AN INVESTIGATION OF FLOODING VELOCITIES

IN COLUMNS PACKED WITH RASCHIG RINGS

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AN INVESTIGATION OF FLOODING VELOCITIES IN COLUMNS PACKED WITH RASCHIG RINGS

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NOMENCLATURE

F = Fraction of free volume in packed tower, cu. ft./cu. ft. tower volume.

g = Acceleration of gravity, ft./sec.^{2}

G = Superficial mass velocity of gas (based on empty column), lb./(sec.)(ft.^{2} cross-sectional area).

L = Superficial mass velocity of liquid (based on empty column), lb./(sec.)(ft.^{2} cross-sectional area).

S = Surface area of packing, ft.^{2}/ft.^{3} tower volume.

t = Temperature of air, $^{\circ}$F.

ΔP = Pressure drop across the packed section, inches of water.

U_G = Superficial gas velocity based on entire column cross-section, ft./sec.

ρ_G = Density of gas, lb./ft.^{3}

ρ_L = Density of liquid, lb./ft.^{3}

μ = Liquid viscosity, centipoise.

Θ = Correction factor for gas density, $\left(\frac{\rho_G}{\rho_a}\right)^{\frac{1}{2}}$ where ρ_a is the density of air.

ABSTRACT

In packed columns used for countercurrent contact of a gas and a liquid, the capacity of the equipment is limited by the tendency of the column to flood when the gas or liquid rate reaches a certain velocity called the flooding velocity. In this investigation, using Raschig rings as the packing material, the variation of flooding velocities with the packing size, packed height, and column diameter were studied. The effect of shaking treatment applied to the packing was also noted. Raschig rings of one-fourth, one-half, three-fourths, and one inch sizes were packed in glass columns varying in diameter from two to eight inches. Packed heights of from one to seven feet were studied.

Procedure in making determinations of flooding velocities consisted in passing air and water in countercurrent flow through the column. The liquid rate was held to an arbitrary value while the air rate was increased in step-wise increments until the flooding condition developed. At each air rate, the pressure drop across the column was allowed to reach a constant value, and readings were then taken of this pressure drop and of the flow rates.

Flooding velocities were best correlated by the method of Sherwood, Shipley and Holloway as modified by Lobo, Friend, Hashmall and Zenz. By this generally accepted correlation, no effect of column diameter or packing size was noted on tests in which the diameter to size ratio was equal to or greater than eight to one. Tests on packed sections with a smaller ratio showed deviations from the other correlated

values, but these deviations were inconsistent with regard to direction.

Flooding velocities and the per cent free volume both showed a decrease with the amount of shaking applied to the packing. However, the application of the Lobo modification of the Sherwood correlation resulted in good agreement between unshaken and gently shaken packed sections. The violently shaken packed sections did not correlate well with the other tests, and showed lower flooding velocities and therefore lower capacities.

Variation in height of the packed section had no effect on the correlated values of the flooding velocities with the exception of one test using one-half inch rings in an eight inch column. This was the only test having a column diameter to packing size ratio of over eight to one in which the effect of height was studied.

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INTRODUCTION

Although the use of packed columns is widespread for the chemical engineering unit operations of absorption, extraction, and distillation, all of the factors affecting their design have not been completely defined. In designing packed towers for counter-current contacting operations involving a liquid and a gas phase, the diameter, and therefore the capacity of the equipment, is largely determined by the liquid and gas rates to be employed. These rates are limited by the tendency of the equipment to flood. The point at which flooding occurs is a function of both the liquid and the gas rates. As either the liquid or the gas rate is increased, the liquid hold-up in the packing increases, the free area available for gas flow decreases, and the pressure drop across the column increases. At a certain velocity, termed the flooding velocity, a point is reached when the liquid retention so reduces the available area for gas flow that the pressure drop increases sharply with a slight increase in gas velocity. A layer of liquid builds up on the top of the packing, and the liquid phase is carried mechanically out of the column. Operating above the flooding point, while possible in some cases, is impractical for economic reasons, since the high pressure drop increases the pumping costs.

The recognized need for an adequate method of predicting the limiting flow rates in packed columns has led to a considerable amount of work on this subject in recent years. A number of publications which give experimental data have appeared. Although an economic balance should determine the best operating condition to be utilized in a packed column, a knowledge of flooding velocities is necessary to calculate the maximum rates of flow. In cases where it is not possible to make an exact economic balance, flooding velocities must be known before the optimum liquid and gas rates can be estimated.

Although several correlations of flooding velocities have been developed, and considerable work has been done with Raschig rings, it was felt that there exists a need for a systematic study of the effects of packing size, column diameter, and packed height in columns packed with Raschig Rings. This investigation was undertaken to obtain data for columns two, four, and eight inches in diameter packed with various heights of one-fourth, one-half, three-fourths, and one inch Raschig rings.

REVIEW OF LITERATURE

Chilton and Colburn (1) investigated the pressure differential across various types of materials in packed columns, both in the dry and wet condition. Baker, Chilton and Vernon (2) studied the distribution of liquid flow throughout the cross section of packed towers. These latter found that a high gas velocity assists in obtaining uniform distribution, and they developed suitable equations for predicting the performance of such towers. Flooding in the investigation of these workers was determined visually.

A graphical method of determining the flooding point was presented by White (3). He plotted, at a constant liquid rate, the pressure drop across the packed column versus the gas rate. Placing the logarithm of the pressure drop along the ordinate and the logarithm of the gas rate along the abscissa the resulting curve was represented by two or three straight-line segments. The point at which the slope of the curve becomes greater than two is defined as the loading point, and the point at which the slope becomes nearly infinite is called the flooding point.

A general correlation for predicting flooding velocities was developed by Sherwood, Shipley and Holloway (4). They varied gas and liquid density and liquid viscosity in a two inch diameter column packed with one-half inch Raschig rings to a height of four feet and correlated the results by plotting:

$$\frac{U_G^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2} \quad \text{versus} \quad \frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$$

where U_G is the superficial gas velocity, g is acceleration of gravity, S is the surface area of the packing, F is the fraction of void space in the packed column, ρ_G and ρ_L are gas and liquid densities, μ is the liquid viscosity, and G and L are gas and liquid mass velocities. All ratios involved in the correlation are dimensionless with the exception of the viscosity factor, which is expressed in centipoise. Data for flooding in larger diameter packed columns, taken from the literature, was shown to give higher flooding points than the data taken in the two inch column, and the curve recommended is based on data from the literature. Sherwood et al. state that their measurements cannot be used for general design purposes because of the large edge effect in a two inch column with one-half inch packing.

Elgin and Weiss (5) conducted tests on four different packing materials in a three inch diameter column using air and water as fluids and found fair agreement with the correlation of Sherwood et al. They presented an empirical linear relationship between the square roots of the superficial gas velocities and the superficial liquid velocities at flooding. However, this method of correlation gave different curves for each size of packing used.

The effect of hysteresis on the flooding point was investigated by Sarchet (6), using an air-water system in an 8 and 21/32 inch diameter column. Operating at constant liquid rates, he approached the flooding point both by increasing the air rate from below the flooding velocity and by decreasing this rate from a higher velocity. These air rates checked within two per cent.

A semi-theoretical equation for flooding velocities was presented by Bertetti (7). However, Bain and Hougen (8), who investigated three oils of different viscosity and three gases, using five different packings in an 8 and 21/32 inch diameter column, could not correlate their results by the Bartetti equation. Bain and Hougen developed the following linear relationship based on the Sherwood, Shipley and Holloway correlation:

$$\text{Log}\left[\frac{U_G^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.16}\right] = b - 1.75\left(\frac{L}{G}\right)^{\frac{1}{4}}\left(\frac{\rho_G}{\rho_L}\right)^{1/8}$$

The value of b appeared to depend on the type of packing. The data of Bain and Hougen were ten per cent above the line given by the Sherwood, Shipley and Holloway correlation at low values of $\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$ and forty per cent below the line at high values.

Comparisons of visual and graphical flooding points were made by Schoenborn and Dougherty (9). In studying the flooding velocities of air and three different liquids, including water, and using five different packings, including one inch and one-half inch Raschig rings, they found the visually determined flooding point approximately equal to the graphical flooding point as defined by White. Schoenborn and Dougherty used a correlation suggested by Colburn to present their data. They plotted

$$\frac{G}{\theta} \quad \text{versus} \quad \frac{L\theta}{G}$$

where θ is a gas density factor equal to unity when air is used.

To bring the data for the different liquids into closer agreement, the $\frac{G}{\theta}$ term was multiplied by a factor involving the kinematic viscosity of the liquid.

Lobo, Friend, Hashmall and Zenz (10) concluded that the major discrepancies in the flooding data reported in the literature were due to incorrect packing characteristics rather than to fundamental differences in experimental techniques. They recalculated all available data by using their experimental values of the S/F^3 term and obtained much closer agreement with the Sherwood, Shipley and Holloway correlation. The method of packing was found to be most significant.

An analogy to flow of vapors through orifices and valves was made to countercurrent flow through packed columns by Zenz (11). An equation is derived which, however, is not valid for high liquid rates.

Lerner and Grove (12) developed a new theory of the mechanism of loading and flooding in packed columns. The mechanism by means of which the gas flowing changes from a continuous into a discontinuous phase is said to be wave formation at the liquid-gas interface. An analogy is made to the phenomenon of two phase flow in pipes.

DESCRIPTION OF EQUIPMENT

The main equipment used for the experimental work consisted of glass columns, packing material, water pumps, air compressors, various metering instruments, and storage tanks. Figure 1 shows a schematic diagram of the apparatus.

Three different glass cylindrical columns were used in this work. The inside diameters of the columns were 1 7/8, 3 7/8, and 7 5/8 inches. The columns will be referred to by their nominal sizes of two, four and eight inches, respectively. Since the cylinders were available in sections four feet high, two sections were mounted together when packed heights of seven feet were desired. A wire mesh screen was used to support the packing. Liquid seal on the bottom of the column was maintained by means of a U-tube through which water from the column returned to the reservoir. Water was pumped from the reservoir through one of three calibrated rotameters to the distribution head. The rotameters covered the range from one-tenth to over fifty pounds of water per minute. Three different distributor heads were utilized. Single metal caps with holes drilled in a concentric circular pattern were used with the two and four inch columns. For the eight inch column, a four prong distributor was used as shown in Figures 2 and 3. The distributor was placed approximately two inches above the top of the packing on all runs.

Air was supplied by the laboratory compressor. For experiments on the eight inch column, the capacity was increased by the installation of an auxiliary compressor. The air passed through a pressure regulator, a cyclone separator, and was metered by one of three stadard orifices, which permitted measurements to 4.5 pounds per minute, the maximum capacity of both compressors. The three orifices consisted of a 1/5 inch orifice in a 3/4 inch pipe, a ½ inch orifice in a one inch pipe, and a 1 3/16 inch orifice in a two inch pipe. The pressure drop across the orifice in use was measured by a water manometer and the upstream pressure by a mercury manometer. Both manometers covered a range of 30 inches and were graduated into tenths of an inch. A glass thermometer was located in the air line below the orifice.

Two pressure taps situated in opposite sides of the column just below the packing support were used to obtain the pressure drop across the packed section. These taps were joined and led to one leg of a water manometer, the other leg being open to the atmosphere. The pressure just above the packing inside the top of the column was found to be indiscernible from atmospheric pressure.

The packing consisted of porcelain Raschig rings manufactured by the United States Stoneware Company. One-fourth, one-half, three-fourths, and one inch sizes were utilized, having wall thicknesses of 1/32, 2/32, 3/32, and 1/8 inch, respectively.

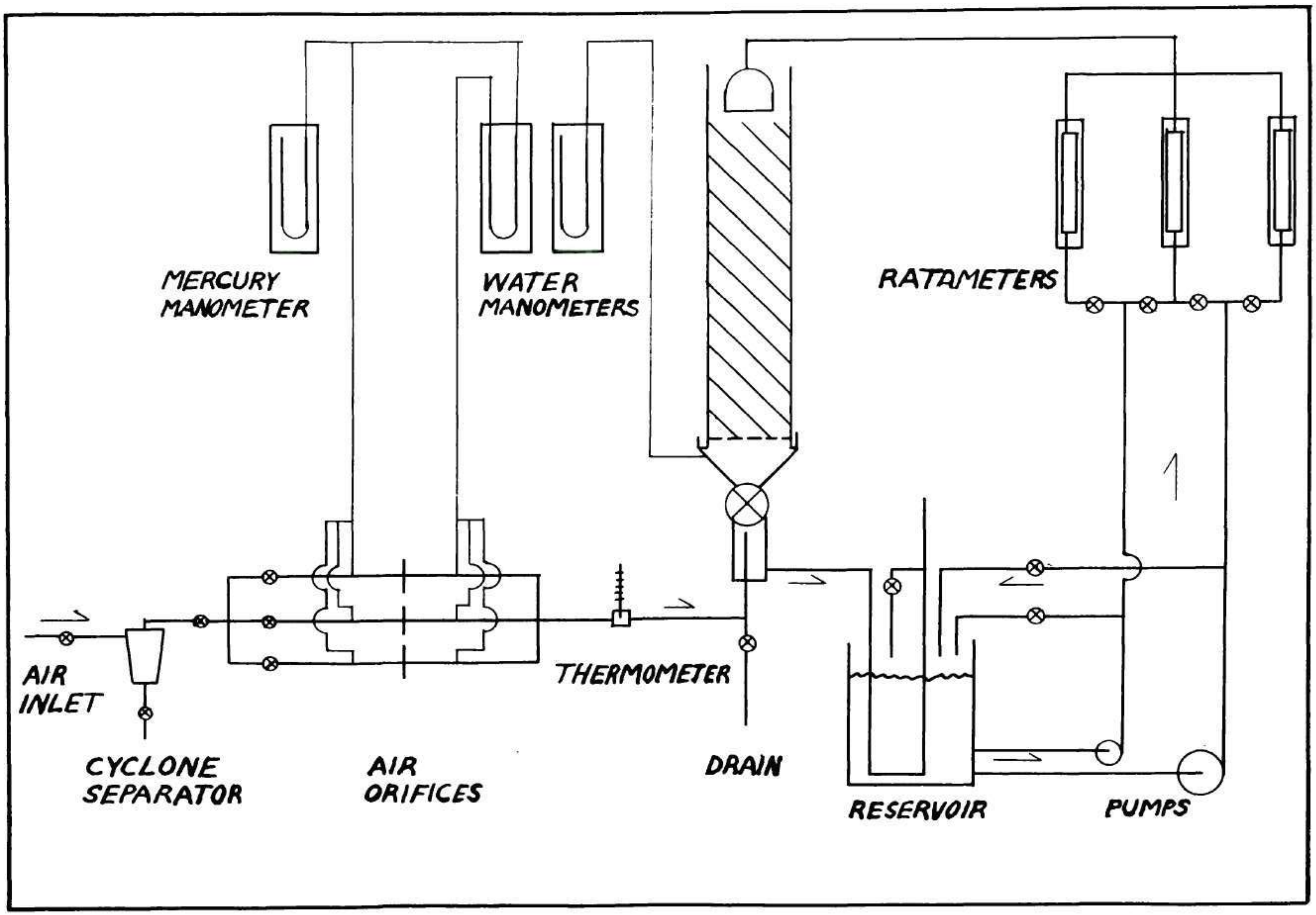


Figure 1. Diagram of Equipment

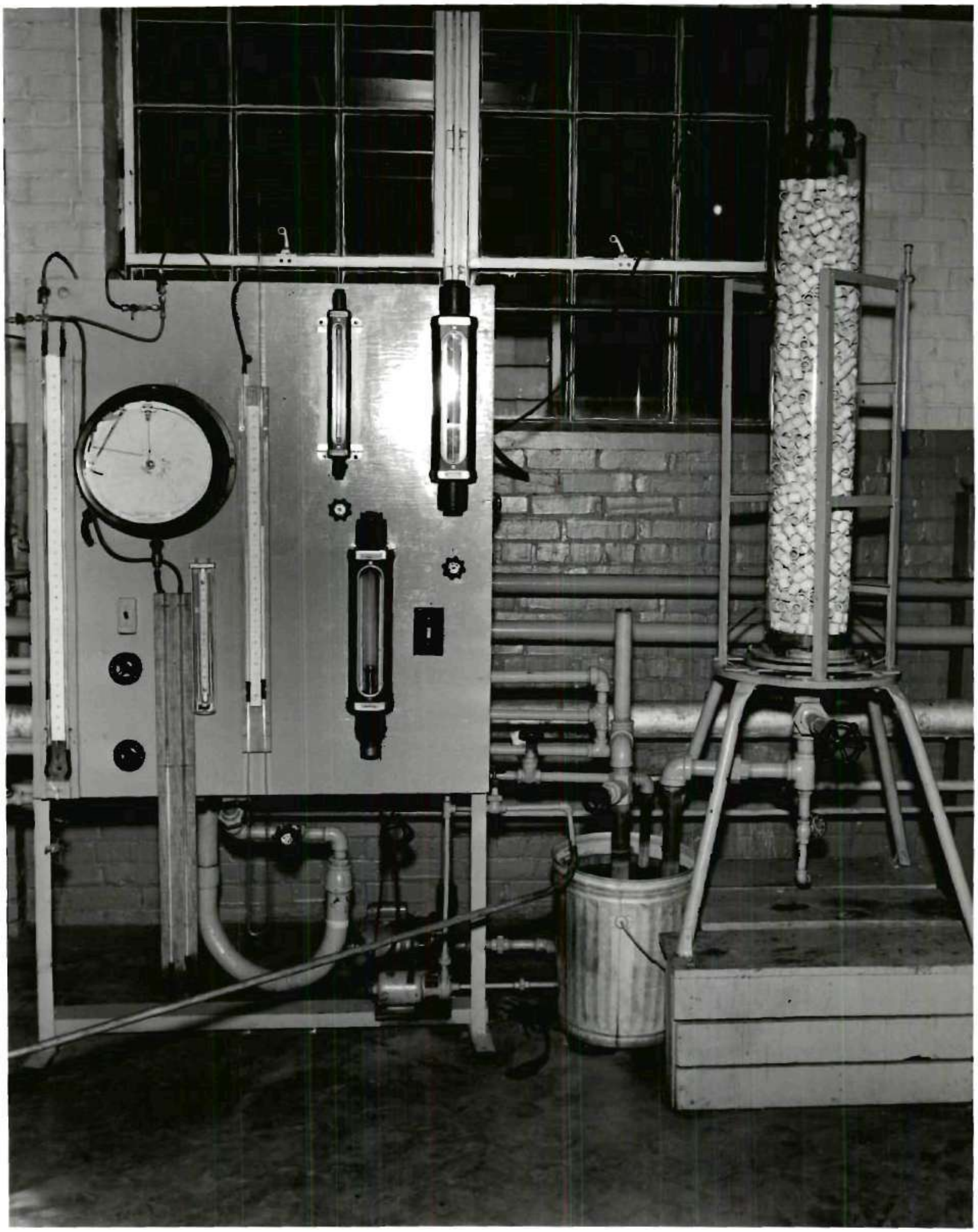


Figure 2. Front View of Equipment.

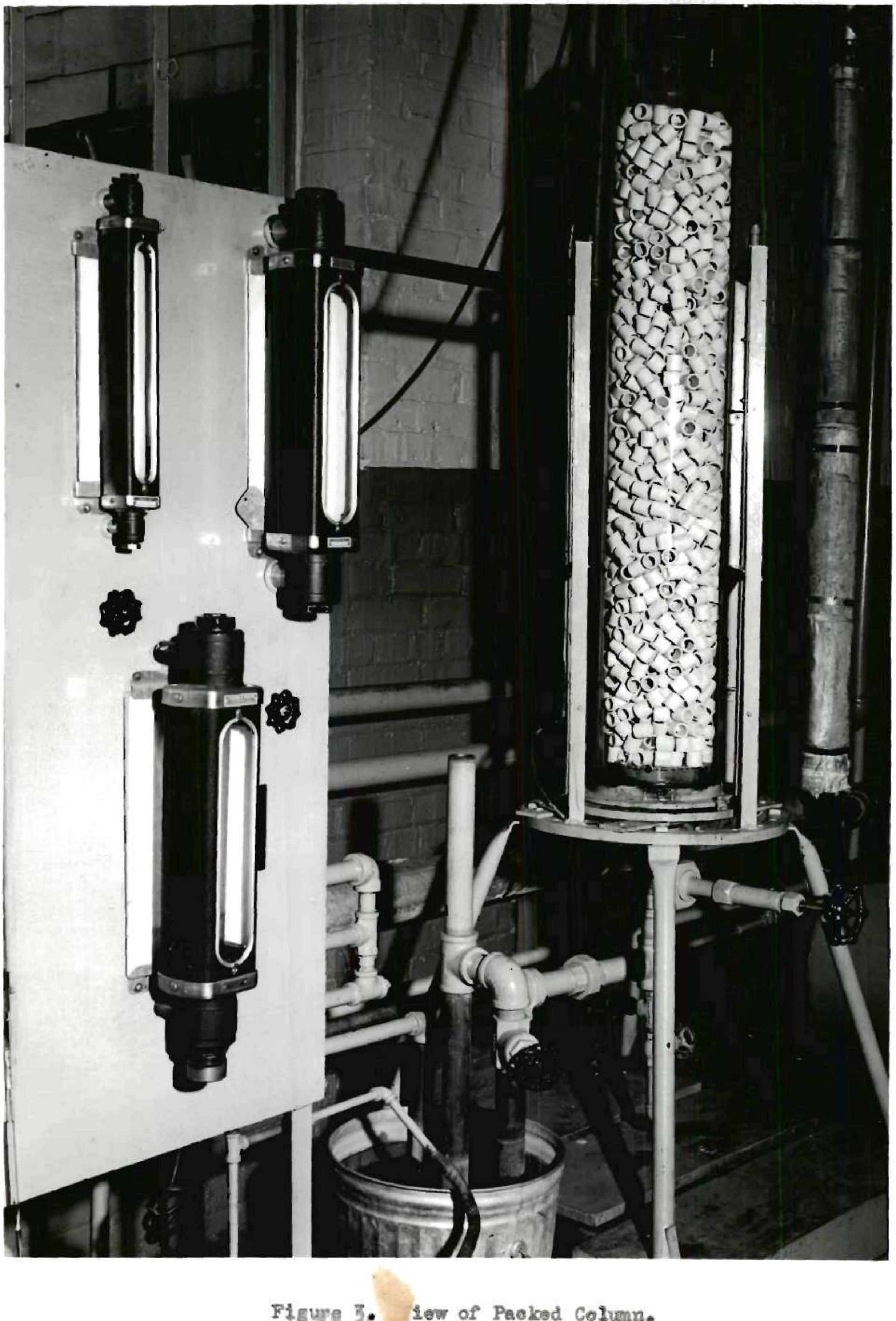


Figure 3. View of Packed Column.

EXPERIMENTAL PROCEDURE

In the experiments described below each column was packed by dropping the Raschig rings individually into the water-filled tower. The rings were added slowly, so that each piece could settle into place without being influenced by the motion of any other piece. In the case of the one-fourth inch rings, the pieces were added from a small vibrator rather than by hand. These precautions seemed justified in view of the assertion of Lobo et al. (10) that the method of packing was a significant variable.

Although some runs were made on packing as added, in most cases the packing was stabilized by partly filling the column with water and passing air up through the column at such a rate that the height of the water reached almost to the top of the packing. This resulted in a mild shaking action applied to the packing simultaneously throughout its entire height. This procedure, referred to in this investigation as standard packing procedure, was followed to guard against shifting of the packing occurring during subsequent runs, and also to allow a closer application of the data to industrial conditions. In two instances, after flooding velocities were determined on the stabilized packing, the packing was violently shaken by a more vigorous application of the above method and another series of flooding tests made.

Flooding determinations were made in essentially the same manner as that used by previous investigations (3, 4, 9, and 10). The liquid flow rate was adjusted to an arbitrary value and the gas velocity increased in small increments until a condition of absolute flooding developed. At each incremental gas rate, the pressure drop across the column was allowed to reach a constant value. Readings were then taken of this pressure drop, the liquid rate, the pressure drop across the orifice, the upstream static pressure and the gas temperature. Since the water temperature was substantially constant and since small variations did not affect the calculations, this measurement was not recorded on all runs.

Since most investigators have found the graphical method of determining the flooding point as suggested by White (3) to be more reliable than the visual method, the former was used in this work. However, the two methods agreed closely, perhaps due to the small increments by which the air velocity was increased in the test procedure.

The flooding condition was characterized by violent entrainment and a build-up of liquid level above the packing. Preliminary tests showed that if the air velocity was increased beyond this point, the uppermost layer of packing would be severely shaken and subsequent runs on the same packed section would indicate lower flooding velocities due to the changed arangement of rings in this top layer. Hence, tests were not conducted beyond this point. All tests were carried out at atmospheric pressure, which was recorded.

The apparatus was flushed out daily and fresh water added to the reservoir.

For tests in which the pressure drop across the column reached a value of over two feet of water, the height of the liquid seal on the bottom of the column was increased by closing the normal overflow valve.

At the completion of each series of flooding velocity determinations on a packed section, air was blown through the column for several hours until the packing was completely dry. The free gas space or void per cent was measured by the addition of water to the dry packing. Since some variation in the inside diameter of each column was noted, the empty volumes of the column were also measured by water additions.

Two different methods of measuring the fractional void space were noted in the literature. The method of addition of water to the dry packing gives a value of F commonly referred to as "dry voids". The other method consists of measuring the amount of water drained off a previously filled packed section. This latter method, based on "drained wet voids", gives a lower value of F due to some of the liquid being retained on the packing. Tests were conducted on one-half inch rings by both methods. The "drained wet voids" basis gave a value of F lower by 0.03 than that found by "dry voids". This was in agreement with measurements made by Summers (14) on one-half inch Berl saddles. Since the majority of other investigators have used "dry voids", and since more consistent results were obtained by this method, it was chosen for this work.

Values of S were calculated from a knowledge of the surface areas and volumes of the individual rings and from the values of F for the particular packed sections.

VISUAL OBSERVATIONS

Raschig rings, particularly in the smaller sizes, exhibited a tendency to pack closely against the walls of the column. The individual rings showed a tendency to assume a position with as large a portion of their surface against the column as possible. In the case of one-fourth inch rings, when the packing was dumped from the column, the attraction of the rings for the wet glass wall was such that the rings nearest the wall remained in place while the other rings dropped out. This effect was in contrast to that observed in the experiments of Metcalfe (13) with Berl saddle and Intalox saddle packings. In spite of this effect, some channeling of the liquid at the walls was noted, increasing as the ratio of column diameter to ring size decreased.

The shaking action described above in the section "Experimental Procedure", had the effect of decreasing the height of the column, thus decreasing the void per cent. The decrease in void per cent, as can be seen from the data, was a function of the amplitude of the shaking action.

The shaking action, in combination with the attraction of the packing for the wall, increased the orientation of the individual rings relative to each other. When the violent shaking action was applied to the one-half inch packing, several sections next to the wall were observed with all the rings lying with their axis parallel to each other.

As the air velocity was increased in the flooding tests, a fluttering condition was noticed at points where the air bubbled through the liquid. This fluttering began from a number of points distributed up and down the column. With further increases in the air rate this fluttering effect increased in violence until at some one height, it completely encircled the column. From this height the flooding spread upwards until it reached the top of the packed section.

Due to the care taken in packing the columns, random distribution of the packing was assured, and as a result, no one height was noted as the point where flooding first occurred.

DISCUSSION OF RESULTS

The reproducibility of the data was good. Several duplicate tests were made. During each set of runs at no time was there a change in the air velocity at which the column flooded, although on some occasions there was a change in the pressure drop across the column at flooding of from one-tenth to three-tenths of an inch of water.

As noted by Lobo et al. (10), the major discrepancies in published flooding velocity data correlated by the method of Sherwood, Shipley, and Holloway (4) are due to the wide range of values reported for S/F^3. (S is the surface area of the packing and F is the fraction free gas space in a packed column). Since the surface area is proportional to the factor (1 - F), the value of the S/F^3 term is quite sensitive to changes in F. For example, for any given packing, a decrease in F from 0.650 to 0.640 causes S/F^3 to increase 7.85 per cent above its former value. For this reason, particular care was taken in packing the column as mentioned above in "Experimental Procedure".

Two correlations of all the data presented in this work are given. The first correlation is by the method of Colburn (Figure 4), and the second by that of Sherwood, Shipley, and Holloway (Figure 5). This latter method was chosen to illustrate the effects of shaking treatment, packed height, column diameter, and packing size on flooding velocities (Figure 6 to 12 inclusive). In presenting a correlation showing the effect of any given one of the variables mentioned above, an effort was made to hold the other variables constant.

Application of the Colburn correlation to the data (Figure 4) resulted as expected in a general trend of higher flooding velocities occurring with the larger packing sizes. Rather than generalize this correlation by displacing the nearly parallel flooding curves in a vertical direction, the more generally accepted Sherwood correlation was used.

This latter method, modified as suggested by Lobo et al. (10) using the actual experimental values of S and F, correlated the data well. (Figure 5). Curves of Sherwood, Shipley, and Holloway, and of Lobo and his co-workers, taken from the literature, are given on this figure, and show that the experimental data is better represented by that of Lobo. The Lobo modification of the Sherwood correlation was used to study the effects of packed height, shaking treatment, column diameter, and packing size.

The effect of packed height on flooding velocities is illustrated in Figures 6 and 7. Using one-half inch rings in a four inch column, packed heights of one, two, three and one-half, and seven feet were studied. No trend was noted, although for low values of $\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$ the two foot section gave lower flooding velocities than the other heights.

A small height effect was observed in the case of one-half inch rings in an eight foot column packed to two and three and one-half foot heights. The two foot section gave increasingly higher flooding points as the value of $\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$ decreased. While the three and one-half and seven foot packed sections of one-half inch rings in a two inch column did not show a height effect, the points deviated somewhat from the curve of Lobo et al. (10). This point will be considered later.

With Berl saddle packing, an effect of height was noted by Metcalfe (13), the higher packed sections giving lower flooding points. The lack of this effect with Raschig rings except in the case mentioned above of one-half inch rings in an eight inch column, might be caused by the tendency of the rings to pack closely to the walls of the column as noted in "Visual Observations". This wall effect could possibly conceal the effect of height. As the ratio of column diameter to packing size increases the percentage of rings near the wall decreases and this tendency of the rings to pack tightly against the column wall becomes relatively less important. In these cases the packed section may show a similar height effect to Berl saddle packing. This theory is in accord with the experimental fact that only at a column diameter to packing size ratio of sixteen to one was there any height effect noted. This particular test on one-half inch rings in an eight inch column was the only one having a ratio of over eight to one on which the effect of height was studied. Thus no definite statement can be made on the theory outlined above.

The variation of flooding velocities with shaking treatment is presented in Figure 8. The data are for one-half inch rings packed one foot high in a four inch column. Although the unshaken section required higher gas rates for flooding than the section packed by the standard packing procedure, the higher void space in the former caused the factor S/F^3 to bring the two sections into good agreement. In the case of the violently shaken section, although the fractional void space decreased by 0.05 from the stabilized section value, the resulting increase in the S/F^3 factor was not enough to bring the data into agreement with the unshaken and the gently shaken sections. In other words, for no shaking and for mild shaking (standard packing procedure), the S/F^3 factor throws the data in line, but for violent shaking the results are off the correlation curve of Lobo. Comparison of data for the same liquid rates shows that, due to this violent shaking, the gas rate at flooding was reduced to seventy per cent of its former value. Similar tests, made with two foot packed sections, but with some reduction in the amount of violence, show that the gas flooding velocity was decreased to eighty-four per cent of normal.

The effect of column diameter is presented in Figures 9 and 10 and that of packing size in Figures 11 and 12. The one-half inch rings in a two inch column (Figures 7 and 10), as mentioned above, and the one inch and three-fourths inch rings in a four inch column (Figure 12), show a deviation from the curve of Lobo. The data falls beneath the curve except for the case of the one inch rings. It is considered significant that all of these discrepancies occurred on the only tests in which the column diameter to packing size ratio was less than eight to one.

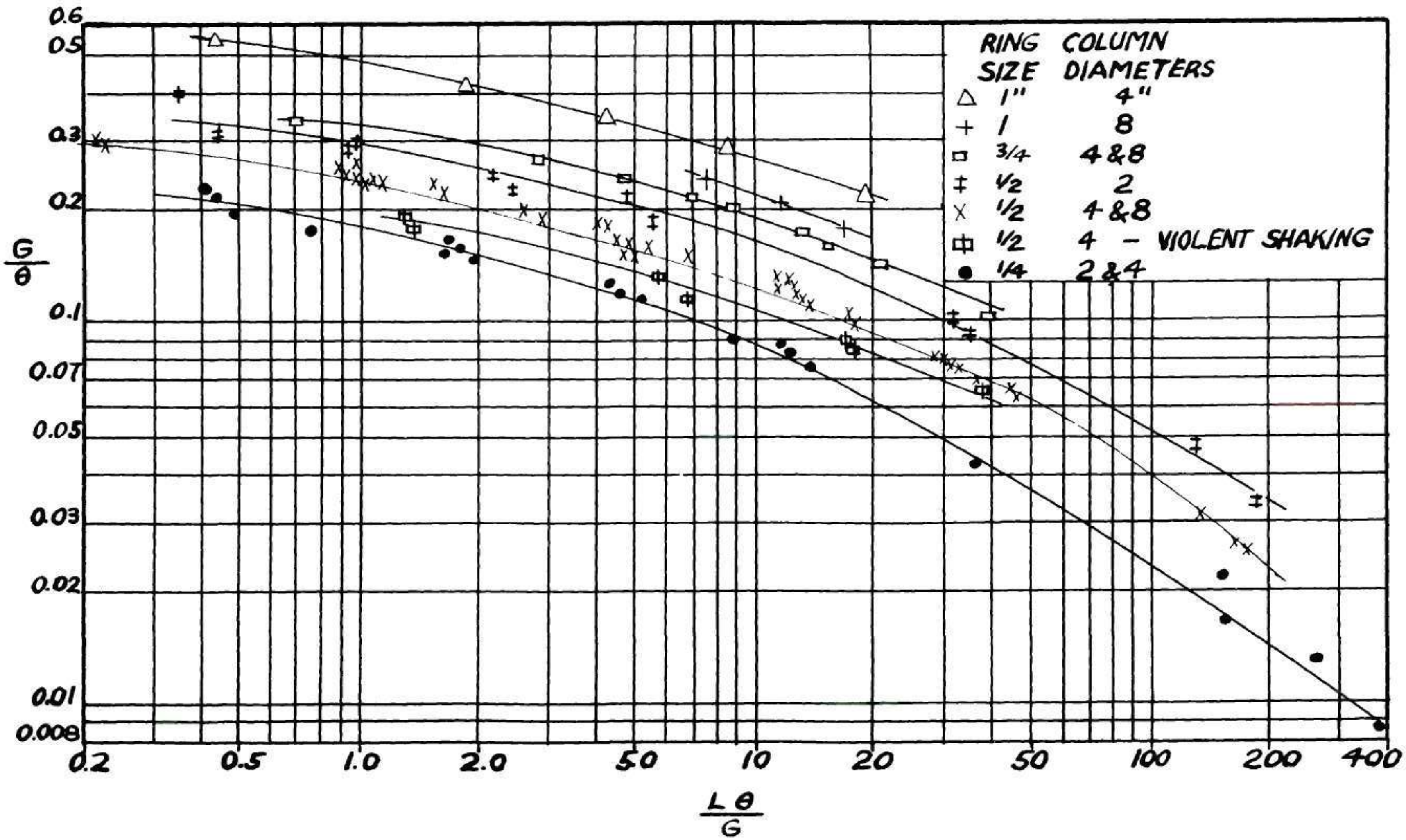


Figure 4. Summary of Data - Colburn Correlation.

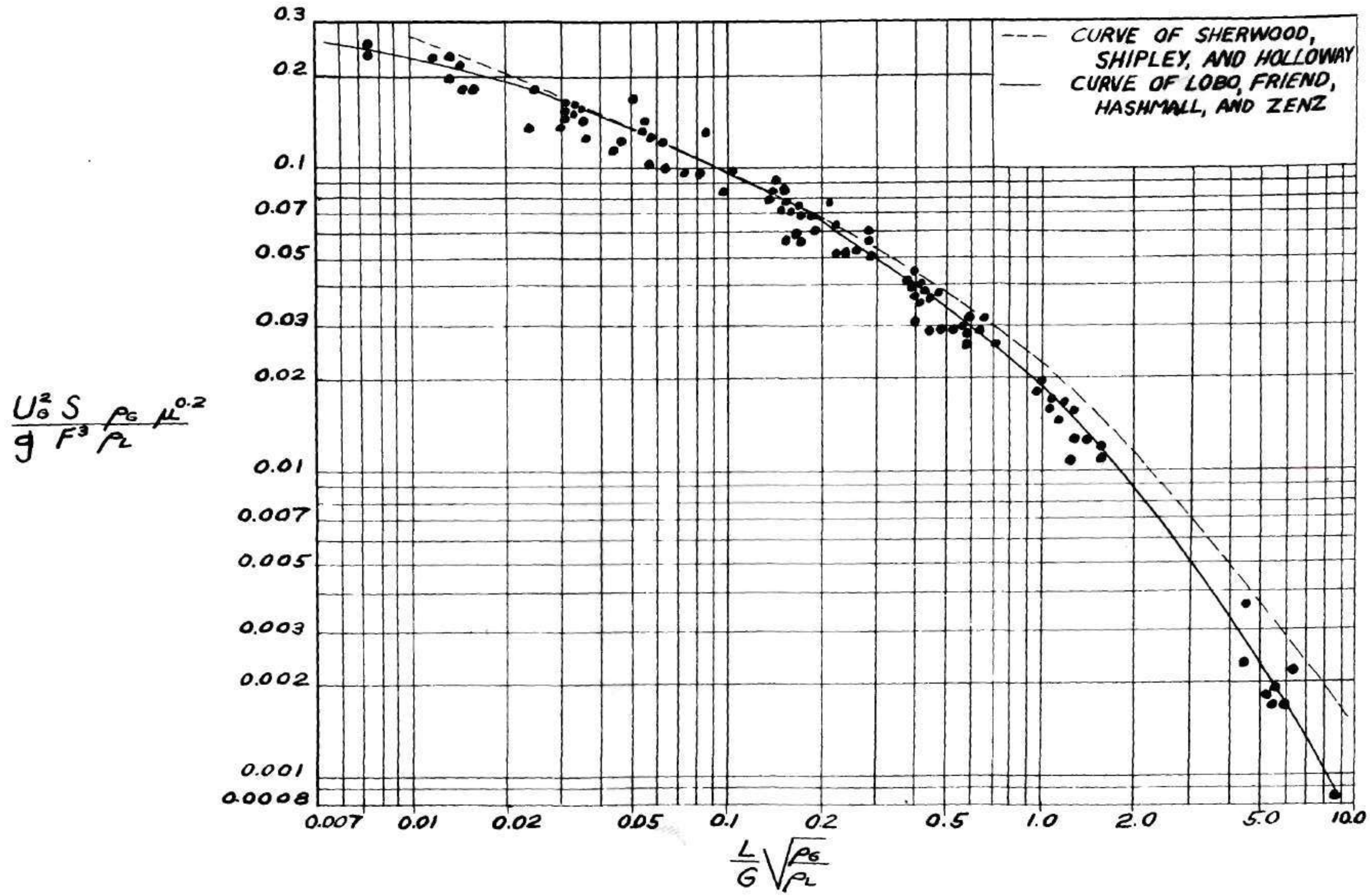
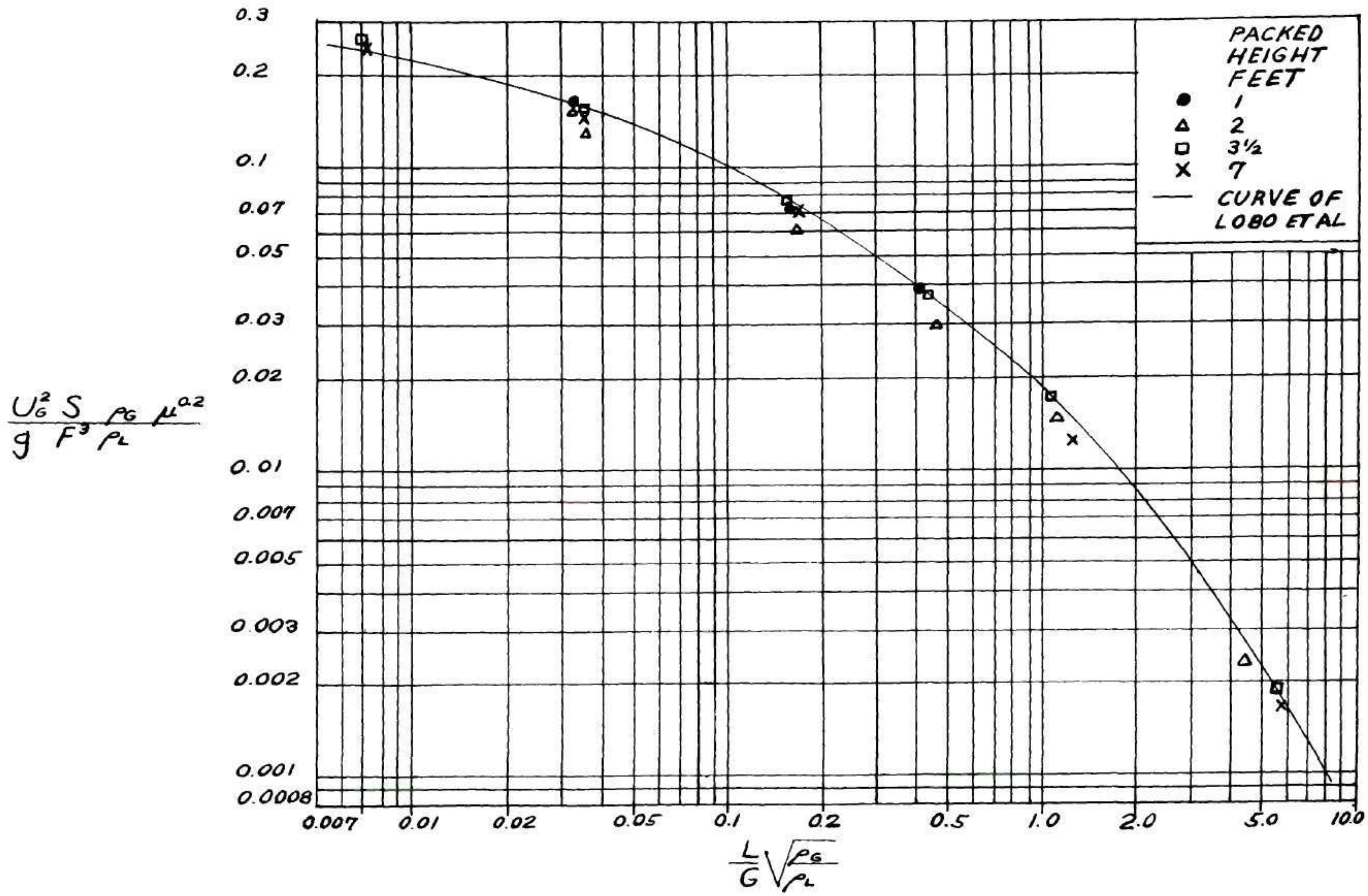


Figure 5. Summary of Data - Sherwood Correlation.



$$\frac{U_G^2}{g}\frac{S}{F^3}\frac{\rho_G}{\rho_L}\mu^{0.2}$$

$$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$$

Figure 6. Effect of Height - One Half Inch Rings, Four Inch Column.

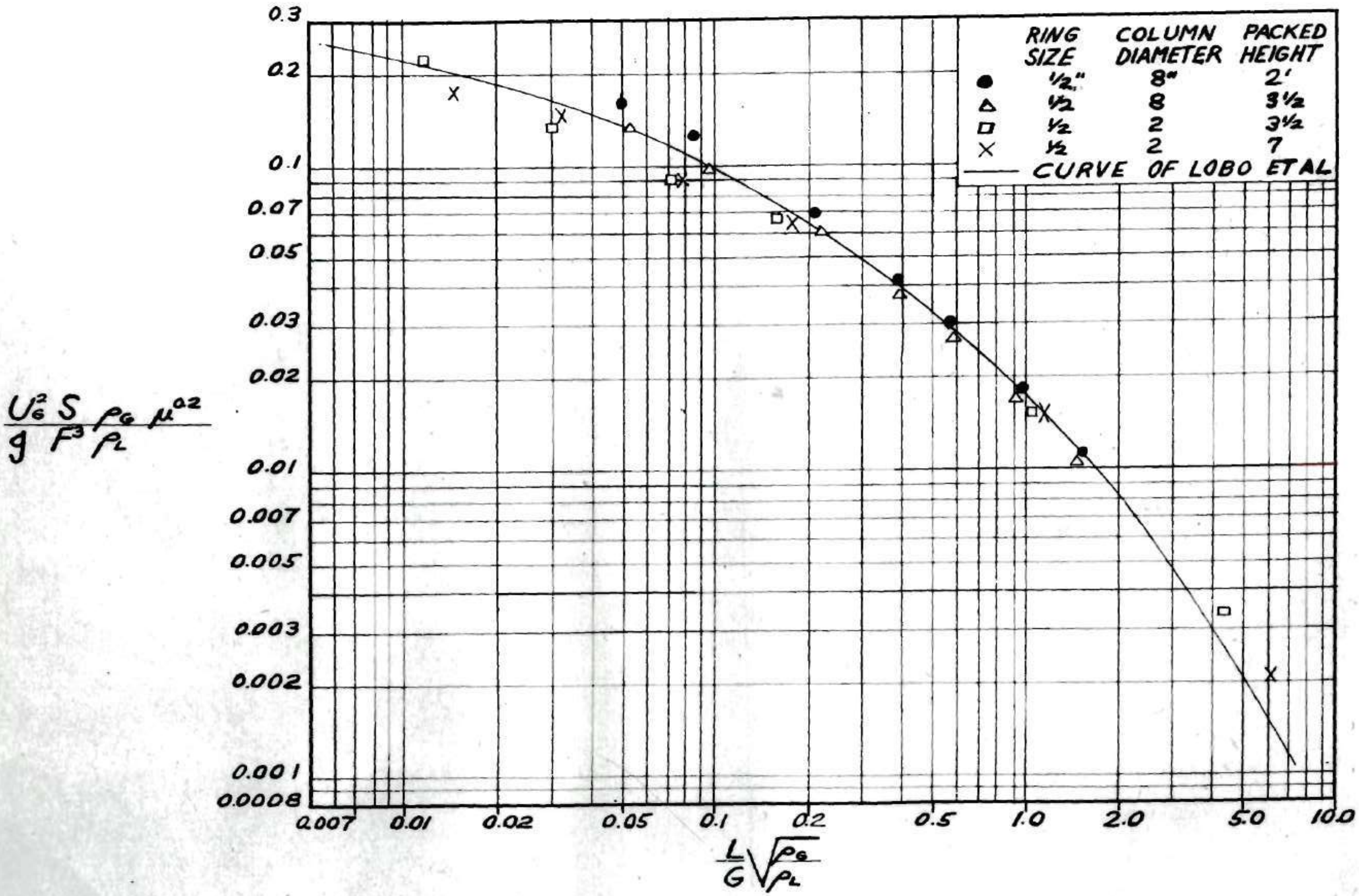


Figure 7. Effect of Height - One Half Inch Rings, Two Inch and Eight Inch Columns.

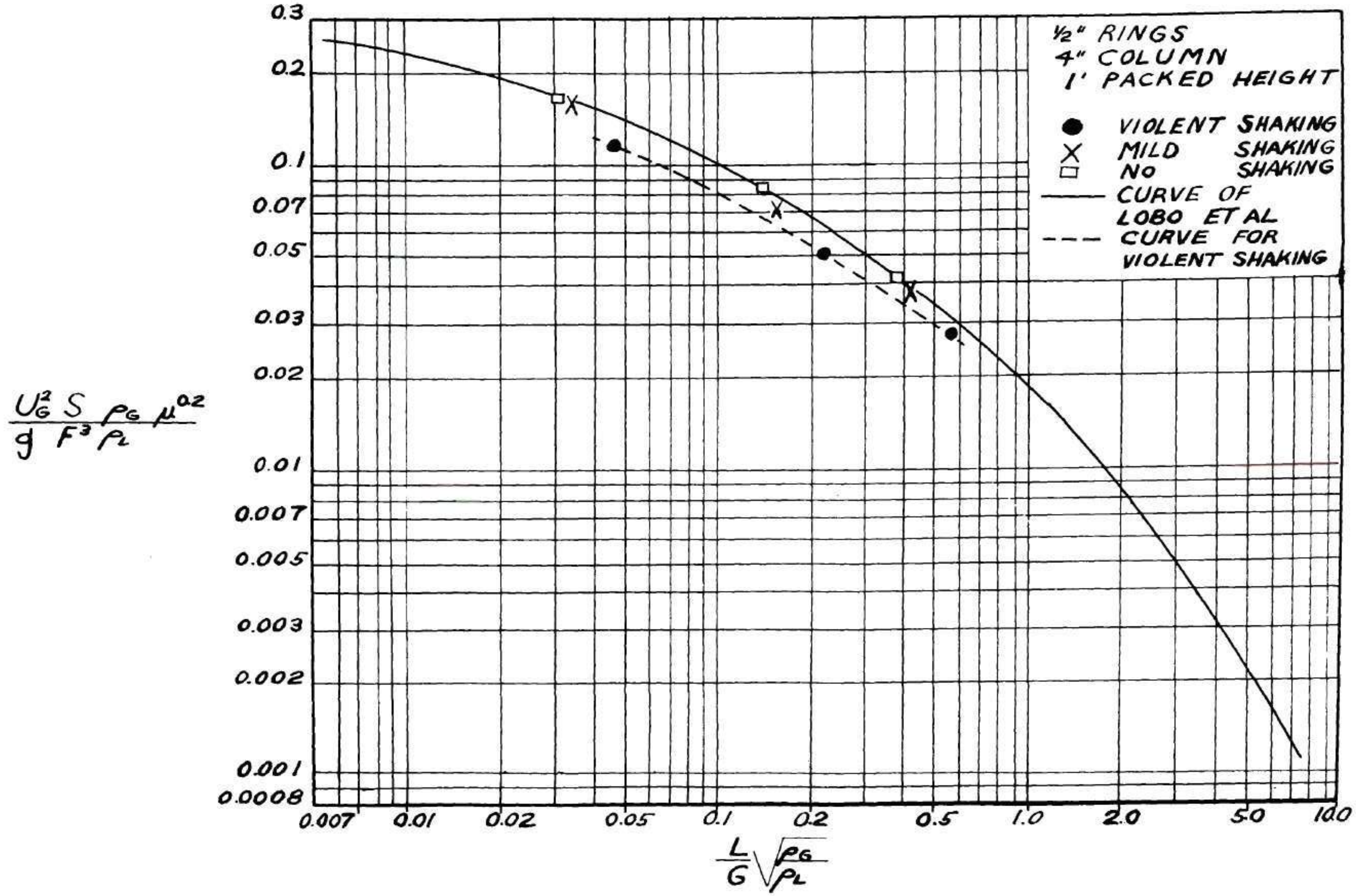


Figure 8. Effect of Shaking Treatment.

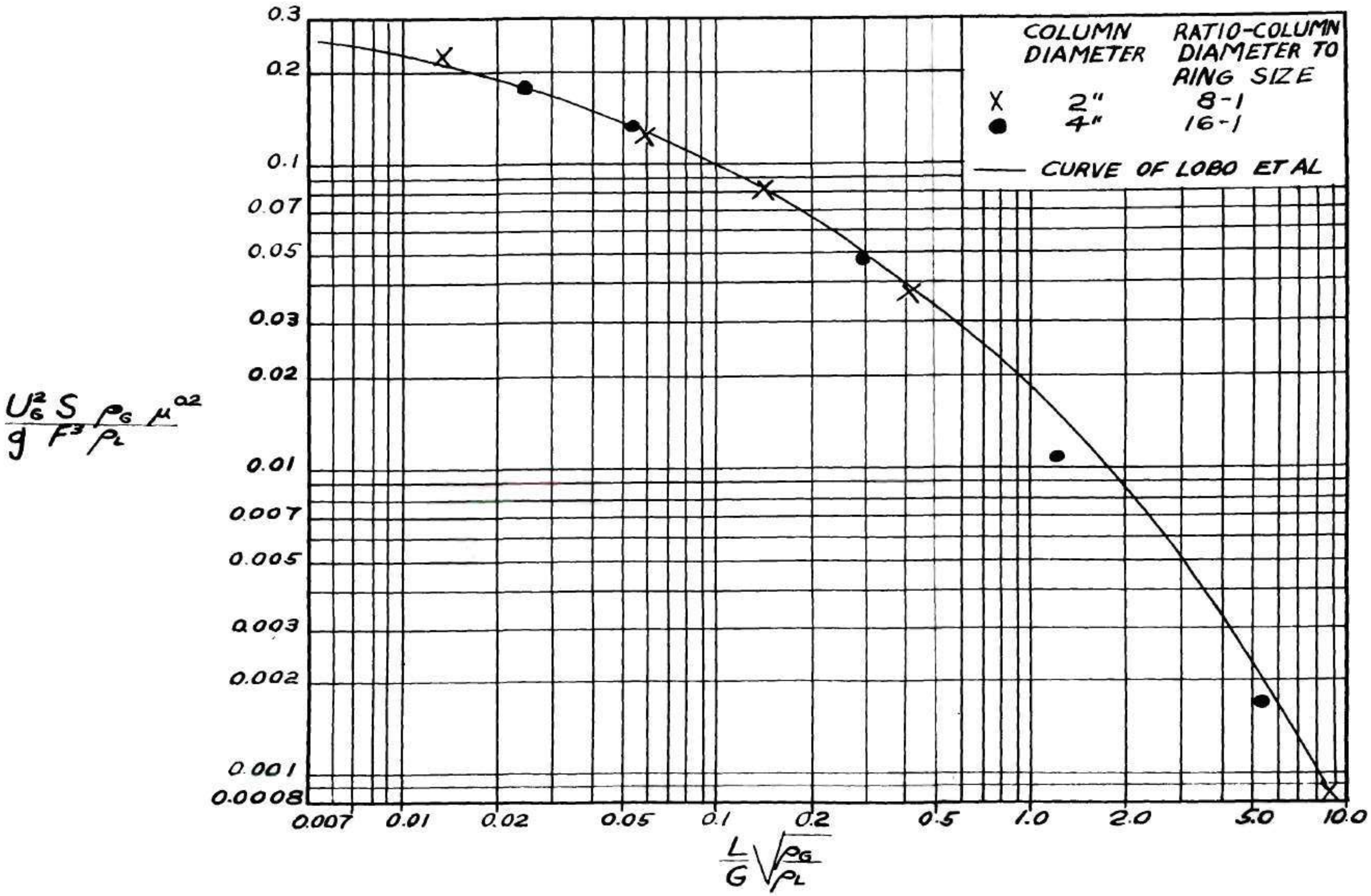


Figure 9. Effect of Column Diameter - One-fourth Inch Rings, Seven Feet Packed Height.

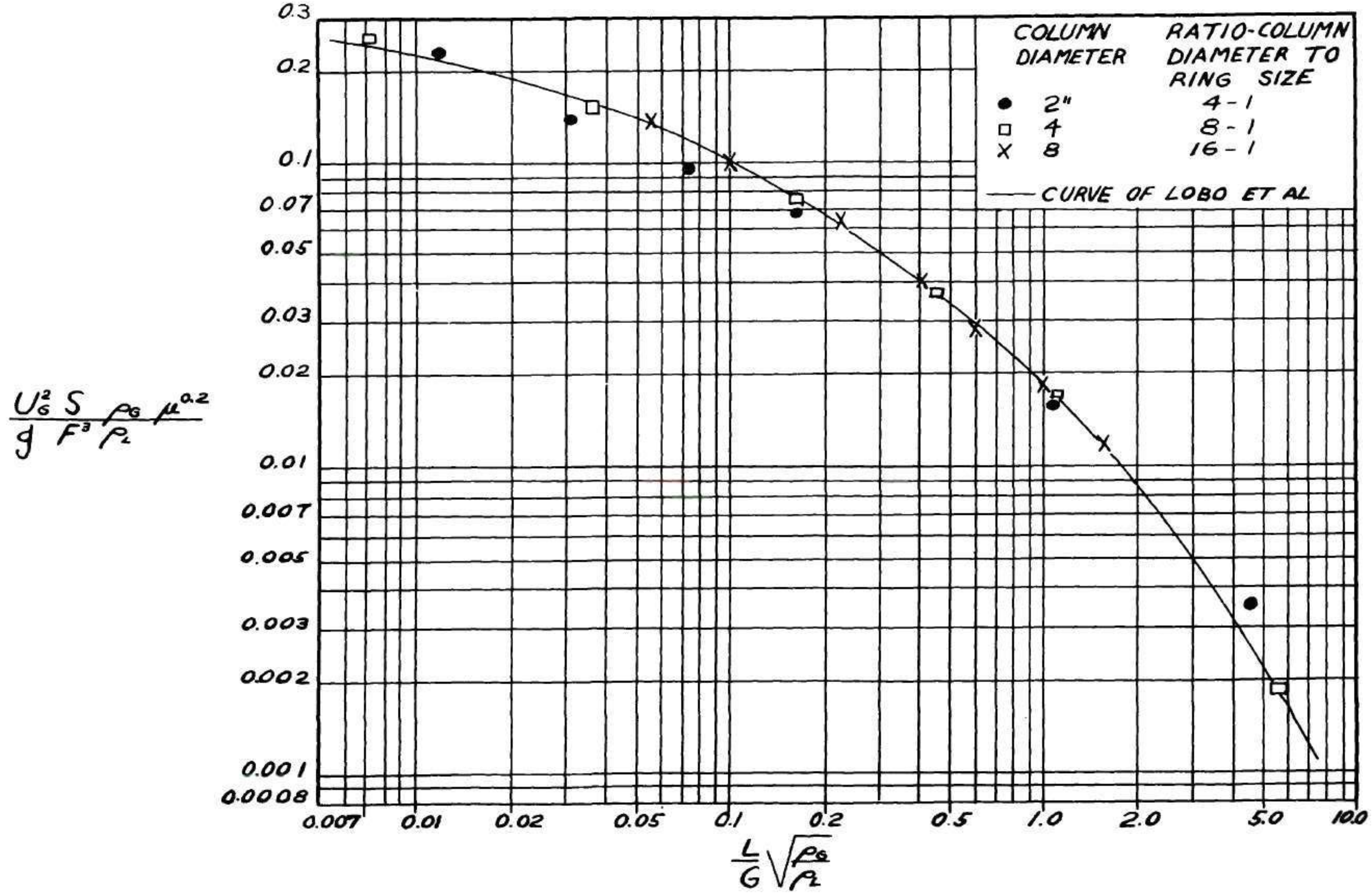


Figure 10. Effect of Column Diameter - One Half Inch Rings, Three and One Half Feet Packed Height.

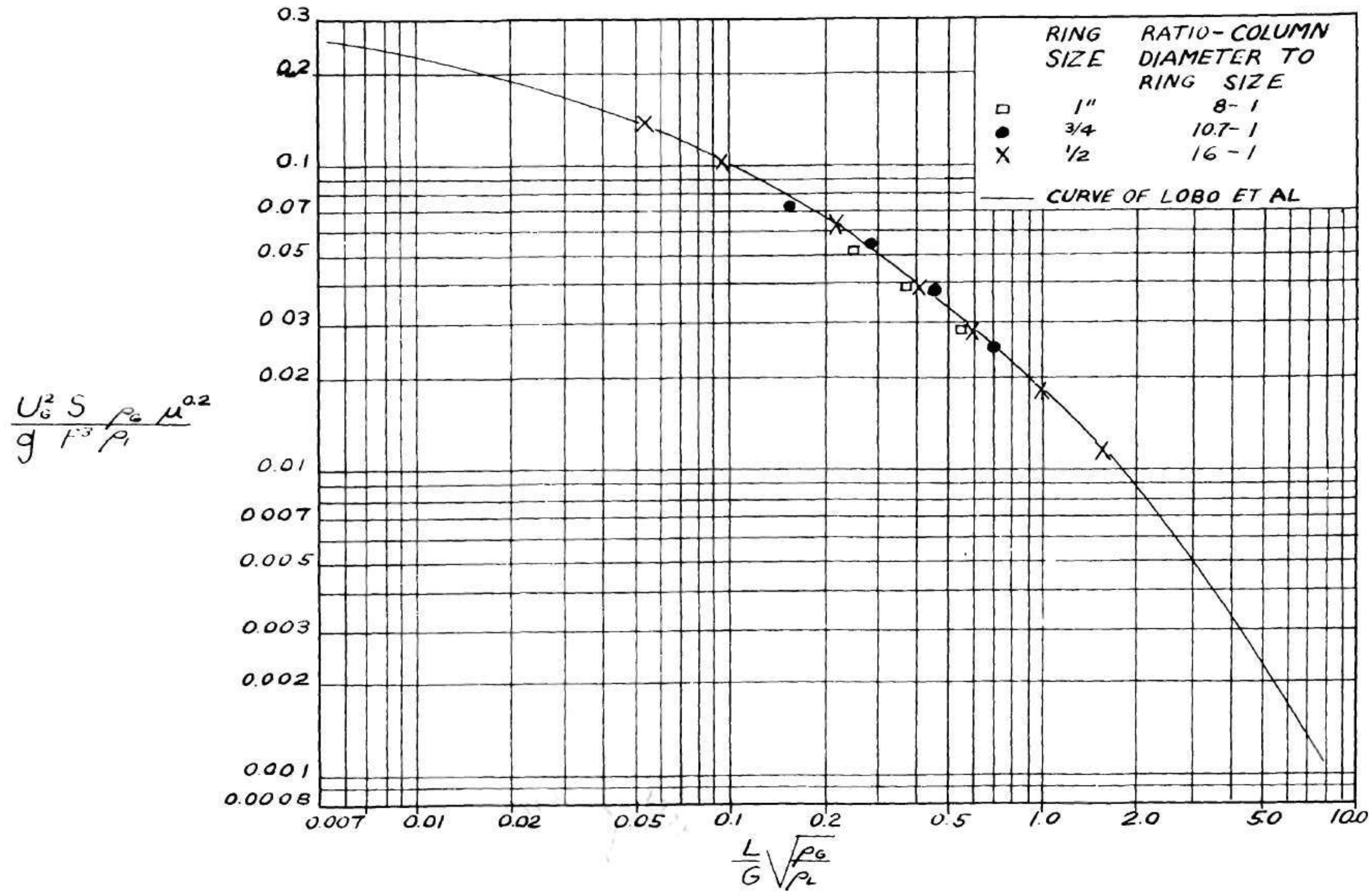


Figure 11. Effect of Packing Size - Eight Inch Column, Three and One Half Feet Packed Height.

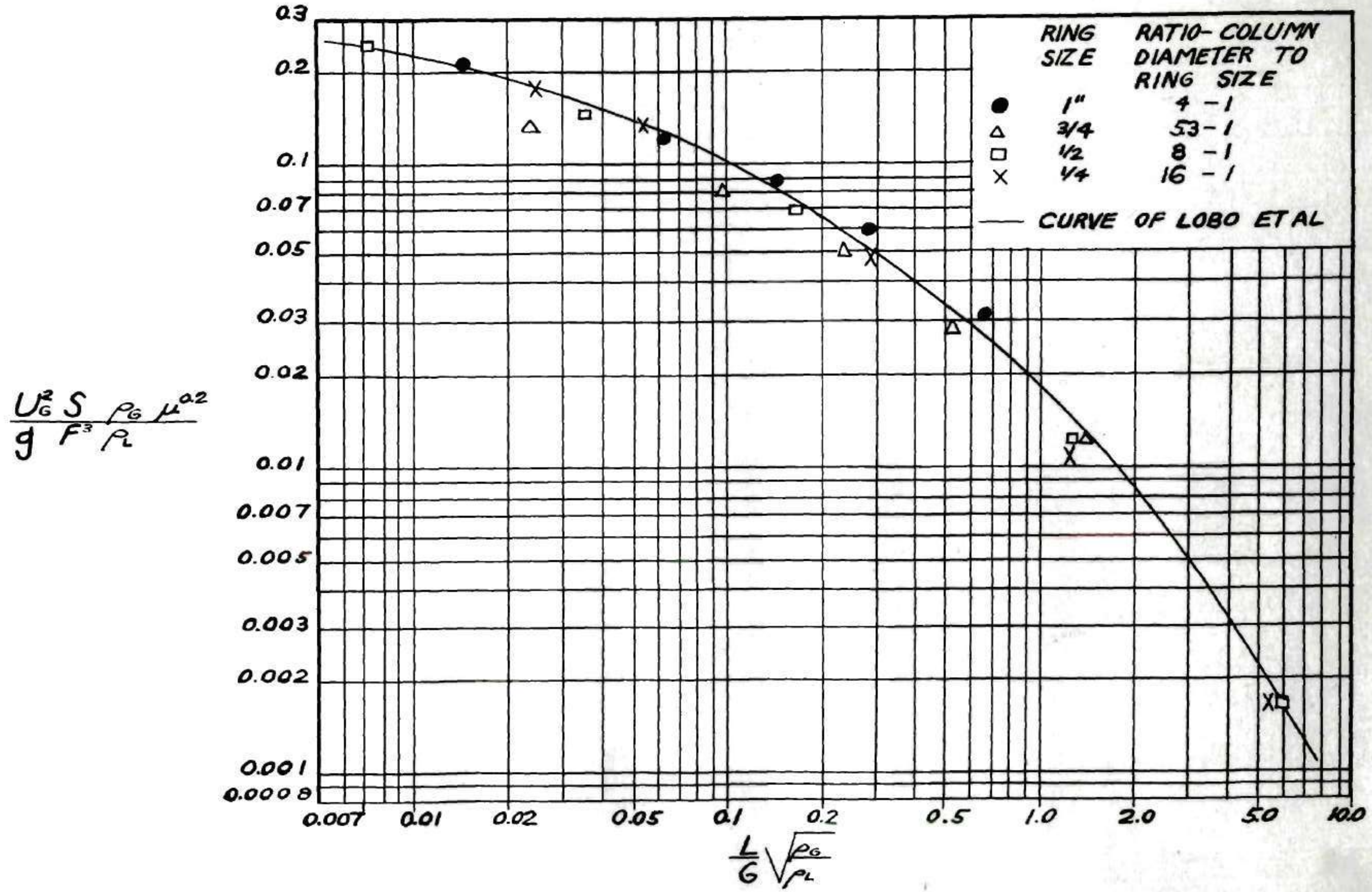


Figure 12. Effect of Packing Size - Four Inch Column, Seven Feet Packed Height.

CONCLUSIONS

From the results of this investigation the following conclusions are drawn:

1. The Lobo, Friend, Hashmall and Zenz (10) modification of the Sherwood, Shipley and Holloway (4) correlation is a valid representation of flooding velocities in Raschig ring packed columns in which the column diameter to packing size ratio is equal to or greater than eight to one. Columns with a smaller ratio should be designed with a greater safety allowance of limiting flow conditions.

2. The general correlation recommended by Sherwood, Shipley, and Holloway (4) does not fit the experimental data at the extreme high and low values of $\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$.

3. Excessive shaking action applied to Raschig rings in packed columns will give a considerable decrease in allowable flow rates.

4. In columns in which the diameter to packing size ratio is equal to or less than eight to one, the height of the packed section does not influence the Sherwood correlation of the flooding velocities. In columns with larger ratios it is possible, but not certain, that an increase in packed height will cause the curve representing the correlated data to be lowered.

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APPENDIX

DATA

Condition of Packing	Air Temp., °F.	Liquid Flow Rate, #/sec.ft.^{2}	Gas Flow Rate #/sec.ft.^{2}	$\frac{L}{G}$	$\frac{U_G^2 S \rho_G \mu^{0.2}}{gF^3 \rho_L}$	$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$	Pressure Drop Across Column, Inches H_2O
1 " Rings	83	2.955	0.1780	16.61	0.0288	0.562	5.9
8 " Column	90	2.375	0.211	11.25	0.0405	0.380	8.9
3½ ' Height	99	1.797	0.242	7.43	0.0533	0.251	8.0
F = 74.1							
S = 55.4							
1 " Rings	78	0.241	0.561	0.429	0.221	0.01450	18.7
4 " Column	78	0.770	0.417	1.850	0.1220	0.0625	17.3
7 ' Height	75	1.495	0.356	4.20	0.0898	0.1419	18.2
F = 77.3	75	2.51	0.296	8.48	0.0616	0.2865	17.6
S = 48.6	75	4.17	0.214	19.50	0.0322	0.659	18.1
3/4 " Rings	95	2.955	0.1408	21.0	0.0252	0.710	16.2
8 " Column	91	2.375	0.1760	13.49	0.0392	0.457	11.0
3½ ' Height	95	1.797	0.211	8.52	0.0565	0.288	10.6
F = 73.7	106	1.115	0.242	4.61	0.0740	0.1558	10.0
S = 76.0							
3/4 " Rings	76	0.241	0.343	0.703	0.1349	0.0237	20.2
4 " Column	76	0.770	0.269	2.86	0.0828	0.0967	20.5
7 ' Height	76	1.495	0.214	6.98	0.0525	0.236	18.9
F = 75.0	76	2.51	0.160	15.68	0.0292	0.530	13.3
S = 72.3	76	4.17	0.104	40.2	0.0124	1.360	12.2
½ " Rings	86	2.955	0.0635	46.5	0.01200	1.571	8.7
8 " Column	86	2.375	0.0811	29.25	0.01960	0.990	9.4
2 ' Height	77	1.797	0.1047	17.15	0.0326	0.580	7.9
F = 62.9	79	1.453	0.1240	11.72	0.0457	0.396	8.1
S = 111.0	84	1.002	0.1590	6.31	0.0753	0.213	7.7
	88	0.546	0.2125	2.57	0.1345	0.0870	11.6
	109	0.363	0.241	1.507	0.1728	0.0509	11.2

Condition of Packing	Air Temp., °F.	Liquid Flow Rate, #/sec.ft.^{2}	Gas Flow Rate, #/sec.ft.^{2}	$\frac{L}{G}$	$\frac{U_G^2 S \rho_G \mu^{0.2}}{g F^3 \rho_L}$	$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$	Pressure Drop Across Column, Inches H_2O
½ " Rings	81	2.955	0.0645	45.8	0.01178	1.549	13.8
8 " Column	84	2.375	0.0816	20.1	0.01887	0.984	13.3
3½ ' Height	76	1.797	0.1010	17.80	0.0289	0.602	10.2
F = 63.6	79	1.453	0.1203	12.07	0.0409	0.408	9.0
S = 109.0	83	1.002	0.1510	6.64	0.0645	0.224	9.8
	87	0.546	0.1910	2.86	0.1035	0.0967	10.1
	98	0.363	0.2235	1.625	0.1415	0.0550	13.1
½ " Rings	88	0.241	0.260	0.927	0.1690	0.0313	4.5
4 " Column	88	0.770	0.185	4.17	0.0855	0.1406	4.2
1 ' Height	88	1.495	0.132	11.33	0.0435	0.383	4.5
Unshaken							
F = 65.2							
S = 104.0							
½ " Rings	84	0.241	0.246	0.980	0.1645	0.0331	6.0
4 " Column	84	0.770	0.164	4.70	0.0729	0.1588	5.2
1 ' Height	84	1.495	0.121	12.35	0.0397	0.417	4.5
F = 64.1							
S = 107.3							
½ " Rings	84	0.241	0.175	1.377	0.1209	0.0465	3.5
4 " Column	84	0.770	0.115	6.70	0.0521	0.226	2.9
1 ' Height	84	1.495	0.085	17.58	0.0284	0.593	5.5
Violently							
Shaken							
F = 59.1							
S = 122.4							

Condition of Packing	Air Temp., °F.	Liquid Flow Rate, #/sec.ft.^{2}	Gas Flow Rate, #/sec.ft.^{2}	$\frac{L}{G}$	$\frac{U_G^2 S \rho_G \mu^{0.2}}{g F^3 \rho_L}$	$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$	Pressure Drop Across Column, Inches H_2O
½ " Rings	70	0.241	0.250	0.964	0.1563	0.0326	11.1
4 " Column	77	0.241	0.226	1.067	0.1278	0.0361	12.1
2 ' Height	77	0.770	0.156	4.93	0.0607	0.1670	10.2
F = 65.2	77	1.495	0.109	13.71	0.0297	0.463	9.5
S = 104.0	74	2.51	0.076	33.1	0.0144	1.120	10.7
	74	3.96	0.0302	131.3	0.00228	4.44	13.0
½ " Rings	65	0.241	0.187	1.29	0.1170	0.0437	11.6
4 " Column	65	0.770	0.136	5.66	0.0618	0.1915	12.2
2 ' Height	68	1.495	0.088	17.00	0.0258	0.575	9.2
Violently Shaken	68	2.51	0.066	38.05	0.01455	1.287	8.8
F = 61.3							
S = 115.7							
½ " Rings	79	0.241	0.261	0.923	0.1579	0.0312	15.5
4 " Column	78	0.770	0.186	4.14	0.0803	0.1400	15.2
3½ ' Height	78	1.495	0.129	11.58	0.0385	0.391	12.2
Unshaken							
F = 66.2							
S = 101.0							
½ " Rings	80	0.063	0.306	0.207	0.263	0.00700	15.4
4 " Column	75	0.241	0.234	1.03	0.1540	0.0348	12.8
3½ ' Height	76	0.770	0.166	4.64	0.0776	0.1570	11.5
F = 63.7	77	1.495	0.116	12.88	0.0378	0.435	9.7
S = 108.5	77	2.51	0.078	32.2	0.0171	1.088	12.2
	77	4.17	0.0255	163.5	0.00183	5.53	24.0

Condition of Packing	Air Temp., °F.	Liquid Flow Rate, #/sec.ft.^{2}	Gas Flow Rate, #/sec.ft.^{2}	$\frac{L}{G}$	$\frac{U_G^2 S \rho_G \mu^{0.2}}{g F^3 \rho_L}$	$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$	Pressure Drop Across Column, Inches H_2O
½ " Rings	79	0.063	0.303	0.209	0.255	0.00707	31.1
4 " Column	82	0.241	0.232	1.039	0.1495	0.0351	25.7
7 ' Height	80	0.770	0.159	4.84	0.0703	0.1637	22.0
F = 63.8	80	2.51	0.067	37.5	0.0125	1.268	18.3
S = 108.3	80	4.17	0.0243	171.7	0.00164	5.80	20.0
½ " Rings	78	0.135	0.389	0.347	0.239	0.01173	16.2
2 " Column	76	0.270	0.299	0.903	0.1410	0.0305	16.0
3½ ' Height	75	0.540	0.248	2.18	0.0971	0.0736	14.6
F = 71.3	75	1.026	0.2135	4.81	0.0721	0.1625	13.4
S = 85.8	76	3.28	0.1020	32.2	0.01643	1.088	12.0
	76	6.39	0.0478	133.5	0.00362	4.51	11.1
½ " Rings	82	0.135	0.307	0.440	0.1830	0.01487	18.6
2 " Column	82	0.270	0.282	0.957	0.1545	0.0323	20.6
7 ' Height	82	0.540	0.222	2.43	0.0957	0.0821	19.0
F = 68.6	82	1.026	0.1882	5.45	0.0687	0.1843	15.9
S = 93.9	82	3.28	0.0927	35.5	0.01668	1.200	10.9
	82	6.39	0.0337	189.5	0.002205	6.40	9.5
¼ " Rings	70	0.126	0.174	0.727	0.1840	0.02455	45.0
4 " Column	76	0.241	0.151	1.595	0.1385	0.0540	43.5
7 ' Height	70	0.770	0.090	8.56	0.0492	0.289	39.0
F = 64.8	70	1.495	0.0420	35.6	0.01071	1.203	32.6
S = 247.5	70	2.51	0.0164	153.0	0.00163	5.17	33.5

Condition of Packing	Air Temp., °F.	Liquid Flow Rate, #/sec.ft.^{2}	Gas Flow Rate, #/sec.ft.^{2}	$\frac{L}{G}$	$\frac{U_G^2 S \rho_G \mu^{0.2}}{g F^3 \rho_L}$	$\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$	Pressure Drop Across Column, Inches H_2O
¼ " Rings	77	3.28	0.0213	154.3	0.00176	5.22	3.3
2 " Column	78	1.026	0.0888	11.55	0.0307	0.391	5.7
1 ' Height	78	0.540	0.1212	4.45	0.0572	0.1505	5.2
F = 70.7	79	0.270	0.1635	1.652	0.1040	0.0559	7.4
S = 206	79	0.090	0.226	0.398	0.1990	0.01346	8.4
¼ " Rings	80	3.28	0.0085	385	0.00036	12.68	21.0
2 " Column	80	1.026	0.0768	13.37	0.0289	0.452	22.0
3½ ' Height	85	0.540	0.1075	5.02	0.0567	0.1695	22.1
F = 67.7	80	0.270	0.1430	1.888	0.1002	0.0638	22.2
S = 227	80	0.090	0.1935	0.465	0.1832	0.01572	24.0
¼ " Rings	70	3.28	0.0128	256	0.00086	8.68	22.5
2 " Column	70	1.026	0.0850	12.07	0.0380	0.408	29.7
7 ' Height	69	0.540	0.1280	4.22	0.0863	0.1425	36.5
F = 66.7	70	0.270	0.1565	1.725	0.1290	0.0583	44.3
S = 234	71	0.090	0.213	0.422	0.238	0.01346	45.8