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UNIVERSITY OF LOUISVILLE

THE CHARACTERISTICS OF FIBERGLAS AS COLUMN PACKING

"

I DESIGN OF COLUMN

II MASS-VELOCITY CHARACTERISTICS

A Thesis

Submitted to the Faculty

of the Graduate School

of the University of Louisville

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF CHEMICAL ENGINEERING

Department of Chemical Engineering

Robert B. Akell

"

June 1946

THE CHARACTERISTICS OF FIBERGLAS AS A COLUMN PACKING

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Robert B. Akell

Approved by the Examining Committee.

Director _____

June 1946

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of Dr. G. C. Williams
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ABSTRACT

A column was designed, built, and operated to determine the mass velocity characteristics of Fiberglas packing. The packed section of the tower was one foot in diameter and ten feet tall, packed with #800 fiber to a density of 4.70 pounds per cubic foot. Air rates up to 6.0 feet per second and water rates up to 80 gallons per minute per square foot were used in pressure drop determinations. The data are presented as pressure drop in inches of water per foot of packing versus gas rate as cubic feet per second per square foot with the water rate as a parameter using both arithmetic and logarithmic coordinates. The latter curves show the upper and lower break points associated with flooding and loading velocities and are considerably higher than those found for other small size packings. Curves are drawn showing the water rate versus air rate with pressure drop as a parameter, which may be used directly for engineering design.

Visual observation revealed that the flooding did not take place with a layer of liquid above the packing, but appeared as layers of froth rising a short distance in the column and quickly dissipating itself. This is attributed to the high percentage of free space in the tower, where the packing serves only to retard free fall of liquid.

INTRODUCTION

In the absorption and distillation industries there is a continual search for better materials and methods for tower packing. One of the newly available substances is a glass which has been blown into long fibers, matted in a jackstraw arrangement, and held together by a fugitive binder. This material has been designated as Owens-Corning Fiberglas.

The characteristics of Fiberglas are comparatively unknown, as very little work has been reported in the literature. The available information points toward it as an extremely useful material, but the existant data are insufficient for engineering design purposes. In an attempt to remedy this situation a column has been designed, built, and operated to determine the characteristics of the packing, and furnish the operating data necessary for general use.

There are certain characteristics which must be known about a packing before a column can be designed and constructed. These are the mechanical properties, mass velocity data, and mass transfer coefficients. The first of these, the mechanical properties, is available from the manufacture and will be briefly reviewed in a later section. This thesis presents results on the second item, mass velocity data; and projected work will present data on mass transfer coefficients.

PART I

DESIGN OF COLUMN

A great deal of experimental work results in data that cannot be used for engineering design because the laboratory equipment is so small that the conditions cannot be duplicated on an industrial scale. In a discussion of the available data in the absorption field Sherwood (1) has said, "The published performance data on packed towers consists principally of laboratory data on small experimental equipment. Actual plant data, or even data on moderately large pilot plants are not plentiful. The available laboratory data fall into two classes: those obtained in towers less than 6 inches in diameter, packed with $\frac{1}{2}$ inch or smaller packing, and data on towers 6 inches to 3 feet in diameter, packed with material $\frac{1}{2}$ inch to 4 inch nominal size. The former are of relatively little value for design purposes, but the latter if used properly serve as a reasonably adequate basis for large scale plant design."

Examination of the literature shows that a great deal of work is done on columns from 3 to 6 inches in diameter and these data have been found to be relatively useless for design of a commercial column with a diameter of 3 feet or more. The results reported in this thesis were planned to be directly applicable to industrial design, which made it essential that the experimental work be done on a column of at least pilot plant size. However, the little data of previous investigators (2,3) that were available indicated very high fluid velocities for this material, which meant that a smaller diameter column would suffice for Fiberglas in comparison with most other packing materials.

In addition to factors affecting engineering design, there are physical and economic considerations in the selection of the experimental column size. The maximum available water rate in the laboratory is of importance when studying flooding velocities since it must be sufficiently high to produce the desired phenomenon. The permissible gallonage rate increases as the square of the column diameter. The required air rate also increases in the same proportions, and the cost of the blower increases in even greater proportion. These factors influence the selection of column diameter, and tend to demand the smallest that will produce results directly applicable to engineering design. For the study of Fiberglas packing a column of one foot diameter represents the result of a consideration of all the factors discussed, and has been used by other investigators.

Two types of data are available in flooding studies: visual data and graphical data. The graphical data are of the greater importance, but the visual studies cannot be neglected until sufficient knowledge of the mechanism of flooding is available. In order to observe the visual phenomena within the column, it must be constructed so that the packing can be seen. This could be done by using an opaque shell with transparent windows, but it would be far better if the entire column were of glass so that the packing would be observed for its entire length. A glass column of considerable length is extremely fragile and inflexible; therefore, it was decided to make the column of glass in two foot sections. This would allow for ease of construction, minimize

the effects of breakage, and further allow for variation of the column height in multiples of two feet.

Besides a tower to contain Fiberglas packing, there are other necessary pieces of apparatus. A top section is needed which will incorporate the liquid inlet and gas exit and contain the liquid distributor. This section must be provided with a pressure tap to be used for measuring column pressure drop. Similarly, a bottom section must be provided which supplies the liquid exit, gas inlet, and gas distributor. A pressure tap also is needed here for column pressure drop. There is little advantage to be gained in making either of these sections transparent, and there would certainly be extreme mechanical difficulties if this were attempted, since liquid distribution across the top of the tower packing can be observed by leaving a small space between the top of the packing in the uppermost glass section and the lower end of the top section. Both of these sections may readily be fabricated of steel.

It is advantageous however, to design the tower so that the bottom section may be removed without dismantling the entire tower. This was done by mounting the glass tower on the top of a plate supported on a stand and bolting the bottom section onto the under side of this plate.

The air to the column is most easily supplied by a motor driven blower. This air supply must be measured and is best done by the inclusion of an orifice flow meter in the line to the tower. Water to top of the tower must also be metered.

At the time of design of the column, consideration was given to the projected absorption work, and provisions made to add the necessary accessories to the original unit. These include a method of supplying and mixing in the air stream an absorbable gas and for withdrawing samples of the mixed gases for analysis. In order to eliminate effects of humidification within the column, provisions are included for humidifying the entering air.

The main and auxiliary apparatus is diagrammatically illustrated in Fig. 1.

A study of each of the above items in the overall construction will show how the above considerations were carried out.

1. Tower

As previously stated, a column one foot in diameter was used: the next consideration was height. The total height available in the laboratory was 17 feet. Of this total height approximately two feet would be required for each of the end sections and an additional two feet for the water trap in the discharge line. This left about 11 feet available for packed column height. Since the column was to be constructed of two foot sections, a height of ten feet was chosen. This height would eliminate any special top or bottom effects within the packing and is within the range of commercial column sizes. It also represents a proper ratio of height to diameter.

Glass tubing was available in the form of Pyrex glass cylinders two feet long with ground ends and an outside diameter of about $1\frac{1}{2}$ inches. The average wall thickness was $\frac{1}{4}$ inch.

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EXPERIMENTAL GAS ABSORBER

Drawn by: R.B. Akell
 Date: 4-30-45

Fig. 1

Material : $\frac{5}{16}$ " steel plate

Fig.2 Plan of Column Flange

The sections were mounted so that each was separated by a steel flange on each side of which was a $1/8$ inch soft rubber gasket. The flange plan is shown in Fig. 2. Each flange had twelve holes. Through six alternate holes were placed tie rods which were fastened to the flange below, and in the other six holes were placed tie rods fastened to the flange above. The rods holding the top glass section were fastened to a flange on the steel top section, and the rods holding the lowest glass section used the tower supporting stand as a base flange. The method of holding the section is illustrated by Figs. 3 and 4. The beam represented by the flange between alternate holes with a central load was believed sufficiently strong for the flange to remain flat when fully loaded. Minor bending could be absorbed by the rubber gasket.

The inside diameter of the steel flange was $11\frac{1}{2}$ inches, while the inside diameter of the glass sections averaged 12 inches. On the slight protruding ridge was placed a $1/8$ inch nichrome rod bent into the shape of a "W". This served as a packing support for each two-foot section and prevented undue slump even at high water loads.

2. Top section.

The top section is pictured in Figs. 5 and 6. As shown in the side view, Fig. 5, the body was made of $1/8$ inch steel plate and the removable top was of $3/16$ inch steel plate. The liquid distributor is located inside of this top section. This distributor consists of a rolled sheet metal tube 11 inches in diameter and 6 inches in height with a sheet metal bottom.

Fig.3 Method of Fastening Sections Together

Fig.4 View of Packed Section

body - $\frac{1}{8}$ " steel plate, welded
 top - $\frac{3}{16}$ " steel plate, welded

Fig.5 Top Section - Side View

Fig.6 Top Section - Top View

A series of 1/8 inch holes on one-inch centers were drilled across the bottom and through the sides. At low liquid rates the liquid would flow out the holes on the bottom; at higher liquid rates the liquid would build up in the distributor and also run out the holes in the side. It had three studs brazed on its sides which extended up through the top section lid. By adjusting nuts on the outside ends of these studs the distributor could be levelled and liquid distribution made uniform.

The upper half of the top section was enlarged to allow the gas to flow around the distributor to the exit located in the center of the lid. The annular space so formed was equal in area to the column cross section.

The liquid inlet through the lid was placed off center because of the central location of the gas exit, but by using 45° ells the liquid was piped to a point just above the center of the liquid distributor.

A 1/8 inch pipe nipple was welded into the top section just above the bottom flange and served as the low pressure connection to the manometer for measuring static pressure and column pressure drop.

3. Bottom section.

The bottom section was made of 3/16 inch steel plate. It has a conical bottom to collect and discharge the liquor. A "U" trap in this line served as a liquid seal. Provision was made for a sight

Fig.7 Bottom Column Section

$\frac{3}{16}"$ steel plate, welded

Fig.8 Bottom Section - Sectional View

Fig. 9 Bottom Section - Top View

Fig.10 Tower Support

glass so that the level of liquid in the bottom section might be observed to see that it did not build up high enough to overflow into the gas inlet, which was located in the side. The gas inlet consisted of a $2\frac{1}{2}$ inch coupling welded into the side of the section. Inside the section a short nipple was screwed into the coupling, and on this was threaded a 90° elbow opening upward. The gas distributor, which was placed on the elbow, was made of a truncated sheet steel cone over which was placed a smaller cone. The bottom section is pictured in Fig. 7 and sketched with the gas distributor in Fig. 8. The plan view of this section is shown in Fig. 9. Provision was also made for the pressure tap connected to the column-pressure-drop manometer which may be seen in Fig. 7.

The bottom section was bolted to the under side of the supporting stand which is sketched in Fig. 10.

4. Blower.

The blower was a Buffalo Forge Blower Model No. 5E with a 15 inch wheel designed to deliver a maximum of 500 cubic feet per minute at 14.9 inches of water pressure. It was equipped with a six inch discharge which was reduced down to four inches, the size of the gas piping used throughout. The blower characteristics were such that it gave a substantially constant pressure over a wide range of capacity. The blower may be seen in Figs. 11 and 12.

5. Humidifier

The humidifier was constructed from a 55 gallon drum with removable

Fig.11 Air Supply System to Column

Fig.12 Blower and Humidifier Section

top. Air entered the side near the bottom, through a four inch opening and passed up through a grid packing $1\frac{1}{2}$ feet deep. The packing was the wooden grid type, with slats $\frac{3}{4}$ inch thick and 3 inch high standing on edge and spaced laterally one inch apart. Succeeding layers were at right angles to each other. Water was sprayed onto the packing by means of a spray head on the end of a $\frac{1}{2}$ inch water line which entered through the top of the drum; excess water drained out the bottom.

Saturated air discharged from the side opposite the entrance near the top and was conducted to the water separator. The separator consisted of a 12 inch cylinder with a conical bottom. Air entered the separator tangentially and the entrained water was removed by the ensuing centrifugal action. Air discharged through the top, and water drained out the bottom. The exit air was found to be essentially free of entrained water. The humidifier and separator may be seen in Fig. 11 and 12.

6. Measurement of inlet water.

The water entering the tower was measured with a rotameter and by-pass arrangement. The rotameter had a capacity of 18.25 gallons per minute and was calibrated by the manufacturer. For water rates above 18.25 gallons per minute a by-pass valve was opened and water was allowed to pass through both the rotameter and by-pass. Flows in this range were calibrated by weighing the discharge water. The rotameter and by-pass are shown in Fig. 13.

Fig.13 Liquid Supply System and
Gas Exit

7. Measurement of inlet gas.

The flow of inlet air was measured by a sharp edge orifice meter inserted in the line entering the bottom section of the column. Because it was planned to make use of a wide range of air flows it was calculated that no single size orifice could cover the range without either reaching pressure differentials that could not be accurately read or pressures that would exceed the pressure rating of the blower. This being the case, two interchangeable orifice plates were designed, each covering a given and overlapping range. This permitted a reasonable reading on the manometers and a reasonable pressure recovery for any range up to blower capacity.

The air line was four inches inside diameter and orifice sizes were two and three inches. The difference in the vena contracta tap locations for the orifices was small and appeared to be within the limits of placement error ($1/8$ inch). A straight run, exceeding minimum requirements, was allowed on both upstream and downstream from the orifice, and straightening vanes were also used upstream from the orifice to insure orifice accuracy.

The two-inch orifice was calibrated by calculation and checked by anemometer readings. The three-inch orifice was calibrated against the two-inch orifice by making the reasonable assumption that any given air flow will produce the same column pressure drop regardless of which orifice is used to measure the flow, and was rechecked by calculation from accepted formulae.

The orifice installation and manometer may be seen in Figs. 11 and 12.

8. Absorbable gas supply.

The absorbable gas to be used in the later work on transfer coefficients was to enter the air line downstream from the orifice through a 1/8 inch pipe bent so that the end inside the pipe discharged along the axis of the air pipe, heading downstream. The end of the gas inlet pipe was placed inside a "hat" mixer. A sheet-metal cylinder $2\frac{1}{2}$ inches in diameter and 5 inches long formed the basis of the mixer. One end of the cylinder was open and the other end was sealed by soldering a flat disc over the end. A sheet-metal flange $2\frac{1}{2}$ inches inside diameter and 4 inches outside diameter was soldered around the open end of the cylinder. The sides of the cylinder were then divided into $\frac{1}{2}$ inch strips running the length of the cylinder; alternate strips were removed. The mixer was welded into position inside the air pipe with the open end of the cylinder towards the column. The gas inlet pipe was placed through a hole in the sealed end of the mixer so that the end of the pipe was in the middle of the cylinder.

Air flowed through the air pipe around the outside of the cylinder and through the slots producing high turbulence. The turbulent air mixed with the absorbable gas and discharged from the mixer.

The supply system may be seen in Fig. 11.

Two 8 inch lengths of $1/8$ inch pipe with one end sealed were drilled over a length of 4 inches, with 5 equidistant, $1/8$ inch holes which passed through one side of the pipe only. They were installed across a diameter in the inlet and exit gas lines with the holes facing downstream and through them samples of the gas were withdrawn for analysis.

The equipment described in this section was not used in the present work on flooding, and the section of air line in which they were installed was replaced by an unobstructed section of the same length.

The arrangement of equipment is shown in the plan and elevation by Fig. 14 and 15.

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Plan View EXPERIMENTAL GAS ABSORBER	
Scale 1"=1'	Fig. 14
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Date: 5-21-45

Humidifier

Separator

Gas Supply

Packed
Column

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Elevation
EXPERIMENTAL GAS ABSORBER

Scale 1"=1'

Drawn by: R.B. Akell

Date: 5-21-45

Fig. 15

PART II

MASS VELOCITY CHARACTERISTICS

HISTORICAL

Gas absorption equipment has not become standardized, and for each specific problem, individual consideration must be given to the design of the tower and its auxiliary equipment. The absorption of gases is usually carried out in a tower packed with some solid material. This solid material or tower packing should have certain desirable properties which have been listed by Badger and McCabe (4) as follows:

1. Large Surface per Unit Volume

This is a very important factor in the value of overall transfer coefficients and has been given prime consideration in absorption calculations where a tower height is required.

2. Low Weight per Unit Volume

This is an important factor in the tower design because it controls the gross weight of material supported by the tower. In many cases the weight of the packing may be greater than the weight of the tower and its auxiliary equipment. If the column is operated at atmospheric, or other low pressure, the side thrust exerted at the base of the column by the packing will be a deciding factor in the thickness of tower shell required.

3. Large Free Cross Section

This factor affects the pressure drop caused by friction in the column, the mass velocity capacity of the column, and the power requirements for gas flow.

4. Large Free Volume

In some absorption work the two phases must be in contact

for a longer period in order to allow time for reactions to take place. However, in most work this factor is of little significance.

5. Small Weight of Liquid Retained

It is usually desirable to remove the liquid from the column as fast as possible since this mechanism decreases the load on the tower; however where reaction time is slow, this may be a disadvantage.

Fiberglas satisfactorily meets all the requirements of a good tower packing listed above, and for comparison, information on Fiberglas furnished by the manufacturer (5) and on other common packings listed by Perry (6) are as follows:

Fiberglas tower packing of #800 fiber may be used in densities of from two to six pounds per cubic foot. Most other packings range from 80 to 100 pounds per cubic foot, a typical one being $\frac{1}{2}$ -1 inch quartz at 88 pounds per cubic foot. A packing having a low value of 29 pounds per cubic foot is 3 inch coke.

The surface area of Fiberglas is between 77 square feet per cubic foot at a density of 2 pounds per cubic foot, to 232 square feet per cubic foot at a density of 6 pounds per cubic foot. The values for common packing material will be between 10 and 30 square feet per cubic foot. However one type of glass ring packing is reported to have values from 131 to 283 square feet per cubic foot at densities from 18.3 to 51.6 pounds per cubic foot.

The nature of Fiberglas, that is long thin fibers, is such that it will have free cross sections approaching that of an empty tower. The free volume will also be high and runs from 98.7% to 96.1%. This can be compared to the usual range of 45% to 65% for most other packings. The amount of liquid retained by the packing is believed to be small.

In addition to those named above there are certain other advantages to Fiberglas. The packing is cheap and is therefore inexpensive for both initial installation and replacement. The mechanical strength of the glass fibers is high enough to support its own weight and the weight of liquid in the tower, and to undergo a degree of compression without undue damage to the fibers. The glass packing is non-porous and relatively inert, and being inorganic it is not subject to rot or decay. It is claimed to withstand weak solutions of alkalies and most acids, except hydrofluoric and hot phosphoric.

Fiberglas has been used as a packing material successfully in a number of applications in the absorption, distillation and extraction fields, but very few reports containing engineering data have been published. Some work in the field of distillation was reported by Minard, Koffolt, and Withrow (2) who give the results of a large number of tests run on binary mixtures. The components of the mixtures were ethanol-water, methanol-water and acetone-water. Their column was one foot in diameter with packed heights of both 1.5 and 6.5 feet

and the Fiberglas was used in a vertical arrangement. They studied the effects of reflux ratio, vapor velocity, and composition on the performance of the material and found that Fiberglas shows good rectifying properties.

Pressure drops were recorded on the 6.5 foot column and are included in the tabular data. However the tables do not include the liquid rate but only imply this rate by the ratio of V/L . Plots showing the effect on the pressure drop of liquid and gas rates are difficult to derive because the data are taken on scattered points. The data are plotted on logarithmic coordinates as the pressure drop versus corrected gas rate, but no differentiation for the different liquid rates occurring is shown, so that the data are of little value. In no case did the column flood even at vapor velocities of 4.90 feet per second, principally because of the limited quantity of steam available. This work leaves a great deal to be desired in establishing pressure drop relationships for Fiberglas packing, especially for absorption work.

Another study of Fiberglas packed columns for distillation work was conducted by Herman and Kaiser (3). The column in this investigation was again one foot in diameter, but the packed height was 5 feet 8 inches, and the Fiberglas was used in a horizontal jackstraw arrangement. Ethyl alcohol and water mixtures were distilled and H.T.U. values calculated. Some pressure drop data were taken mostly at reflux rates of $V/L = 1$. No attempt is made to use these data other than to present

them principally because of their scattered nature. They were however able to produce flooding at a vapor velocity of 4.5 feet per second with $V/L = 1.24$; at this point the recorded pressure drop was 8.30 inches of water per foot of packing.

The authors state that they found that the column operated most efficiently just below the flooding point, which exemplifies the importance of determining just where this phenomenon will occur with Fiberglass packing.

THEORETICAL

Friction drop data on packing materials are important not only for determining power requirements for gas flow but also as they define certain maximum fluid flow rates. These maximum flow rates are generally spoken of in terms of loading and flooding points. The definitions of these points are divided into visual methods and graphical methods.

The loading point is defined visually as the point at which drops of liquid are carried up and out of the top of the tower by the gas stream (7): the flooding point is likewise defined as the point at which no greater quantity of circulating liquid will flow through the packing (3) or is the point where the liquid cannot penetrate the tower and is held as a layer on top of the packing (7).

In defining these points graphically a logarithmic plot of pressure drop versus gas rate for a given water rate is used. This curve is considered to be expressed by straight line segments with two rather sharp breaks where the slopes change. The lower break point is called the loading point, and the upper break point is called the flooding point.

The graphical means has been reported as a more nearly exact value because of the methods used, and is the better method of definition for comparison between packings. There does not seem to be any definite relationship between graphical and visual points; some observers report the graphical values to be higher while others report the opposite (9,10).

The theories explaining the mechanism of flooding and loading

are few and by no means complete. It is believed by Chilton and Colburn (11) that the pressure drop in a packed column is largely the result of the expansion and contraction losses in the gas flowing through the irregular orifices in the packing and that only about 10 per cent of the pressure drop is the result of true skin friction. Expansion losses, contraction losses, and skin friction are all proportional approximately to the square of the gas rate. The Fannings equation for friction in pipes relates the pressure drop to the square of the fluid velocity and is used as the basis for a number of empirical equations giving pressure drop in a packed column.

The Fannings equation is given as

$$\Delta P = \frac{2fL \rho_c u_c^2}{g D}$$

A modification of this equation as presented by Sherwood (12) purporting to give the pressure drop for any packed tower is

$$\Delta P = \frac{2f' A_w A_p A_L \rho_c u_c^2 L}{g d_p}$$

The wall effect factor, A_w , corrects for error introduced when a large particle size packing is used and thus creates a greater percentage of voids near the wall and increasing the gas flow there. The friction drop for such a tower will be lower than one in which the ratio of particle size to tube size is not so great. This same correlation was used by Perry (13) and Walker, Lewis, McAdams, and Gilliland (14)

for expressing pressure drop. In addition the latter point out that the friction factor, f' , is probably some function of the liquid and gas velocity and suggest that at flooding, the ratio of gas to liquid velocity will be a function of the gas and liquid density and the gas velocity. By equating the liquid head in the column to the friction head of the gas, they arrive at the following relationship

$$\frac{\rho_g}{\rho_l} \cdot \frac{u_g^2}{2gm} = \phi \left(\frac{u_g}{u_l} \right)$$

They show a plot of the data of several investigators using a number of packing materials with good correlation.

More nearly exact formulas can be formulated for individual styles of packing. Mach (15) has developed equations giving the pressure drop for Raschig rings and Berl Saddles. These are presented by Badger and McCabe (16) in the following form

For Raschig rings - dry

$$\Delta P = \frac{0.0846 L u_g^{1.85} \rho_g^{0.83}}{D^{1.27}}$$

For Raschig rings - wet with water

$$\Delta P = \frac{0.0000894 \rho_g^{0.83} L u_g^{1.8}}{D^{1.27}} \left[1405 + \frac{\rho_g^{0.42} u_l}{D^{0.64}} \right]$$

However these equations hold true only below the loading point.

The equations above have in common a factor equivalent to the "nominal size" of the packing unit, but they are concerned with

packing materials of such a nature that the ratio of the largest to the smallest dimensions is less than 5 to 1. With Fiberglas packing, in which the packing diameter is 0.008 inches and the length is greater than 4 inches, the ratio will be greater than 500 to 1. Thus the choice of the proper value of "nominal diameter" is of the utmost importance and the great degree of difference between the range of these ratios makes it doubtful if the same basis of correlation could be used for Fiberglas packing as has been used for other materials.

An interpretation of the actual mechanism of flooding has been presented by Sarchet (10) using as a basis the study of the logarithmic plot of pressure drop versus gas rate. If a typical curve for a constant liquid rate, high enough to produce flooding and loading, is examined, the following characteristics will be noted. The lower portion, below loading, is a straight line having a slope of 1.8 to 2.0. This would indicate that the pressure drop is varying approximately as the square of the gas velocity and inversely as the diameter of the orifices formed by the packing. As pointed out by Chilton and Colburn (11), this indicates that the liquid is flowing over the packing in a continuous, and more or less undisturbed film. These conditions prevail up to the loading point where the increased friction of the gas is sufficient to cause an increase in liquid holdup. This decreases the orifice diameter and causes the pressure drop to increase at a greater power of the gas velocity. Examination of the plot shows that the pressure drop is now increasing

at a power of 3.0 to 4.0 of the gas velocity.

Holdup in the tower gradually increases until layers of water begin to collect in or at the top of the packing. As this condition is reached, the pressure drop increases greatly with only a slight increase in gas velocity. This is evidenced by another change in slope of the curve to an almost vertical line or one of infinite slope. Because of the great increases in pressure drop above the flooding point, the power necessary to force volumes of the gas through the tower is greatly increased. Therefore, operation of a tower above the flooding point has been considered uneconomical, and because droplets of liquid may be sprayed out of the top of the tower at velocities between loading and flooding, towers are generally not operated at velocities above the loading point.

The explanation of the mechanism of flooding and loading given above is based principally on the fact that with large, granular type packings, the liquid is flowing over the packing in a continuous film. The diameter of the glass fibers in a Fiberglas packing is too small to support this type of liquid movement, and because of the high free space present offers a different type of liquid movement. Liquid flow in a Fiberglas tower is more closely related to the free fall in an empty tower and effect of the presence of this packing is only to retard this free fall. A theory to explain the effects in a Fiberglas packed tower will have to be based on this principle.

An investigation of flooding velocities was undertaken by Bain and Hougen (17) using systems other than air and water in

order to provide more data on the effects of liquid viscosity and gas density. Tests were conducted in a glass tower using three oils of different viscosity and three gases, namely, air, hydrogen, and carbon dioxide and using five different packings, namely, two sizes each of Raschig rings and Berl saddles, and $\frac{1}{2}$ inch single turn wire helices. They concluded that flooding velocities should be established from measurements of the upper break point in the logarithmic plot of pressure drop versus gas velocity curves and not from visual appearance of the tower during flooding, because they found that the packings used did not all visually flood in the same manner. With the Raschig rings it was found that a layer of oil built up on top of the packing, while with Berl saddles the layer of oil built up on the packing support. The wire helices exhibited quite different characteristics and flooding would take place as follows: as flooding was approached, slugs of oil mixed with air, as foam, were lifted a short distance and were then dissipated. As the velocity increased, these slugs were lifted higher and higher until they finally broke through to the top of the packing and surged up as a liquid layer. This layer quickly dissipated and another slug would immediately start from the bottom of the tower and rise through the top. Immediately after a slug of foam passed through any given section, that section would return to normal operation.

This unusual behavior of wire helices is accounted for by their unique construction. They were made of 16-gage wire,

with a single, $\frac{1}{2}$ inch turn and with a pitch equal to the gage of the wire. The per cent voids was 82.00, the surface area per cubic foot was 108 square feet, and the individual void openings were about $\frac{1}{8}$ to $\frac{1}{4}$ inch. These properties approximate those of Fiberglas, so it was expected that Fiberglas would flood in a similar manner.

The data were correlated on the basis of variable groupings used by Sherwood, Shipley, and Holloway (18):

$$\frac{u_g^2 S}{g F^3} \left(\frac{\rho_g}{\rho_l} \right) \mu^n = y$$

$$\frac{W}{G} \left(\frac{\rho_g}{\rho_l} \right)^{1/2} = x$$

The groups are dimensionless with the exception of the viscosity term μ^n , and they found that the exponent, n , of this term should be used as 0.16 instead of the value of 0.20 as used by Sherwood, Shipley, and Holloway. When values of y were plotted against $x^{1/4}$ on semilogarithmic paper, two parallel straight lines resulted. One line represented the flooding velocity data for Berl saddles and the other all the data for rings and helices. They believe the line for saddles is unique because of the momentary reversal of flow of liquid in passing down over this packing. The resultant equation for flooding velocity is

$$\log \left[\frac{u_g^2 S}{g F^3} \left(\frac{\rho_g}{\rho_l} \right) \mu^{0.16} \right] = b - \left(\frac{W}{G} \right)^{1/4} \left(\frac{\rho_g}{\rho_l} \right)^{1/8}$$

where $b = 0.22$ for Raschig rings and wire helices

$b = 0.26$ for Berl saddles

The average deviation of their data from this equation was
 ± 6 per cent.

EXPERIMENTAL PROCEDURE AND RESULTS

The glass column sections were packed with Fiberglas before they were placed in position. The method of packing recommended by the manufacturer was used. In this procedure, the column section was placed in a horizontal position and a strip 10 inches wide and 23 inches long was laid in curving to fit the circumference of the tube. All Fiberglas segments were cut from 20 by 25 inch pads as supplied by the manufacturer. Eight other Fiberglas strips of varying width were placed chordwise in the section filling the tube from the bottom to a diameter. A duplicate set of Fiberglas strips was used to pack the other half of the section. Figure 16 illustrates the position of the packs on a cross section

Fig. 16 Sketch of column cross section showing position of Fiberglas pads.

Each section was thus packed to a length of 23 inches, leaving a one inch opening at the top, through which water

distribution was observed. The water soluble, cellosize binder was removed during initial operation of the column. The quantity of binder was between 5 and 10% and an average of 7.5% was used in the calculation of packing density.

Table I gives the weight of Fiberglas packed into each of the sections.

Table I
Column Packing Data

Section From Bottom	Weight of Fiberglas Pounds
1	7.50
2	7.50
3	7.69
4	7.83
5	<u>7.62</u>
Total weight of packing	38.19
Less estimated 7.5% binder	<u>2.86</u>
Packing without binder	35.33
Average weight of packing in each section	7.06
Volume of each section	1.504 cubic feet
Average packing density	4.70 pounds / cubic foot

The surface area of the packing was computed from an adaptation of the empirical formula supplied by the manufacturer, using the

density of the glass as 155 pounds per cubic foot and the diameter

of the fiber as 0.008 inches or 0.00067 feet: $S = \frac{4C}{dB}$

The surface area for the packing density of 4.70 pounds per cubic foot is 181 square feet per cubic foot.

Water distribution in the tower was observed during the washing operation and was found to consist of a large number of small rivulets spaced about 2 inches apart and flowing in a continuous stream. From these observations, and those made during the first trial runs, it was apparent that water rates, much higher than the capacity of the rotameter, would have to be used to produce flooding at the lower air rates.

It was shown by Kroll and Fairbanks (19) that globe valves could be used as flow meters and that flow curves for various valve settings were reproducible. The globe valve in the rotameter by-pass was calibrated by discharging the water into a weigh tank; at the same time the position of the float when the by-pass was open was recorded. The data are given in Table II.

From the data in Table II and from information furnished by the rotameter manufacturer, three curves were drawn. The first, a plot of the rotameter calibration as furnished, was used in the range of 0 to 18.25 gallons per minute and is shown in Fig. 17. The second, Fig. 18 is a plot showing the position of the rotameter float when the by-pass valve is fully open and covers the range from 18 to 50 gallons per minute. The last of the three, Fig. 19 is a

Table II

Inlet Valve and By-Pass Rotameter Calibration

By-Pass Valve Open

Inlet Valve No. of turns open	No. Runs Averaged	Rotameter Reading	Time to Collect 350#	Water Rate lbs/min gpm		
0.1	2	no reading	2'55.0"	120	14.4	
0.20	6	useful range	12	2'18.2"	152	18.4
0.24	4		50	1'55.6"	181	21.8
0.30	6		106	1'30.3"	233	27.9
0.35	4		150	1'15.2"	279	33.3
0.40	2		190	1'04.8"	324	38.8
0.44	4		200	1'00.9"	345	41.4
0.50	2		233	52.9"	397	47.5
0.56	4		250	49.1"	428	51.2
useful range	0.60	2	off scale	46.7"	449	53.7
	0.70	4	off scale	43.0"	490	58.6
	0.80	4	off scale	39.4"	533	63.9
	0.90	4	off scale	34.8"	604	72.2
	1.00	4	off scale	31.4"	668	80.2

Fig.17 Rotameter Calibration Curve

Fig.18 By Pass Rotameter Calibration Curve

Fig.19 Inlet Valve Calibration Curve

calibration of the main inlet water valve and was used only in the range of 50 to 80 gallons per minute. Use of these three curves offered equivalent accuracies for the entire flow range.

The orifice plates for gas measurement were made from 16 gage stainless steel with accurate openings of 2.000 and 3.000 inches. Rate of flow through the two-inch orifice was calculated from the gas flow equation given by Rhodes (20) with orifice coefficients taken from the same source.

$$Q = C'D_p^2 \sqrt{H P' T S' M B'}$$

The results of this calculation were checked by anemometer readings and are presented in Fig. 20 showing the air flow rate versus orifice pressure differential. The three-inch orifice was calibrated by assuming that the same column pressure drop was produced by a given air flow regardless of the orifice used, and using this information to determine orifice coefficients from which the entire flow range was calculated. The two-inch orifice was used in the range of 80 to 180 cubic feet per minute and the three-inch from 120 to 260 cubic feet per minute (see Fig. 21).

The first trial runs indicated that water flows as high as 60 gallons per minute (76.3 gallons per minute per square foot) and air rate as high as 250 cubic feet per minute (53 feet per second) would be needed to produce flooding in the range desired. First runs were made on the dry tower by setting a low air rate, and reading the column pressure drop after equilibrium was reached.

Fig.20 2 inch Orifice Calibration Curve

Fig.21 3inch Orifice Calibration Curve

The delay to obtain constant pressure drop values was found to be only two to three minutes, but varied with air rates. The air rate was then slightly increased and another set of readings taken.

This procedure was repeated up to the maximum air rate.

The process for wet tower conditions was similar in that the water flow was set at a given rate and the air variation process repeated until the entire possible range of air rates was covered. Other water settings were made until the entire field was covered. The data are listed for ten water rates from 0 to 74.8 gallons per minute per square foot in Tables IV to XIII in Appendix. Data at other water rates were also taken, but it was found that the water rate increments were too small to be readily plotted. When the points were placed on the graphs, it was found that more data were necessary in certain areas, and reruns were made by making spot settings on air and water rates for readings. It was shown by check readings that it was immaterial whether equilibrium conditions were approached from high or low rates of fluid flows.

The tabular data were plotted by using one of the three variables, water rate, as a parameter and plotting the other two. Three families of curves are presented. First, with water rate as a parameter, an arithmetic plot is shown in Fig. 22 showing the pressure drop versus air rate. The same data are plotted with logarithmic coordinates in Fig. 23. These latter curves show the typical break points at loading flooding velocities. Accurate positioning and shapes of the curves

FIG.22 EXPERIMENTAL COLUMN PRESSURE DROP CURVES

were assured by checking these two sets of curves against each other. Extension of the logarithmic curves determined the manner of approach to the origin on the arithmetic plot.

In the third set of curves, Fig. 24, the pressure drop was used as the parameter, and the data were plotted with arithmetic coordinates. These curves show the pressure drop for any given set of water and air rates.

All points of original data are shown on Fig. 22, but are omitted from the other figures for the sake of clarity.

During all the runs, the column was watched for visual effects. The water distribution was observed through the column between each section and was the same as previously described, that is, small continuous streams, and was consistent from section to section throughout the column. Below flooding velocities some slight channeling took place at the wall, but the amount appeared to be only a small percentage of total flow.

Just below the flow considered as visual flooding there was some increase in liquid holdup evidenced by frothing just above the flanges. On closer approach, the amount of this air-water froth increased until at the point considered to be visual flooding, the froth would surge upward from the flange and dissipate after rising about one foot. Immediately, another layer would surge upward and also dissipate. The water surges would initiate from any of or all the flanges, and there seemed to be no correlation in the number

Fig. 23 Logarithmic Pressure Drop Curves

FIG.24 PRESSURE DROP-FLUID VELOCITY CURVES

of points at which this took place. At no time, however, did a layer of water build up on top of the packing, nor were water droplets sprayed out of the top of the tower.

DISCUSSION OF RESULTS

Examination of the data presented in Fig. 22 shows that they are in good agreement with each other and exhibit the general characteristics of pressure drop curves. The curves plotted using logarithmic coordinates are similar to those found in the literature in that they show the typical breaks in slope at flooding and loading points. The points of data fall close to the linear correlation and the curve families show regularity with respect to slope and position of the break points. Check readings and duplicate runs indicated that the values were accurate, and reproducibility was high.

The slopes of the logarithmic curves differed from those reported in the literature for most other packings below the loading points. The measured values gave 1.4 for all water rates, compared to a slope from 1.7 to 2.0 previously found for other packing materials. This might indicate that the pressure drop mechanism is different for a packing such as Fiberglas, in which the liquid phase is flowing in a retarded free fall movement.

This variation is also established by Fig. 25 (21) which shows the pressure drop through dry packing for five different packings and on which the data for Fiberglas have also been plotted. The slopes for 1 inch Raschig rings, 1 inch Berl saddles, 3 inch spiral tile, drip point grids, and wood grids are all about 1.70, while the slope for Fiberglas is about 1.40. This figure also shows the relative pressure drops for the packings plotted: the drop for

Fig. 25 PRESSURE DROP in Dry Packing

Fiberglas is about $1/3$ to $1/4$ that for 1 inch Raschig rings and about $1/2$ to $1/3$ that for 1 inch Berl saddles. However, the drop for Fiberglas is about twice that for 3 inch spiral tile, about 4 times that for drip point grids, and about 7 times that for wood grids. This trend would be followed similarly for wet packing but pressure drop alone does not dictate the usefulness of a packing for an absorption system.

Comparison of the pressure drop data in wet packings with the results of Minard, Koffolt, and Withrow (2) shows that there is substantial agreement. Calculations for their liquid rates in the column were based on the gas rate, and the ratio V/L as reported. Several runs from each of the systems, methanol-water and alcohol-water, were selected on the basis of representing their widest range of variables. These are tabulated in Table III. With their gas rates and liquid rates, pressure drops were read from Fig. 24 of this work and are also compared with their experimental values in Table III. The variations are negligible and are within experimental accuracies for systems of different materials.

The small magnitude of this variation indicates that their pressure-drop values correlate excellently with this investigation. However the usefulness of their data for absorption design is limited because the liquid rates (less than two gallons per minute per square foot) are only a small part of the range of liquid rates reported here (0-80) and are far below those most to be desired.

Table III

Results of Other Investigators

Run	Vapor Velocity	V/L	Column Pressure Drop	Liquid Rate	Column Pressure Drop
	FPS		In.H ₂ O/FT	GPM/SQFT	In.H ₂ O/FT
<u>Data of Minard, Koffolt, Withrow</u>				<u>Calculated</u>	
System; Methanol-Water					
C-1	3.40	1.21	0.22	1.80	0.18
C-20	3.30	1.75	0.12	0.56	0.17
D-4	1.71	1.50	0.05	0.75	0.08
D-9	4.90	1.50	0.26	1.85	0.30
System; Ethanol-Water					
E-9	1.69	1.22	0.06	0.95	0.08
E-17	3.38	1.86	0.26	1.14	0.18
<u>Data of Herman and Kaiser</u>				<u>Calculated</u>	
System: Ethanol-Water					
4	1.4	1.14	0.27	0.77	0.06
9	4.5	1.24	8.30	3.47	0.27
12	3.9	1.00	0.60	2.47	0.22
14	3.0	1.25	0.60	1.50	0.14

Examination of the work of Herman and Kaiser (3) also shows low liquid rates as given by their data in Table III. The tabulated data again represent a selection of the maximum range of variables used, and were calculated on the same basis as that of Minard, Koffolt, and Withrow. The pressure drop data are in wide disagreement with both the data of Minard, Koffolt, and Withrow and this author, and the magnitude and diversity of the pressure drops is such as to cast doubt on its accuracy. A pressure drop of 8.30 inches of water per foot of packing as given in their Run 9 is much higher than any reported in the literature for any other packing.

Pressure drops for packing have been investigated by numerous groups. In correlating the results of their own work, Bain and Hougen (17) used the variable groupings of Sherwood, Shipley and Holloway (18) previously described in this thesis. This same grouping was used for the flooding data obtained with Fiberglas and is plotted in Fig. 26 together with the curves of Bain and Hougen. The line for Fiberglas falls considerably above those for Raschig rings and wire helices, and for Berl saddles, and has a negative slope about 60% less than that of the other curves. The groupings include three variables which were constant in this work, gas density, liquid density and liquid viscosity, and so the effects of these are unknown for this packing. The present data indicate that this arrangement is not a universal correlation and that other packings digress from the single line, similar to

Fig. 26 Flooding Velocity Correlation by Method of Bain and Hougen

Berl saddles, which had been considered as unique.

In discussing the paper of Bain and Hougen, Bertetti (22) presented a correlation

$$\nu^a u_L^b + \nu^a \left(\frac{\rho_G}{\rho_L} \right)^c u_G^b = \beta$$

in which β is a packing constant, and a, b , and c are constants defined as follows

$$a = \frac{r}{3-r} ; \quad b = \frac{2-r}{3-r} ; \quad c = \frac{1}{3-r}$$

where r is a constant proportional to the packing roughness.

By letting $r = 0.16$ he obtained the resulting equation

$$\nu^{0.056} u_L^{0.65} + \nu^{0.056} \left(\frac{\rho_G}{\rho_L} \right)^{0.35} u_G^{0.65} = \beta$$

which if valid should result in straight lines with a slope of -1 and an intercept representing the packing constant β . The data of Bain and Hougen were correlated by him on this basis and although he considered the results in fair agreement, Hougen differed considerably and said (23) "The 45° lines in his plot are not in best agreement with the experimental data." This plot is reproduced in Fig. 27 with the addition of the data for Fiberglas. It is evident that a line as proposed by Bertetti cannot possibly represent these data. Bertetti's correlation included the term kinematic viscosity, but since this appears

in both the abscissas and the ordinates it will only affect the intercept; however, a change in the exponent of the other terms would affect the slope. The correlations developed for flooding points are not sufficient to represent the data on all types of packing by a single line and even if by different lines they are not necessarily parallel.

The data presented here for Fiberglas are satisfactory for engineering design, but since a sufficient number of factors were not varied it is impossible to correlate them on all the groupings suggested for other packings by other investigators.

FIG 27 CORRELATION OF FLOODING DATA WITH BERTETTI'S EQUATION

SUMMARY AND CONCLUSIONS

The experimental procedure for this investigation was simple and straightforward, and the data which were obtained were reproducible to a high degree. The results which may be drawn from the various correlations are consistent within themselves and, in general, consistent with other published investigations.

An analysis of results leads to the following conclusions:

1. As a packing, Fiberglas has high flooding velocities which lie between those of small size, large surface area packings, such as Berl saddles and Raschig rings, and those of the large size, low surface area packings, such as grids.
2. Fiberglas exhibits visual flooding characteristics that differ from most packings which flood by retaining a layer of liquid on top of the packing, in that Fiberglas floods by producing quickly dissipated layers of liquid-gas froth within the packing. This manner of flooding had been previously described for only one other packing, i.e. wire helices, which it somewhat resembles in physical form.
3. The differences in flooding mechanism results in curves which are dissimilar to those of other packings when the flood-data are compared on any of the widely different correlations proposed by other investigators.

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APPENDIX

NOMENCLATURE

- A_L = a correction for the wetting of the packing by the circulating solvent, no units, (a function of the liquid rate, unity for dry packing)
- A_p = a correction factor for hollow packing, no units, (a function of nominal packing size and varying with the packing shape)
- A_W = wall effect factor, no units, (a function of the ratio of particle diameter to tube diameter)
- B = density of glass used in forming the fiber
- B' = gas base factor dependent upon basis for Q for orifice measurements
- C = apparent density of packing in pounds per cubic foot
- C' = coefficient of discharge for the orifice, no units,
- d = diameter of glass fiber in feet
- d_p = nominal particle size of the packing in feet
- D = diameter of tower in feet
- D_p = internal diameter of pipe in inches
- f = friction factor, no units, (a function of the Reynold's number)
- f' = modified friction factor, no units, (a function of a modified Reynold's number)
- F = fractional voids in packing, no units
- g = acceleration of gravity in feet per second per second
- H = square root of the maximum pressure differential in inches of water under air
- L = length or height of tower in feet
- m = mean hydraulic radius (free volume divided by the total contact area)
- M = moisture correction for measured gas
- P = pressure in pounds per square foot

NOMENCLATURE (Cont.)

- P' = pressure factor = $237.1 \sqrt{P_o}$, where P_o is the absolute operating pressure, inches of mercury
- Q = gas flow at specified temperature and pressure in cubic feet per hour
- S = surface area of packing per unit volume in square feet per cubic foot
- S' = specific gravity correction = square root of the reciprocal of the specific gravity of the gas using air as the reference point
- T = temperature factor = ratio of the square root of the absolute temperature of the gas at 60° F and under operating conditions.
- u_g = gas velocity in feet per second based on total cross section of the tower
- u_l = liquid velocity in feet per second (superficial)
- W = mass velocity of liquid in pounds per hour per square foot of superficial column area
- μ = liquid viscosity in centipoises
- ν = kinematic viscosity in centistokes
- ρ_g = gas density in pounds per cubic foot
- ρ_l = liquid density in pounds per cubic foot

Table IV

Column Pressure Drops - Water Rate = 0 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
8	2	2.93	94.0	1.99	0.80
9	2	3.08	96.5	2.04	0.83
1	2	3.32	100.0	2.12	0.90
10	2	4.07	110.5	2.34	1.00
2	2	4.97	122.0	2.59	1.17
11	2	4.97	122.0	2.59	1.17
187	3	0.62	132.0	2.79	1.45
3	2	6.20	136.5	2.90	1.40
12	2	6.94	145.0	3.08	1.44
4	2	7.38	150.0	3.18	1.55
13	2	8.75	163.5	3.47	1.71
5	2	9.00	166.0	3.52	1.80
172	3	1.11	171.0	3.62	2.05
14	2	10.28	177.0	3.76	1.90
15	2	10.28	177.0	3.76	1.90
6	2	10.30	177.5	3.77	1.91
7	2	10.30	177.5	3.77	1.91
188	3	1.24	180.0	3.81	2.05
173	3	1.57	202.0	4.26	2.50
189	3	1.75	212.0	4.51	2.58
174	3	2.08	232.0	4.95	3.06

Table IV cont.

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
190	3	2.15	236.0	5.01	3.03
191	3	2.69	268.0	5.67	3.50
183	3	2.81	273.0	5.81	3.67

Table V

Column Pressure Drops - Water Rate = 14.6 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
33	2	2.87	93.0	1.96	1.02
29	2	3.12	97.0	2.05	1.09
30	2	5.21	125.0	2.65	1.48
193	3	0.57	126.0	2.68	1.60
208	3	0.58	127.0	2.70	1.72
28	2	7.00	146.0	3.09	1.84
209	3	0.85	154.0	3.21	2.07
31	2	8.17	158.5	3.37	1.96
194	3	1.02	164.5	3.48	2.14
210	3	1.07	168.0	3.56	2.33
32	2	10.34	177.5	3.78	2.24
211	3	1.23	179.0	3.80	2.52
145	2	11.60	188.5	4.00	3.30
195	3	1.44	195.0	4.09	2.69
196	3	1.77	213.0	4.53	3.15
197	3	2.02	228.5	4.93	3.62
198	3	2.51	257.5	5.45	4.22

Table VI

Column Pressure Drops - Water Rate = 23.2 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
40	2	2.94	94.0	1.99	1.11
41	2	3.64	105.0	2.31	1.30
42	2	5.00	123.0	2.60	1.57
43	2	6.03	134.5	2.86	1.88
166	3	0.88	154.0	3.26	2.10
44	2	8.63	162.5	3.45	2.29
45	2	10.05	175.0	3.72	2.38
143	2	11.40	187.0	3.92	3.22
167	3	1.52	198.0	4.20	3.06
186	3	1.70	209.0	4.44	3.45
200	3	1.86	218.0	4.64	3.62
169	3	1.99	227.0	4.81	4.06
201	3	2.06	231.0	4.90	4.06
185	3	2.09	232.5	4.95	4.10
202	3	2.35	248.0	5.26	4.53
184	3	2.45	254.0	5.39	4.55
168	3	2.73	270.0	5.72	5.12
203	3	2.79	272.0	5.79	5.06

Table VII

Column Pressure Drops - Water Rate = 28.5 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
46	2	2.78	91.0	1.93	1.15
47	2	3.63	104.5	2.21	1.33
48	2	5.24	125.0	2.66	1.72
49	2	6.76	142.5	3.03	2.19
176	3	0.80	148.0	3.12	2.19
50	2	8.43	160.5	3.41	2.42
51	2	9.81	173.5	3.68	2.72
177	3	1.16	175.0	3.70	2.72
142	2	11.27	186.0	3.94	3.12
178	3	1.46	194.0	4.12	3.16
204	3	1.71	209.5	4.45	3.59
179	3	1.83	217.0	4.61	3.80
205	3	1.98	225.0	4.78	4.08
182	3	2.13	236.0	5.00	4.51
206	3	2.33	247.0	5.23	4.65
181	3	2.50	257.0	5.44	5.12
180	3	2.67	267.0	5.64	5.70
207	3	2.82	273.0	5.81	5.85

Table VIII

Column Pressure Drops - Water Rate = 34.6 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
52	2	2.73	90.0	1.92	1.22
53	2	3.53	103.0	2.18	1.51
54	2	4.63	118.0	2.50	1.74
105	3	0.50	119.0	2.52	1.68
116	3	0.53	123.0	2.60	1.86
88	3	0.54	123.5	2.61	1.85
55	2	6.48	140.0	2.97	2.17
89	3	0.77	145.5	3.07	2.28
117	3	0.83	150.0	3.18	2.40
56	2	8.53	161.5	3.43	2.63
57	2	9.99	175.0	3.70	3.10
118	3	1.22	179.5	3.79	3.09
141	2	11.16	185.0	3.92	3.34
90	3	1.41	189.0	4.05	3.55
119	3	1.57	201.0	4.26	3.69
91*	3	1.89	221.0	4.69	4.63
92*	3	2.13	235.0	4.99	6.75
93*	3	2.21	240.0	5.09	6.80
106*	3	2.29	244.5	5.19	7.25

* Visual Flooding in Column

Table IX

Column Pressure Drops - Water Rate = 42.4 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
58	2	2.80	92.0	1.94	1.31
59	2	3.95	109.0	2.30	1.61
108	3	0.52	121.0	2.57	2.03
121	3	0.53	123.5	2.60	1.97
60	2	5.39	127.5	2.70	2.06
94	3	0.60	130.0	2.74	2.30
107	3	0.60	130.0	2.74	2.32
120	3	0.70	139.0	2.94	2.31
61	2	7.13	147.5	3.12	2.44
95	3	0.80	148.0	3.13	2.52
122	3	0.89	155.0	3.28	2.54
62	2	8.45	161.0	3.41	2.72
123	3	1.11	171.0	3.62	3.06
63	2	9.80	173.0	3.67	3.07
140	2	10.90	182.5	3.87	3.48
96	3	1.33	186.0	3.94	3.72
124	3	1.44	193.0	4.09	3.69
97	3	1.71	210.0	4.45	5.23
98*	3	1.87	220.0	4.66	7.55
99*	3	1.93	223.0	4.73	7.40
109	3	1.93	223.0	4.73	7.70

* Visual Flooding in Column

Table X

Column Pressure Drops - Water Rate = 52.8 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
64	2	2.69	90.0	1.91	1.38
154	2	2.99	95.0	2.01	1.30
130	2	3.03	95.5	2.02	1.34
131	2	3.87	108.0	2.29	1.60
65	2	3.93	108.5	2.30	1.78
100	3	0.50	119.0	2.52	1.74
110	3	0.50	119.0	2.52	2.20
125	3	0.51	120.0	2.54	2.09
132	2	5.01	122.5	2.60	1.88
66	2	5.33	126.5	2.69	2.19
153	2	5.33	126.5	2.69	2.25
133	2	5.68	130.5	2.77	2.11
126	3	0.68	138.0	2.91	2.40
134	2	6.58	141.0	2.99	2.33
152	2	6.78	143.5	3.04	2.55
67	2	6.97	145.0	3.08	2.57
101	3	0.80	148.0	3.12	2.90
135	2	7.50	151.0	3.21	2.60
151	2	8.01	156.5	3.32	2.90
127	3	0.92	158.0	3.33	2.87

Table X cont.

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
136	2	8.62	162.5	3.45	2.98
68	2	8.78	164.0	3.48	3.18
128	3	1.02	164.5	3.49	3.09
137	2	9.27	168.5	3.57	3.23
102	3	1.10	170.0	3.60	3.69
111	3	1.10	170.0	3.60	3.40
69	2	9.52	171.0	3.62	3.53
129	3	1.15	173.0	3.66	3.49
150	2	10.35	178.0	3.77	3.75
114	3	1.26	181.0	3.84	4.71
138	2	10.86	182.0	3.86	3.81
103	3	1.33	186.0	3.94	5.44
115	3	1.40	190.0	4.04	6.11
112	3	1.43	193.0	4.08	7.15
104*	3	1.50	197.0	4.17	8.75
113*	3	1.50	197.0	4.17	8.70

* Visual Flooding at Bottom of Column

Table XI

Column Pressure Drops - Water Rate = 59.8 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
212	2	3.05	95.5	2.02	1.73
158	3	0.47	116.0	2.44	2.65
213	2	5.12	124.0	2.63	2.20
157	2	5.56	129.0	2.74	2.35
214	2	7.05	146.5	3.10	2.73
156	2	7.54	152.0	3.22	3.00
159	3	0.90	156.0	3.29	3.75
215	2	8.38	160.0	3.40	3.19
216	2	9.37	169.5	3.59	3.93
160	3	1.13	172.0	3.65	5.55
155	2	9.83	173.5	3.68	4.10
217	2	9.91	174.0	3.69	4.33
161*	3	1.17	175.0	3.70	7.10

* Visual Flooding

Table XII

Column Pressure Drops - Water Rate = 61.8 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
76	2	2.68	89.5	1.90	1.71
224	2	2.80	92.0	1.94	1.94
244	2	2.84	93.0	1.95	1.78
235	2	3.07	96.0	2.04	1.59
77	2	4.03	110.0	2.33	2.19
245	2	4.15	111.0	2.36	2.33
236	2	4.34	114.0	2.42	2.02
223	2	4.39	115.0	2.43	2.16
78	2	5.27	125.5	2.67	2.72
246	2	5.29	126.0	2.68	2.68
222	2	5.76	131.5	2.80	2.77
237	2	6.32	138.0	2.93	2.73
247	2	6.36	138.5	2.94	3.20
219	2	6.70	142.5	3.02	3.20
79	2	6.79	143.0	3.04	3.65
238	2	6.93	145.0	3.08	3.32
243	2	7.03	146.0	3.10	3.35
239	2	7.14	147.0	3.12	3.58
248	2	7.23	148.5	3.15	3.81
221	2	7.30	149.0	3.16	4.45

Table XII cont.

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
80	2	7.43	150.0	3.19	5.13
81	2	7.43	150.0	3.19	6.01
240	2	7.65	153.0	3.24	4.18
249	2	7.65	153.0	3.24	4.18
220	2	7.70	153.5	3.25	4.05
250	2	7.71	154.0	3.26	4.68
241	2	7.75	156.0	3.31	5.38
242	2	8.05	157.0	3.33	6.68

Table XIII

Column Pressure Drops - Water Rate = 74.8 GPM/SQFT

Run No.	Orifice Diameter	Orifice P	Volumetric Flow	Superficial Gas Velocity in Column	P Column
	inches	in. H ₂ O	CFM	CFS/SQFT	in. H ₂ O
82	2	2.63	89.0	1.88	1.76
225	2	2.82	92.0	1.95	2.21
83	2	3.84	108.0	2.28	2.26
226	2	4.12	111.0	2.35	2.56
84	2	4.96	122.0	2.59	2.73
227	2	5.65	130.0	2.76	3.34
85*	2	5.76	131.5	2.80	4.20
228	2	5.89	132.5	2.83	3.95
229	2	6.20	136.5	2.90	4.55
86**	2	6.32	138.0	2.93	5.48
87	2	6.40	138.5	2.94	6.90
230	2	6.40	138.5	2.94	6.40
231	2	6.50	140.0	2.97	5.75
232*	2	6.70	142.5	3.02	6.75
233	2	6.90	144.5	3.07	7.55
234	2	7.10	147.0	3.11	8.75

* Visual Flooding at Top of Column

** Visual Flooding at Bottom of Column

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