5.0 RESULTS AND DISCUSSION

5.1 Gas Holdup

Gas holdup as a function of several variables was measured in 5-in. and 12-in.-diameter columns using various liquid systems. The variables were: column diameter, liquid velocity, gas velocity, entrance effects, presence of solids, physical properties of the liquid phase. In addition, several correlations were tested to determine the best one that could predict the experimental data reasonably well for all the liquid systems tested.

Table 6 lists the operating conditions for the experimental runs. Sand was used in all experiments using the solid phase. The particle size varied from 20/30 mesh to -140 mesh, and the solid concentrations varied from 5 to 20 lb/ft^3. The liquid phases studied were water, tetralin, ethylene glycol, and mixtures of various concentrations of ethylene glycol and water. Three different distributor configurations (absence of a distributor, distributor #1 and distributor #2) and two different columns (5- and 12-in. in diameter) were used. Liquid velocity was varied between 0.0 and 0.05 ft/sec, and gas velocity was varied between 0.0 and 0.45 ft/sec.

The operating conditions encompass the operating conditions at the Wilsonville Pilot Plant and two possible configurations (series vs. parallel) being considered for the demonstration plant dissolvers. In addition to the experiments listed in Table 6, a photographic technique was used to determine the fraction of large bubbles present in the column and the effect of different distributors.

5.1.1 Effect of Column Diameter

For a given superficial gas velocity, gas holdup is shown independently of column diameter. Our earlier results using air/water systems clearly indicated that increasing the column diameter from 5 to 12 in. had no appreciable effect on gas holdup. Results obtained with

Table 6

Operating Conditions

Column diameter (In.)	System	Distributor[a] configuration	Range of: Gas velocities (ft/sec)	Liquid velocities (ft/sec)	Solids particle size (mesh)	Solids concentration (lb/ft^3)
12	Air/water	1	0.0-0.37	0.0-0.06	0	0
12	Air/water	1	0.0-0.37	0.0-0.08	-100	5
12	Air/water	1	0.0-0.37	0.0-0.05	-100	11
12	Air/water	1	0.0-0.37	0.0-0.05	20/30	5
12	Air/water	1	0.0-0.37	0.0-0.05	20/30	13
12	Air/water	0	0.0-0.43	0.0-0.05	0	0
12	Air/water	0	0.0-0.43	0.0-0.05	20/30	5
12	Air/water	0	0.0-0.43	0.0-0.04	-140	5
12	Air/water	2	0.0-0.43	0.0-0.05	0	0
12	Air/water	2	0.0-0.43	0.0-0.05	20/30	5-20
12	Air/water	2	0.0-0.43	0.0-0.05	-140	5
5	Nitrogen/tetralin	-	0.0-0.40	0	0	0
5	Air/glycol	-	0.0-0.40	0	0	0
5	Air/90% glycol-10% water	-	0.0-0.40	0	0	0
12	Nitrogen/tetralin	1	0.0-0.39	0	0	0
12	Nitrogen/tetralin	1	0.0-0.39	0.02-0.05	-140	5
12	Nitrogen/tetralin	1	0.0-0.39	0.02-0.05	60/80	5
12	Air/glycol	1	0.0-0.39	0	0	0
12	Air/90% glycol-10% water	1	0.0-0.39	0	0	0
12	Air/70% glycol-30% water	1	0.0-0.39	0	0	0
12	Air/50% glycol-50% water	1	0.0-0.39	0	0	0

[a] 1,Distributor #1; 2, Distributor #2; 0, absence of a distributor

tetralin (Figure 8) confirmed this. This finding also agrees with results of other investigators, who concluded that gas holdup is independent of column diameters above a diameter of 3 in. (25).

Most of the published gas holdup data were obtained from small diameter columns (6 inches or less). The effect of column diameter on gas holdup in viscous liquid has not been fully investigated by using large diameter columns. In this study, we found that gas holdup in ethylene glycol (20 cP) is higher in a 5-in. diameter column than in a 12-in. diameter column (Figure 9). It is speculated that the effect of column diameter on gas holdup for viscous materials may differ from that for systems of low viscosity, i.e. the minimum diameter above which column diameter has no effect on gas holdup may be larger for more viscous materials. We hypothesize that the larger gas holdup in the 5-in. column for ethylene glycol is due to wall effects. However, due to the limited data, we could not determine the above mentioned minimum diameter for ethylene glycol system.

5.1.2 Effect of Liquid Velocity

Gas holdup in a bubble column is independent of liquid velocity. This was confirmed for both air/water and nitrogen/tetralin systems and is true irrespective of the presence or absence of solids. Figures 10 and 11 plot typical data from the two different liquid systems used in this study. Data obtained with different distributor configurations also shows that gas holdup is independent of liquid velocity.

5.1.3 Effect of Gas Velocity

Gas holdup increases with an increase in superficial gas velocity, in all the systems studied (Figures 12 and 14). The figures clearly show that the dependence of gas holdup on linear gas velocities can

FIGURE 8
EFFECT OF COLUMN DIAMETER ON GAS HOLDUP
TETRALIN/NITROGEN

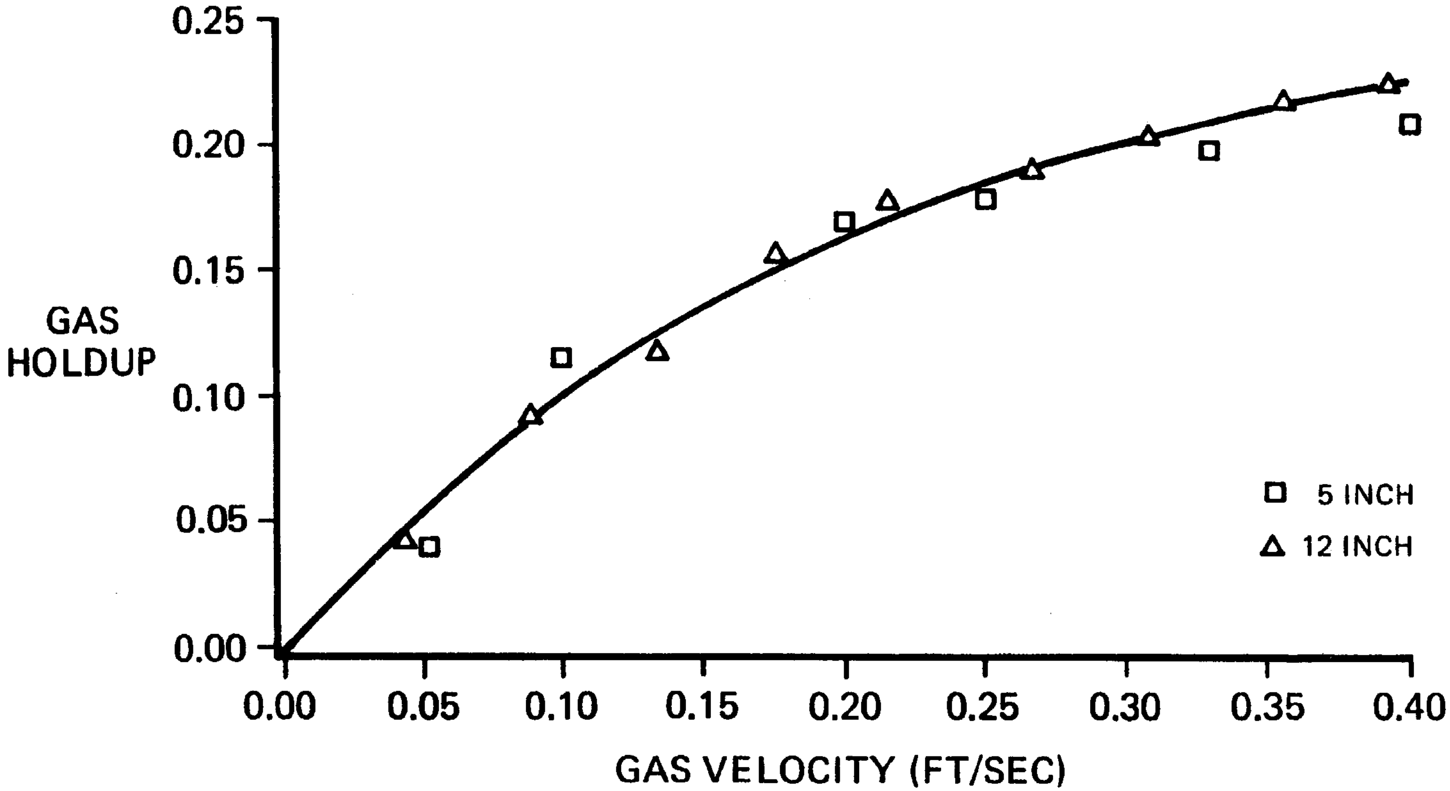


Figure 9

Effect of Column Diameter on Gas Holdup
(Air/Glycol)

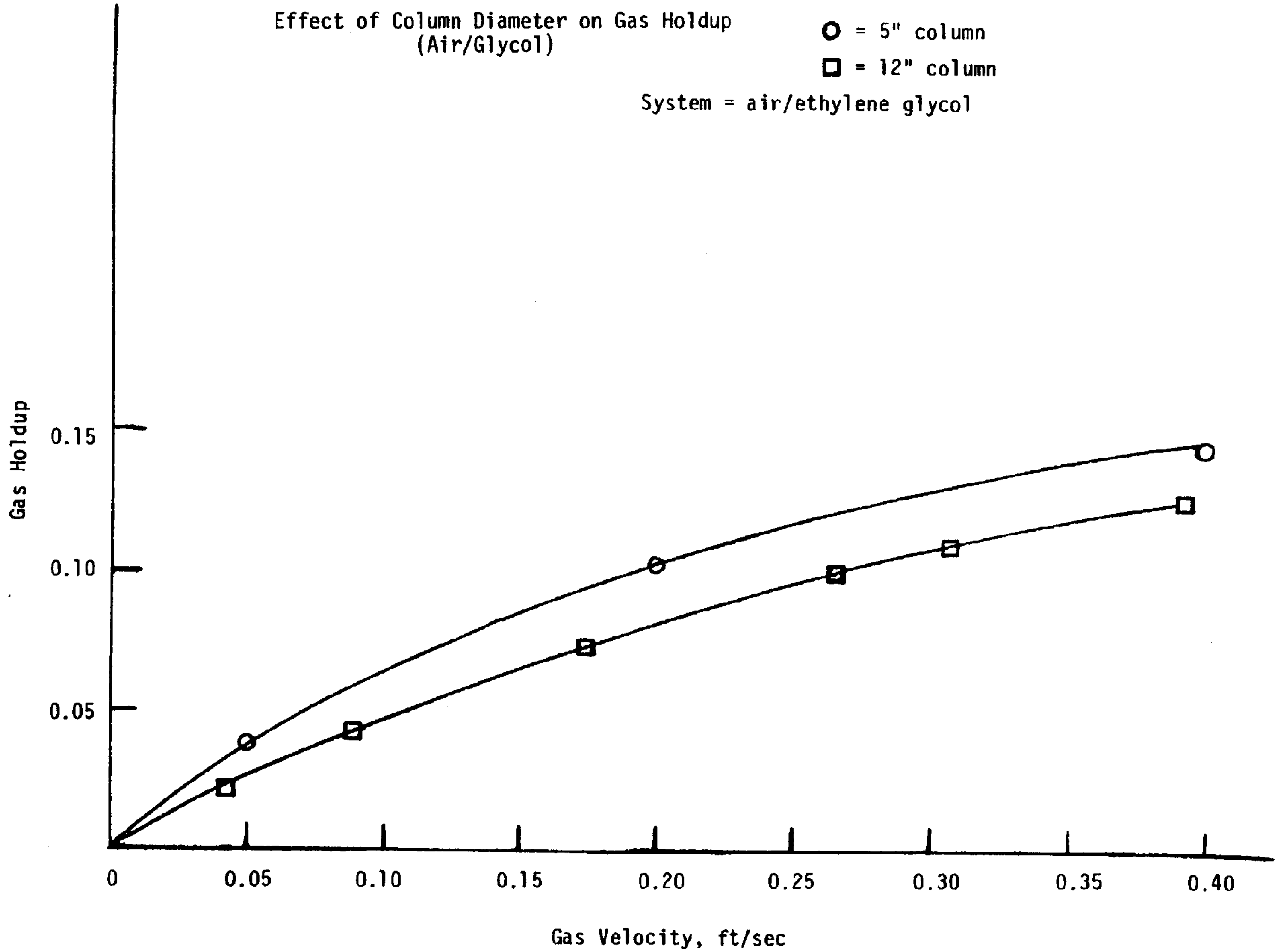
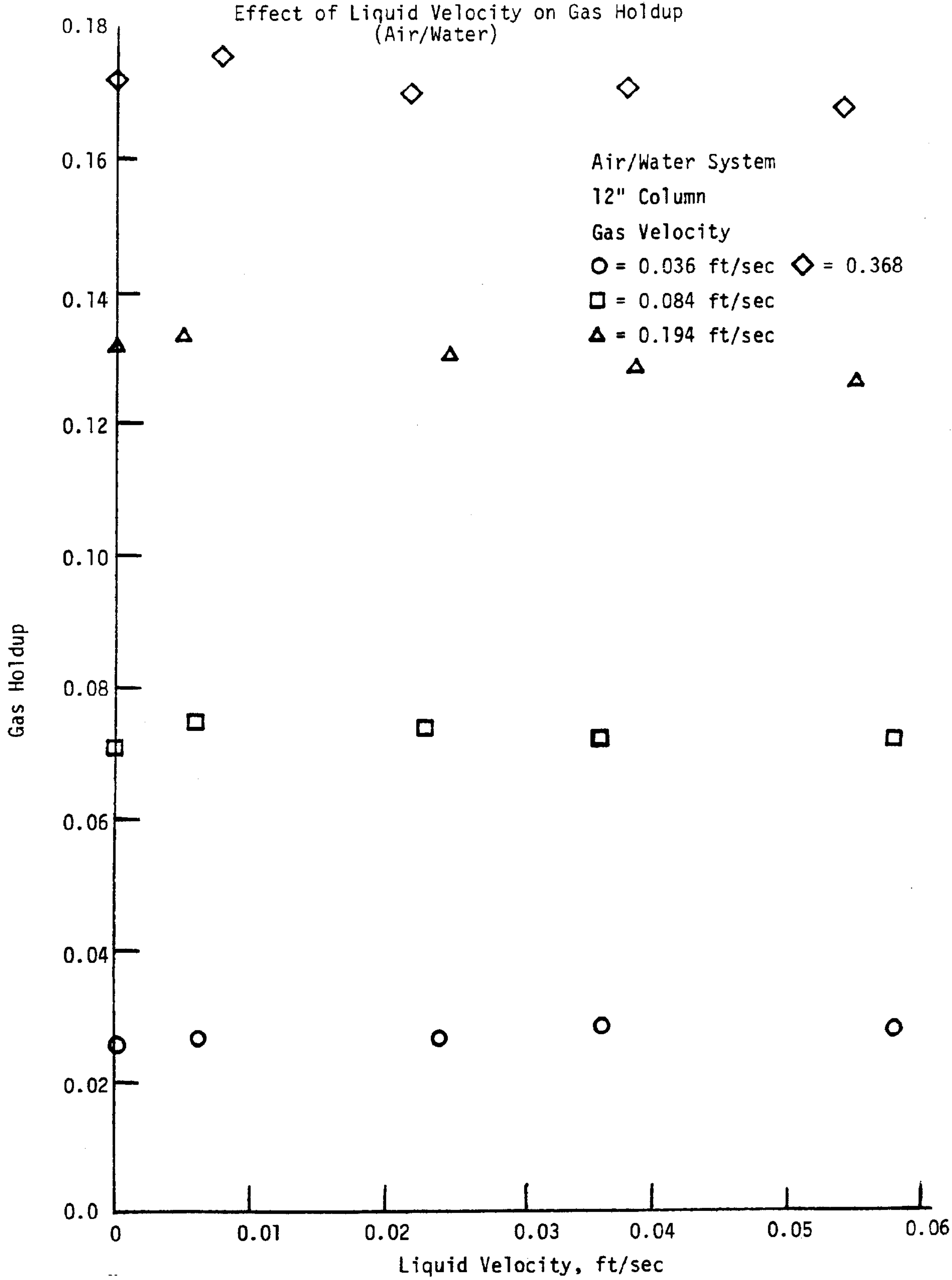


Figure 10

Effect of Liquid Velocity on Gas Holdup
(Air/Water)



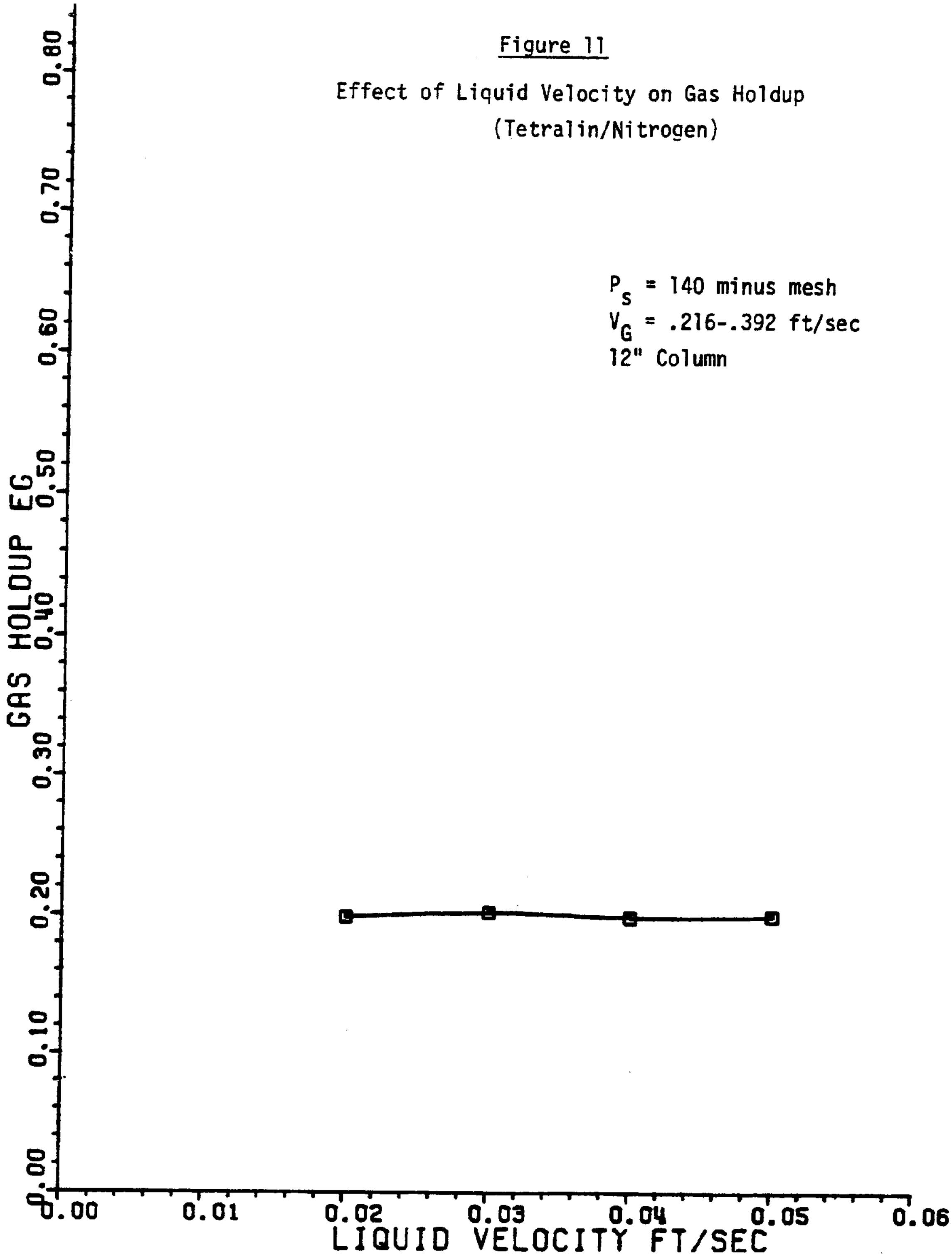


Figure 11
Effect of Liquid Velocity on Gas Holdup
(Tetralin/Nitrogen)
P_s = 140 minus mesh
V_G = .216-.392 ft/sec
12" Column
GAS HOLDUP EG
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.00
0.01
0.02
0.03
0.04
0.05
0.06
LIQUID VELOCITY FT/SEC

Figure 12

Effect of Gas Velocity on Gas Holdup
(Air/Water)

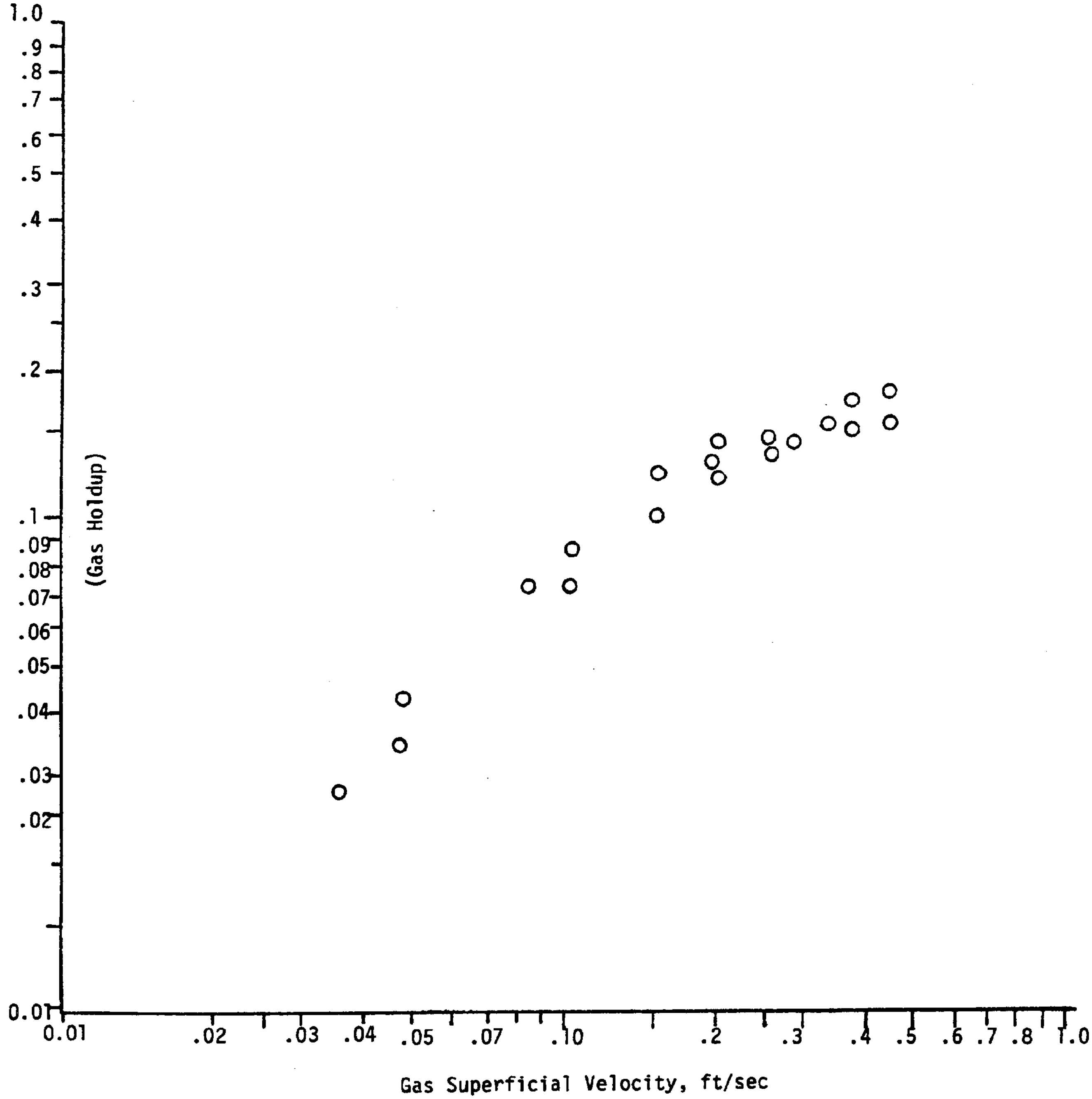


Figure 13

Effect of Gas Velocity on Gas Holdup
(Tetralin/Nitrogen)

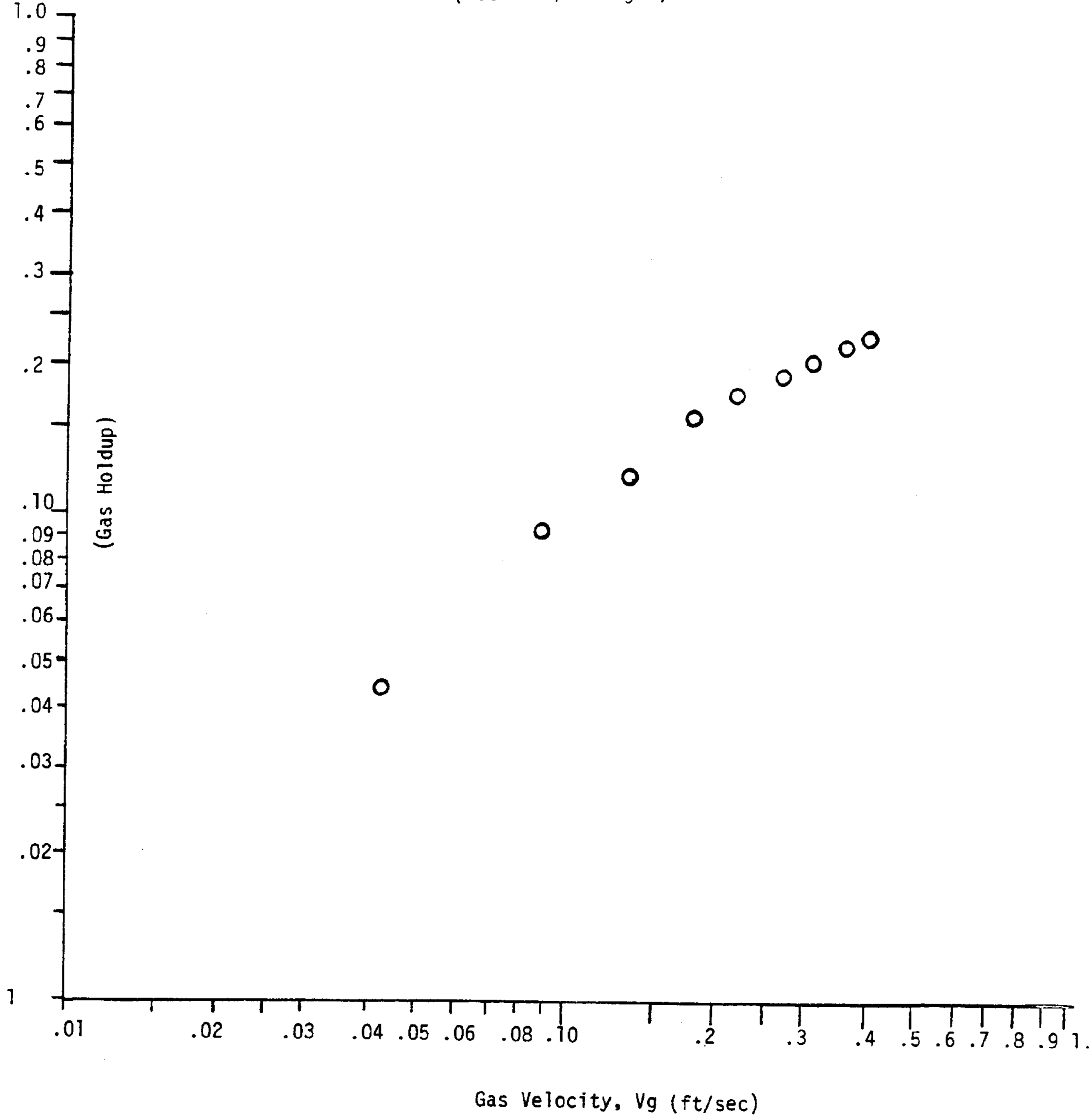
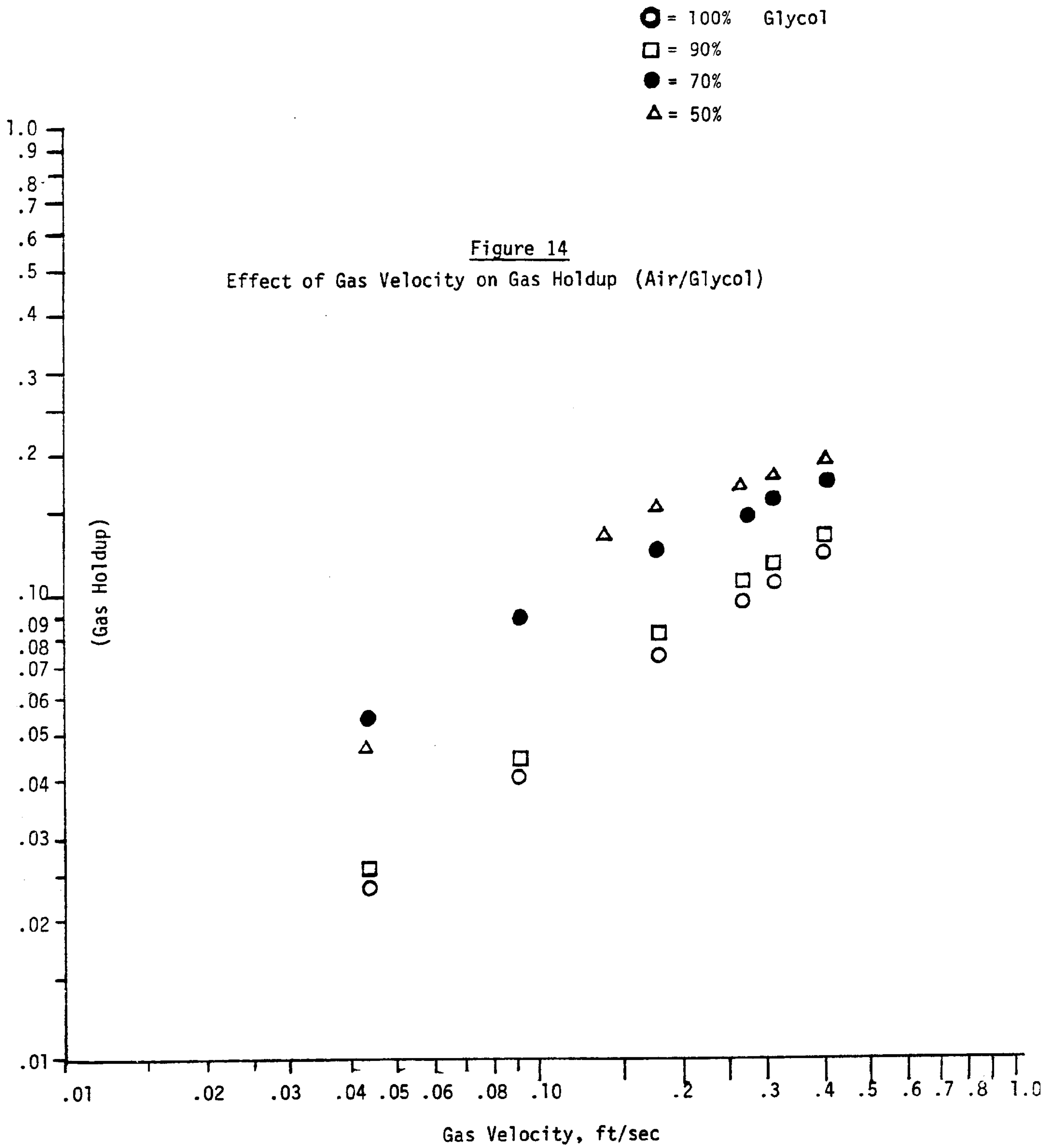


Figure 14

Effect of Gas Velocity on Gas Holdup (Air/Glycol)



be described fairly well by a straight line on a log-log plot for all the systems studied. This indicates that gas holdup varies exponentially with linear gas velocity; in other words, gas holdup is proportional to $(V_g)^x$, where V_g is the linear gas velocity and x is an exponent. The value of the exponent was calculated by a regression analysis on the data (see Table 7). It is interesting to note that for four of the six systems studied, the exponent is nearly the same. For low concentrations of glycol (50 and 70 wt%) the exponents were different. This difference is not clearly understood. Perhaps the physical properties of the system may have had an effect on the exponent. Nonetheless, the range of the exponents listed in Table 7 (0.52-0.79) agrees with the values reported by other investigators.

5.1.4 Effects of Solids

The presence of solids has a minimal effect on gas holdup. A decrease in gas holdup was observed at very high gas velocities (0.3 ft/sec) in the presence of fine particles (-100 mesh). In this project, extensive data were obtained using an air/water/sand system, and limited experiments were conducted using a nitrogen/tetralin/sand system.

Figure 15 shows the effect of solid particles on gas holdup using the air/water/sand system. At low superficial gas velocities (up to 0.10 ft/sec), solids did not change the gas holdup appreciably. However, at high velocities of solids decreased gas holdup.

Certain conditions also affected the influence of solids concentration on gas holdup. In the presence of small particles, such as -100 mesh sand, gas holdup decreased, compared to the two-phase system, as gas velocity and solids concentration increased. A 13.9% reduction was measured for a solids concentration of 11 lb/ft^3 at a superficial gas velocity of 0.368 ft/sec.

Table 7

Value of Exponent for Various Systems

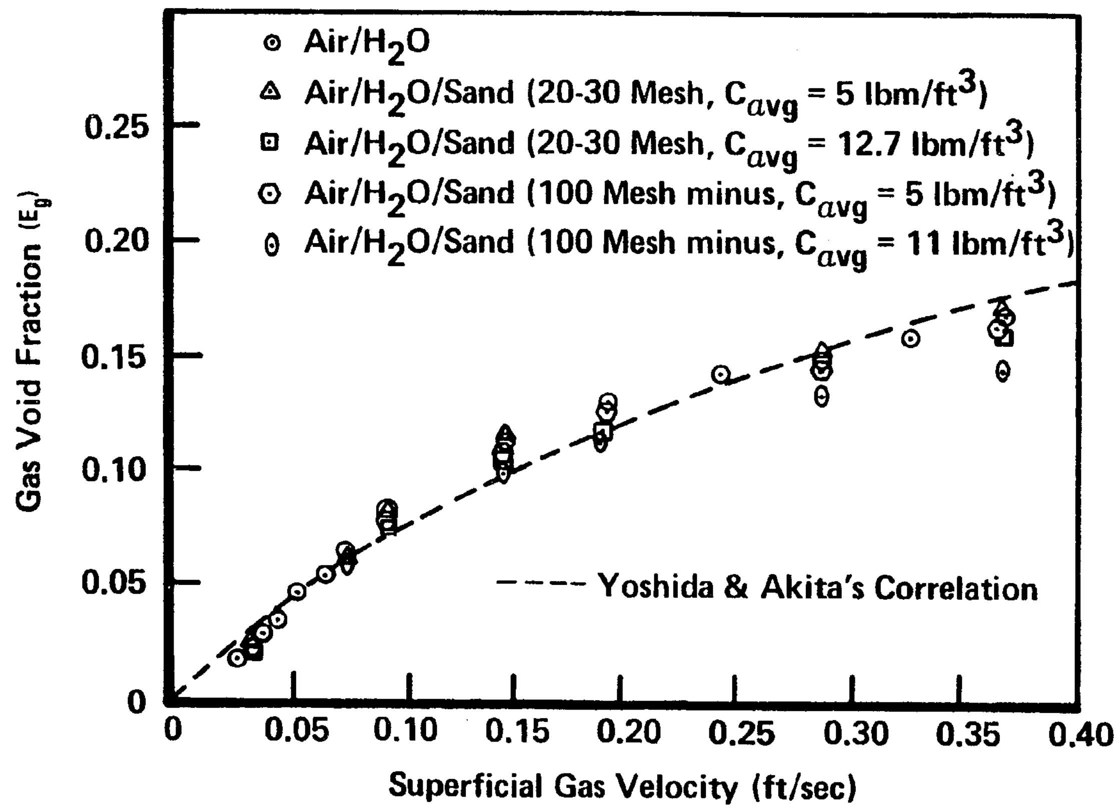
$$\varepsilon_g \;\alpha\; (V_g)^b$$

ε_g = gas holdup
V_g = ags velocity
b = exponent

System	Value of exponent, b
Air/water	0.79
Nitrogen/tetralin	0.73
Air/100% glycol	0.77
Air/90% glycol	0.75
Air/70% glycol	0.52
Air/50% glycol	0.64

Figure 15

Effect Of Solids On Gas Holdup In 12-Inch Diameter Column



The larger particle-size solids decreased gas holdup only at the highest gas velocity and at high solids concentration (12.7 lb/ft^3). The magnitude was less than that for the smaller size material. At lower concentration no change was observed.

Gas holdup was also influenced by particle suspension in this flow regime. The 20-30 mesh sand in this work settled mainly at the bottom of the 12-in. diameter column and reduced gas holdup less than the -100 mesh suspended particles. The suspended particles may have enhanced the coalescence of gas bubbles more effectively than the settled solids, thus reducing in gas holdup more. Therefore, the effect of increasing solid concentration could be related to an increase in bubble coalescence, In any event, with the exception of high concentration of fine particles, the presence of solids did not significantly affect gas holdup.

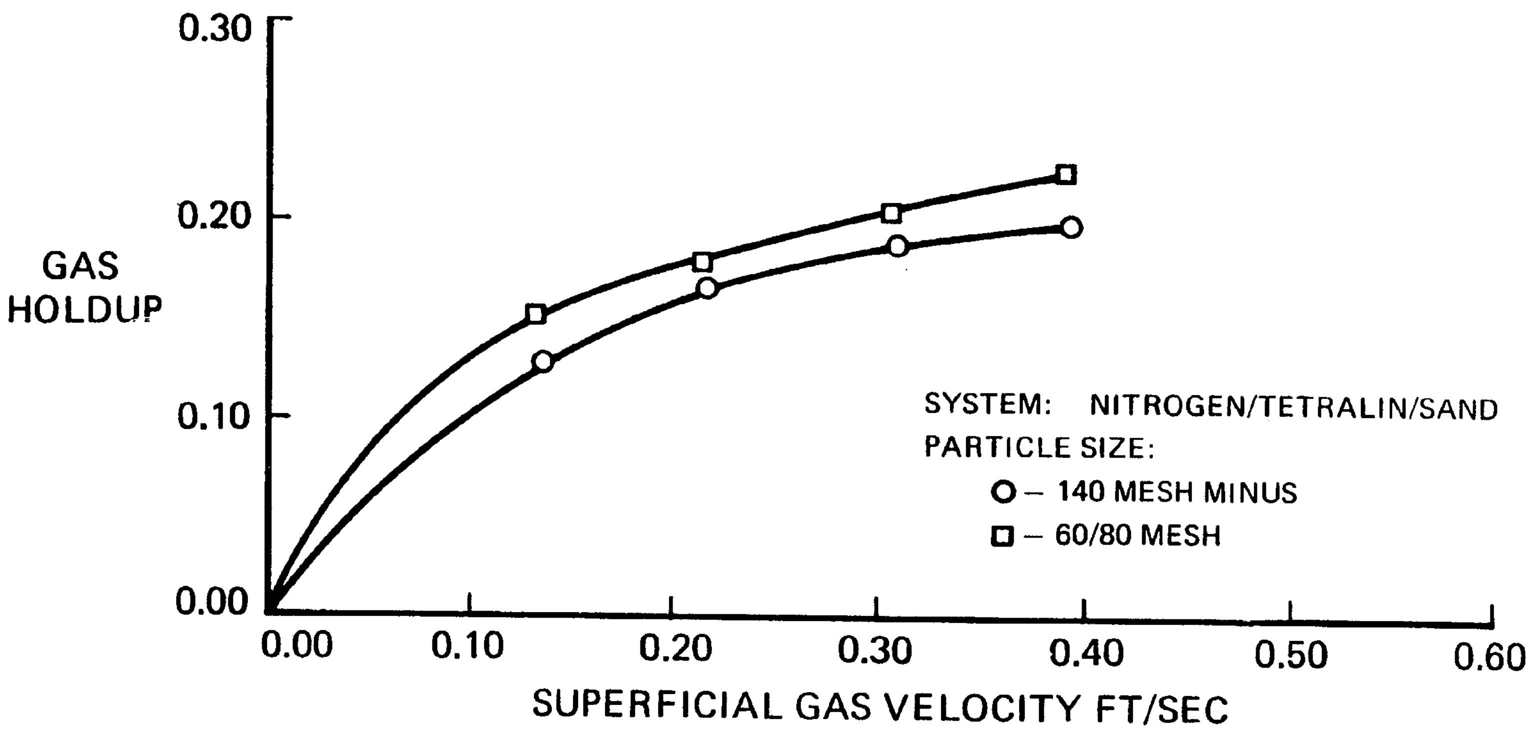
Figure 16 shows the effect of solid particles on gas holdup using the nitrogen/tetralin/sand system. Addition of 60/80-mesh sand resulted in negligible changes in gas holdup; however, gas holdup data for the -140 mesh minus sand was about 4-5% lower. These findings agree with data obtained for the air/water/sand system.

5.1.5 Effect of Distributors (Entrance Effects)

The presence or absence of a distributor does not seem to markedly affect gas holdup and negligible differences were found in the values of gas holdup for two different types of distributors.

Gas holdup values were determined for the air/water and air/water/sand system for three different distributor configurations: distributor #1 (7 bubble caps), distributor #2 (19 openings but no bubble caps), and without either distributor, gas velocities varied from 0.05 to 0.43 ft/sec, and liquid velocities ranged from 0.01 to 0.05 ft/sec.

FIGURE 16
EFFECT OF SOLID PARTICLES ON GAS HOLDUP



Overall gas holdup was not influenced by entrance effect, as shown in Figures 17 through 22. These figures compare gas holdup data obtained from the three different distributor configurations under various experimental conditions (presence and absence of liquid flow and solid particles). Except for the case without a distributor at high gas velocities, negligible differences exist in the gas holdup values.

At higher gas velocities, an unusual behavior was observed in the absence of a distributor. The liquid level at the top of the column periodically surged such that the liquid level would rise above the exit line and then suddenly drop a few inches below the exit line. This phenomenon occurred at gas velocities above 0.2 ft/sec. Because of this surging behavior, the holdup data at high gas velocities in the absence of a distributor may be substantially in error. Periodic gas slugs that were observed in the column in the absence of the distributor are suspected to be the major cause of the surging behavior.

However, the presence of these huge bubbles (slugs) did not appreciably change the holdup values, indicating that the true fraction of large bubbles in the column at a given time may be quite small. Gas holdup data alone cannot sufficiently reflect the size of the bubbles present in the column. Because no attempt was made to measure bubble sizes experimentally, a photographic method was developed to identify the fraction of gas-void volume occupied by large gas bubbles.

The photographic method was detailed in Section 4.3. Gas holdup is normally measured by stopping the flow of liquid and gas into the column and measuring the drop in liquid height. In the photographic method, the drop in the liquid level at the top of the column was measured every second after the liquid and gas flows had been shut off. Data were taken at various liquid and gas velocities and with distributors #1 and #2 in place.

The data were interpreted assuming that large bubbles rise faster than smaller bubbles. A limitation of the photographic method is that it cannot quantitatively measure bubble size. However, one can

Figure 17. **EFFECT OF DISTRIBUTOR PLATE ON GAS HOLDUP IN THE ABSENCE OF LIQUID FLOW AND SOLID PHASE**

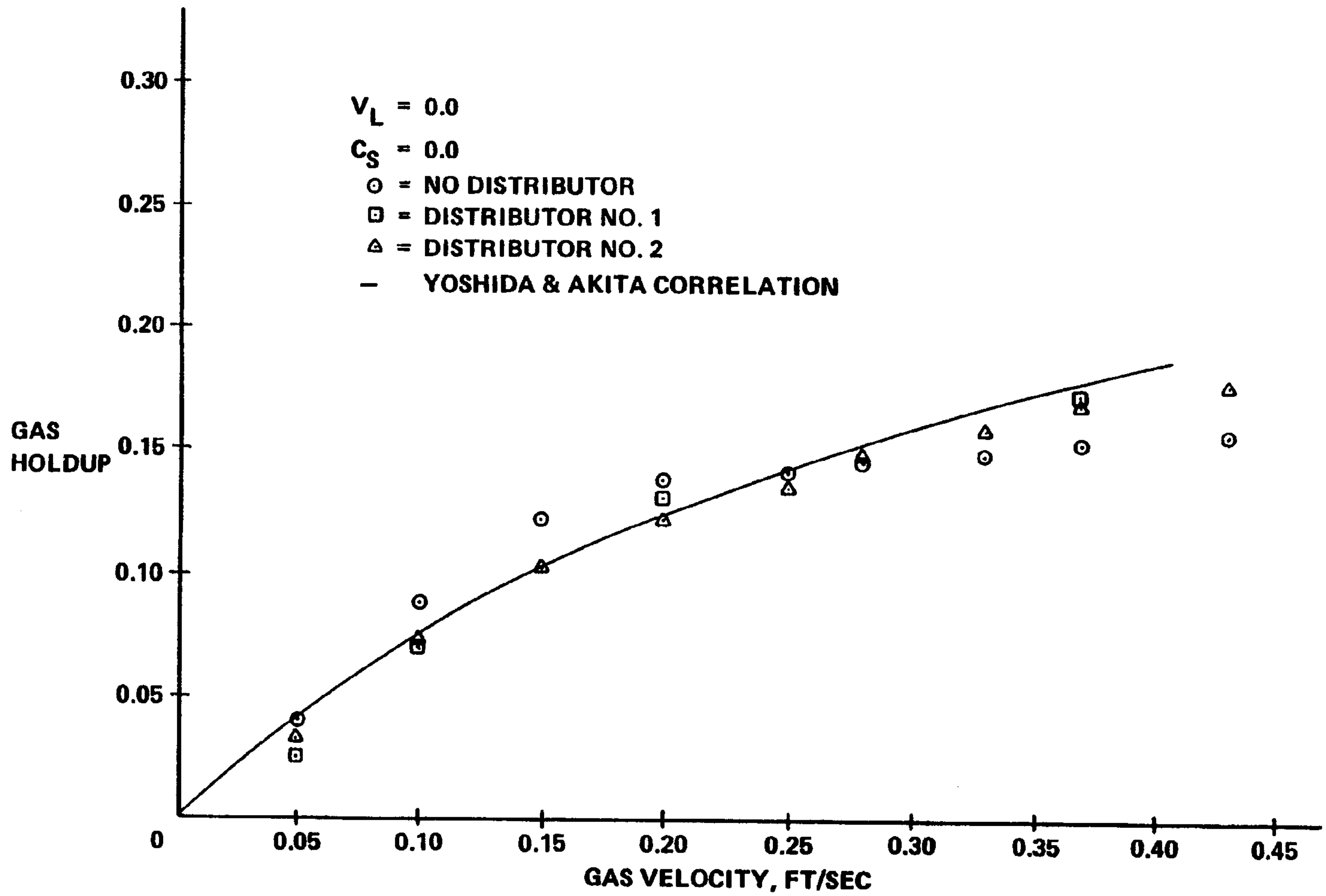


Figure 18. **EFFECT OF DISTRIBUTOR PLATE ON GAS HOLDUP AT LOW LIQUID VELOCITY WITH HIGH CONCENTRATION OF LARGE SOLID PARTICLES**

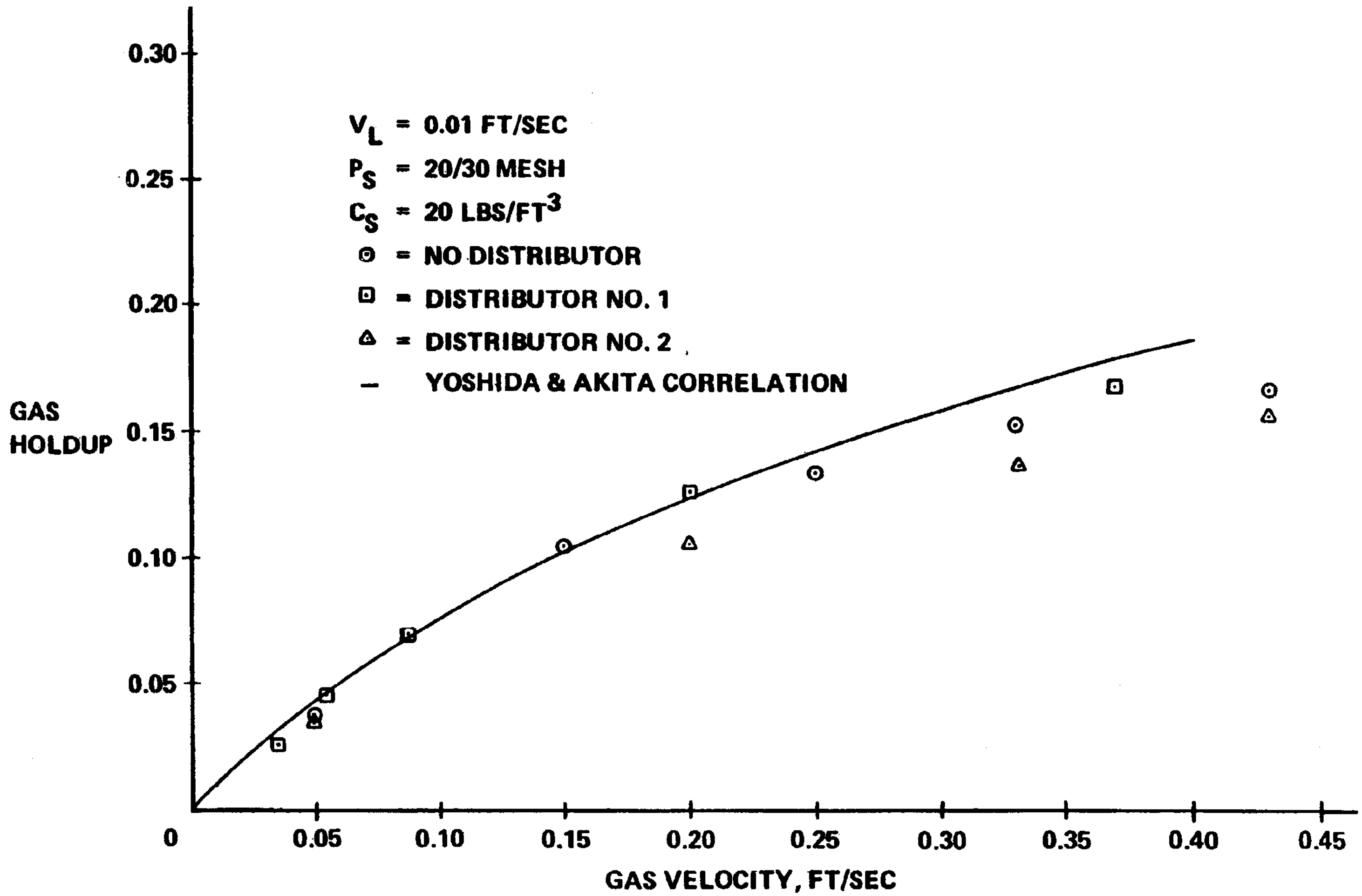


Figure 19. EFFECT OF DISTRIBUTOR PLATE ON GAS HOLDUP AT HIGH LIQUID VELOCITY WITH LOW CONCENTRATION OF LARGE SOLID PARTICLES

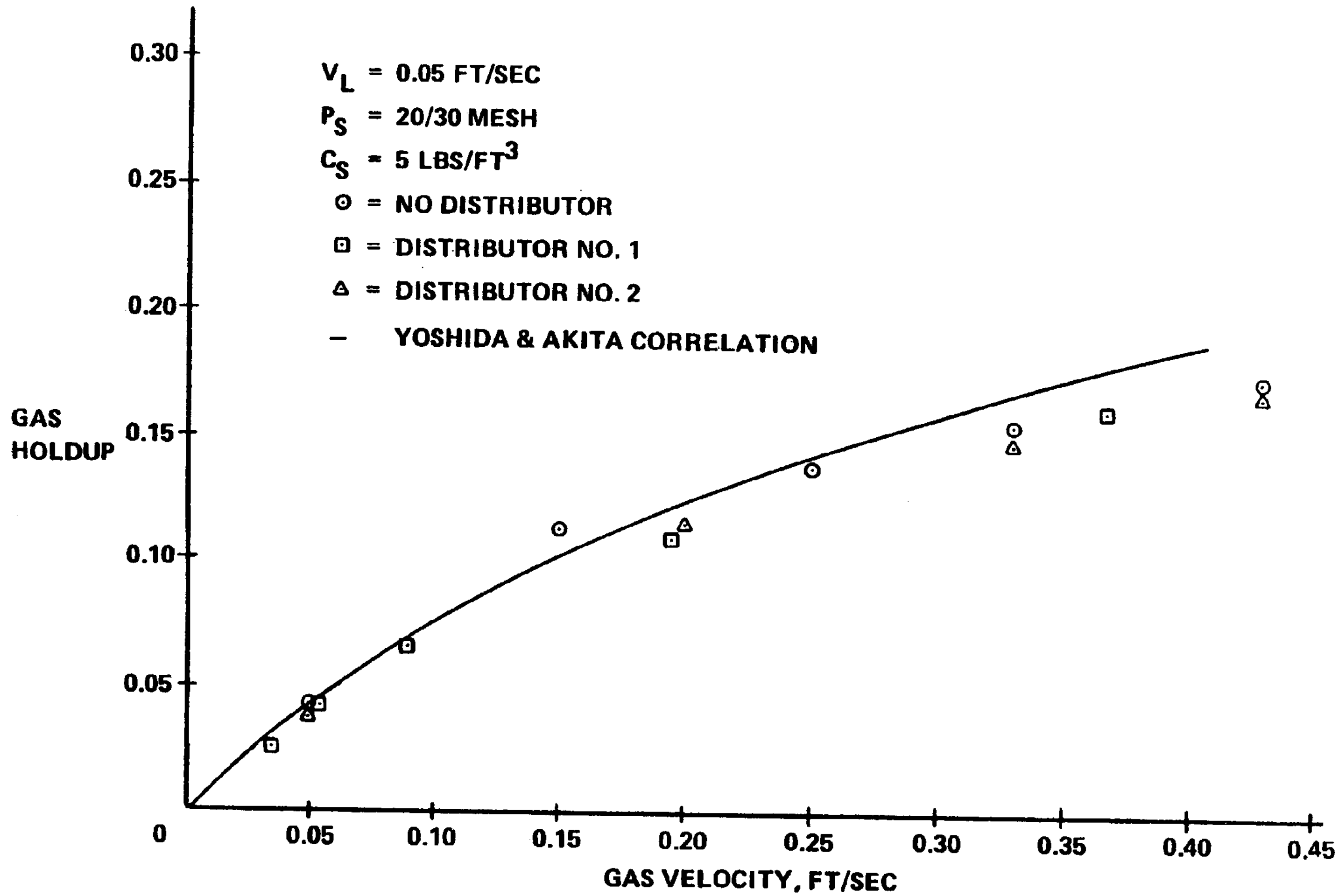


Figure 20. EFFECT OF DISTRIBUTOR PLATE ON GAS HOLDUP AT LOW LIQUID VELOCITY WITH NO SOLIDS

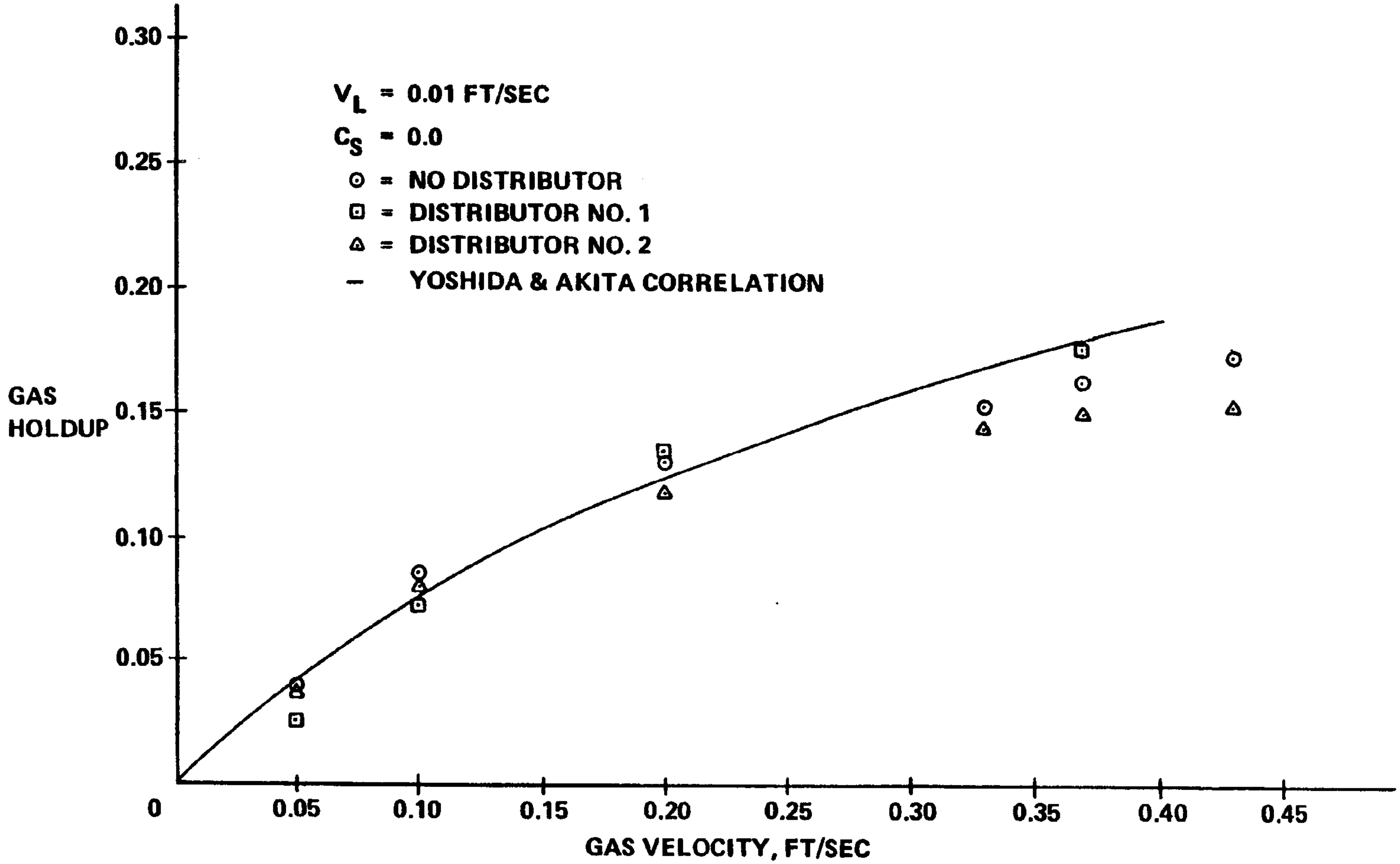


Figure 21. EFFECT OF DISTRIBUTOR PLATE ON GAS HOLDUP AT HIGH LIQUID VELOCITY WITH LOW CONCENTRATION OF FINE PARTICLES

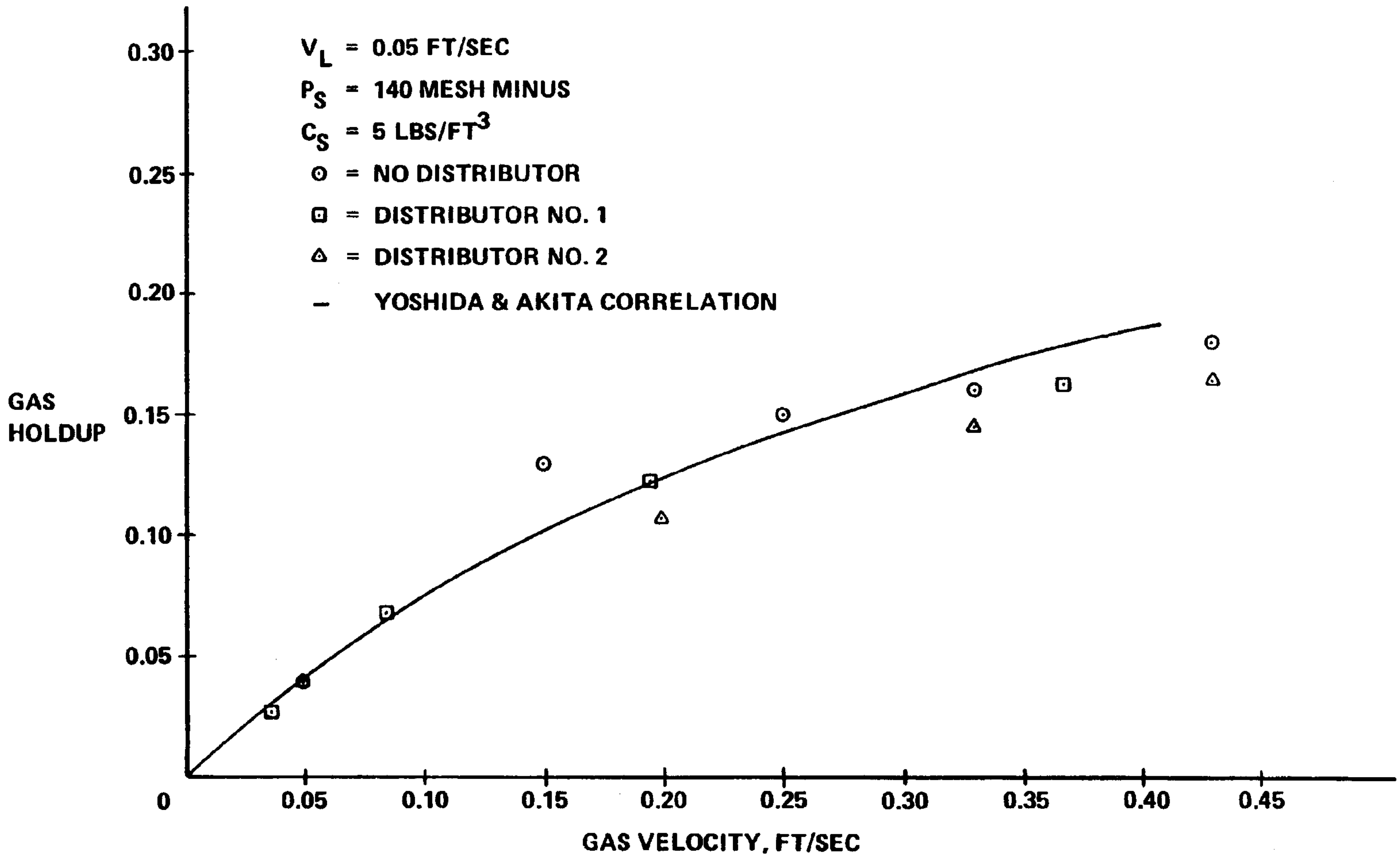
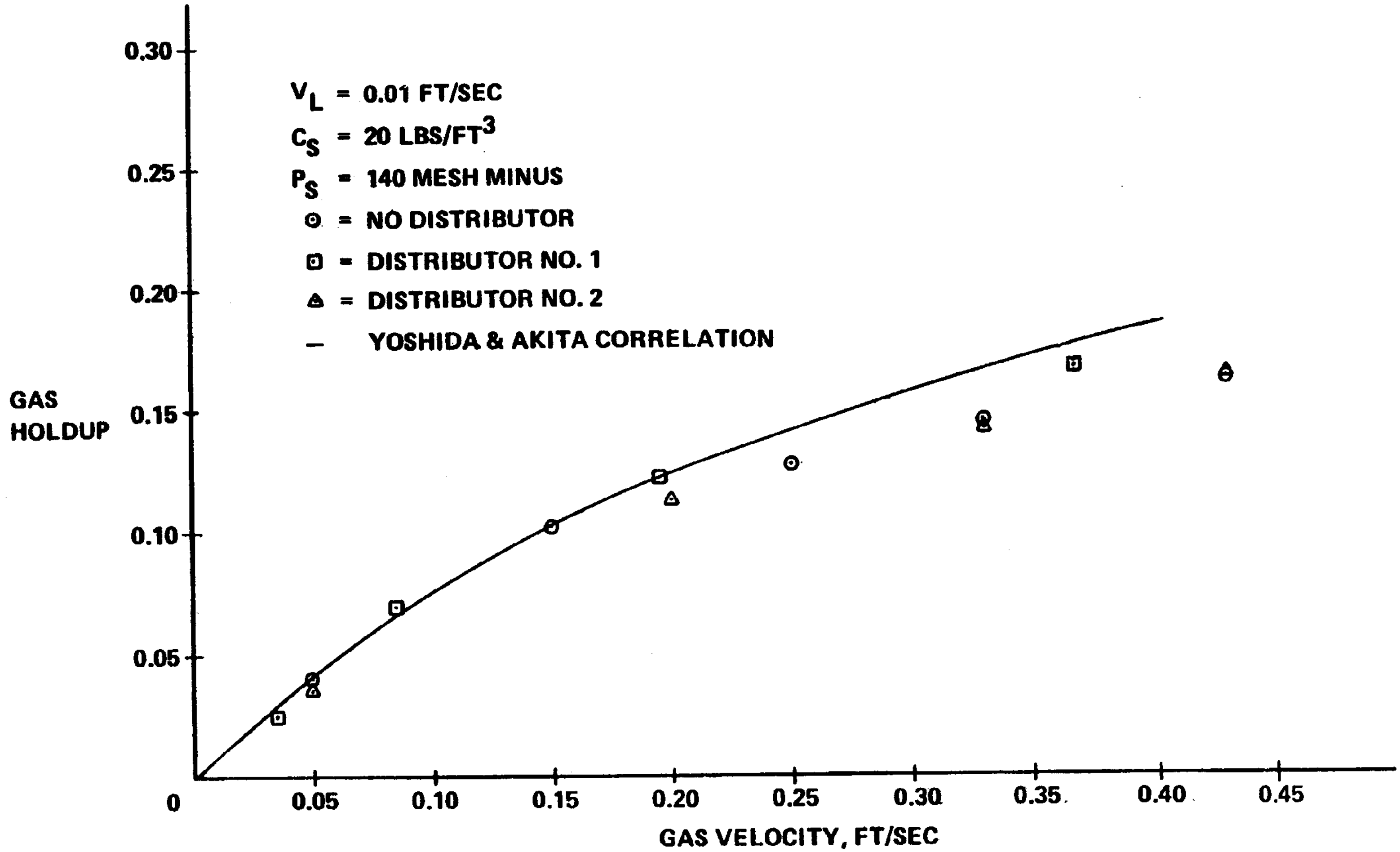


Figure 22. **EFFECT OF DISTRIBUTOR PLATE ON GAS HOLDUP AT LOW LIQUID VELOCITY WITH HIGH CONCENTRATION OF FINE PARTICLES**



characterize the bubble population in the column into two distinct groups: (1) a group of bubbles of about the same size rising in the column with a constant velocity and (2) a group of bubbles of various sizes, but larger than those belonging to the first group, and also rising at a faster rate. Observations indicated that the drop in liquid level (after the gas and liquid flows had been shut off) is very unsteady in the beginning, but becomes smooth with time, indicating the possibility of at least two different rates of drop in liquid level. Our objective was to determine these two different rates and the fraction of large bubbles present in the column.

Our results showed that the fraction of large bubbles increases with gas velocity, (see Figures 23 thru 31). Figures 23-26 represent data taken using distributor #1 and Figures 27-31 represent data taken with distributor #2. The figures indicated that two different rates of drop in the liquid level do exist. The bars indicated that the liquid level was unsteady and represented the low and high values observed from the photograph. Looking at a series of photographs taken at 1-sec intervals one can see the change in the behavior of liquid level. Figures 32 and 33 are two typical photographs taken 3 and 21 sec respectively, after the gas and liquid flows were stopped by closing the bottom valve. In Figure 32 the liquid level was not horizontal, and the liquid was very turbulent. Twenty-one seconds after the valve was closed, the liquid level was still dropping; however, as can be seen from Figure 33 the liquid level was now horizontal.

The type of distributor used does not affect the fraction of large gas bubbles, indicating that the bubble size distribution in this column is practically independent of the distributor design. Figures 23-31 clearly indicate that, for similar operating conditions, use of either distributor produced identical results. Hence, the results will be discussed together.

Figure 23. **RATE OF THE AERATED LIQUID LEVEL DROP**

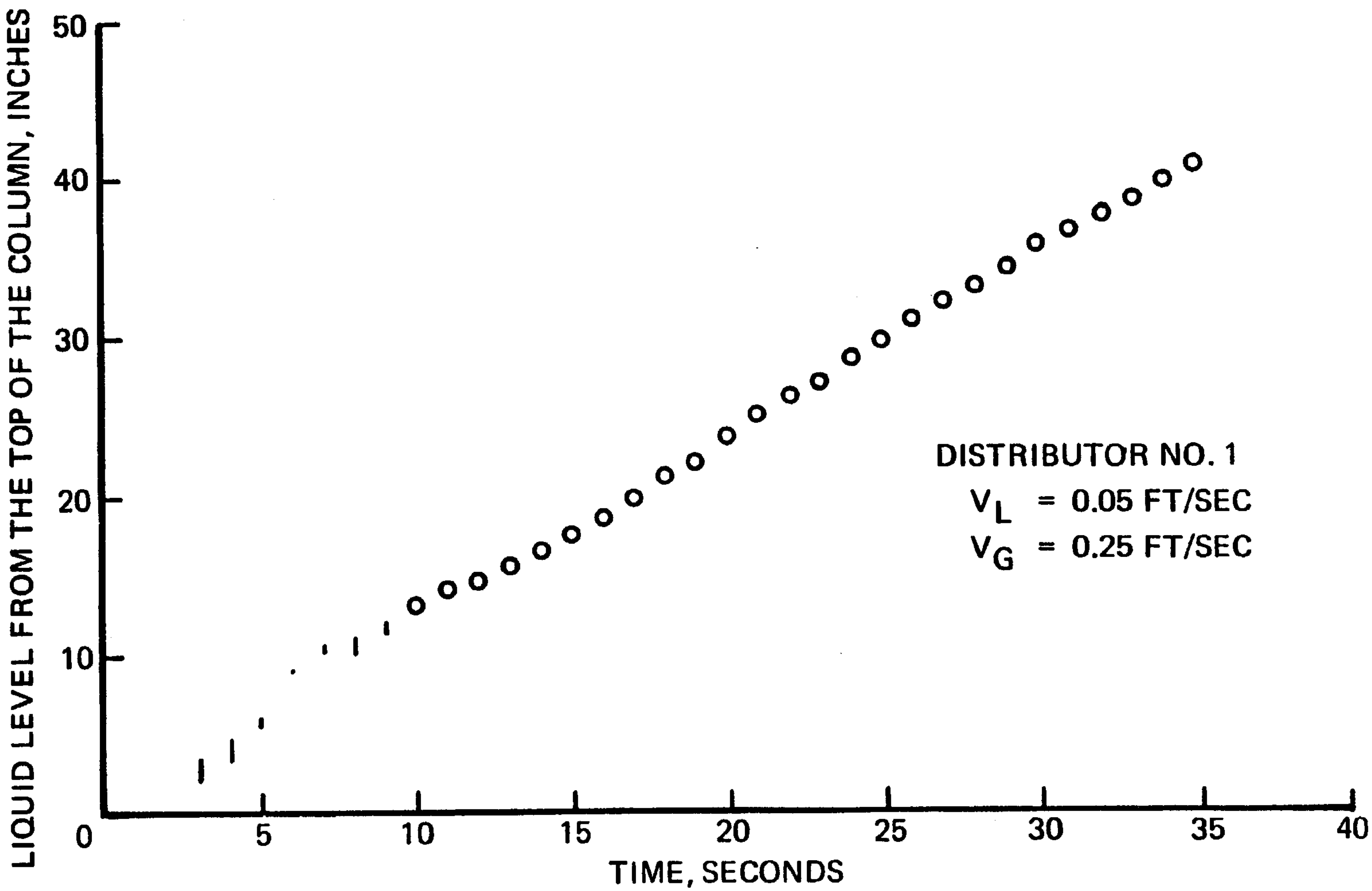


Figure 24. RATE OF THE AERATED LIQUID LEVEL DROP

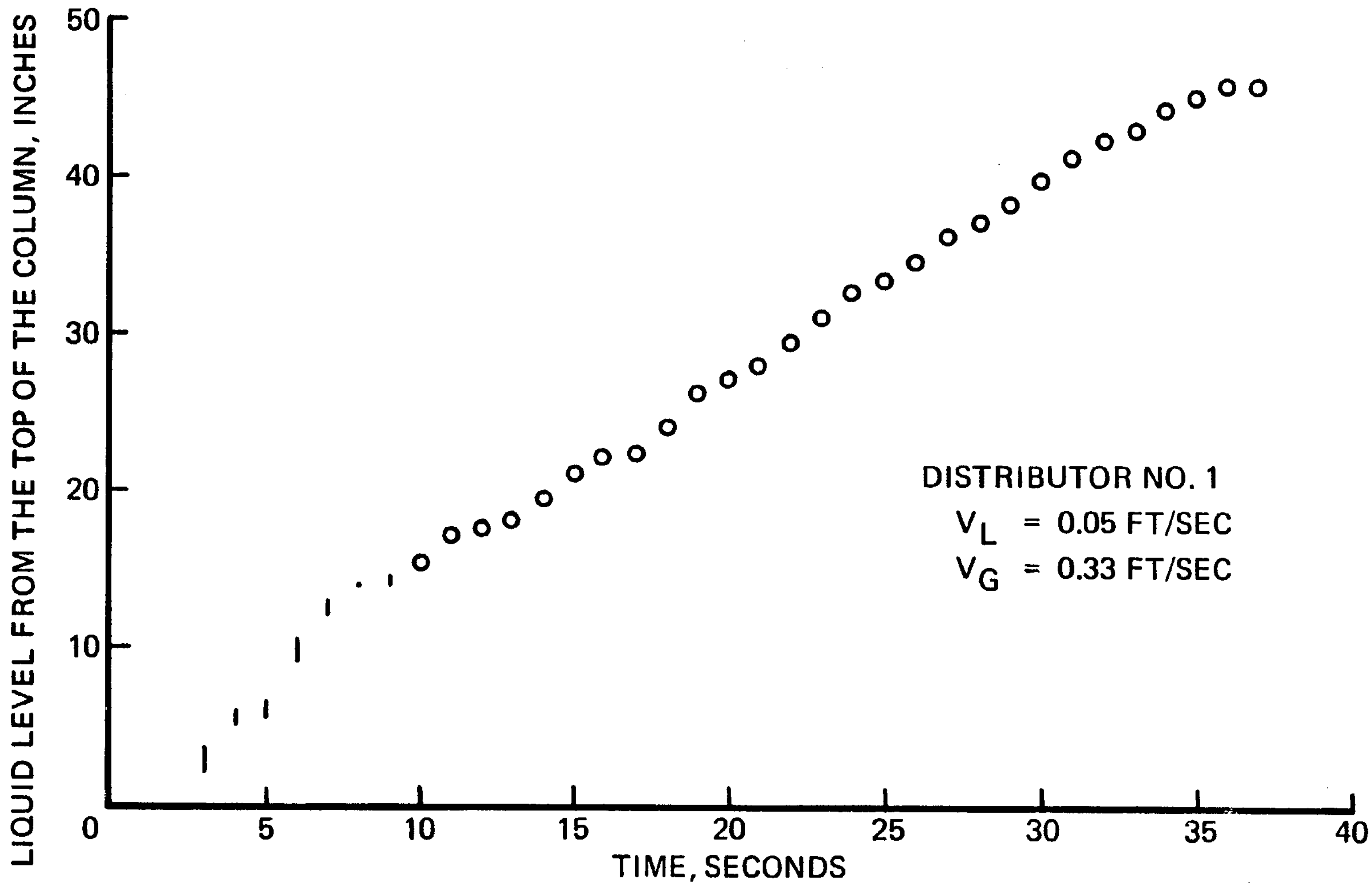


Figure 25. RATE OF THE AERATED LIQUID LEVEL DROP

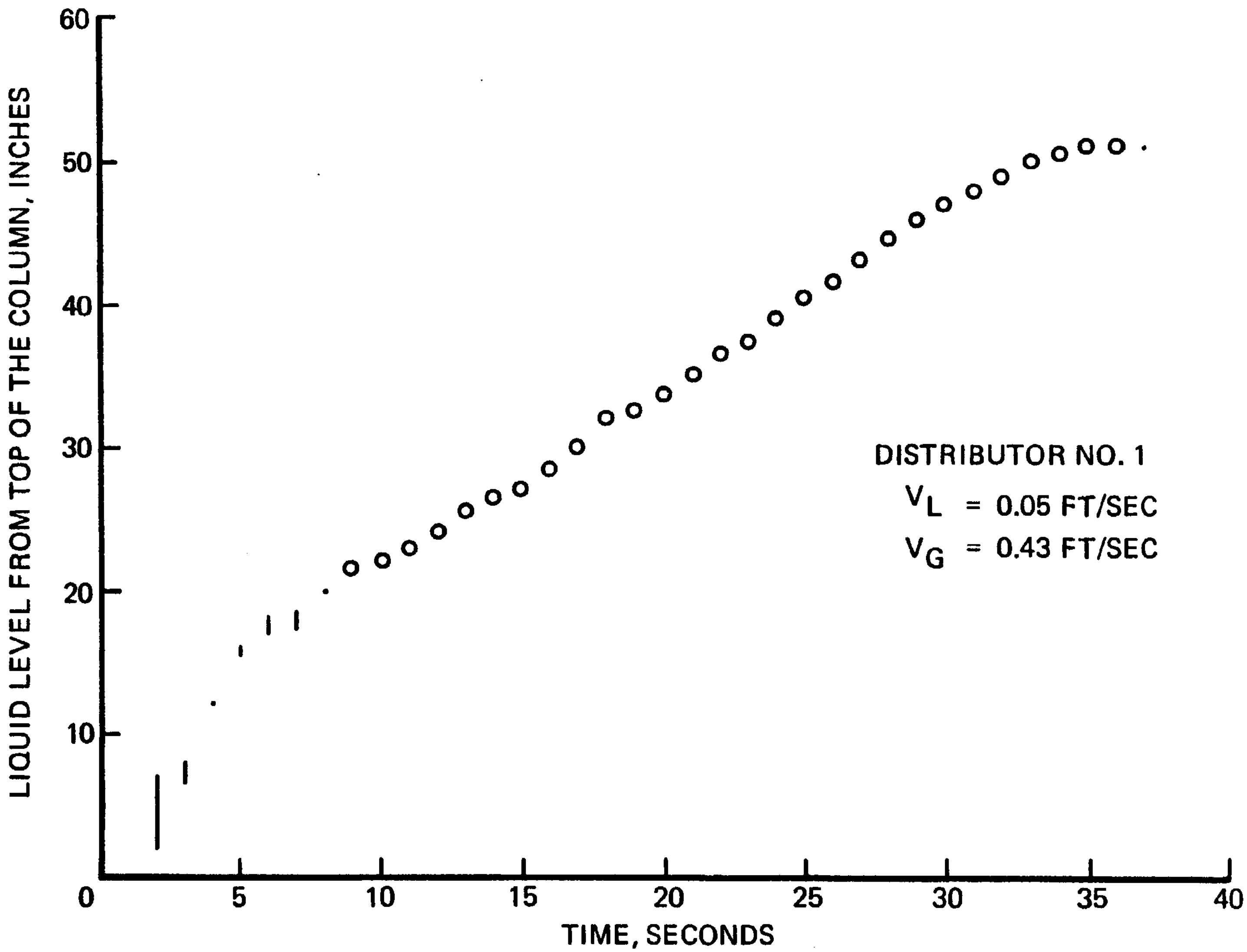


Figure 26. RATE OF THE AERATED LIQUID LEVEL DROP

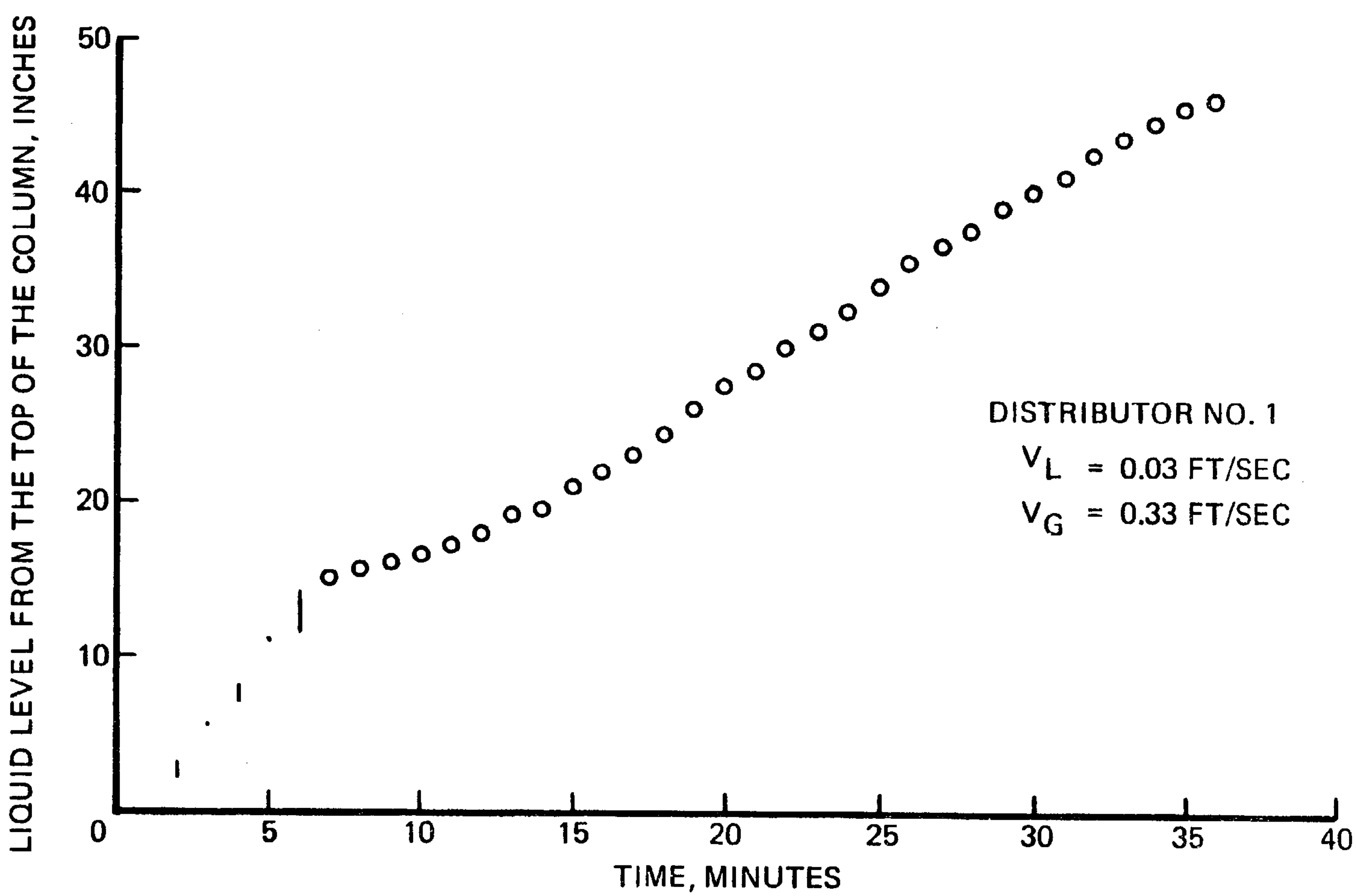


Figure 27. **RATE OF THE AERATED LIQUID LEVEL DROP**

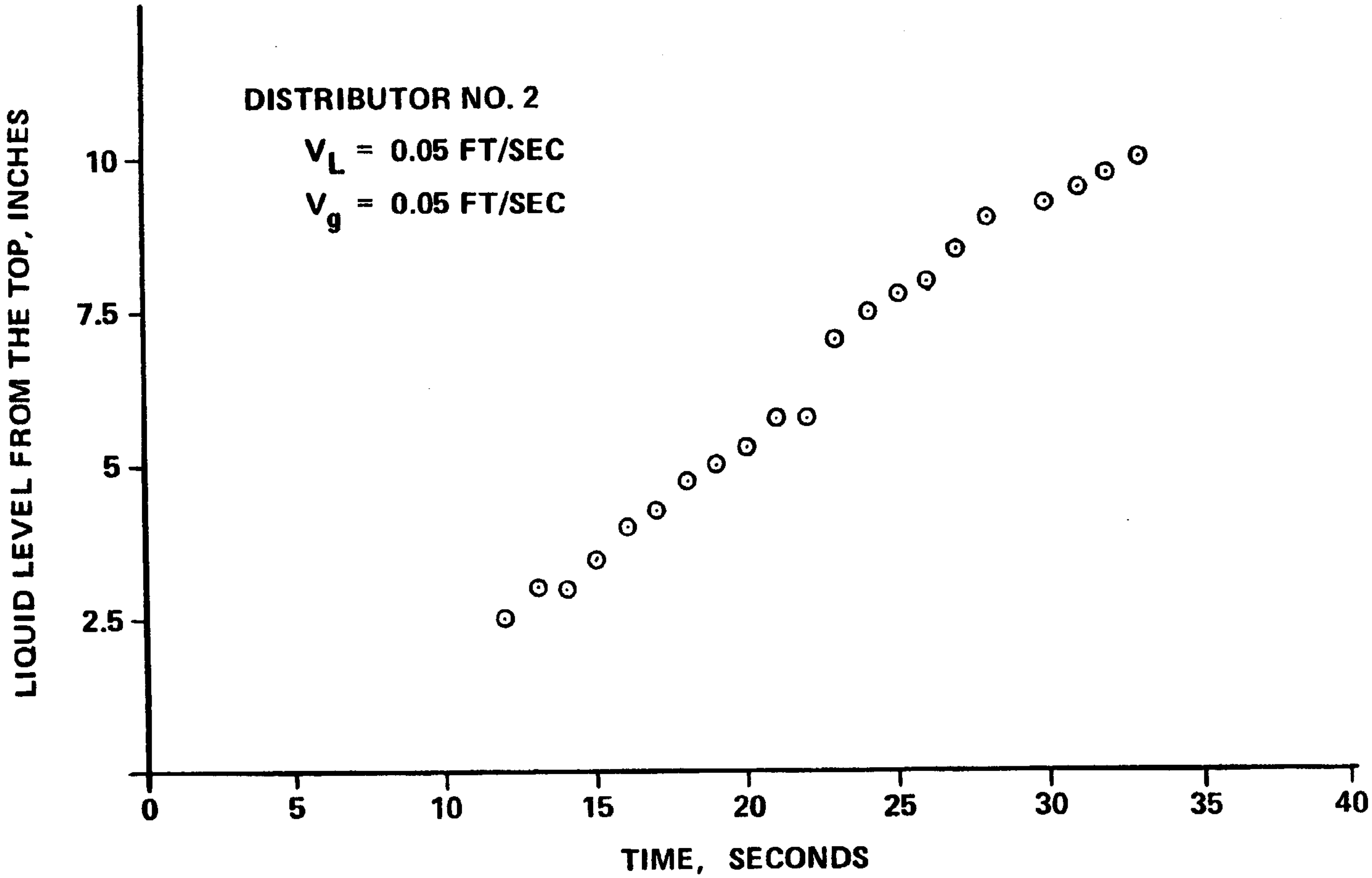


Figure 28. **RATE OF THE AERATED LIQUID LEVEL DROP**

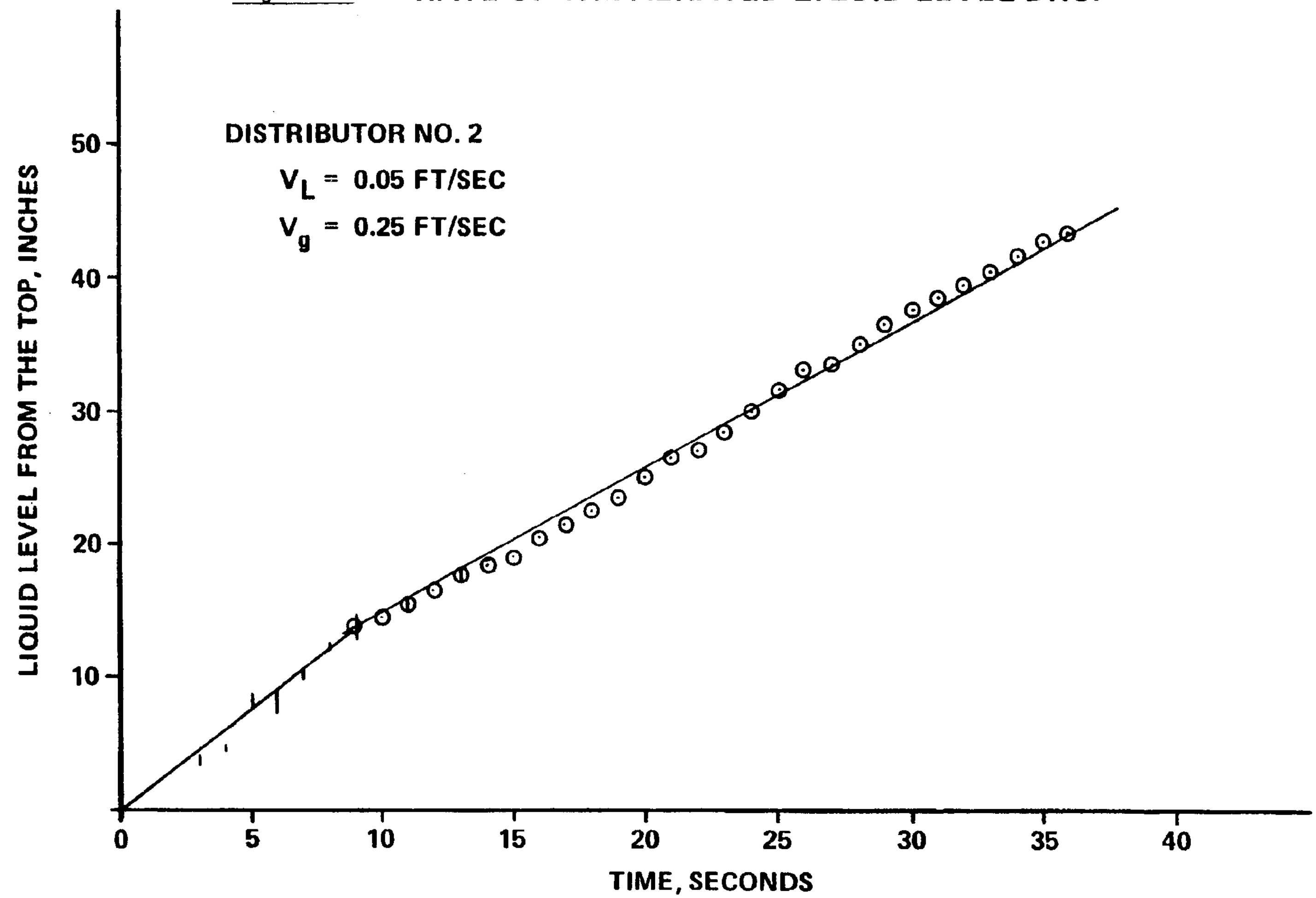


Figure 29. RATE OF THE AERATED LIQUID LEVEL DROP

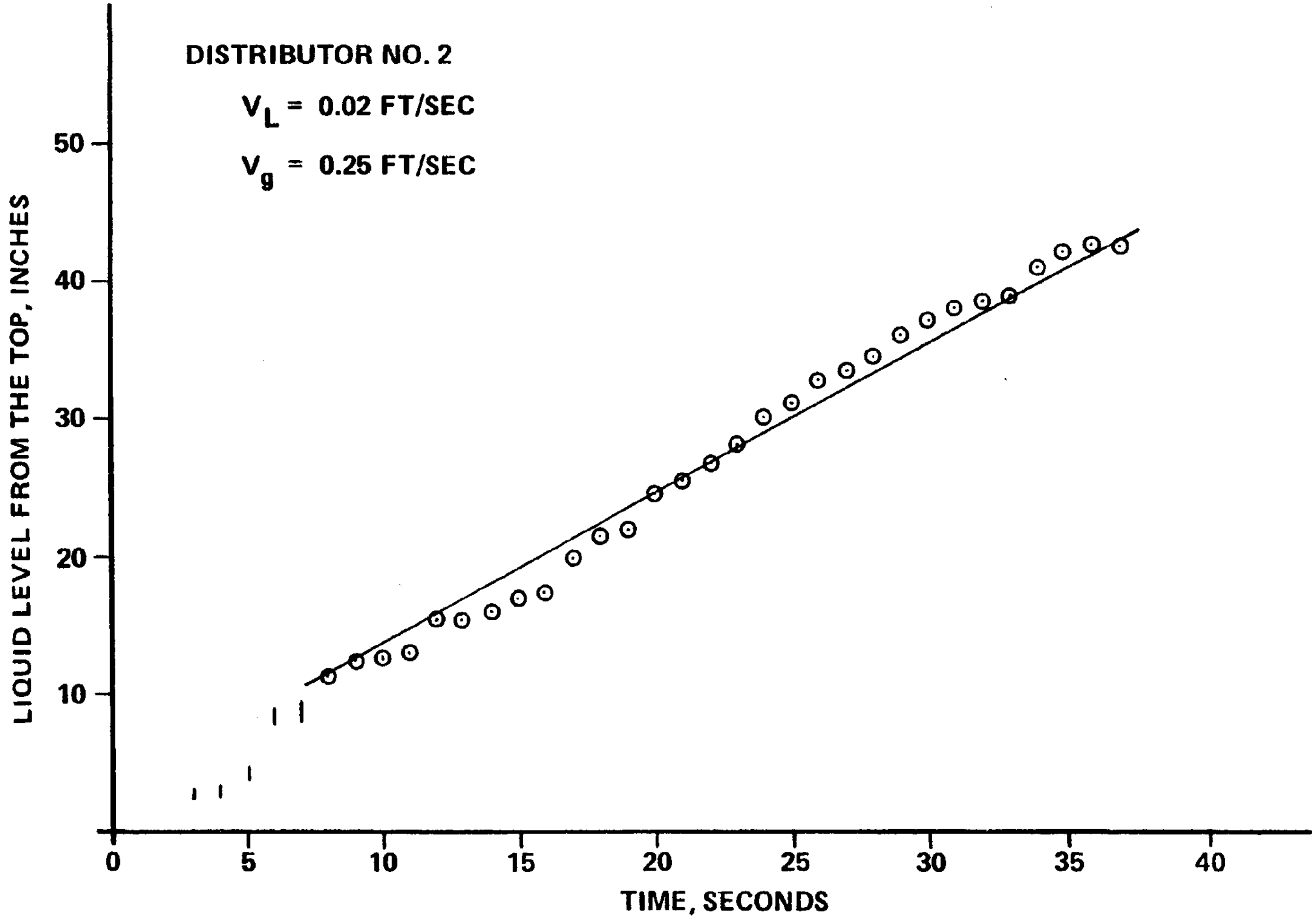


Figure 30. **RATE OF THE AERATED LIQUID LEVEL DROP**

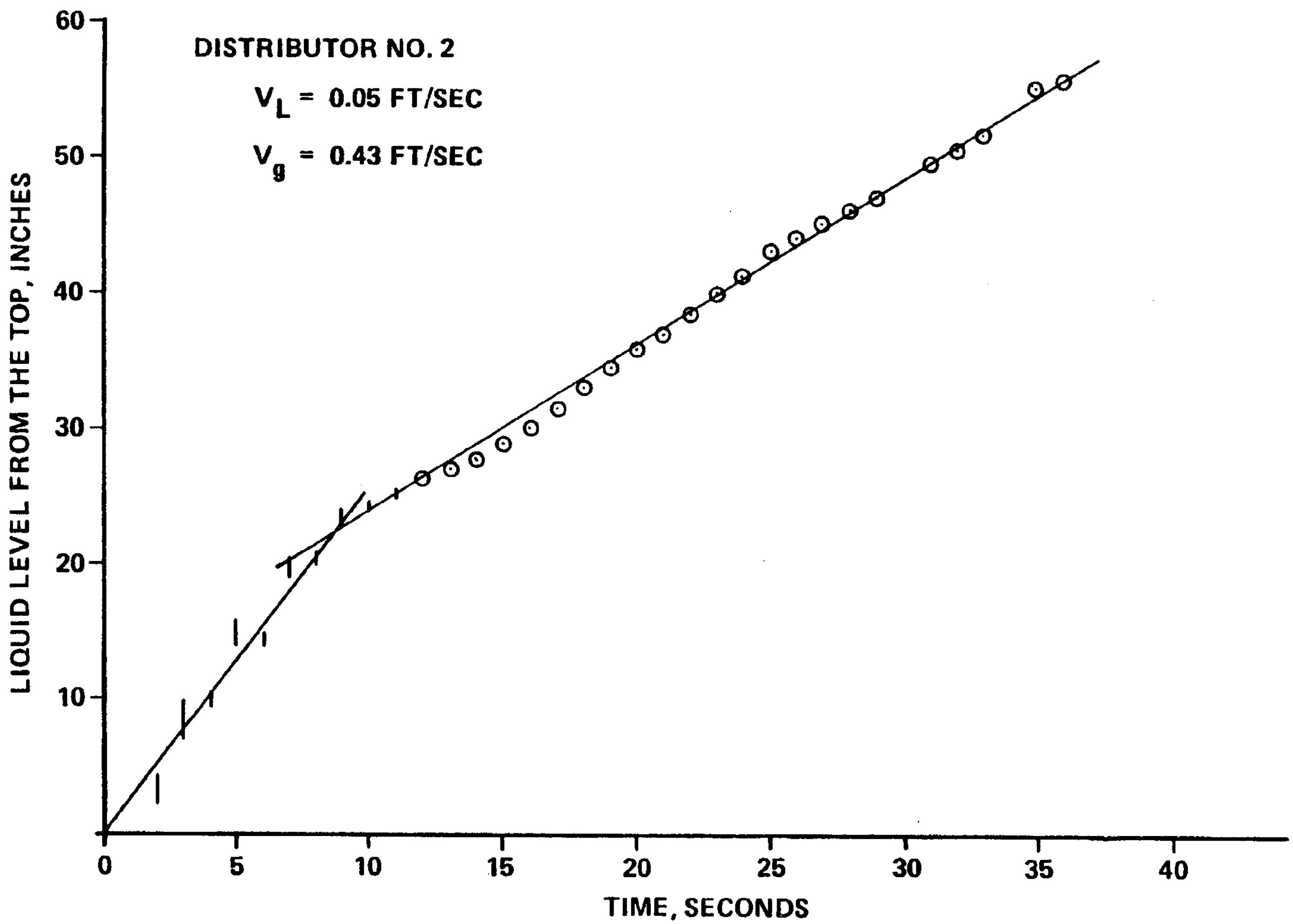
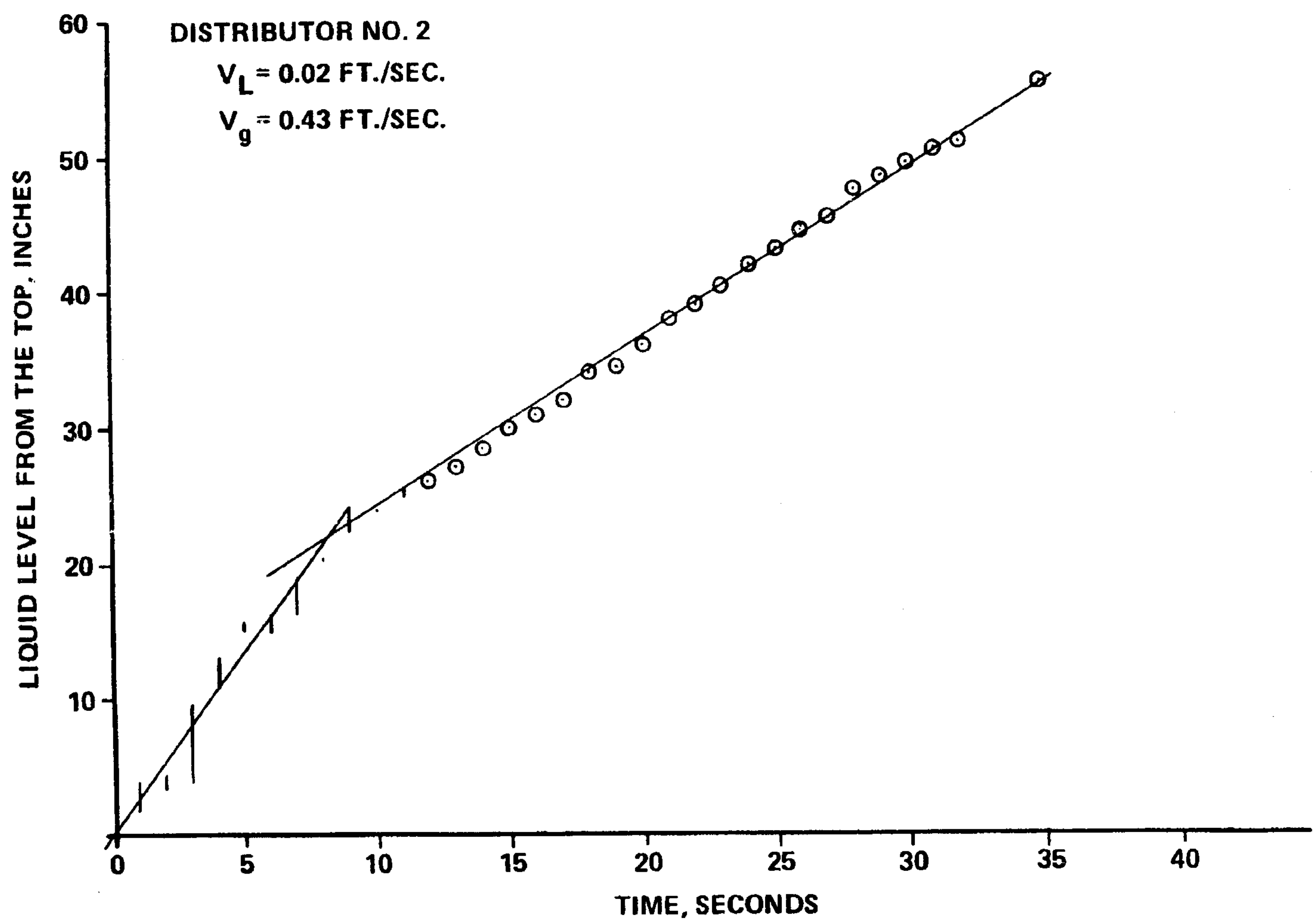


Figure 31. **RATE OF THE AERATED LIQUID LEVEL DROP.**



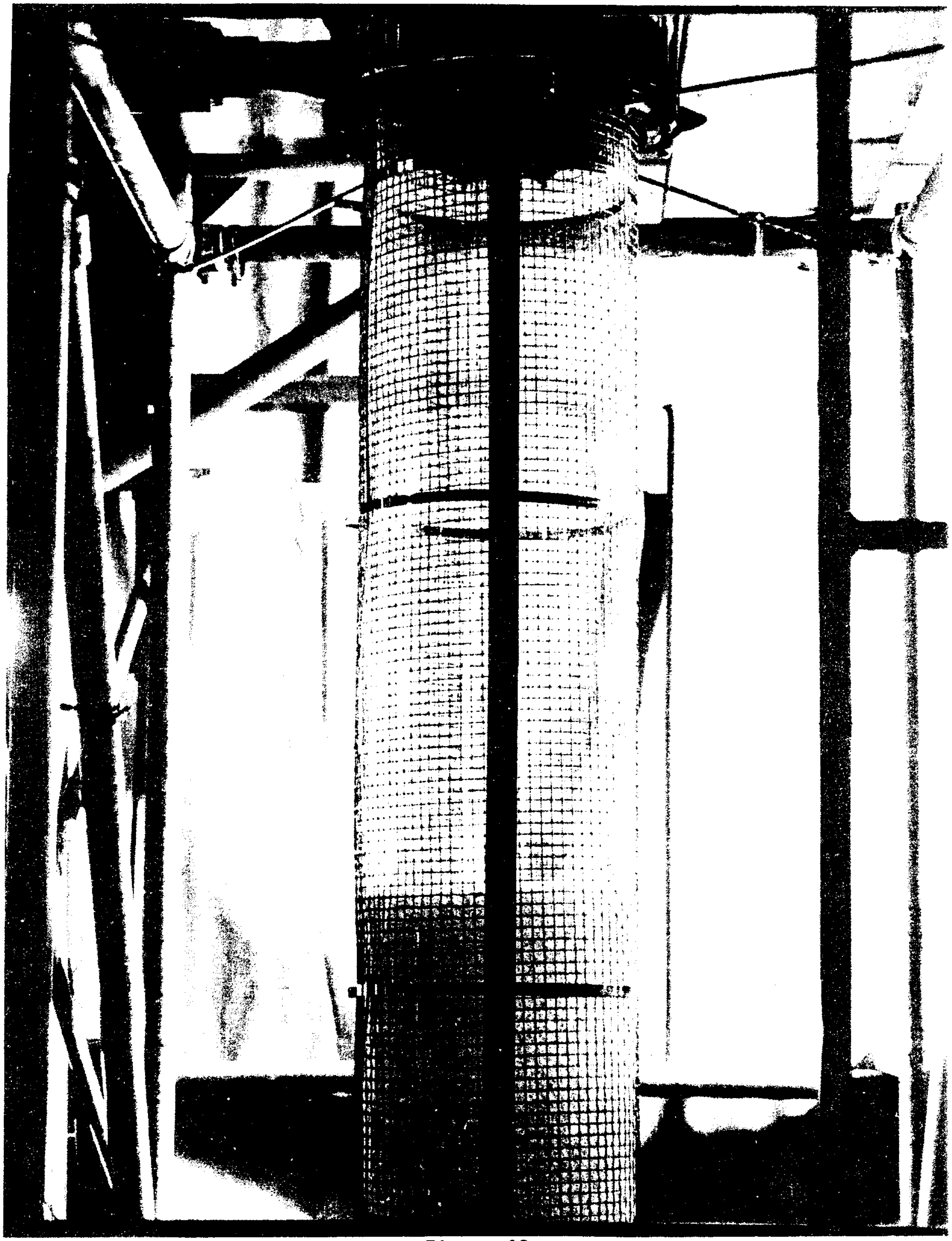


Figure 32

Photograph of Liquid Level (Three seconds after closing the valve)

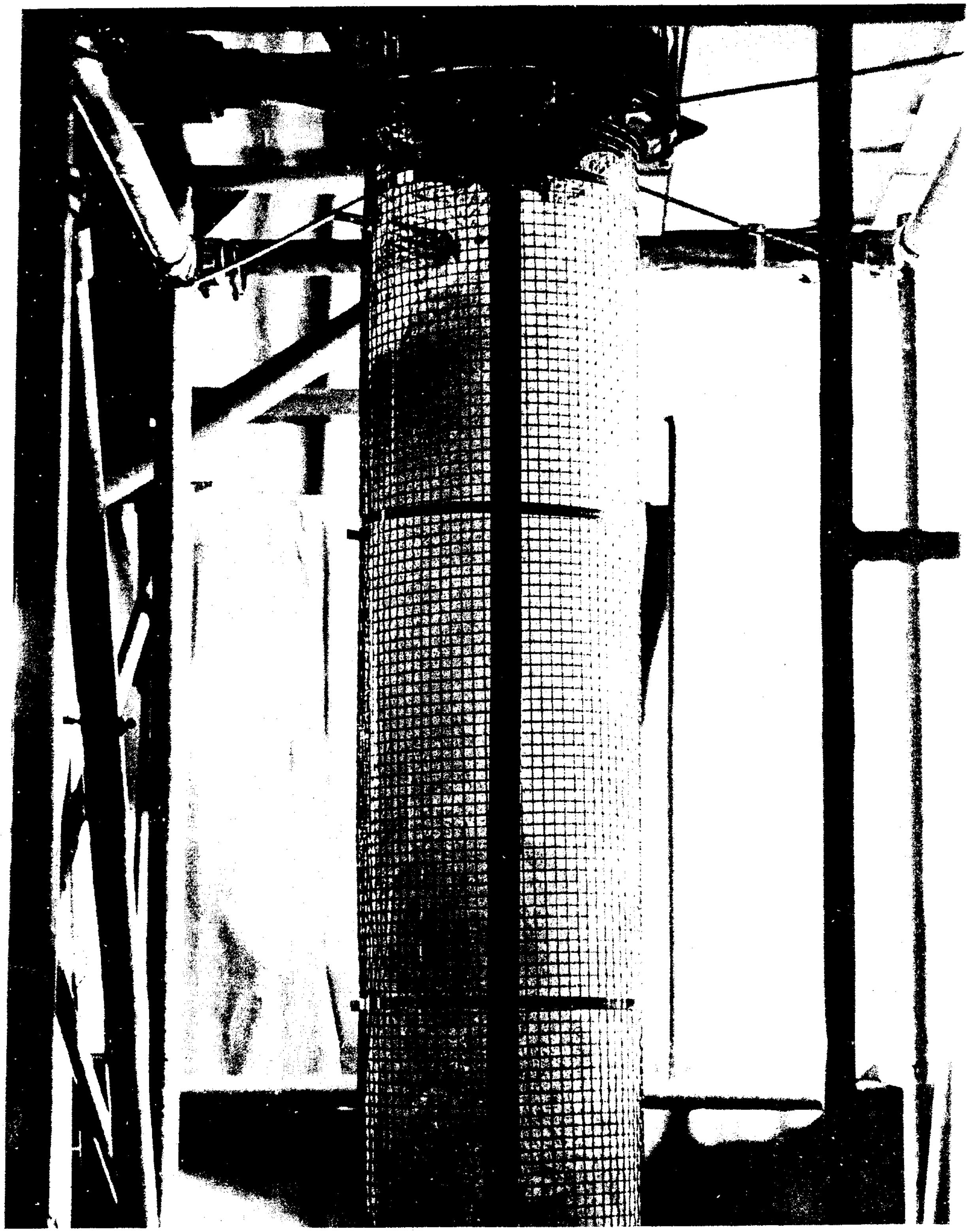


Figure 33

Photograph of Liquid Level (Twenty-one seconds after closing valve)

The photographic technique confirms some of our earlier results and provides a few qualitative conclusions: bubble size distribution as well as gas holdup are independent of liquid velocity. A change in liquid velocity from 0.02 to 0.05 ft/sec did not change the rate of liquid level drop or the final liquid level. This behavior was observed at two different gas velocities (0.25 and 0.43 ft/sec), which suggests a that this behavior is more than coincidence.

The fraction of large bubbles in the column increases with gas velocity. At very low gas velocities, the transition between the two distinct regions could not be seen because of the obstruction caused by the connecting flanges in the column. However, Figure 27 suggests that the fraction of large bubbles in the column, if any, is very small at a gas velocity of 0.05 ft/sec. Increasing the velocity from 0.25 to 0.43 ft/sec results in an increase of the large bubbles from 31 to 43%. The graphs also reveal that the average size of the smaller bubbles (a group of bubbles of about uniform size) is independent of gas velocity, even though the fraction of large bubbles in the column increases with gas velocity. Superimposing Figures 23-31, which are plotted for different gas velocities, reveals that the data points are parallel, indicating that the slopes are the same. Because the slopes correspond to the average velocity of the small bubbles, this finding of parallel data points at different gas velocities means that the small-bubble rise velocities are independent of gas velocity.

Our results indicate that distributor configuration does not affect bubble-size distribution or the average gas holdup. However, we have not measured or attempted to measure local gas holdup values. These values might differ in the vicinity of the distributor. The large L/d ratio (25) of the 12-in.-diameter column may help to diminish entrance effects on gas holdup.