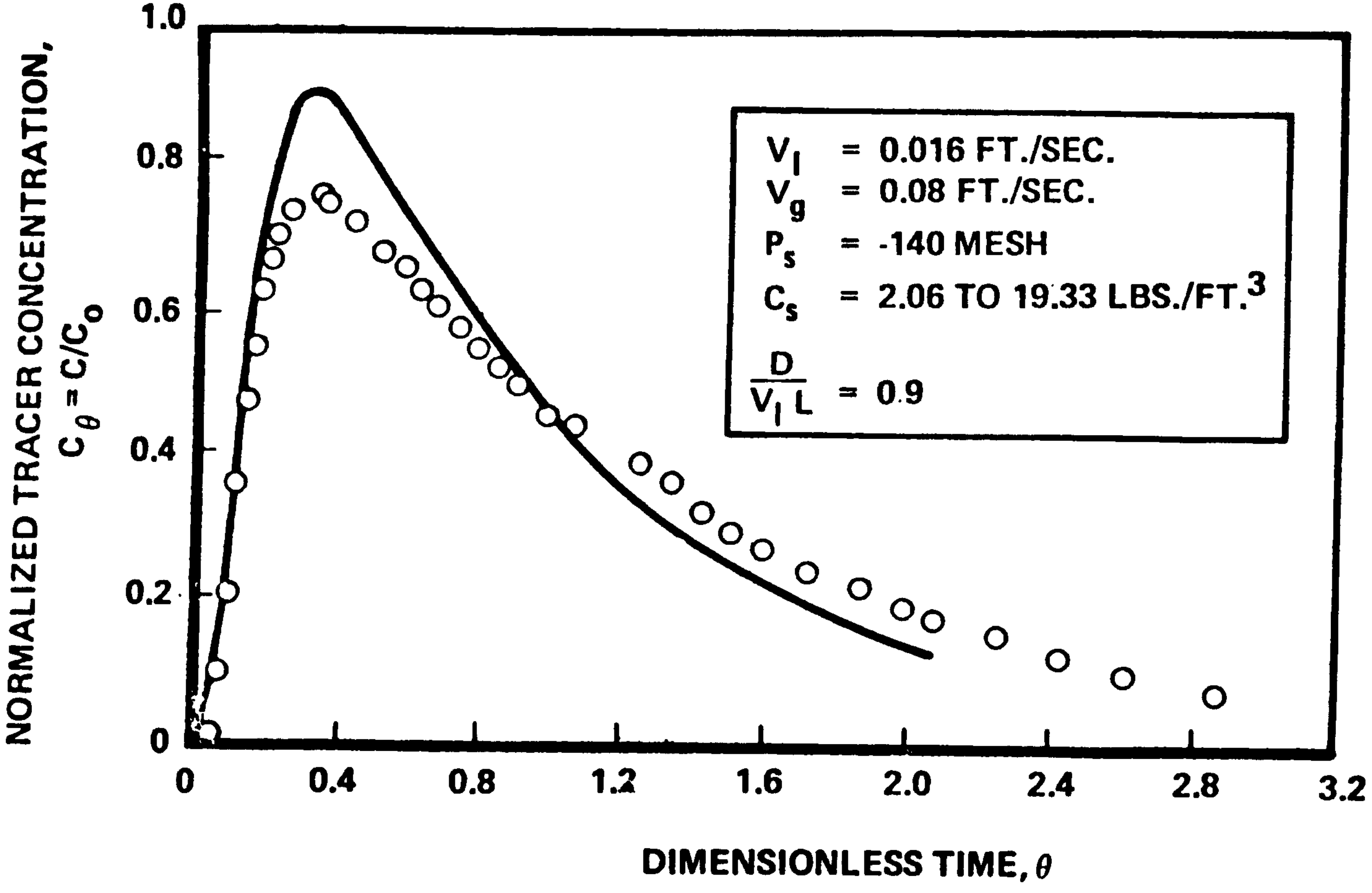

NORMALIZED TRACER CONCENTRATION, $C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
DIMENSIONLESS TIME, θ
V_l = 0.016 FT./SEC.
V_g = 0.08 FT./SEC.
P_s = -140 MESH
C_s = 2.06 TO 19.33 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.9

FIGURE A-2

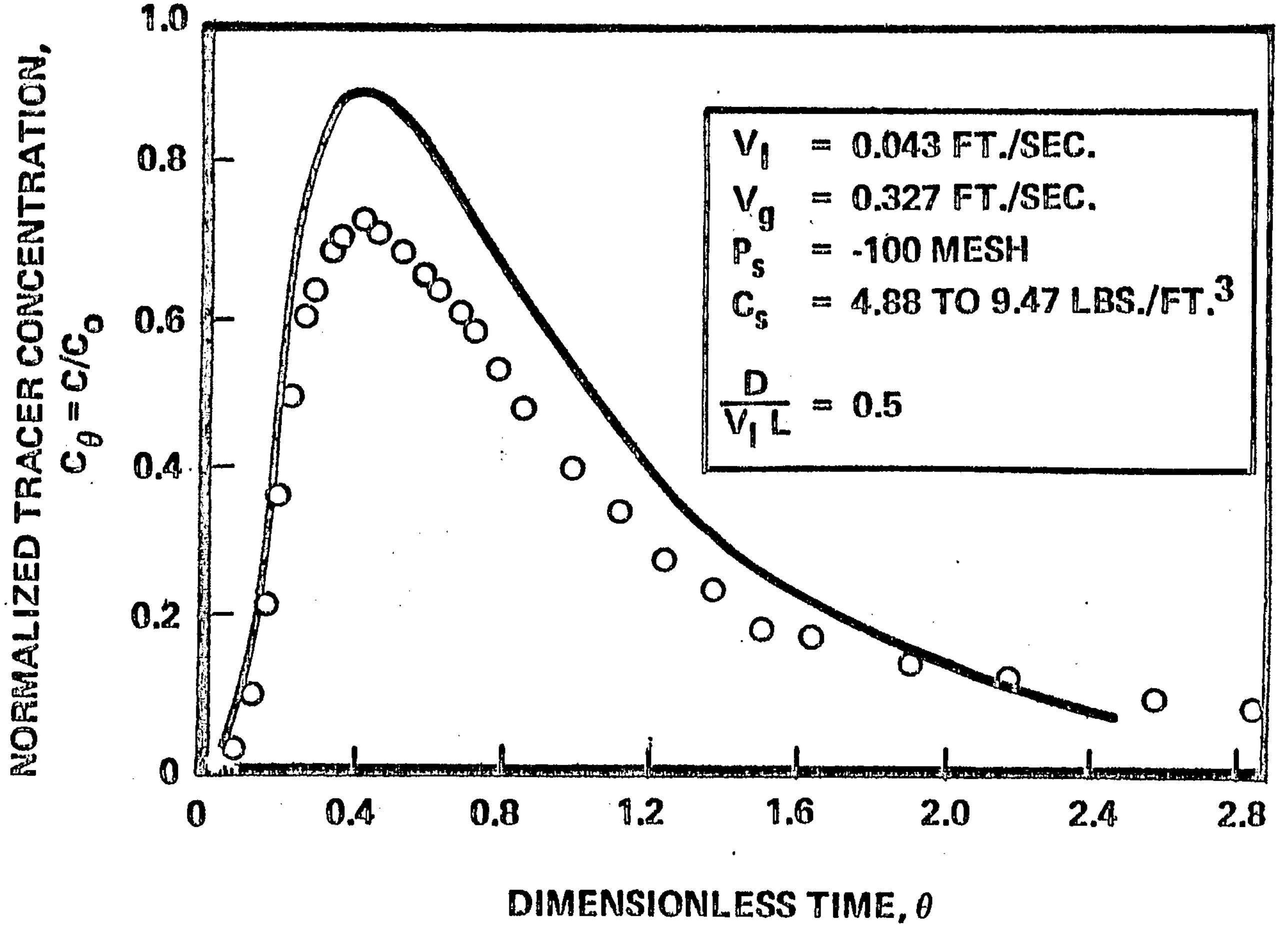

1.0
0.8
0.6
0.4
0.2
0
NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
DIMENSIONLESS TIME, θ
V_l = 0.043 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = -100 MESH
C_s = 4.88 TO 9.47 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.5

FIGURE A-3

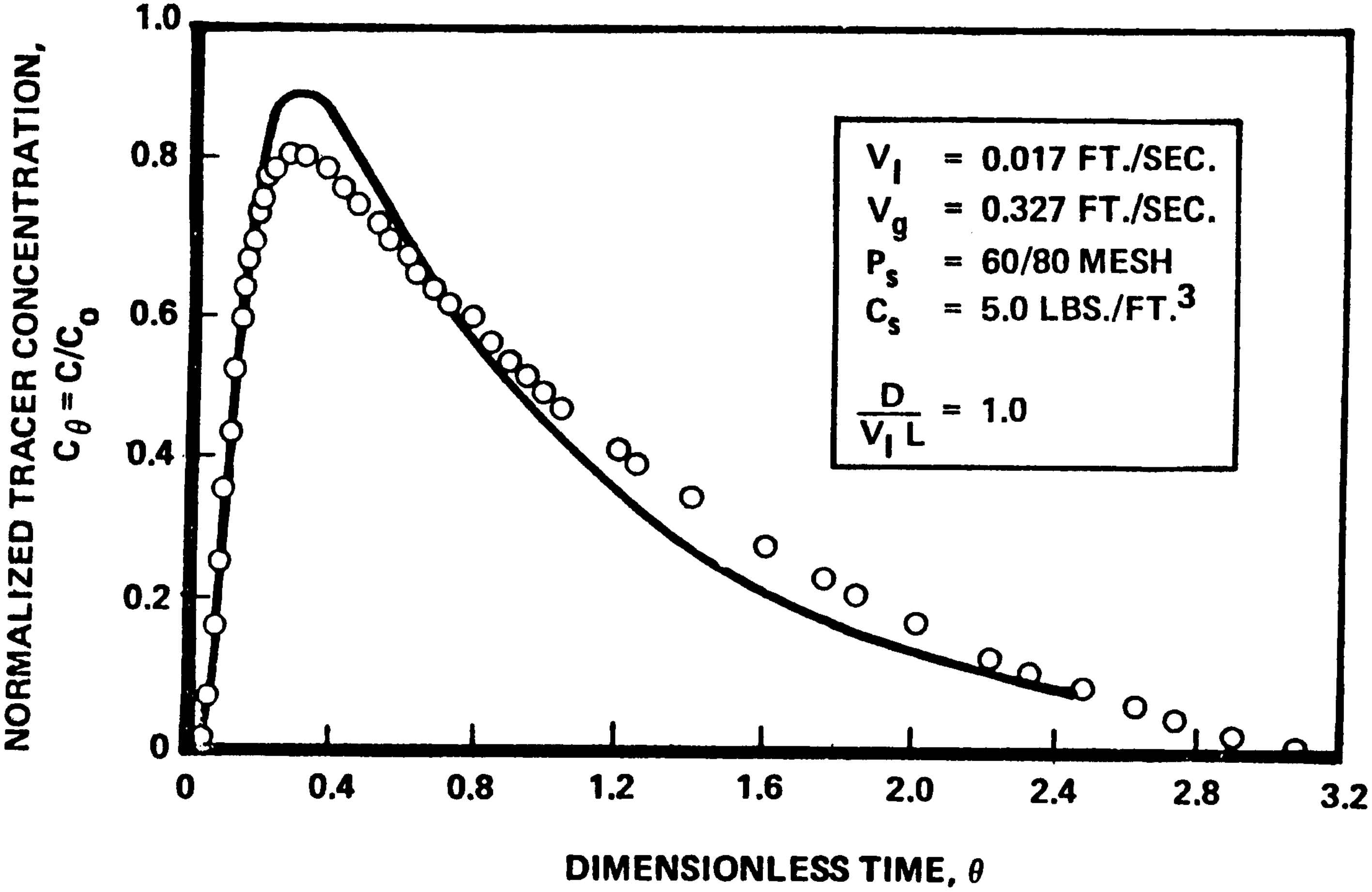

NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
DIMENSIONLESS TIME, θ
V_l = 0.017 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 1.0

FIGURE A-4

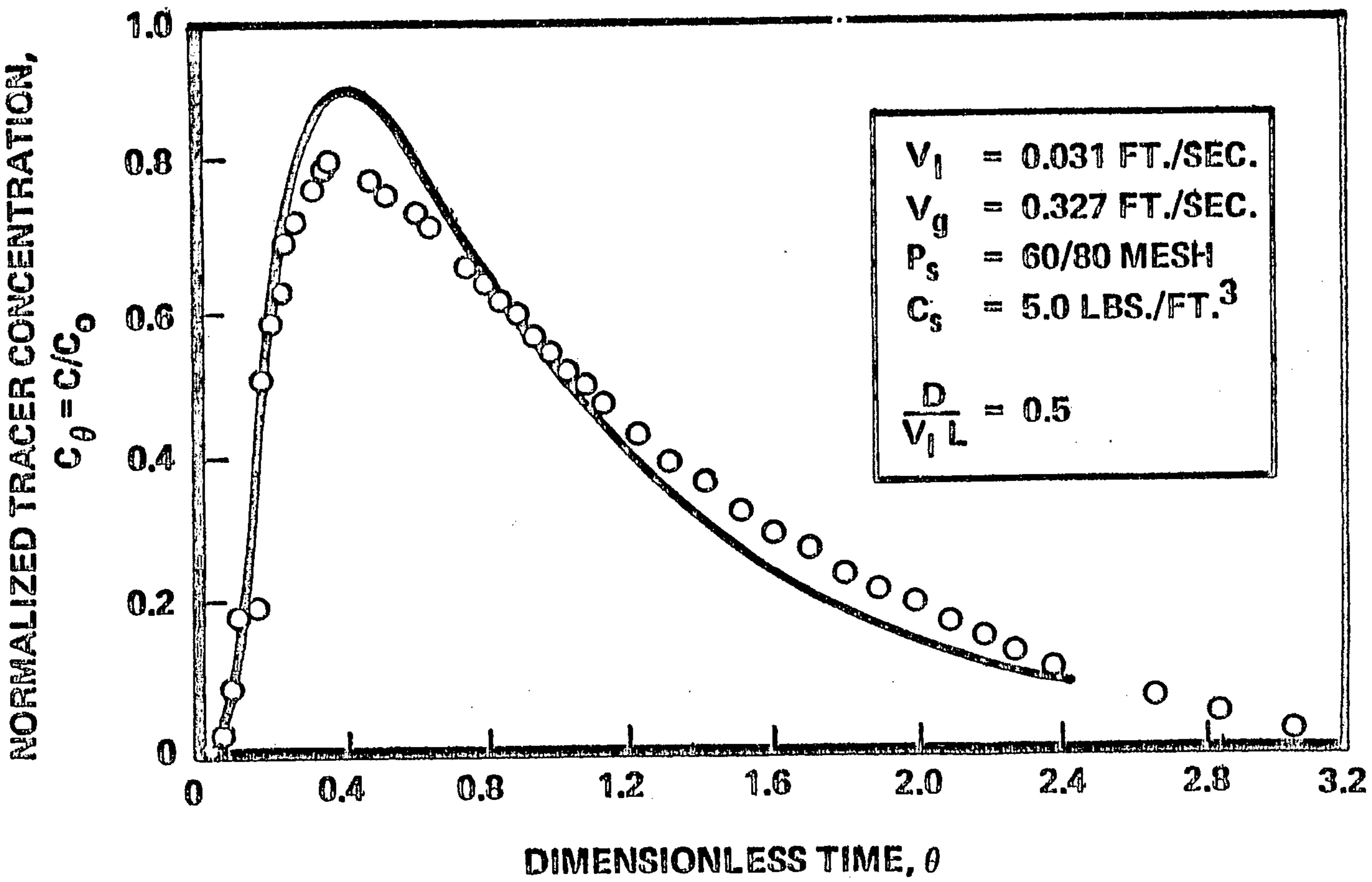

NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_0$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
DIMENSIONLESS TIME, θ
V_l = 0.031 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.5

FIGURE A-5

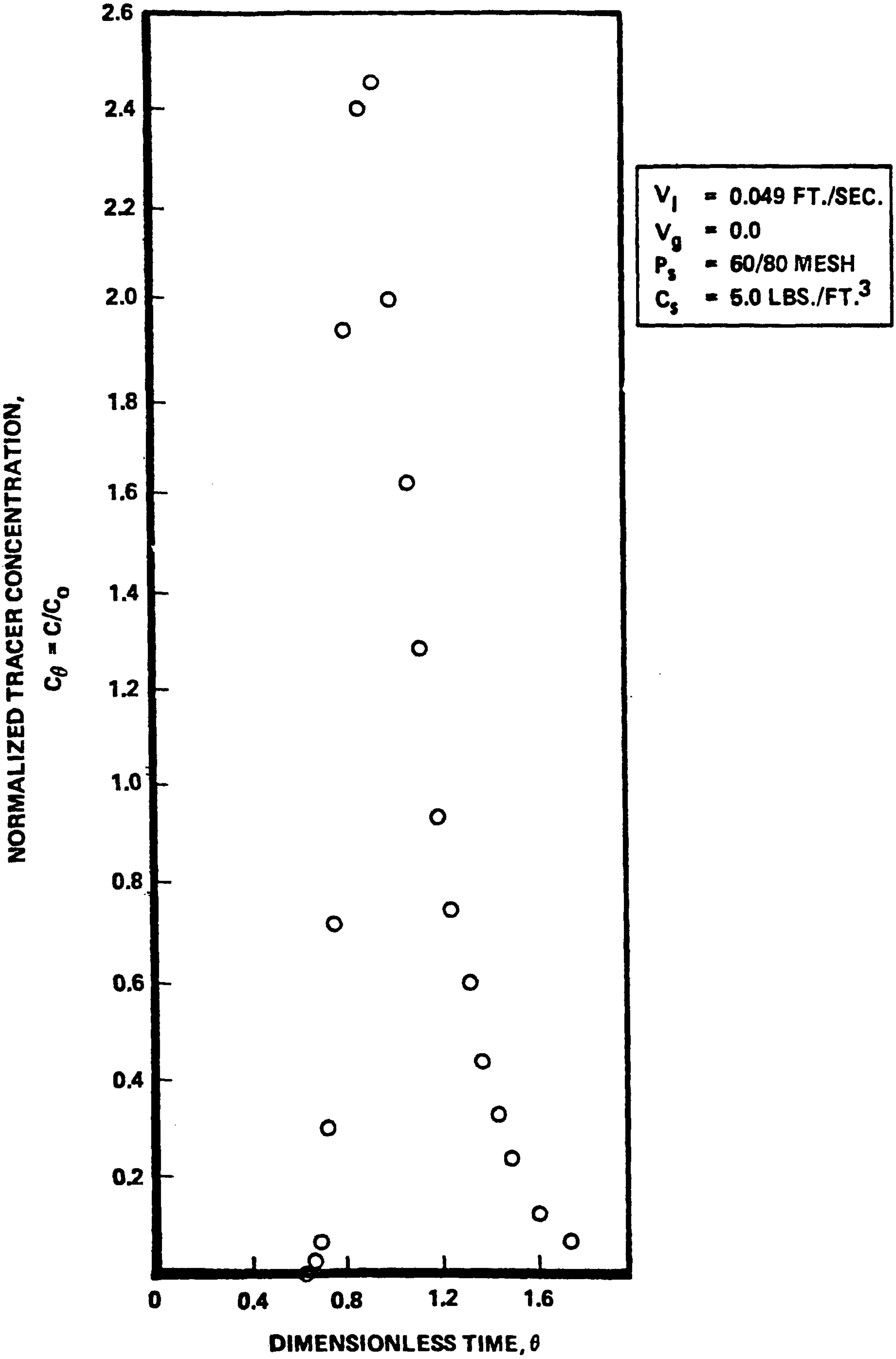

NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_0$
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0.4
0.8
1.2
1.6
DIMENSIONLESS TIME, θ
V_l = 0.049 FT./SEC.
V_g = 0.0
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}

FIGURE A-6

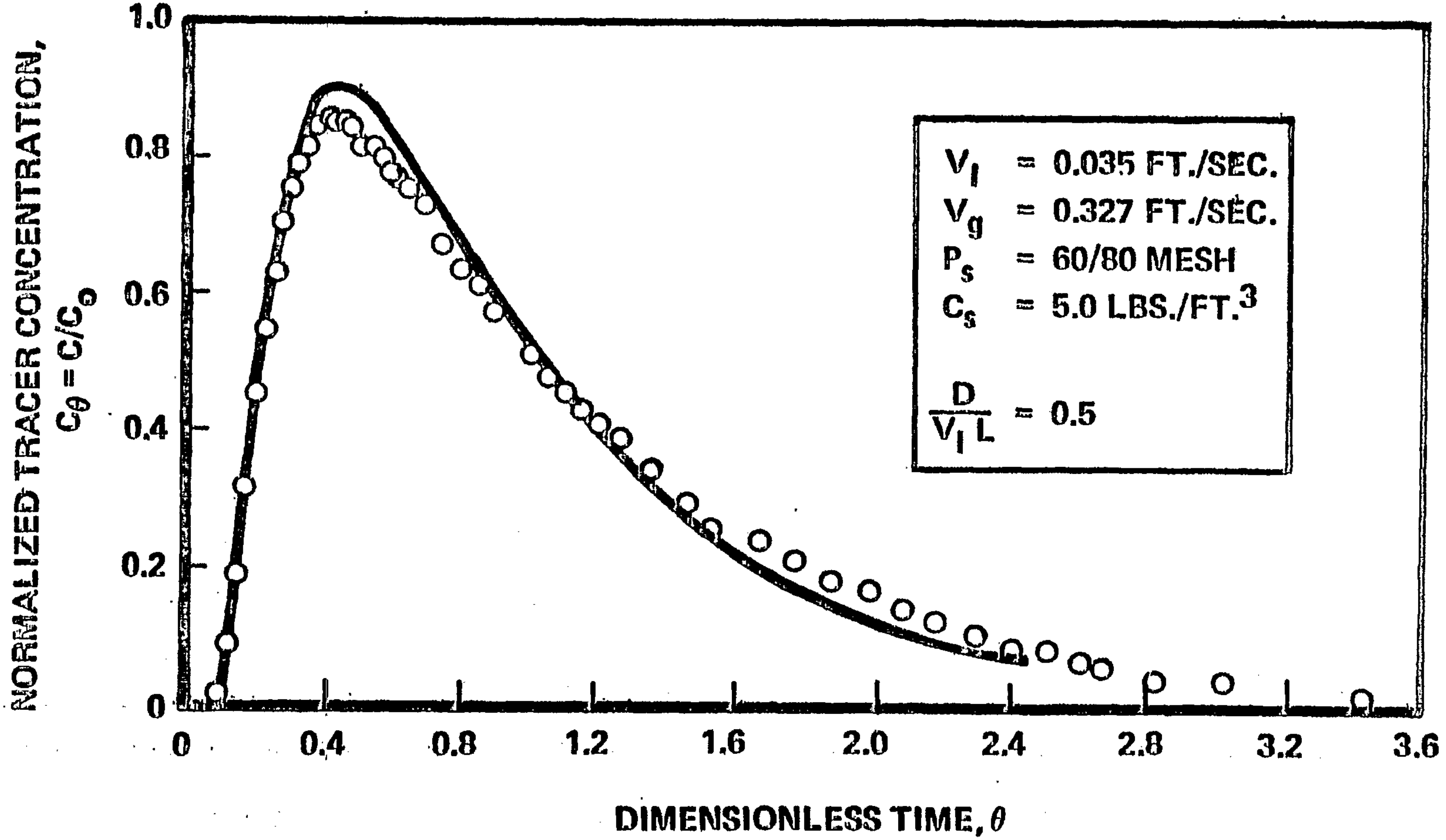
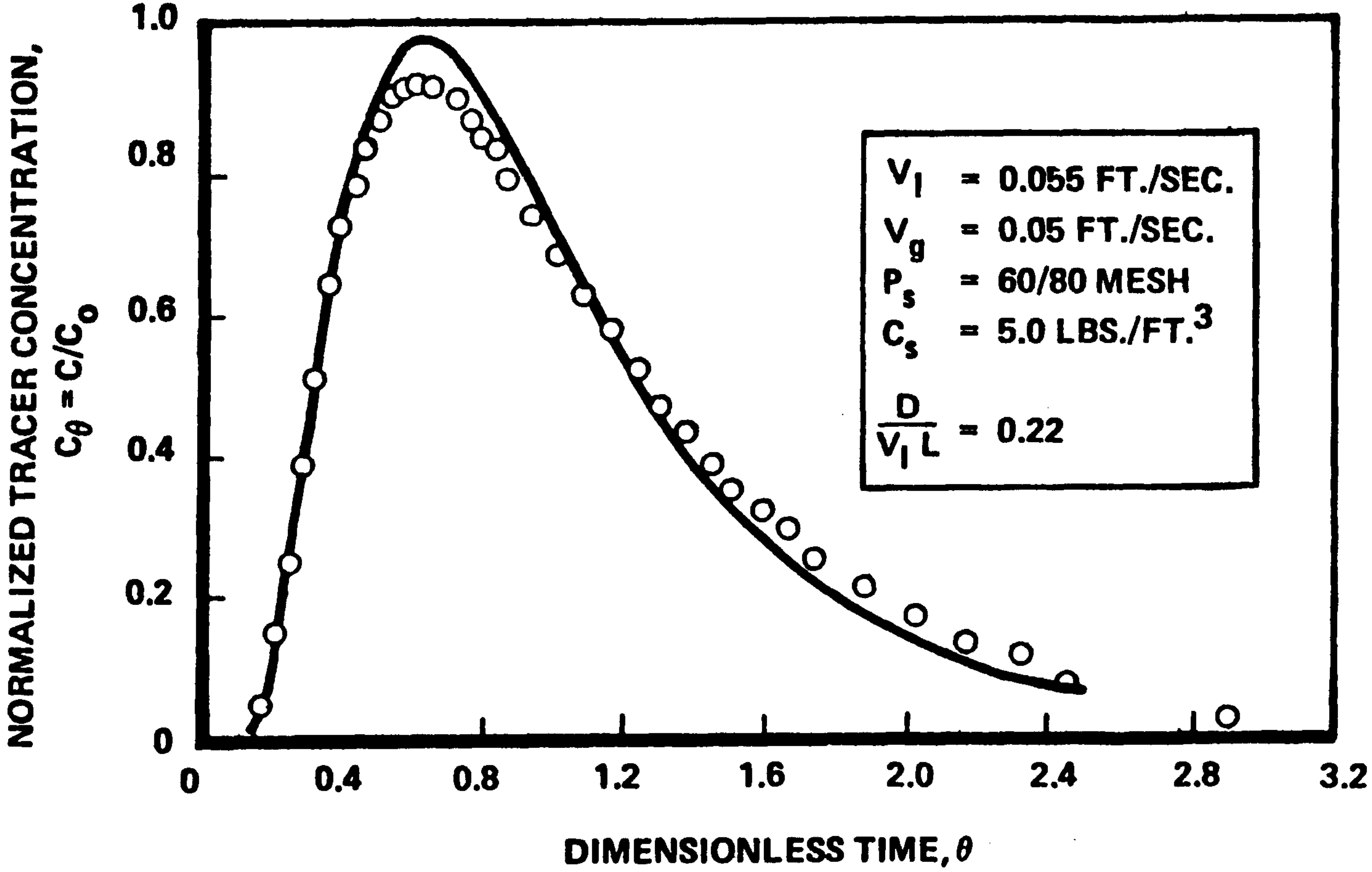

NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
DIMENSIONLESS TIME, θ
V_l = 0.035 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.5

FIGURE A-7



NORMALIZED TRACER CONCENTRATION, $C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
DIMENSIONLESS TIME, θ
V_l = 0.055 FT./SEC.
V_g = 0.05 FT./SEC.
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.22

FIGURE A-8

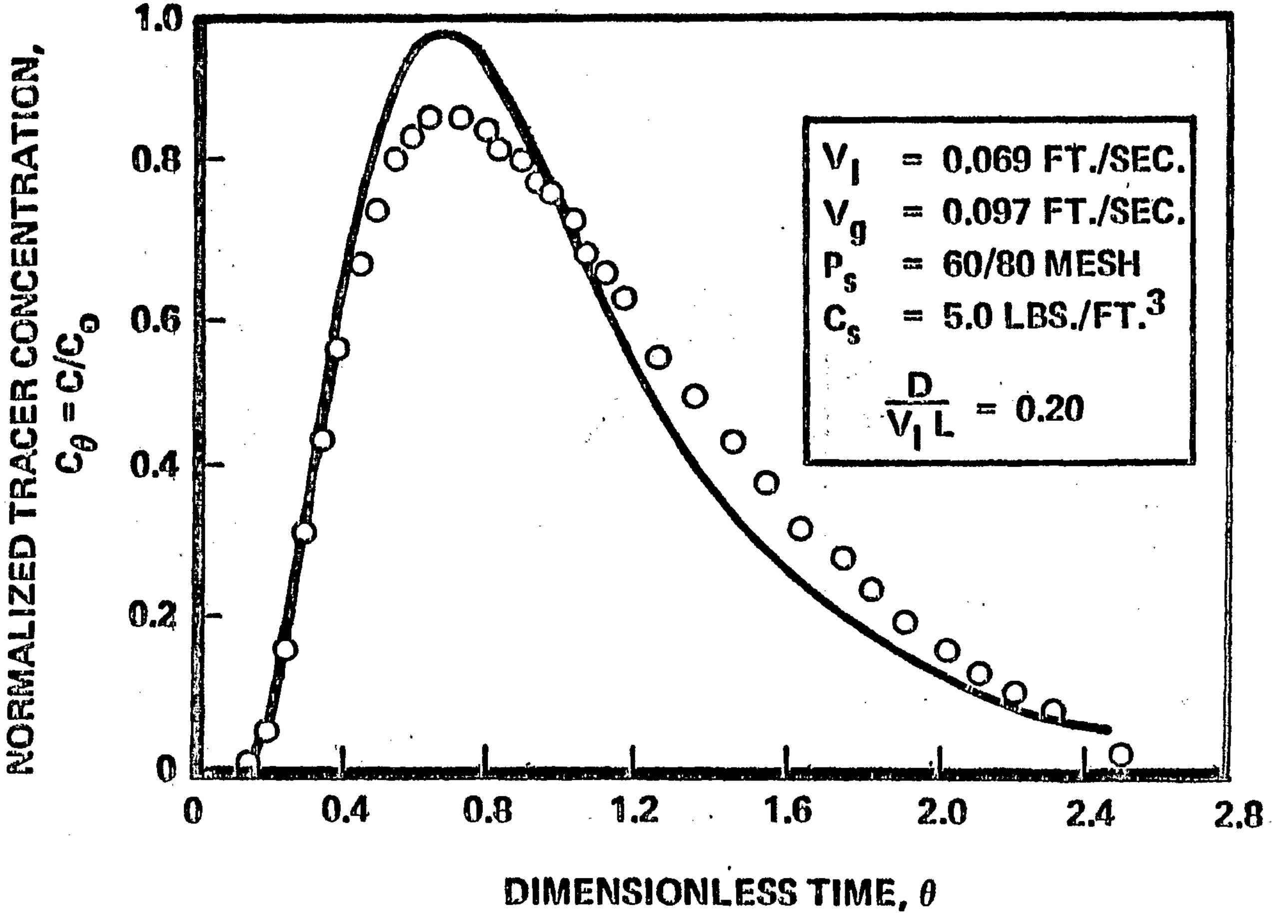

1.0
0.8
0.6
0.4
0.2
0
NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
DIMENSIONLESS TIME, θ
V_l = 0.069 FT./SEC.
V_g = 0.097 FT./SEC.
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.20

FIGURE A-9

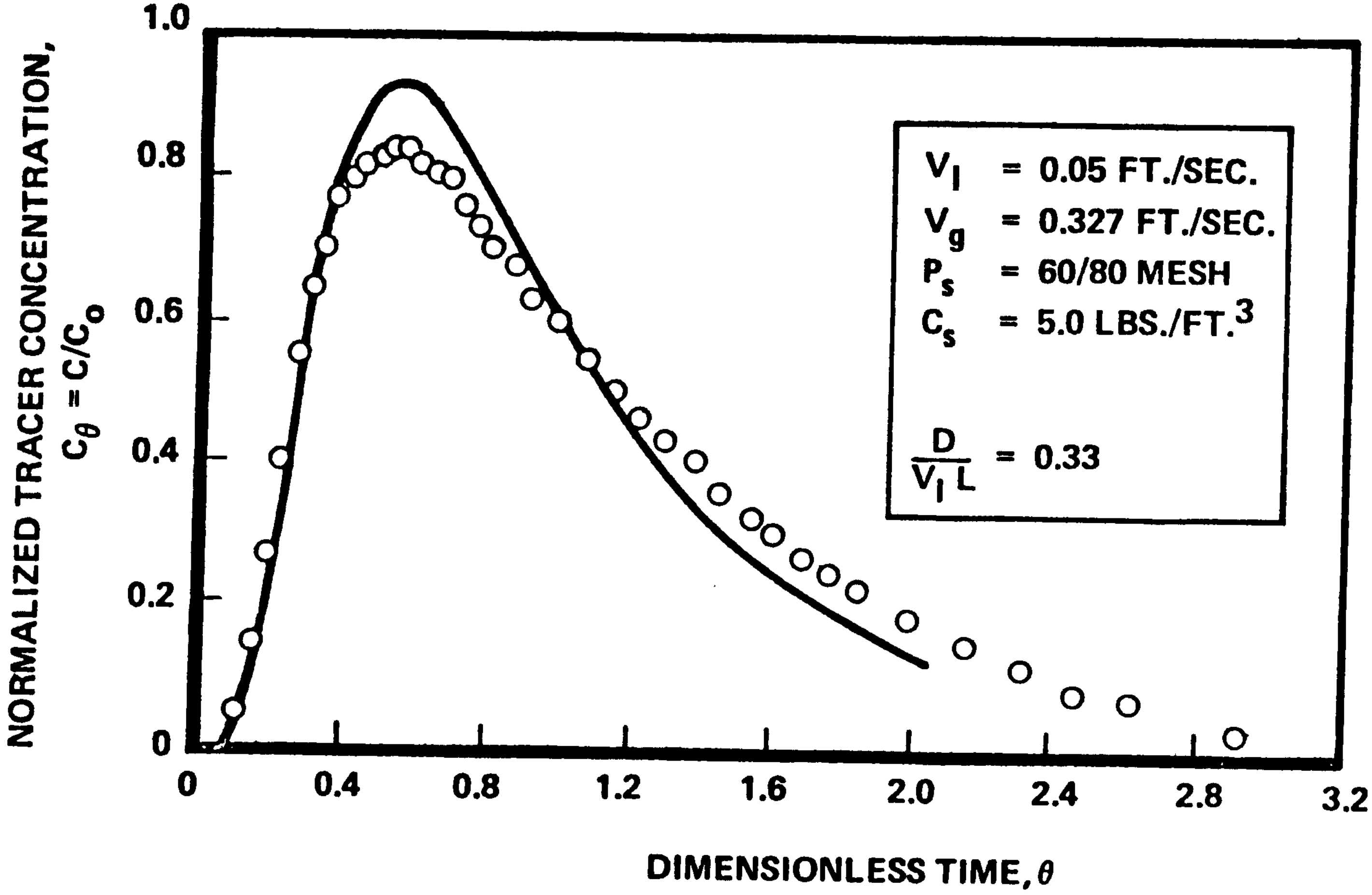

NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
DIMENSIONLESS TIME, θ
V_l = 0.05 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.33

FIGURE A-10

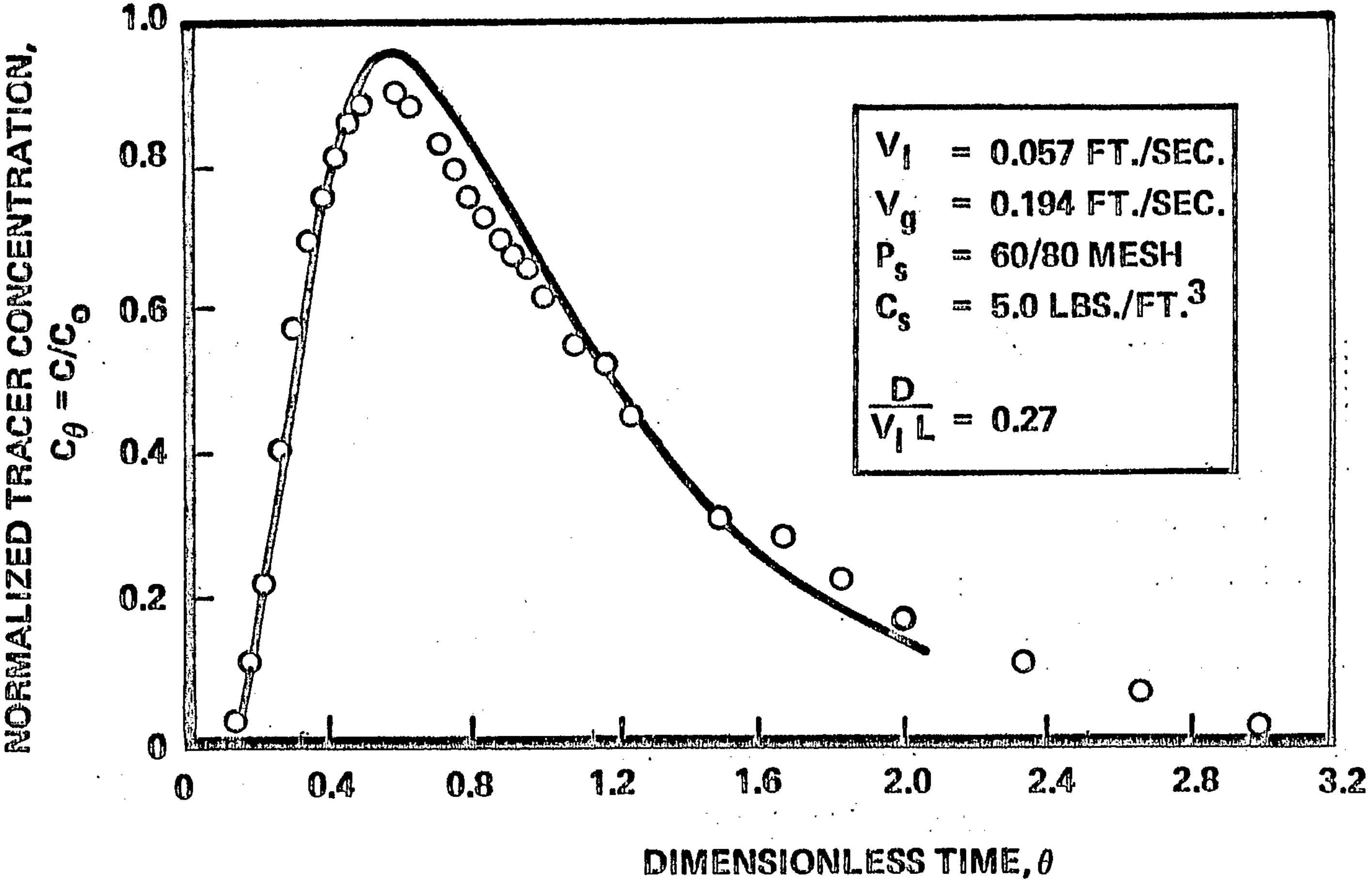

NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
DIMENSIONLESS TIME, θ
V_l = 0.057 FT./SEC.
V_g = 0.194 FT./SEC.
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.27

FIGURE A-11

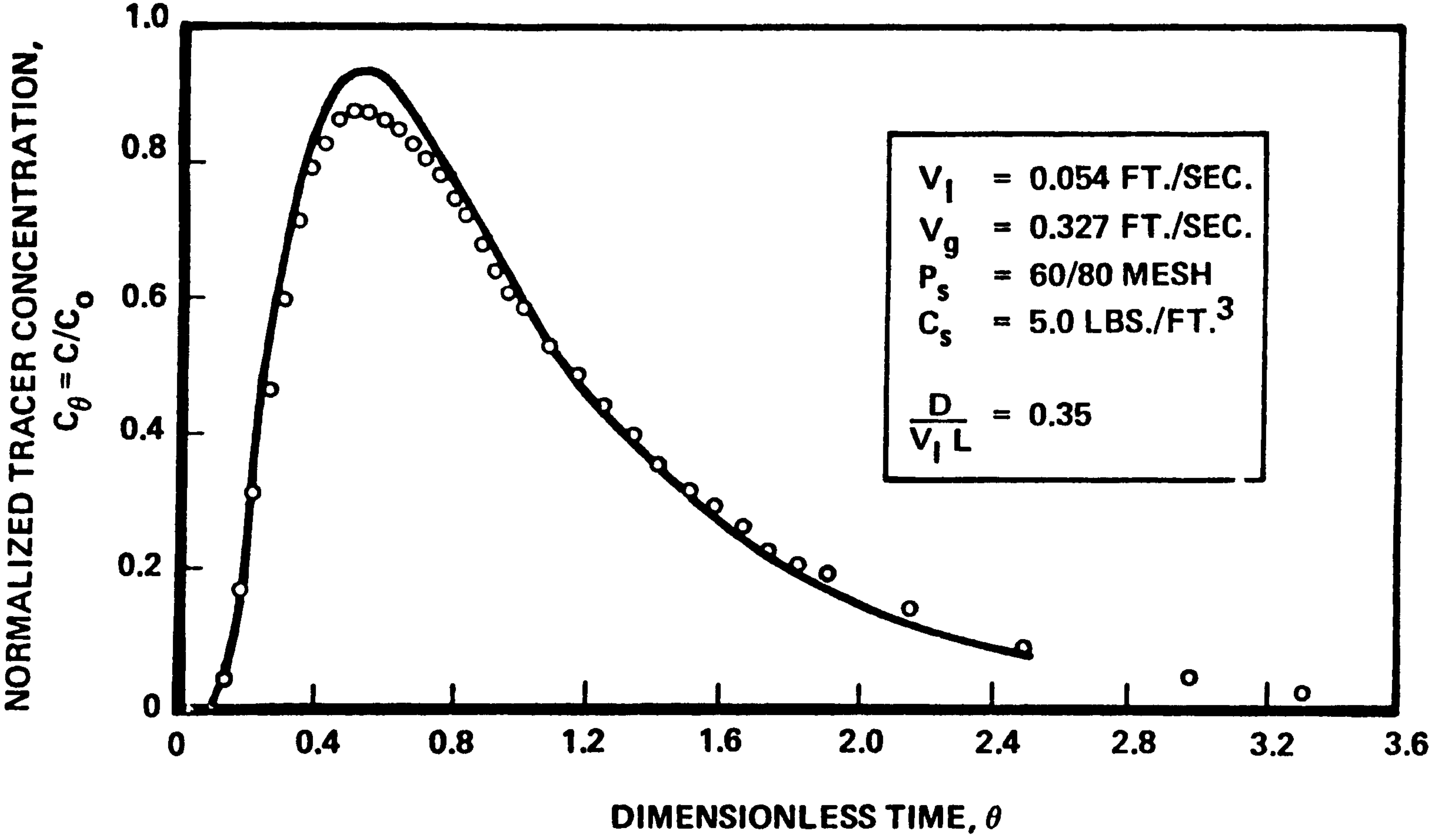

NORMALIZED TRACER CONCENTRATION, $C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
DIMENSIONLESS TIME, θ
V_l = 0.054 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = 60/80 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.35

FIGURE A-12

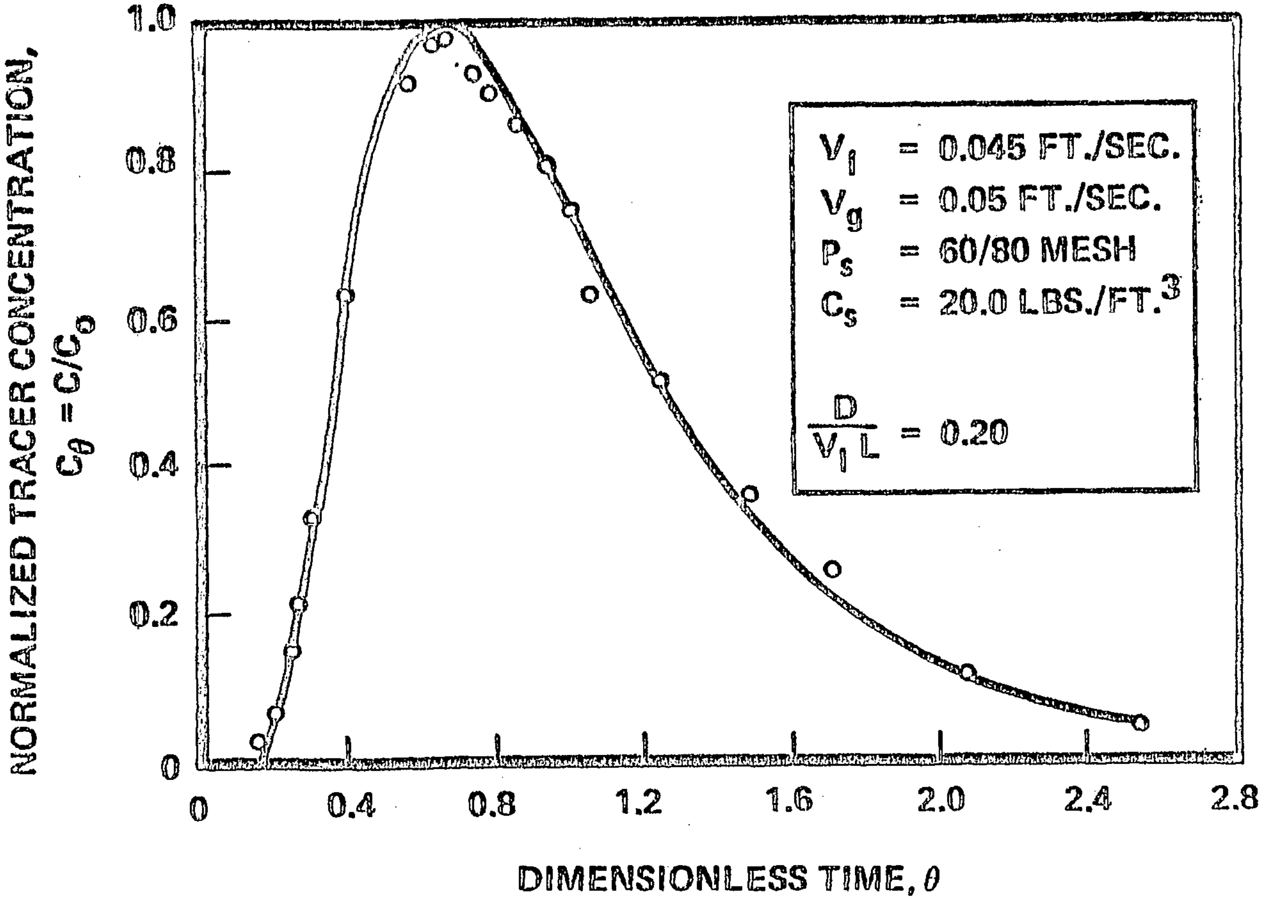

NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
DIMENSIONLESS TIME, θ
V_l = 0.045 FT./SEC.
V_g = 0.05 FT./SEC.
P_s = 60/80 MESH
C_s = 20.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.20

FIGURE A-13

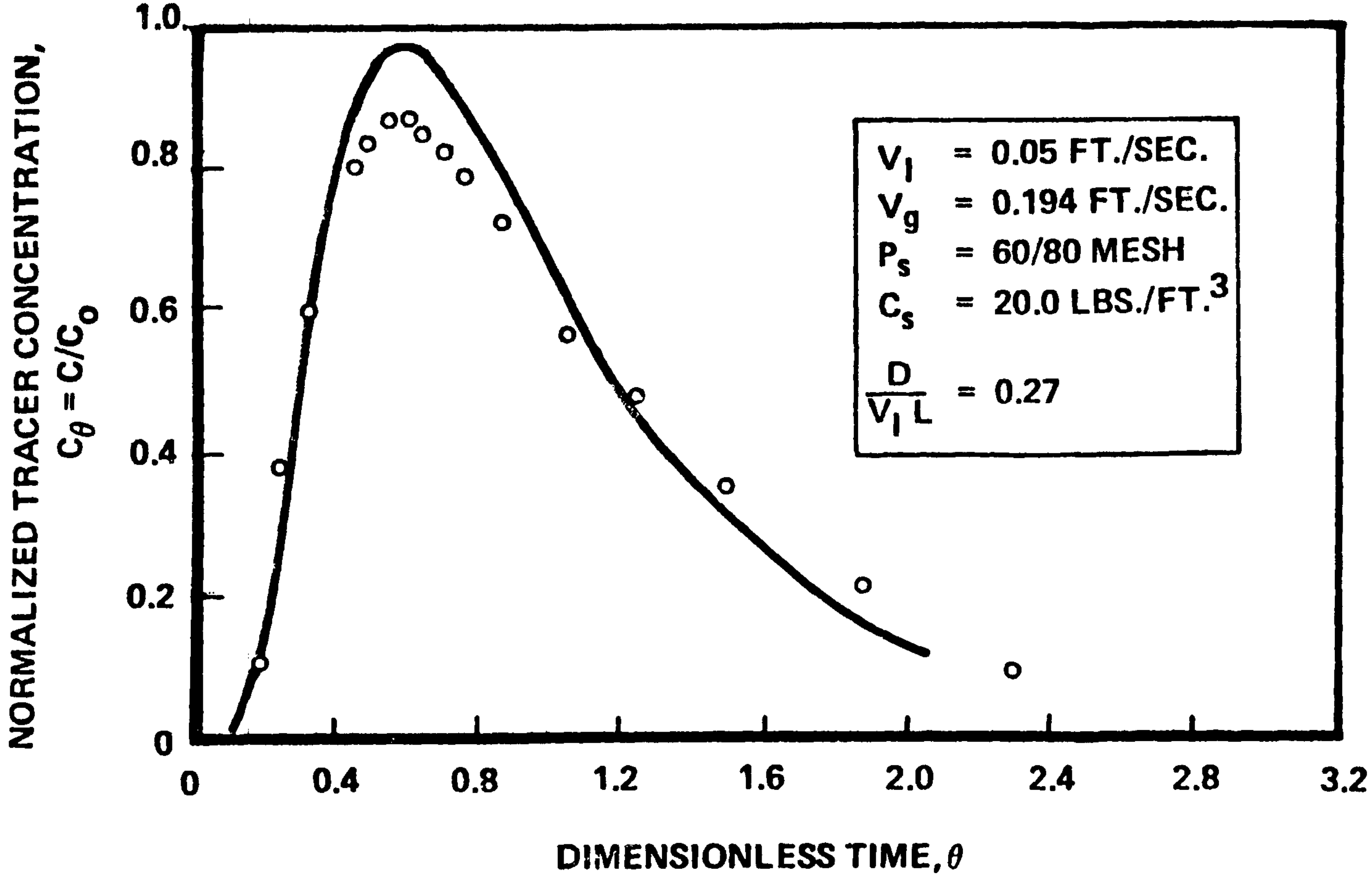
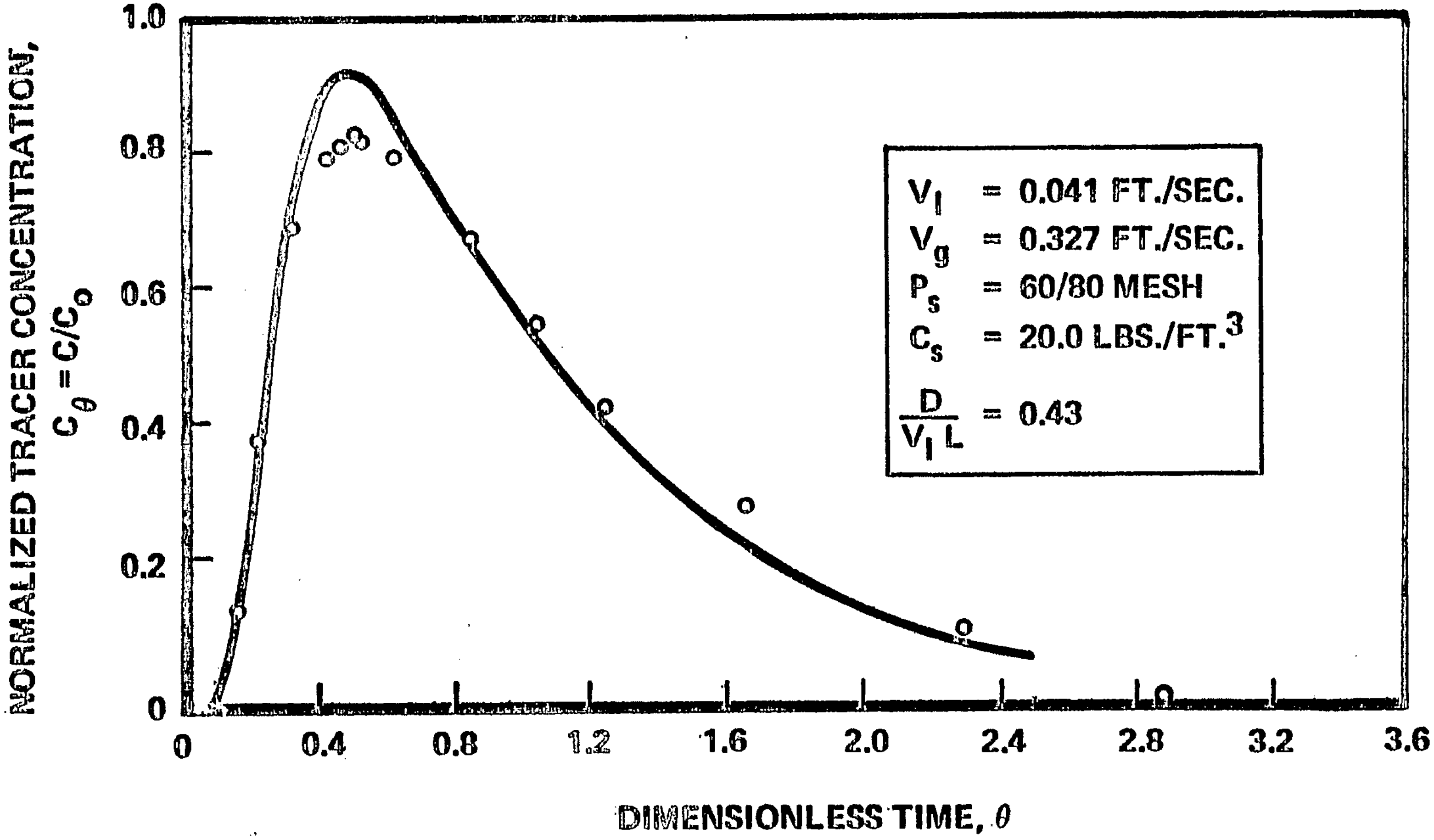

NORMALIZED TRACER CONCENTRATION, $C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
DIMENSIONLESS TIME, θ
V_l = 0.05 FT./SEC.
V_g = 0.194 FT./SEC.
P_s = 60/80 MESH
C_s = 20.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.27

FIGURE A-14



NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
DIMENSIONLESS TIME, θ
V_l = 0.041 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = 60/80 MESH
C_s = 20.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.43

FIGURE A-15

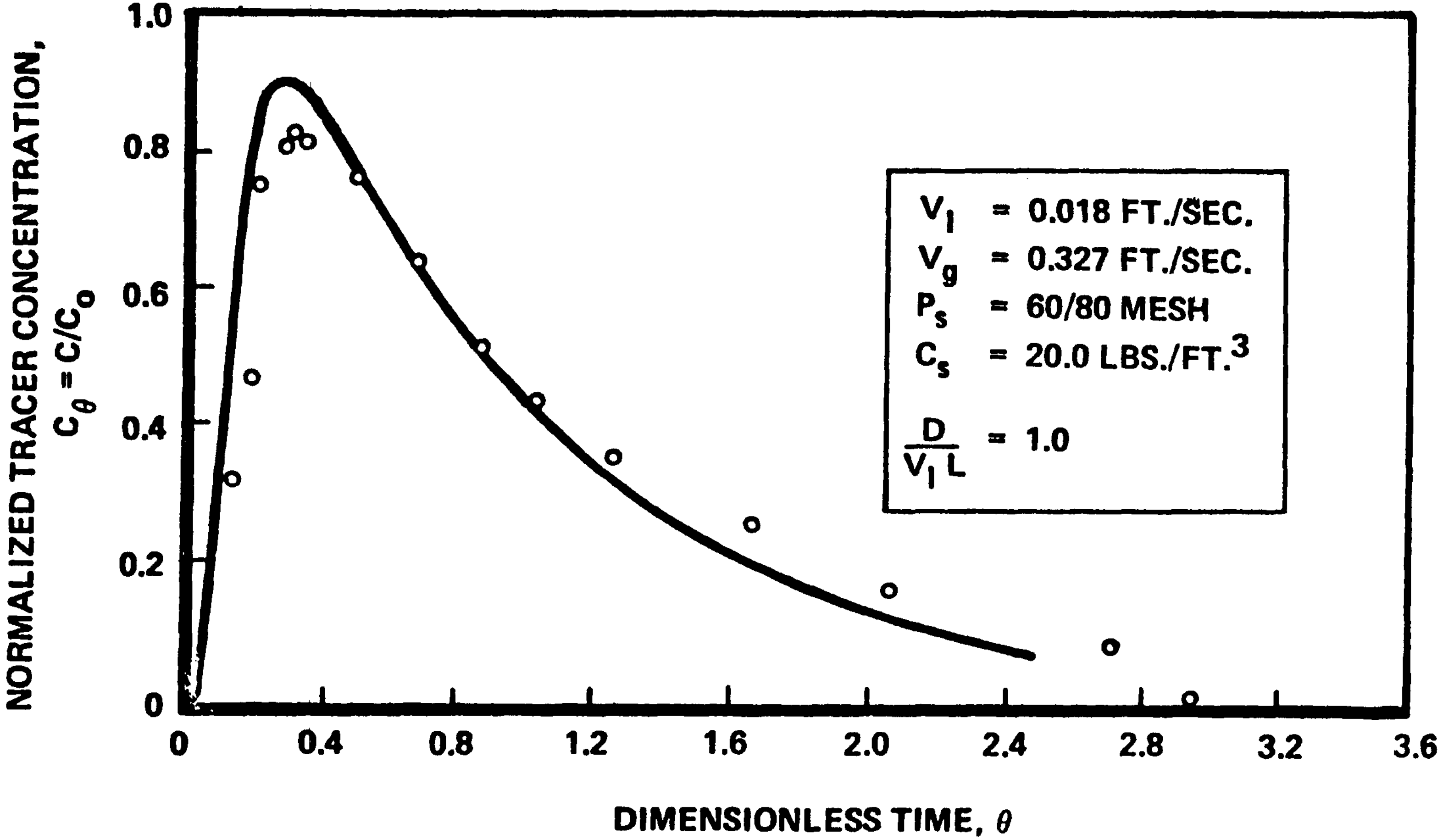
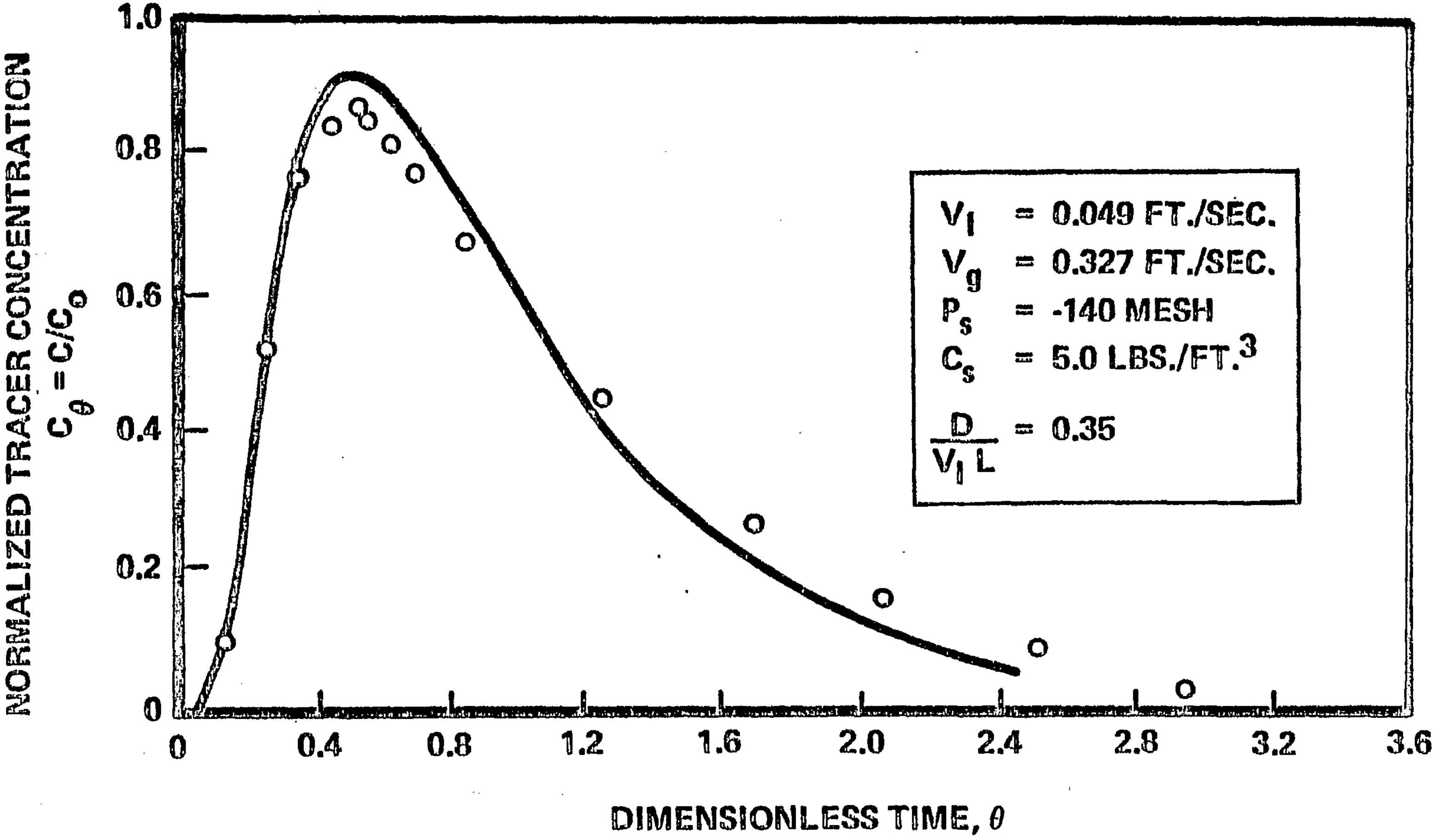

NORMALIZED TRACER CONCENTRATION,
$C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
DIMENSIONLESS TIME, θ
V_l = 0.018 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = 60/80 MESH
C_s = 20.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 1.0

FIGURE A-16


NORMALIZED TRACER CONCENTRATION
$C_\theta = C/C_o$
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
DIMENSIONLESS TIME, θ
V_l = 0.049 FT./SEC.
V_g = 0.327 FT./SEC.
P_s = -140 MESH
C_s = 5.0 LBS./FT.^{3}
$\frac{D}{V_l L}$ = 0.35

Appendix (B)

Solid Dispersion - Batch Experimental Data

(Tables B-1 through B-12)

Table B-1

Batch Experimental Data

Column Diameter = 5"
Particle Size = 60/70 Mesh
Type of Particle Used = Glass Beads
Type of Experiment = Batch
Solids Concentration = 7.4 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3				Height of Settled Solids, inches
	L = 0.327'	L = 1.473'	L = 2.577'	L = 3.66'	
0.05	2.49	0.73	0.32	0.18	1.8
0.10	5.91	2.73	0.67	0.18	1.3
0.15	11.39	4.04	1.13	0.50	0.0
0.20*	14.59	5.27	2.35	0.64	0.0
0.33*	16.93	6.99	2.12	1.03	0.0
0.43*	15.08	5.55	2.11	0.91	0.0

* Complete suspension

Table B-2

Batch Experimental Data

Column Diameter = 5"
Particle Size = 60/70 Mesh
Type of Particle Used = Glass Beads
Type of Experiment = Batch
Solids Concentration = 28.2 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3				Height of Settled Solids, inches
	L = 0.327'	L = 1.473'	L = 2.577'	L = 3.66'	
0.05	68.70	2.10	0.67	0.65	12.1
0.10	64.06	4.39	3.51	0.96	11.8
0.15	71.60	17.95	4.87	1.56	7.8
0.20	49.23	31.54	10.55	2.75	1.3
0.33*	51.32	34.99	13.63	4.08	0.0
0.43*	50.59	35.08	15.13	4.99	0.0

* Complete suspension

Table B-3

Batch Experimental Data

Column Diameter = 5"
Particle Size = 140/170 Mesh
Type of Particle Used = Glass Beads
Type of Experiment = Batch
Solids Concentration = 7.6 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3				Height of Settled Solids, inches
	L = 0.327'	L = 1.473'	L = 2.577'	L = 3.66'	
0.05	10.97	7.60	5.36	2.66	0.0
0.10*	9.79	7.72	4.98	3.63	0.0
0.15*	10.50	7.98	5.62	3.71	0.0
0.20*	10.09	7.76	5.55	3.83	0.0
0.33*	11.11	7.29	5.69	3.56	0.0
0.43*	9.44	7.79	5.66	3.79	0.0

* Complete suspension

Table B-4

Batch Experimental Data

Column Diameter = 5"

Particle Size = 140/170 Mesh

Type of Particle Used = Glass Beads

Type of Experiment = Batch

Solids Concentration = 28.6 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3				Height of Settled Solids, inches
	L = 0.327'	L = 1.473'	L = 2.577'	L = 3.66'	
0.05	34.59	28.63	20.46	16.03	1.3
0.10	34.75	29.46	23.53	19.01	0.0
0.15*	33.65	29.80	24.63	20.14	0.0
0.20*	34.23	30.05	25.54	20.24	0.0
0.33*	33.65	30.18	25.13	19.64	0.0
0.43*	33.69	28.93	25.67	20.30	0.0

* Complete suspension

Table B-5

Batch Experimental Data

Column Diameter = 5"
Particle Size = 60/70 Mesh
Type of Particle Used = Sand
Type of Experiment = Batch
Solids Concentration = 7.6 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3				Height of Settled Solids, inches
	L = 0.327'	L = 1.473'	L = 2.577'	L = 3.66'	
0.05	0.61	0.67	0.57	0.25	2.8
0.10	2.61	1.47	0.82	0.40	2.3
0.15	3.05	2.00	1.00	0.51	1.3
0.20	--	5.17	2.42	0.99	0.0
0.27*	15.43	8.21	3.16	1.45	0.0
0.33*	15.10	7.04	2.91	1.75	0.0
0.43*	15.66	7.33	3.24	1.38	0.0

* Complete suspension

Table B-6

Batch Experimental Data

Column Diameter = 5"
Particle Size = 60/70 Mesh
Type of Particle Used = Sand
Type of Experiment = Batch
Solids Concentration = 29.4 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3				Height of Settled Solids, inches
	L = 0.327'	L = 1.473'	L = 2.577'	L = 3.66'	
0.05	47.77	1.16	0.82	0.54	11.8
0.10	51.37	1.61	1.25	0.66	11.3
0.15	56.65	1.61	1.66	0.94	10.3
0.20	57.93	4.23	2.52	0.75	9.8
0.28	54.57	8.84	3.29	1.45	9.8
0.33	57.59	12.84	4.00	1.51	9.3
0.43	56.42	11.57	4.90	1.46	7.3

Table B-7

Batch Experimental Data

Column Diameter = 5"
Particle Size = -140 Mesh
Type of Particle Used = Silica
Type of Experiment = Batch
Solids Concentration = 7.6 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3				Height of Settled Solids, inches
	L = 0.327'	L = 1.473'	L = 2.577'	L = 3.66'	
0.05	3.12	3.30	3.39	3.35	1.0
0.10*	8.45	8.19	7.83	7.71	0.0
0.15*	6.94	7.73	7.70	7.50	0.0
0.20*	8.39	8.34	7.97	7.16	0.0
0.28*	7.26	8.17	8.43	6.38	0.0
0.33*	8.36	7.34	6.91	7.28	0.0
0.43*	8.35	7.99	7.41	6.53	0.0

* Complete suspension

Table B-8

Batch Experimental Data

Column Diameter = 5"

Particle Size = -140 Mesh

Type of Particle Used = Silica

Type of Experiment = Batch

Solids Concentration = 29.4 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3				Height of Settled Solids, inches
	L = 0.327'	L = 1.473'	L = 2.577'	L = 3.66'	
0.05	--	13.88	13.87	13.84	8.3
0.10	29.50	29.44	29.02	28.25	1.3
0.15*	29.21	29.14	27.59	28.24	0.0
0.20*	29.77	29.32	28.83	28.25	0.0
0.28*	29.60	29.68	29.25	28.70	0.0
0.33*	30.16	29.17	28.39	28.32	0.0
0.43*	32.11	29.15	31.90	31.75	0.0

* Complete suspension

Table B-9

Batch Experimental Data

Column Diameter = 12"
Particle Size = 60/80 Mesh
Type of Particle Used = Sand
Type of Experiment = Batch
Solids Concentration = 6.2 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3						Height of Settled Solids, inches
	L = 0.0'	L = 5.00'	L = 10.05'	L = 15.09'	L = 20.13'	L = 25.17'	
0.05	63.97	1.14	0.55	0.32	0.18	--	15.0
0.10	71.60	2.10	0.72	0.39	0.24	0.18	13.5
0.15	65.50	3.25	1.18	0.50	0.23	0.13	11.0
0.19	68.14	3.83	1.40	0.55	0.28	0.11	8.5
0.24	71.11	4.16	1.89	0.62	0.29	0.12	8.0
0.28	44.75	8.79	2.96	0.80	0.43	0.18	2.5
0.33	40.05	9.25	2.19	0.76	0.43	0.11	2.0
0.37*	48.62	10.35	0.89	0.50	--	0.27	0.0

* Complete suspension

Table B-10

Batch Experimental Data

Column Diameter = 12"
Particle Size = 60/80 Mesh
Type of Particle Used = Sand
Type of Experiment = Batch
Solids Concentration = 25.2 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3						Height of Settled Solids, inches
	L = 0.0'	L = 5.00'	L = 10.05'	L = 15.09'	L = 20.13'	L = 25.17'	
0.05		49.63	2.75	1.35	0.91	0.65	75.0
0.10		9.65	5.13	2.34	1.13	0.68	60.3
0.15		31.84	6.70	2.89	1.30	0.72	60.3
0.19		34.60	11.55	4.07	1.91	0.77	50.8
0.24		33.77	11.87	4.94	2.20	1.05	35.9
0.28		35.10	17.31	7.43	3.61	2.06	34.4
0.33		37.47	18.99	8.09	3.75	2.73	26.3
0.37		35.59	22.00	8.63	4.29	3.03	17.5

Table B-11

Batch Experimental Data

Column Diameter = 12"
Particle Size = -140 Mesh
Type of Particle Used = Silica
Type of Experiment = Batch
Solids Concentration = 6.2 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3						Height of Settled Solids, inches
	L = 0.0'	L = 5.00'	L = 10.05'	L = 15.09'	L = 20.13'	L = 25.17'	
0.05	57.83	4.11	3.86	4.00	3.75	3.81	9.0
0.10	7.19	5.73	5.40	4.44	4.85	4.69	7.5
0.15*	8.45	6.65	5.99	5.51	5.22	5.30	0.0
0.19*	8.36	6.73	6.17	5.85	6.11	4.96	0.0
0.24*	8.52	6.99	6.29	5.72	5.56	5.05	0.0
0.28*	8.36	6.99	6.46	5.77	6.10	5.23	0.0
0.33*	8.34	7.12	6.14	5.95	6.22	4.94	0.0
0.37*	8.32	6.80	6.35	5.68	6.43	5.25	0.0
0.43*	9.03	6.99	6.26	5.80	5.33	5.15	0.0

* Complete suspension

Table B-12

Batch Experimental Data

Column Diameter = 12"
Particle Size = -140 Mesh
Type of Particle Used = Silica
Type of Experiment = Batch
Solids Concentration = 25.2 lbs/ft^3

Gas Velocity ft/sec	Solids Concentration, lbs/ft^3						Height of Settled Solids, inches
	L = 0.0'	L = 5.00'	L = 10.05'	L = 15.09'	L = 20.13'	L = 25.17'	
0.05		9.97	8.07	7.77	7.75	7.88	61.0
0.10		13.38	12.73	12.27	12.04	11.82	53.0
0.15		26.23	25.59	24.98	24.36	23.07	9.0
0.19*	27.58	26.33	25.50	24.51	24.77	23.97	0.0
0.24*	28.63	26.79	26.06	25.57	24.87	23.24	0.0
0.28*	27.14	26.36	25.62	25.09	24.76	23.89	0.0
0.33*	27.62	26.71	25.97	24.62	24.59	23.76	0.0
0.37*	27.79	26.58	25.07	24.52	24.32	23.77	0.0
0.43*	27.67	26.88	26.93	25.21	25.02	23.54	0.0

* Complete suspension

Appendix (C)

Corrections for Misprint in First Quarterly Report

TABLE (16)

CORRELATIONS FOR PREDICTING AXIAL DISPERSION COEFFICIENTS

Kato and Nishiwaki(4)

$$E_{ZL} = \frac{V_G D \left(1 + 6.5\ Fr_G^{0.8}\right)}{13\ Fr_G}$$

Towel and Ackerman(28)

$$E_{ZL} = 1.23\ D^{1.5}\ V_G^{0.5}$$

Cova(2)

$$E_{ZL} = 0.0759\ V_G^{0.32}\ \rho_L^{0.07}$$

Deckwer, et al(1)

$$E_{ZL} = 0.678\ D^{1.4}\ V_G^{0.3}$$

Hikita and Kikukawa(3)

$$E_{ZL} = (0.366 + 0.674\ V_G^{0.77})\ D^{1.25}\ (1/\mu_L)^{0.12}$$

Baird and Rice(6)

$$E_{ZL} = 0.35\ D^{4/3}\ (V_G g)^{1/3}$$

Ying(49)

$$E_{ZL} = 0.27\ D\ V_G \left(\frac{Dg}{V_G^2}\right)^{0.32}$$

Where Fr_G = Froude Number = $\sqrt{V_G^2/gD}$

E_{ZL} = axial dispersion coefficient, (ft^2/sec)

V_G = gas superficial velocity (ft/sec)

D = column diameter (ft)

ρ_L = liquid density (gm/cm^3)

μ_L = viscosity of liquid (cp.)

g = acceleration of gravity (ft/sec^2)

TABLE (17)

Comparison of Axial Dispersion Coefficients in Liquid Phase for the 5" Column

	Predicted Axial Dispersion Coefficient (ft^2/sec)						Experimental Axial Dispersion Coefficient (ft^2/sec)	
Gas Velocity (ft/sec)	Kato & Nishiwaki	Towel & Ackerman	Cova	Deckwer	Hikita & Kikukawa	Baird & Rice	C_S = Zero	C_S = 16 wt% P_S = 30/45 mesh
0.02	0.129	0.047	0.022	0.088	0.134	0.091	0.0663	0.0442
0.09	0.157	0.155	0.035	0.138	0.158	0.155	0.0909	0.0614
0.33	0.229	0.190	0.053	0.204	0.219	0.239	0.1842	0.0810

TABLE (18)

Comparison of Axial Dispersion Coefficients in Liquid Phase for the 12" Column

	Predicted Axial Dispersion Coefficient (ft^2/sec)							Experimental Axial Dispersion Coefficient (ft^2/sec)		
Gas Velocity (ft/sec)	Kato & Nishiwaki	Towel & Ackerman	Cova	Deckwer	Hikita & Kikukawa	Baird & Rice	Ying	C_S=ZERO	C_S=5 lb/ft^3	C_S=20 lb/ft^3
0.0500	0.4995	0.2750	0.0291	0.2760	0.4331	0.4096	0.2789	0.405	0.297	0.304
0.0970	0.5445	0.3831	0.0360	0.3367	0.4778	0.5097	0.3541	0.485	0.341	0.295
0.1940	0.6256	0.5418	0.0449	0.4145	0.5567	0.6407	0.4545	0.495	0.364	0.366
0.3270	0.7243	0.7034	0.0531	0.4848	0.6510	0.7611	0.5484	0.614	0.471	0.376

C_S = Solids Concentration

Particle Size = 20/30 Mesh

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