

PREDICTION OF LIQUID HOLDUP IN FALLING FILM
OVER AN EXTERNAL-PACKED POROUS MEDIUM

by

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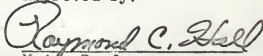
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INTRODUCTION

Mass transfer, the movement of one or more components between phases, occurs in many operations of chemical engineering. The phases may be vapor-liquid, vapor-solid, liquid-liquid, liquid-solid and solid-solid. Examples of mass transfer include the washing of ammonia from a mixture of ammonia and air by means of liquid water, the separation of crude petroleum into gasoline, kerosine, fuel oil and other products, recovery and concentration of penicillin using cyclohexane as a solvent, and cooling a space vehicle by evaporation of a solid into the atmosphere.

In the problem of removing a solute component from a large quantity of inert gas by absorption into a liquid solvent the rate of mass transfer, using the two film concept, may be controlled by either the liquid phase stagnant layer or the gas phase stagnant layer. The removal of water vapor from air by absorption into glycol is an example of such a problem.

If the absorption column is of the exterior flow type and if the natural air currents are to be relied upon, the influence of gas phase velocity on the thickness of the gas phase stagnant layer is a factor which is essentially beyond the operational control. In the practical operation of such a column it may be desirable to alter or adjust the depth of liquid held on the surface of the column. Thus the factors which influence the liquid holdup need to be identified and the manner in which these factors come into play needs to be determined.

The exterior packed tower for the material transfer between

the gas and the liquid phase, as used in this study, differed from the conventional type of packed tower in that the liquid was caused to flow on the outside of the unit rather than through the inside of the tower and in that the packing consisted of a porous medium, such as corduroy cloth, rather than of usual packing materials such as Raschig rings or Berl saddles. In the exterior packed tower the area of contact between the liquid and gas phases is not appreciably increased by the packing; rather the packing serves to insure a continuous liquid surface over all exterior regions of the tower and also to maintain or control the depth of liquid over various regions of the surface. In essence, changing the depth of liquid, i.e., the holdup on the surface of the exterior packed tower is the same as changing the space velocity for the unit.

Primarily the basic theoretical studies of liquid holdup have been and are currently confined to flows inside packed tower for operations such as absorption and extraction. Application of exterior packed towers in mass transfer operations appears to be a relatively recent innovation, hence studies of liquid holdup in these columns have received no attention. The approach for studying the liquid holdup in falling films over an external packed tower as presented in this report is mainly to investigate the feasibility of utilizing the equipment for absorption of water vapor from atmospheric air and in general for future absorption and extraction work.

Review of Literature

The first attempt to measure the liquid holdup in conventional packed columns is perhaps that of Appel and Elgin (1). In the course of investigating the performance of a packed solvent extraction column using the system of toluene, benzoic acid and water, these investigators found that the holdup is dependent on the flow rate of the discontinuous phase. Gaylor and Pratt (2) developed a relation for the fractional holdup of dispersed phase in terms of fluid and packing characteristics and then used this relation to determine the approximate superficial area of contact between phases in packed extraction columns.

Lockhart and Martinelli (3) measured the holdup in pipes of varying diameter for four types of isothermal two-phase flow. They correlated their observed liquid holdup against a parameter X , the square-root of the ratio of the pressure drop for the liquid flowing alone to the pressure drop for the gas flowing alone. The parameter X was found to be a function of the physical properties of liquid and of gas. Hughmark and Pressburg (4) developed a statistical correlation for holdup which included the fluid physical properties, total mass velocity and gas-liquid ratio for gas-liquid flow in a vertical pipe.

The interest in measuring the liquid holdup on flat plates is mainly due to the desire to measure the thickness of the liquid film. Dukler and Bergelin (5) have treated this subject more rigorously and have developed equations using the Von Karman velocity distribution which relate liquid film thickness in concur-

rent, gas-liquid flow to the flow rates, physical properties of the fluids and energy loss. Recently Portlaski (6) made an extensive study of falling liquid films and compared the different approaches for film thickness over a smooth vertical plate.

Based upon this review of the literature, it appears that no one has, previous to this study, used dimensional analysis to develop a form which will predict the liquid holdup as a function of liquid and tower properties. Numerous workers have dealt empirically with liquid holdup in conventional packed towers, but no work has been done on the holdup on exterior packed columns. Considerable work, both theoretical and practical has been done on the liquid retained on a flat smooth plate; however none of this work has been extended to a surface covered with a cloth or other porous media.

Objectives

The objectives of this research project were:

1. To study the mechanism of falling liquid film flow over an external packed porous medium.
2. To study the liquid holdup in falling film for different thicknesses of porous medium over a range of liquid flow using different physical properties.
3. To correlate the results of this study by dimensional analysis in order to obtain a relation for predicting the liquid holdup in equipment of this type.

DIMENSIONAL ANALYSIS

Theory

An initial insight into the behavior of a physical system can often be obtained by dimensional analysis of the variables that characterize the definite physical system. Dimensional analysis entails certain assumptions and limitations inherent in this method of correlation; although it does not give the investigator any new information about the exact behavior of this situation, it is a powerful preliminary tool.

The result of dimensional analysis of a problem is a reduction of the number of variables in the problem. The advantage gained by this will be clear if one considers the labor that is required for the experimental determination of a function. A function of one variable may be plotted as a single curve. A function of two variables is represented by a family of curves, one curve for each value of the second variable and so on. If, for example, five experimental points are required to plot a curve, twenty-five points are required to plot a chart of five curves, one hundred and twenty-five points are required to plot a set of five charts, etc. This situation quickly gets out of hand, particularly if each point entails much expense as is not unusual. Evidently, a reduction of the number of variables in a problem greatly amplifies the information that is obtained from a few experiments. Consequently, dimensional analysis is an important mathematical tool of the experimenters.

There are two methods, Rayleigh's method and Buckingham Pi's

method which have been frequently used in order to apply dimensional analysis in a given situation. The theory and the application of both of these methods have been treated extensively by Perry (7) and Langhaar (8). The final result will be the same whichever may be the method used for dimensional analysis.

Application to the Present Problem

When a liquid is flowing over an external-packed porous medium, it is reasonable to expect that the liquid holdup on the tower will depend upon the physical properties of the liquid and of the tower. An equation can be derived by dimensional analysis to predict the liquid holdup over the tower by considering the variables involved in the system. Either the Rayleigh's method or the Buckingham Pi's method can be used. In view of the simplicity and straight and straightforward nature of the Rayleigh's method, this method was followed here. The complete derivation of the equation from the first principles is shown in the Appendix. The final equation is

$$\frac{H}{L\rho} = K \left[\frac{Lu\rho}{\mu} \right]^b \left[\frac{\mu}{(\rho g_c L \sigma)^{1/2}} \right]^n \left[\frac{L^2 \rho^2 g_c}{\mu^2} \right]^h \left[\frac{\sigma_c}{L} \right]^m (\epsilon)^s \quad (1)$$

where H = holdup per unit area, g./sq.cm.

L = characteristic length, cm.

ρ = density of the liquid, g./cc.

μ = viscosity of the liquid, g./((cm.)(sec.))

u = velocity of the liquid, cm./sec.

σ = surface tension of the liquid, dynes/cm.

δ_c = thickness of the cloth, cm.

ϵ = porosity of the cloth, dimensionless

g_c = gravity constant

g_L = local gravity, cm./sec.²

K, b, n, h, m and s are arbitrary constants.

The groups $L\rho/\mu$, $H/(\rho g_c L \sigma)^{\frac{1}{2}}$ and $L^3 \rho^2 g_L / \mu^2$ are recognized as the well known Reynolds number, the Ohnesorge number and the Galileo number respectively.

In any dimensional analysis problem, one should be cautious to use the correct form of variables involved in deriving the equation. The mere fact a group is dimensionless should not induce one to use the variable without discretion. For the present problem all the variables are well defined and quite evident except the characteristic length L. In the first group $H/L\rho$, if cylindrical coordinates are used, H is the mass per unit area, measured in θ and z directions, and ρ is the mass per unit volume in θ , z and r directions. So L, the characteristic length, should be one which can be compared with film thickness in r directions. Therefore, an appropriate choice for this is the thickness of the cloth δ_c .

Perry (9) considers the flow of fluids through consolidated porous medium similar to that through beds of granular solids. The modified Reynolds number for flow through the porous medium containing a bed of particles is given by $D_p G / \mu$, where D_p is the average particle diameter, defined as the diameter of a sphere of the same volume as the particle, G is the fluid superficial mass velocity based on empty cross-section, and μ is the viscosity of

the liquid. If it is assumed that the packing, corduroy cloth, is made of uniform spherical particles, the modified Reynolds number $D_p G / \mu$, can be used for the present problem. Therefore, the characteristic length for this group is average particle diameter D_p . Similarly, the particle diameter can be used for the Ohnesorge number and the Galileo number.

The holdup will be influenced by the thickness of the cloth, δ_c . As developed, the general form of the equation includes the group δ_c / L . It is reasonable to assume that δ_f , the depth of liquid on an uncovered surface at a given flow rate, can be taken as the reference characteristic length. Actually, as shown in the treatment on film thickness without the cloth covering (page 25), the δ_f becomes tower diameter when the liquid flow rate is included. The form δ_c / δ_f is retained because it tends to give a better physical picture of the phenomenon involved.

The final form of the equation after introducing the correct form of characteristic length is:

$$\frac{H}{\delta_c \rho} = K \left[\frac{D_p G}{\mu} \right]^b \left[\frac{\mu}{(\rho \epsilon_c D_p \sigma)} \right]^n \left[\frac{D_p^3 \rho^2 \epsilon_I}{\mu^2} \right]^h \left[\frac{\delta_c}{\delta_f} \right]^m (\epsilon)^s \quad (2)$$

Assumptions Made in this Study

The following assumptions were made during this study:

1. Under the conditions in which these studies were made, it was found by measurement that the composition of the liquid remained substantially unchanged over the length of the tower. Hence it was assumed that the influence of the gas phase on

- the behavior of the liquid was insignificant and the properties of the liquid were constant throughout a given run.
2. There is no velocity slip between the liquid and the tube wall.
 3. End effects, both at the top and bottom were of minor consequence.
 4. Holdup in the liquid distributor is negligible.

DESCRIPTION OF EQUIPMENT

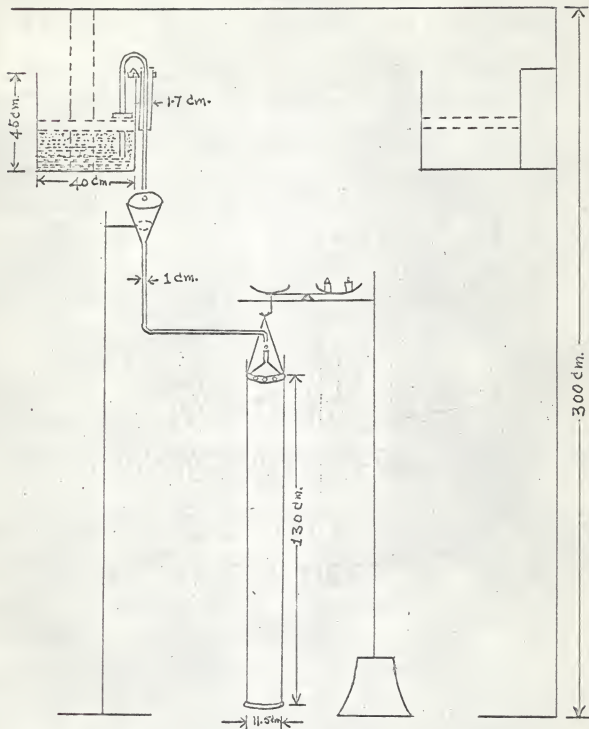
The physical layout of the components of the system is shown in PLATE I. Two stainless steel tanks 40 cm. in diameter and 45 cm. in height mounted 300 cm. above the reference level were used for storage of liquid. To maintain a constant feed to the tower, the tanks were provided with polyurethane foam floats (see PLATE I) which moved with the level of the liquid so that the head available for flow remained constant. The tower was fed with liquid through one-eighth inch, three-sixteenth inch and one-fourth inch outside diameter copper tube syphons. To obtain freedom of movement, the syphons were mounted on polyurethane foam floats and were guided by teflon collars mounted in a one centimeter steel pipe.

PLATE II shows the towers used for this study. The towers were made of stainless steel tube 11.5 cm. in diameter, 130 cm. in height and six-tenths millimeter wall thickness. They were wrapped with corduroy cloth covering of different thicknesses with the ridges running forty-five degrees to the horizontal. The liquid flowed over an inverted cone which served to distribute

EXPLANATION OF PLATE I

Illustration of experimental equipment layout.

PLATE I



EXPLANATION OF PLATE II

Photograph showing the columns of 11.5 cm. in diameter and 130 cm. in height used in the experiment. The columns at the sides are covered with corduroy cloth and the middle one shows an uncovered surface.

PLATE II



the liquid uniformly. From the distributor, the liquid flowed into the cloth covering and down the tower. PLATES III and IV give an idea of the feeding and distributor system.

The cloth covering served three purposes: (a) It acted as a holdup agent for the liquid. (b) It acted as a surface agent to minimize channelling, i.e., it served to spread the liquid more evenly over the tower. (c) The cloth covering which was wrapped at forty-five degrees from the horizontal caused the liquid to flow in a spiral path around the column instead of following a vertical path.

A balancing tower method for weighing of the holdup was devised to record the weight of the column and its contents during the experiment. With the given loads it was found that the balance used would readily respond to a change in mass of considerably less than 0.5 g. The details of this device are shown in PLATE V.

OPERATIONAL PROCEDURE

Method of Operation

The method of operation used was as follows:

1. The weight of the tower with dry cloth covering was noted first.
2. The flow of liquid was started in one of the syphon tubes and the rate was then adjusted to the desired value by varying the head available for flow.
3. When the holdup on the column at the required flow rate was steady for more than 30 min., the weight of the tower and its

EXPLANATION OF PLATE III

Photograph showing the two arrangements for feeding and for distributing the liquid over the tower. Wrinkles on the packing surface can be observed.

PLATE III



EXPLANATION OF PLATE IV

Photograph showing the flow of liquid over the packing surface in a spiral path around the column for a flow rate of 40 cc./min. Slight overlapping of the packing can be observed.

PLATE IV



EXPLANATION OF PLATE V

Photograph showing the device for weighing the column
and its contents.

PLATE V



- contents were noted. Two samples of liquid one at the inlet and the other at the outlet were taken to check the liquid concentration and to estimate the change in the concentration which might have occurred over the tower.
4. Next, the liquid flow rate was adjusted to a new value and the procedure repeated to get the holdup on the column at various flow rates.
 5. Measurements were taken at flow rates ranging from about ten to about seventy cubic-centimeters per minute with intervals of about ten cubic-centimeters. The range selected was based on preliminary trials for flow rates; at the maximum value, flooding of the tower (a continuous stream of liquid over and exterior to the packing surface) was observed and in the vicinity of the lower flow rates, a condition of only partial wetting was noticed.

Sampling Procedure and Measurement of Variables

The variables recorded were 1. temperature, 2. inlet solution flow rate, 3. solution concentration at the inlet and outlet and 4. cloth thickness and porosity. The methods of measuring the variables and analyzing the samples were as follows:

1. Temperature

The temperature was recorded for each run at the time of solution sampling. The temperature was fairly constant at 25°C throughout this study sometimes varying from 24° to 26°C.

2. Inlet solution flow rate

The inlet solution flow rate was measured by collecting

the discharge from the syphon tube for a period of two minutes. The solution was collected in a cylinder graduated in tenths of a cubic-centimeter.

3. Solution samples

The solution samples were taken in small covered glass bottles. The samples were analyzed on a refractometer. The calibration of the refractometer was performed by Livingston (10). PLATE A-1 in the Appendix is the result of the calibration.

4. Cloth thickness and porosity

The cloth thickness was measured with a Frazier compressor. With this instrument the cloth thickness at different pressures, ranging from 0.1 to 3.0 lb./sq.in.abs., was noted and the plot of the data when extrapolated to zero pressure was taken as the thickness of the cloth.

As the thickness measured by the above method was suspected to have insufficient sensitivity, a point micrometer was used to get the actual thickness. In all the cases eight layers of cloth folded in different ways were used to get an average thickness. PLATE VI shows the micrometer used for this purpose.

Porosity of the cloth was measured by determining the bulk volume of a section of the cloth and then the volume occupied by the cotton alone, the difference being the porosity of the cloth. Sample calculation A-1 in the Appendix shows the results and the sensitivity of the method used.

EXPLANATION OF PLATE VI

Photograph showing the micrometer used for measuring the cloth thickness. It can be observed that the pointer is just touching the cloth surface.

PLATE VI



Properties of the Liquids

The density, viscosity and surface tension of water were taken from the Lange's Handbook of Chemistry and that of glycol solutions from the experimental data of the Dow Chemical Company (11). The reliability of the viscosity data of glycol solutions was checked using a standard Ostwald Viscometer and the results were found to be in close agreement with the Dow data. Sample calculation A-2 in the Appendix shows these results.

The glycol solutions were prepared by mixing know volumes of 95% propylene glycol and distilled water and the compositions were checked by refractometer.

Film Thickness Without Cloth Covering

Film thickness δ_f without cloth covering was obtained by writing equations of momentum over a section of the tower and finding the velocity distribution inside the liquid film. The film thickness is given by

$$\delta_f = \left[\frac{3\mu Q}{\pi D G \rho} \right]^{1/3} \quad (3)$$

Complete derivation of this equation using the equations of continuity and motion as tabulated by Bird (12) is shown in the Appendix.

Measurement of Particle Diameter of the Fibres in the Packing Cloth

When considering granular materials, the average particle diameter may be defined as the diameter of a sphere having the

same volume as the particle. When all of the particles of the porous medium are of the same size, the screen size (D_{ave}) is frequently used for D_p .

The average particle diameter can be determined if the permeability of the porous medium is known. Thus if the permeability of the exterior packing can be found, an effective D_p can be calculated. The standard method for estimating the air permeability of textile fabrics is given by the method described in A.S.T.M. standards(13). Essentially the method consists in measuring the volumetric flow rate of air through a known area of the fabric at a stated pressure drop. The air permeability of the fabric is then expressed in cubic-feet of air per minute per square foot of fabric at a stated pressure drop across the cloth. Neither the equipment nor the facilities for conditioning of the air to A.S.T.M specifications were available, moreover it was felt that the sensitivity of this method, on a single layer of cloth, would not be high, a simple method, using simple and readily available equipment was sought.

A method for finding the permeability of any porous medium is based on the classical experiment originally performed by Darcy in 1856. The experiment was slightly modified to suit the present case. PLATE A-2 in the Appendix shows the details of the equipment used. A cylindrical sample of porous material having cross-sectional area A and length L was formed by covering a test tube with a number of layers of cloth over which a polyethylene sheet was fixed. Care was taken to insure that there were no regions through which channelling could occur between the wall of

the tube and the cloth or between the cloth and the interior plastic sheet.

The principle as given by Muskat (14) consists of measuring the volume flux per unit area of a fluid of known viscosity through a linear sample of the medium together with measuring the pressure gradient which induces that flux and then calculating the permeability k by the equation,

$$k = \frac{\mu v}{dp/dx} \quad (4)$$

The superficial velocity v can be calculated by knowing the volume of liquid Q collected in a unit time and cross-sectional area A . As no external pressure is applied, the pressure causing the flow is the head of liquid h . Since the liquid is incompressible, the pressure gradient dp/dx is uniform along the length of flow and has a value,

$$\frac{dp}{dx} = \text{constant} = \frac{\rho gh}{L} \quad (5)$$

Inserting the value of v and dp/dx into equation (4), k may be calculated.

$$k = \frac{\mu QL}{A\rho gh} \quad (6)$$

This relationship is known as Darcy's Law which defines permeability in terms of measurable quantities.

Scheidegger (15) has discussed in detail Kozeny's theory which is a widely accepted explanation for permeability as conditioned by the geometrical properties of a porous medium. This theory represents the porous medium by an assemblage of channels

of various cross-sections but of definite length. The Navier-Stokes equations are solved simultaneously for all channels passing through a cross-section normal to the flow in the porous medium. Finally the permeability of the medium is expressed in terms of the specific surface of the porous medium which is a measure of a properly defined hydraulic radius. The relation between permeability k and specific surface S is called the "Kozeny equation" and is as follows,

$$k = \frac{C\epsilon^3}{S^2} \quad (7)$$

The number C is known as the "Kozeny constant" and depends on the geometrical form of the capillary tube cross-section. For a circle $C = 0.50$, for a square $C = 0.5619$ and for an equilateral triangle $C = 0.5974$. The specific surface is in turn used to define the mean particle diameter D_p :

$$D_p = \frac{6}{S} \quad (8)$$

This definition is chosen because for sphere equation (8) gives just D_p equal to diameter of the sphere. Sample calculation A-3 in the Appendix shows the calculation of particle diameter using both Darcy's law and the Kozeny equation.

Six liquids were investigated in this work (water and five different concentrations of propylene glycol solution). The absolute viscosity of the liquids used varied between 30 centipoises for 95 percent propylene glycol to 0.88 centipoise for water, and the surface tension of the solutions ranged from 36 to 72 dynes/cm. respectively. There was not much change in the density of the

liquids used, the variation being from 1.0 to 1.04 g./cc.

Three different types of corduroy cloth, the thickness varying from 0.1098 to 0.188 cm. were used in this study.

All these data are given in Table A-1 of the Appendix.

RESULTS

Experimental Results

Experimental liquid holdup measurements were obtained for water and for various concentrations of propylene glycol over flow rates ranging from 10 to 75 cc./min. Duplicate runs were averaged together; runs that were not duplicated were reported alone. The results of these measurements were plotted against the liquid flow rates down the tower and the curves are shown in PLATES VII through XI. Table A-1 in the Appendix gives the values of variables used and actual data obtained from the experiment.

A careful examination of semi-logarithmic plots of liquid flow rates versus holdup as shown in PLATE XII indicates that there is an abrupt change in the slope of the lines at flow rates below 20 cc. The slope of the lines is almost constant for flow rates of 20 to 50 cc./min., however above this region there is another change in the slope of the lines.

Based on the usual observation of the behavior and nature of the flow patterns, it is believed that in the lower range of flow rates, upto 20cc./min., the increase in liquid holdup is dependent chiefly upon the increase in the liquid flow through the packing. In the intermediate range from 20 to 50 cc./min., the increase in

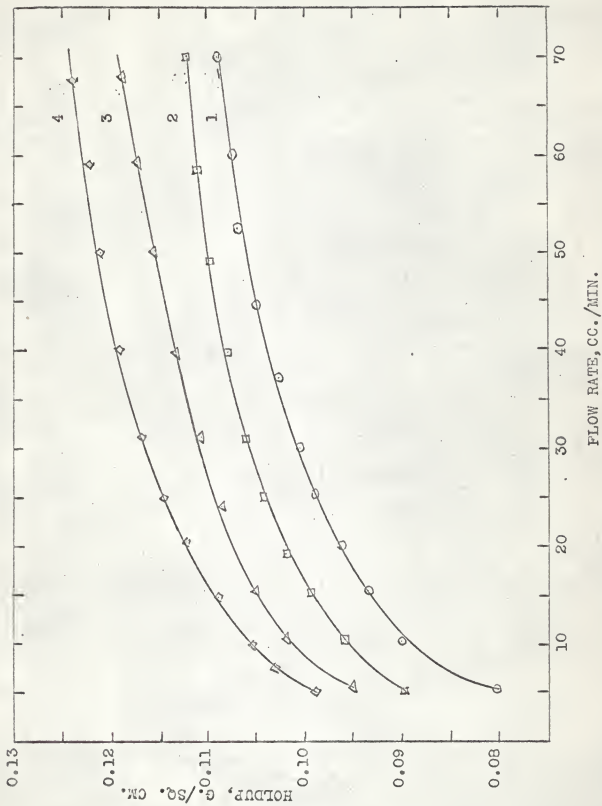
EXPLANATION OF PLATE VII

Experimental liquid holdup measurements for water and for various concentrations of propylene glycol.

Cloth: $\delta_c = 0.1098$ cm., $D_p = 0.002675$ cm. and $\mu = 0.81$

<u>Curve</u>	<u>Concentration % by wt. of glycol</u>	<u>ρ g./cc.</u>	<u>μ poises</u>	<u>σ dynes/cm.</u>
1	water	1.000	0.0088	72.0
2	52.0	1.036	0.055	44.0
3	74.0	1.040	0.13	40.0
4	82.5	1.039	0.18	38.0

PLATE VII.



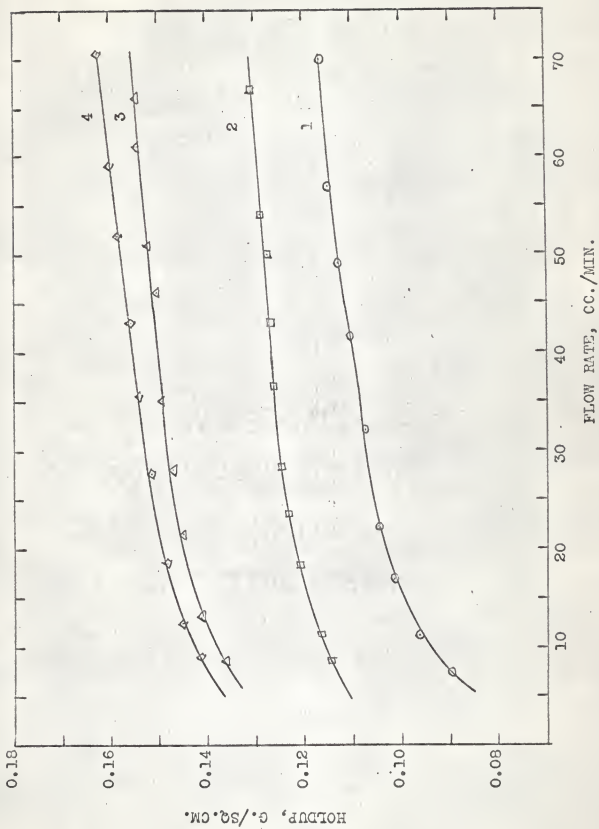
EXPLANATION OF PLATE VIII

Experimental liquid holdup measurements for water and for various concentrations of propylene Glycol.

Cloth: $\delta_c = 0.127$ cm., $D_p = 0.002675$ cm., and $\mu = 0.82$

<u>Curve</u>	<u>Concentration % by wt. of Glycol</u>	<u>ρ, g./cc.</u>	<u>μ, poises</u>	<u>σ, dynes/cm.</u>
1	water	1.00	0.0088	72.0
2	32.0	1.023	0.028	49.0
3	70.5	1.04	0.105	41.5
4	90.0	1.037	0.27	37.3

PLATE VIII

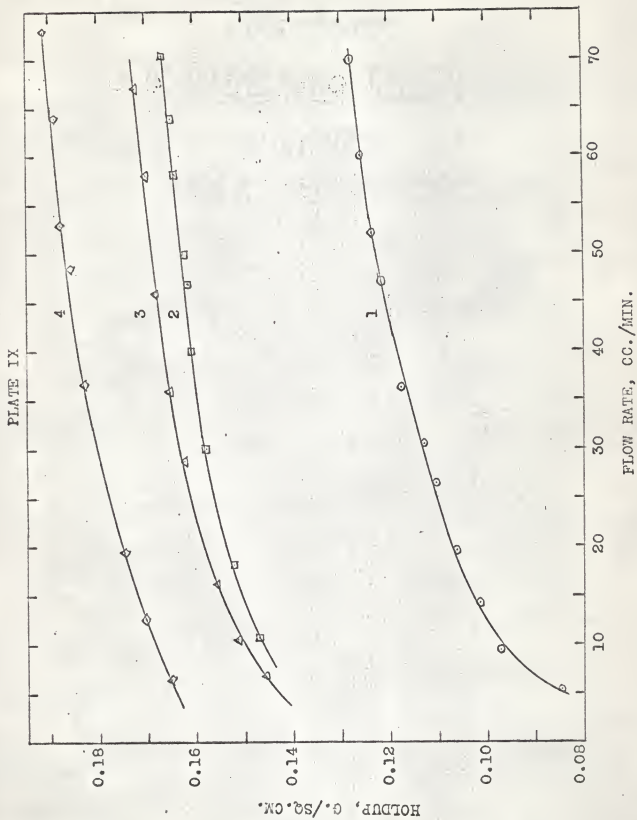


EXPLANATION OF PLATE IX

Experimental liquid holdup measurements for water and for various concentrations of propylene glycol.

Cloth: $\delta_c = 0.188$ cm., $D_p = 0.00248$ cm. and $\mu = 0.82$

<u>Curve</u>	<u>Concentration % by wt. of Glycol</u>	<u>ρ g./cc.</u>	<u>μ poises</u>	<u>σ dynes/cm.</u>
1	water	1.00	0.0088	72.0
2	70.5	1.04	0.105	41.5
3	83.0	1.038	0.19	38.3
4	94.0	1.036	0.30	36.7



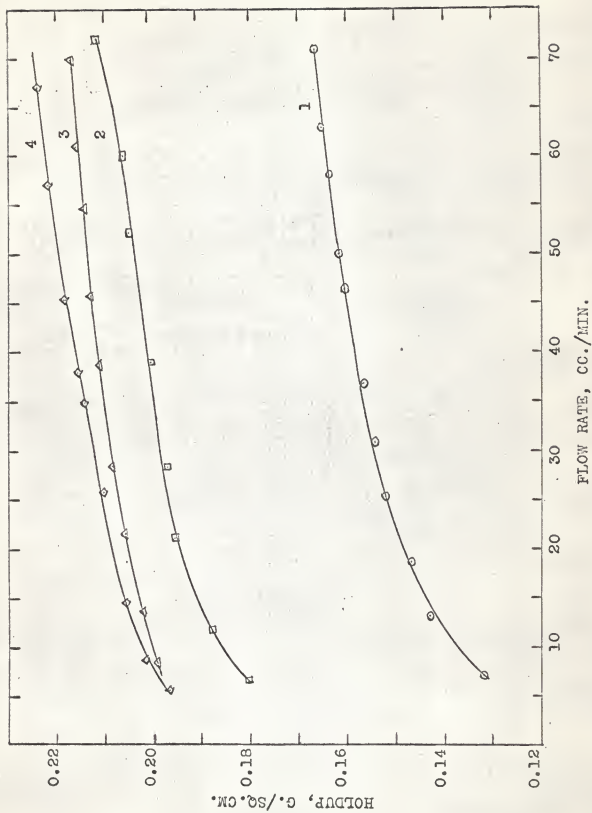
EXPLANATION OF PLATE X

Experimental liquid holdup measurements for water and for various concentrations of propylene glycol.

Cloth: $\delta_c = 0.2196$ cm, $D_p = 0.002675$ cm, and $\mu = 0.81$

<u>Curve</u>	<u>Concentration % by wt. of glycol</u>	<u>ρ g./cc.</u>	<u>μ poises</u>	<u>σ dynes/cm.</u>
1	water	1.00	0.0088	72.0
2	70.5	1.04	0.105	41.5
3	83.0	1.036	0.19	38.3
4	94.0	1.036	0.30	36.7

PLATE X



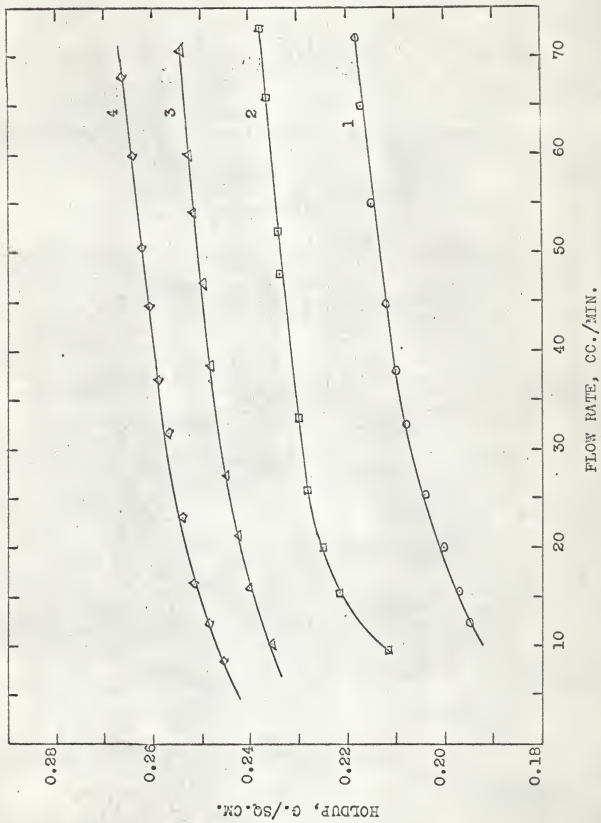
EXPLANATION OF PLATE XI

Experimental liquid holdup measurements for water and for various concentrations of propylene glycol.

Cloth: $\delta_c = 0.3294$ cm., $D_p = 0.002675$ cm. and $= 0.81$

<u>Curve</u>	<u>Concentration % by wt. of glycol</u>	<u>ρ g./cc.</u>	<u>μ poises</u>	<u>σ dynes/cm.</u>
1	water	1.00	0.0088	72.0
2	32.0	1.023	0.028	49.0
3	70.5	1.04	0.105	41.5
4	90.0	1.037	0.27	37.3

PLATE XI

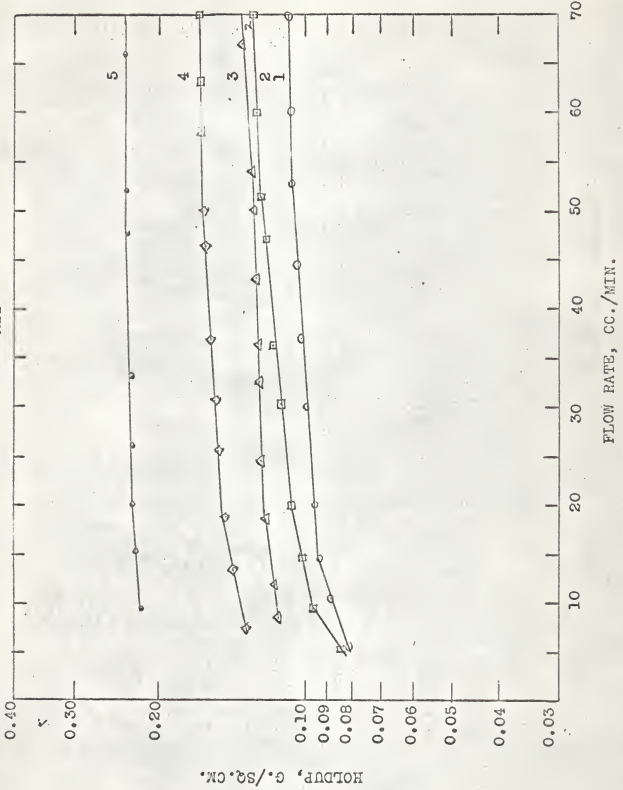


EXPLANATION OF PLATE XII

Representative semi-logarithmic plots of liquid flow rate versus holdup.

<u>Curve</u>	<u>Concentration of liquid</u>	<u>Cloth thickness</u>
1	water	0.1098 cm.
2	water	0.188 cm.
3	32% glycol	0.127 cm.
4	water	0.2196 cm.
5	water	0.3294 cm.

PLATE XII



holdup is controlled by the increase in the liquid flow over the packing. Finally in the upper range of flow rates between 50 to 70 cc./min., the increase in the liquid holdup is caused by the quantity of liquid flowing exterior to the packing. The diagram below shows three types of flow. Although these effects are not markedly seen in other flow rate versus holdup curves, still it



Flow through
packing



Flow over
packing



Flow exterior
to packing

is expected that this sort of behavior exists in all the concentrations studied.

Calculated Results

The uniformity in the nature of the liquid flow rate versus holdup curves suggests that the error introduced in interpolating the holdup data for intermediate flow rates is completely negligible. By using flow rates of multiples of 10 viz., 10, 20, 30, etc., the amount of work involved in the calculation of dimensionless groups is made much simpler. As explained previously, below

10 cc./min., only partial wetting of the column was noticed, and in the vicinity of 70 cc./min. flooding of the tower, i.e., a continuous stream of liquid on the packing surface was observed. To avoid these two extremities, it was decided to correlate the results for flow rates above 10 cc./min. and below 70 cc./min.

To obtain the best fit of the data to equation (2), a least squares analysis using the "IBM 1620 Scrap" program (16) was made on the computer. Twenty sets of readings, each set consisting of five observations, were used in the analysis. The data analyzed covered five flow rates of 20, 30, 40, 50 and 60 cc./min., five cloth thicknesses ranging from 0.1098 cm. to 0.329 cm. and strength of solutions varying from pure water to 94 percent propylene glycol. The numerical values for the arbitrary constants of equation (2), obtained by the least square analysis are

$$K = 1467.$$

$$b = -0.043$$

$$n = 0.75$$

$$h = 0.46$$

$$m = -0.36$$

$$s = 2.01$$

The resulting correlation for liquid holdup is as follows:

$$\frac{H}{\delta_c P} = 1467 \left[\frac{\mu}{D_p G} \right]^{-0.043} \left[\frac{\mu}{(\rho \epsilon_c D_p \sigma)} \right]^{-0.75} \left[\frac{D_p^3 \rho^2 g_L}{\mu^2} \right]^{0.46} \left[\frac{\delta_f}{\delta_c} \right]^{0.36} \left[\epsilon \right]^{2.01}$$

..... (9)

The observed holdup and calculated holdup using the above

Table 1. Difference, H, between observed holdup and calculated holdup directly and as a percent of the observed holdups.

S_c cm.	Strength : of sol. : % by wt. : of glycol:	Q : cc./min.:	H		ΔH : (H_{expt} - H_{calc})	$\frac{\Delta H}{H_{\text{expt}}}$ %
			: g./sq. cm.:	: g./sq. cm.:		
			: Experi- mental	: Calcu- lated		
0.1098	water	20	0.0964	0.0904	0.0060	6.22
		30	0.1005	0.0931	0.0074	7.36
		40	0.1036	0.0952	0.0084	8.11
		50	0.1058	0.0969	0.0089	8.42
		60	0.1076	0.0981	0.0095	8.83
0.1098	52.0	20	0.1027	0.1074	-0.0047	4.58
		30	0.1060	0.1109	-0.0049	4.62
		40	0.1083	0.1132	-0.0049	4.52
		50	0.1101	0.1152	-0.0051	4.63
		60	0.1114	0.1166	-0.0052	4.66
0.1098	74.0	20	0.1072	0.1100	-0.0028	2.61
		30	0.1107	0.1219	-0.0112	10.12
		40	0.1133	0.1250	-0.0117	10.31
		50	0.1157	0.1271	-0.0114	9.87
		60	0.1175	0.1288	-0.0118	9.62
0.1098	82.5	20	0.1126	0.1199	-0.0073	6.48
		30	0.1166	0.1235	-0.0069	5.92
		40	0.1195	0.1260	-0.0065	5.44
		50	0.1213	0.1282	-0.0068	5.68
		60	0.1229	0.1301	-0.0072	5.86
0.2196	water	20	0.1478	0.1440	0.0038	2.57
		30	0.1537	0.1493	0.0044	2.86
		40	0.1580	0.1530	0.0050	3.16
		50	0.1610	0.1553	0.0057	3.54
		60	0.1636	0.1576	0.0060	3.67
0.2196	70.5	20	0.1940	0.1870	0.0070	3.61
		30	0.1985	0.1931	0.0054	2.72
		40	0.2020	0.1972	0.0048	2.38
		50	0.2044	0.2005	0.0039	1.91
		60	0.2064	0.2036	0.0028	1.36
0.2196	83.0	20	0.2048	0.1911	0.0137	6.68
		30	0.2082	0.1970	0.0112	5.37
		40	0.2109	0.2018	0.0091	4.31
		50	0.2135	0.2048	0.0087	4.07
		60	0.2154	0.2081	0.0073	3.55

Table 1. (continued)

δ_c	Strength :	Q	H	H	ΔH	$\frac{\Delta H}{H_{\text{expt}}}$
cm.	of sol. :	cc./min.:	g./sq. cm.:	g./sq. cm.:	($H_{\text{expt}} - H_{\text{calc}}$) :	%
	% by wt. :		Experi-	Calcu-	Healc)	
	of glycol:		mental	lated		
0.2196	94.0	20	0.2079	0.1941	0.0138	6.64
		30	0.2119	0.2002	0.0117	5.53
		40	0.2159	0.2045	0.0114	5.29
		50	0.2195	0.2085	0.0110	5.02
		60	0.2222	0.2112	0.0110	4.95
0.3294	water	20	0.2011	0.1910	0.0101	5.02
		30	0.2067	0.1971	0.0096	4.64
		40	0.2110	0.2011	0.0099	4.69
		50	0.2139	0.2047	0.0092	4.31
		60	0.2164	0.2081	0.0083	3.83
0.3294	32.0	20	0.2249	0.2273	-0.0024	1.07
		30	0.2291	0.2344	-0.0047	2.05
		40	0.2318	0.2400	-0.0082	3.54
		50	0.2341	0.2440	-0.0099	4.22
		60	0.2359	0.2476	-0.0117	4.96
0.3294	70.5	20	0.2420	0.2463	-0.0043	1.78
		30	0.2452	0.2541	-0.0089	3.62
		40	0.2480	0.2601	-0.0121	4.88
		50	0.2500	0.2660	-0.0160	6.40
		60	0.2529	0.2682	-0.0153	6.04
0.3294	90.0	20	0.2525	0.2531	-0.0006	0.24
		30	0.2568	0.2630	-0.0038	1.48
		40	0.2595	0.2688	-0.0093	3.58
		50	0.2618	0.2740	-0.0122	4.66
		60	0.2640	0.2765	-0.0125	4.74
0.127	water	20	0.1033	0.1020	0.0013	1.26
		30	0.1071	0.1053	0.0018	1.68
		40	0.1102	0.1079	0.0023	2.09
		50	0.1127	0.1098	0.0029	2.58
		60	0.1149	0.1110	0.0039	3.40
0.127	32.0	20	0.1216	0.1218	-0.0002	0.17
		30	0.1247	0.1254	-0.0007	0.56
		40	0.1261	0.1282	-0.0021	1.66
		50	0.1276	0.1305	-0.0029	2.27
		60	0.1292	0.1321	-0.0029	2.24

Table 1. (continued)

S_c	Strength :	Q	H	H	ΔH	ΔH
cm.	of sol. :	cc./min.:	g./sq.cm.:	g./sq.cm.:	(H_{expt} - H_{calc})	$\overline{H_{\text{expt}}}$
	% by wt. :	of glycol:	Experi- mental	Calcu- lated	H_{calc}	%
0.127	70.5	20	0.1446	0.1331	0.0115	7.85
		30	0.1479	0.1371	0.0108	7.31
		40	0.1501	0.1403	0.0098	6.52
		50	0.1520	0.1430	0.0090	5.82
		60	0.1534	0.1446	0.0088	5.73
0.127	90.0	20	0.1491	0.1364	0.0127	8.51
		30	0.1522	0.1408	0.0114	7.48
		40	0.1550	0.1442	0.0108	6.96
		50	0.1576	0.1466	0.0110	6.98
		60	0.1601	0.1484	0.0117	7.30
0.188	water	20	0.1071	0.1240	-0.0169	15.76
		30	0.1130	0.1280	-0.0150	13.28
		40	0.1192	0.1309	-0.0117	9.82
		50	0.1232	0.1330	-0.0098	7.94
		60	0.1254	0.1350	-0.0096	7.65
0.188	70.5	20	0.1532	0.1603	-0.0071	4.63
		30	0.1577	0.1652	-0.0075	4.76
		40	0.1606	0.1690	-0.0084	5.23
		50	0.1631	0.1719	-0.0088	5.39
		60	0.1648	0.1742	-0.0094	5.71
0.188	83.0	20	0.1579	0.1646	-0.0067	4.25
		30	0.1624	0.1699	-0.0075	4.61
		40	0.1660	0.1735	-0.0075	4.52
		50	0.1683	0.1769	-0.0086	5.11
		60	0.1702	0.1790	-0.0088	5.16
0.188	94.0	20	0.1760	0.1667	0.0093	5.28
		30	0.1811	0.1720	0.0091	5.02
		40	0.1844	0.1755	0.0089	5.82
		50	0.1872	0.1788	0.0084	4.48
		60	0.1895	0.1811	0.0084	4.43

equation are given in Table 1. Representative curves of observed and calculated holdups for five selected solution concentrations are shown in PLATES XIII and XIV.

Comparison of Experimental and Calculated Results

The proposed correlation was compared with experimental data by determining ΔH which is the difference between the observed holdup and the calculated holdup. Table 1 shows the comparisons by presenting ΔH as a percent of the observed holdup. PLATE XV

Table 2. Regression Analysis of Correlated Results.

Group	F ratio for the Experiment	F value at 5% level	Significance at 5% level
All groups included	152.8 (5,94)	2.31 (5,94)	Significant
Reynolds number	6.38 (1,94)	3.95 (1,94)	Significant
Ohnesorge number	30.50 (1,94)	3.95 (1,94)	Significant
Galileo number	38.41 (1,94)	3.95 (1,94)	Significant
(δ_c/δ_f) group	198.41 (1,94)	3.95 (1,94)	Significant
Porosity group	2.89 (1,94)	3.85 (1,94)	Not significant
Correlation Coefficient squared for the whole experiment		$R^2 = 0.89$	
overall Correlation Coefficient for the least square fit		$R = 0.944$	

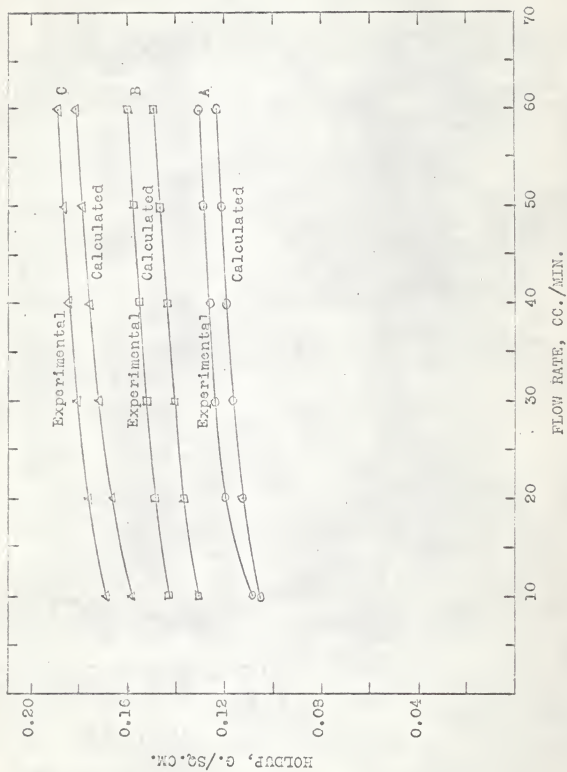
is a plot of experimental holdup versus calculated holdup. The

EXPLANATION OF FIGURE XIII

Experimental and calculated liquid holdups.

<u>Curves</u>	<u>Concentration % by wt. of glycol</u>	<u>Cloth thickness</u>
A	82.5	0.1068 cm.
B	90.0	0.127 cm.
C	94.0	0.188 cm.

PLATE XIII

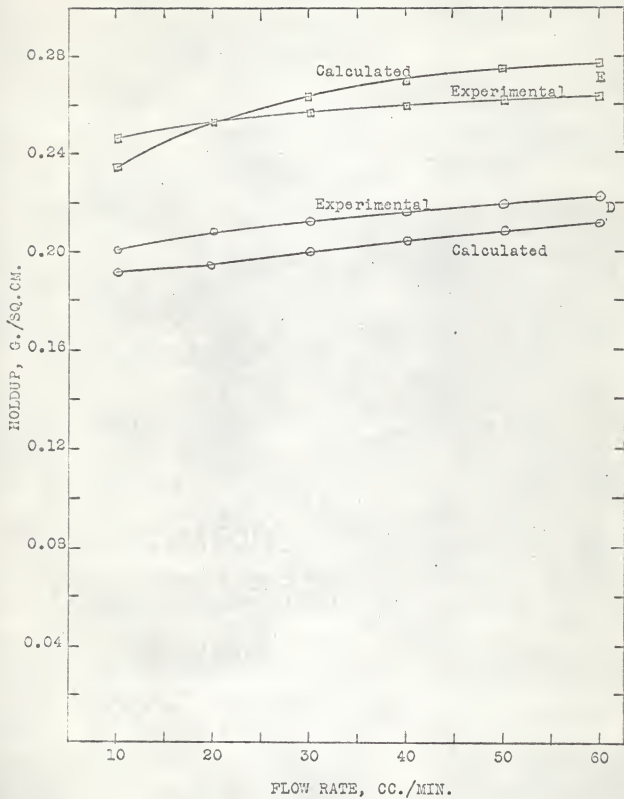


EXPLANATION OF PLATE XIV

Experimental and calculated liquid holdups.

<u>Curves</u>	<u>Concentration % by wt. of glycol</u>	<u>Cloth thickness</u>
D	94.0	0.2196 cm.
E	90.0	0.3294 cm.

PLATE XIV



EXPLANATION OF PLATE XV

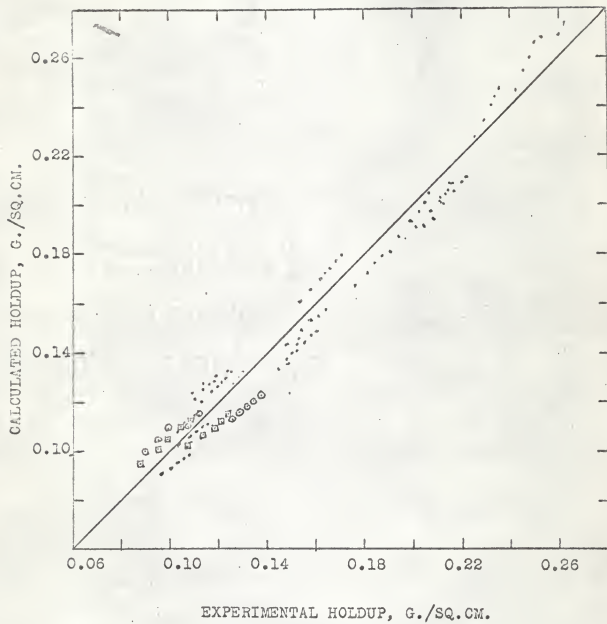
Experimental liquid versus calculated liquid holdup.

Dots represent data for 11.5 cm. diameter tower

■ represent data for 9.0 cm. diameter tower

○ represent data for 5.2 cm. diameter tower

PLATE XV.



minimum and maximum percent deviation from observed holdup was 0.17 and 15.76 respectively. The average percentage deviation for all the observations was 5.05. 55 percent of the points lie within 5 percent of the correlation and 96 percent of the points fall within the range of 10 percent.

A multiple linear regression analysis was also obtained from the computer program. The overall correlation coefficient for the least square fit was 0.944 and the F ratio for all the groups included was 152.8. The results are summarized in Table 2. Details of the multiple linear regression analysis are completely dealt by Fryer (17) and Volk (18).

Applicability of the Holdup Correlation for other Physical Systems

The measurement of particle diameter of the porous medium as discussed before was based on the permeability calculated from Darcy's Law, which in turn was used to get the specific surface of the packing by the Kozeny equation. Thus, the particle diameter is given by

$$D_p = \left[\frac{36 \mu_f Q L_m}{0.56 \epsilon^3 A_m \rho_f g H_f} \right]^{\frac{1}{3}} \quad (10)$$

The subscript f refers to the fluid used for finding the volume Q through the porous medium and m for the porous medium. The value of the Kozeny constant has been taken as 0.56 since the cloth was woven on square pattern. The equation (10) may be used for finding the particle diameter of any porous medium if a simple experiment as described in this paper can be performed.

The proposed correlation for the liquid holdup

$$\frac{H}{\delta_c \rho} = K \left[\frac{D_o G}{\mu} \right]^b \left[\frac{\mu}{(\rho \epsilon_c D_p \sigma)^{1/3}} \right]^n \left[\frac{D_o^3 \rho^2 \epsilon_L}{\mu^2} \right]^h \left[\frac{\delta_c}{\delta_f} \right]^m (\epsilon)^s \quad (2)$$

can be written in a form to include the dimensions of the tower, the properties of the liquid and the characteristics of the packing. In the above equation H , mass of liquid per unit external surface area of the tower, was function of the tower diameter D_T and the length L_T . G was the superficial mass velocity of the liquid based on the empty cross-section and was therefore a function of the tower diameter and the thickness of the cloth. The film thickness δ_f without the cloth covering was calculated by taking into consideration the flow rate and the properties of the liquid and the tower diameter. Thus the equation for the total liquid holdup on the tower becomes

$$\text{Total liquid holdup} = K \pi D_T L_T \delta_c \rho \left[\frac{D_p \pi D_T \delta_c}{\mu} \right]^b \left[\frac{\mu}{(\rho \epsilon_c D_p \sigma)^{1/3}} \right]^n \left[\frac{D_o^3 \rho^2 \epsilon_L}{\mu^2} \right]^h \left[\frac{\delta_c \pi D_T \rho \epsilon}{3 \mu Q} \right]^{m/3} (\epsilon)^s \quad (11)$$

Written in functional form

$$\text{Total liquid holdup} = f(D_T, L_T, \rho, \mu, \sigma, \delta_c, k, \epsilon) \quad (12)$$

As the derived equation takes into account all the variables involved in a system, it is applicable to any other system which involves different sizes of the tower, different properties of the liquid and different characteristics of the packing.

The above analysis was confirmed experimentally by using two other sizes of the tower, varying in the external diameter and the length and with 0.1098 cm. cloth thickness. Table 3 shows these results and PLATES XVI and XVII give an idea of the agreement between the observed holdup and the calculated holdup.

Table 3. Experimental and liquid holdups for tower diameter of 5.2 cm. and 9.0 cm.

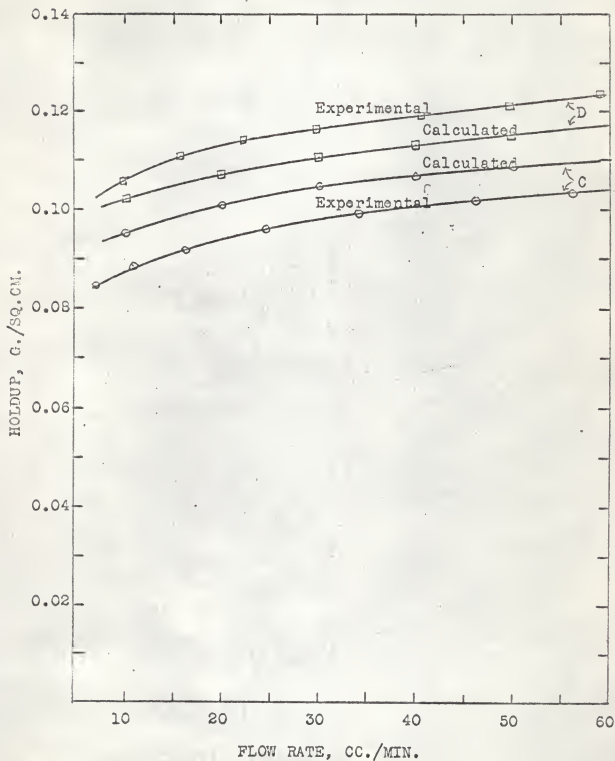
External dia. of the tower:	Concentration of liquid: D_T % by wt. of Glycol:	Cloth thickness: δ_c , cm.	Q : per min.:	H : per cm. Expt.:	H : per sq. cm. calculated:	$\frac{\Delta H}{H_{\text{Expt.}}}$ %
5.2	water	0.1098	20	0.0985	0.1058	7.41
			30	0.1030	0.1091	5.82
			40	0.1062	0.1110	4.41
			50	0.1084	0.1130	4.24
			60	0.1102	0.1148	4.16
5.2	95.0	0.1098	20	0.1230	0.1130	8.13
			30	0.1282	0.1162	9.35
			40	0.1315	0.1183	10.01
			50	0.1342	0.1207	10.05
			60	0.1366	0.1230	9.95
9.0	water	0.1098	20	0.0932	0.1010	8.37
			30	0.0977	0.1050	7.48
			40	0.1004	0.1064	5.97
			50	0.1023	0.1090	6.54
			60	0.1035	0.1100	6.28
9.0	95.0%	0.1098	20	0.1130	0.1070	5.31
			30	0.1165	0.1108	5.48
			40	0.1191	0.1132	5.40
			50	0.1213	0.1150	5.19
			60	0.1236	0.1164	5.49

EXPLANATION OF PLATE XVI

Experimental and calculated liquid holdup curves
using a tower of 9.0 cm. external diameter and
142.0 cm. long.

<u>Curves</u>	<u>Concentration of liquid</u>	<u>Cloth thickness</u>
C	water	0.1098 cm.
D	95.0% glycol	0.1098 cm.

PLATE XVI

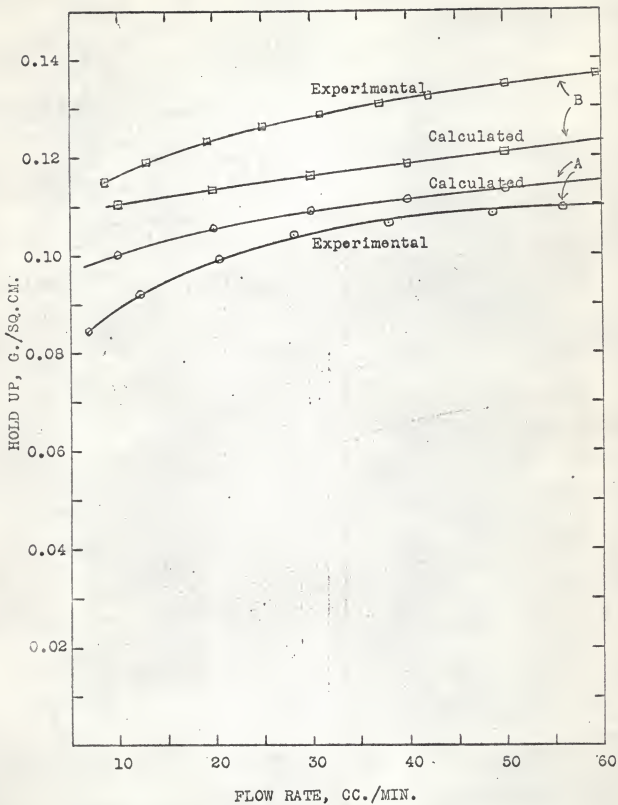


EXPLANATION OF PLATE XVII

Experimental and calculated liquid holdup curves
using a tower of 5.2 cm. external diameter and
146.0 cm. long.

<u>Curves</u>	<u>Concentration of liquid</u>	<u>Cloth thickness</u>
A	water	0.1098 cm.
B	95.0% glycol	0.1098 cm.

PLATE XVII



DISCUSSION

Influence of Physical Properties of the System on the Holdup Correlation

The deviation of liquid holdup from the observed data may depend on some or all of the following sources of variation: concentration of the liquid, thickness and method of packing and nature of flow. Table 4 gives the values of the mean percentage deviations for these three sources of variation. A careful study of the Table 4 shows that the variations in the mean percentage deviations between the concentrations and between the flow rates are almost insignificant, whereas the variations between the thicknesses of the cloth are significant. Also there is a decreasing trend in the percentage deviation as the cloth thickness

Table 4. Mean percentage deviations for concentration, thickness of the cloth and nature of flow. (Data taken from Table 1).

Source of variation		Mean percentage deviation
Concentration:	water	5.69
	70-80% glycol	5.45
	80-95% glycol	5.15
Thickness of the cloth :	0.1098 cm.	7.37
	0.127 cm.	5.43
	0.188 cm.	6.92
	0.2196 cm.	3.45
	0.3294 cm.	3.99
Flow rate:	20 cc./min.	5.16
	30 cc./min.	5.55
	40 cc./min.	5.46
	50 cc./min.	5.51
	60 cc./min.	5.49
Grand mean of all observations		5.55

is increased.

Based upon the inference drawn from the magnitude of the mean percentage deviations, it is expected that the measurement of the cloth thickness and the method of wrapping the column influence the liquid holdup determinations. Care was taken to wrap the columns on the same pattern and without any overlapping but slight change in the method of packing may cause discrepancies in the holdup data. It was observed that with continuous usage, the packing became loosened from the main body of the column and a form of wrinkles developed on the packing surface (see PLATE III). This distortion of the packing might have changed the porosity of the cloth as a whole and caused a different flow pattern on the column. These two reasons, overlapping of the packing and wrinkles on the packing surface probably explain the variations in the mean percentage deviations between the thicknesses of the cloth.

Significance of Dimensionless Groups in the Holdup Correlation

The significance of an individual group which contributes to the liquid holdup correlation can be judged by its F ratio obtained from the multiple linear regression analysis. The F ratios for the experiment and F values at 5 percent level for all the groups considered for the holdup correlation are given in Table 2. The first four groups, the Reynolds number, the Ohnesorge number, the Galileo number and (δ_c/δ_f) group are significant at 5 percent level as shown by their F values.

The important group in the whole analysis is the porosity of

the packing medium. It was not possible to vary the porosity over wide limits as cloth of such types were not readily available. The porosity throughout the whole experiment was almost constant. The F ratio for this group is 2.89 which is not significant at 5 percent level and therefore not contributing its measure in the development of the holdup correlation. To show that by inclusion of this group in the equation, has improved the correlation, the computer program was run without the porosity group. The correlation coefficient was once again the same indicating the porosity group has no bearing on the proposed correlation in the present case. This group is retained, however, because it is believed that it should be significant. It is suggested that it should not be dropped until its true significance has been established experimentally.

The correlation coefficient between the observed holdup and the corresponding calculated holdup is $R = 0.944$ which indicates a high level of significance of the fit of the equation to the data. About 89 percent (R^2) of the observed variability among the holdups is assignable to multiple linear regression analysis on the five groups considered for the holdup correlation. Nearly 11 percent ($1-R^2$) of the observed variability remains unexplained. Probably this might be due to the experimental errors or there might be some other factors that have not been included which could influence the holdup on the column.

CONCLUSIONS

A mechanism has been proposed for the falling liquid film

flow over an external-packed porous medium.

An equation has been developed which can be used to predict the liquid holdup on the exterior packed column by considering the physical properties of the liquid and of the holdup medium. This equation for the present is restricted to the cases where the porosity of the cloth is the same as that used in the above study.

All the groups included in the holdup correlation are significant and nearly one-tenth of the observed variability among the holdups remains unexplained.

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The invaluable sacrifices of my family, particularly my wife Sushila and daughter Jyoti, which made this work possible deserve mention.

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TABLE OF NOMENCLATURE

Letters

Q = volumetric flow rate of liquid	cc./min.
H = liquid holdup	g./sq.cm.
ρ = density of the liquid	g./cc.
μ = viscosity of the liquid	poises
σ = surface tension of the liquid	dynes/cm.
L = characteristic length	cm.
D = diameter	cm.
l = length of the tower	cm.
G = mass velocity of the liquid	g./sq.cm.)(sec.)
v = superficial velocity	cm./sec.
δ = thickness	cm.
ϵ = porosity of the cloth	dimensionless
S = specific surface of the porous medium	sq.cm./cc.
k = permeability of the porous medium	sq.cm.
g = acceleration due to gravity	cm./sec. ²
C = Kozeny constant	dimensionless

Subscripts

c = cloth	ave = average
f = film	r = refers in r direction
L = local	θ = refers in θ direction
m = porous medium	z = refers in z direction
p = particle	
T = tower	

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APPENDIX

Derivation of Equations

Equation 1

Rayleigh's Method of Dimensional Analysis

From the known characteristics of the process, it is expected that the holdup per unit area H depends on a number of quantities which are listed below.

Quantity	Symbol	Dimensions
Holdup per unit area	H	ML^{-2}
Characteristic length	L	L
Velocity of the liquid	u	LT^{-1}
Density of the liquid	ρ	ML^{-3}
Viscosity of the liquid	μ	$ML^{-1}T^{-1}$
Surface tension of the liquid	σ	FL^{-1}
Newton's Law conversion factor	ϵ_c	$MLF^{-1}T^{-2}$
Local gravity	g_L	LT^{-2}
Thickness of the cloth	δ_c	L
Porosity of the cloth	ϵ	dimensionless

The postulated equation for this problem can be written in the following general form

$$H = f(L, u, \rho, \mu, \sigma, \epsilon_c, g_L, \delta_c, \epsilon) \quad (1)$$

If the above equation is a relationship derivable from basic laws, all terms in the function must have the same dimensions as those of the left hand side of the equation (1). Then any term in the

function must conform to the dimensional formula.

$$H = K(L)^a (u)^b (\rho)^c (\mu)^d (\sigma)^e (\epsilon_c)^f (\epsilon_L)^h (\delta_c)^m \quad (2)$$

Since the porosity ϵ has no dimensions, it does not appear in the above equation.

Substituting the dimensions for the quantities in the equation (2)

$$\begin{aligned} ML^{-2} = & K(L)^a (LT^{-1})^b (ML^{-3})^c (ML^{-1}T^{-1})^d (FL^{-1})^e \\ & \cdot (MLF^{-1}T^{-2})^f (LT^{-2})^h (L)^m \end{aligned} \quad (3)$$

Since the equation is assumed to be dimensionally homogeneous, the exponents of the individual primary units on the left hand side of equation (3) must be equal to those on the right hand side. This gives following set of equations:

$$\text{Exponents of L} \quad -2 = a + b - 3c - d - e + f + h + m \quad (4)$$

$$\text{Exponents of M} \quad 1 = c - d + f \quad (5)$$

$$\text{Exponents of T} \quad 0 = -b - d - 2f - 2h \quad (6)$$

$$\text{Exponents of F} \quad 0 = e - f \quad (7)$$

Here there are eight unknowns but only four equations. Four of the unknowns can be found in terms of the remaining four. Arbitrarily four letters must be retained. The final result is equally valid for all choices but which four letters should be retained is left to the judgement of the investigator. For this problem it is decided to retain the exponents for the velocity u , the surface tension σ , local gravity ϵ_L and the thickness of the cloth δ_c . The letters b , e , h and m will be retained and the remaining four are eliminated.

$$\text{From equation (7)} \quad f = e \quad (8)$$

$$\text{From equation (6)} \quad d = -b - 2e - 2h \quad (9)$$

$$\text{From equation (5)} \quad c = 1 + b + e + 2h \quad (10)$$

$$\text{From equation (4)} \quad a = 1 + b + e + 3h - m \quad (11)$$

By substituting the values for the letters a, c, d and f from equations (8) to (11), equation (2) becomes

$$H = K(L)^{1+b+e+3h-m} (\mu)^b (\rho)^{1+b+e+2h} (\mu)^{-b-2e-2h} \cdot (\sigma)^e (\epsilon_c)^e (\delta_L)^h (\delta_c)^m \quad (12)$$

By collecting all factors having integral exponents in one group, all factors having exponents b in the second, e in the third, h in the fourth and m in the fifth

$$\frac{H}{L\rho} = K \left[\frac{L\mu\rho}{\mu} \right]^b \left[\frac{L\rho\sigma\epsilon_c}{\mu^2} \right]^e \left[\frac{L^3\rho^2\epsilon_L}{\mu^2} \right]^h \left[\frac{\delta_c}{L} \right]^m \quad (13)$$

The final form of the correlation for the holdup including porosity ϵ can be written as

$$\frac{H}{L\rho} = K \left[\frac{L\mu\rho}{\mu} \right]^b \left[\frac{\mu}{(L\rho\sigma\epsilon_c)^{\frac{1}{2}}} \right]^n \left[\frac{L^3\rho^2\epsilon_L}{\mu^2} \right]^h \left[\frac{\delta_c}{L} \right]^m \left[\epsilon \right]^s \quad (14)$$

Equation 2

Derivation of the Equation for Liquid Film Thickness Without Cloth Covering
(See Reference 11)

In the derivation of the equation for liquid film thickness, the following assumptions are made.

1. The density and viscosity of the liquid remain constant.
2. The liquid behaves as a Newtonian fluid.

In steady laminar flow the liquid moves in straight lines, the velocity components v_r and v_θ are zero. There is no pressure gradient in any direction. For this system, all terms of the equation of continuity as written in cylindrical coordinates are zero and the equation of motion reduces to

$$\mu \left[\frac{1}{r} \frac{d}{dr} \left(r \frac{dv_z}{dr} \right) \right] = - \rho g \quad (1)$$

Integration of this equation twice with respect to r and use of the boundary conditions $v_z = 0$ at $r = R$ and $v_z = \text{finite}$ at $r = aR$ gives

$$v_z = \frac{\rho g R^2}{4\mu} \left[2a^2 \ln(r/R) - (r/R)^2 + 1 \right] \quad (2)$$

The volume flow rate Q is obtained by the integration of the velocity distribution:

$$Q = \int_0^{2\pi} \int_R^{aR} v_z r dr d\theta \quad (3)$$

Inserting the value of v_z and integrating the equation (3) with respect to r and θ ,

$$Q = \frac{\pi \rho g R^4}{8\mu} (4a^4 \ln a - 3a^4 + 4a^2 - 1) \quad (4)$$

The film thickness δ_f is calculated by assuming $aR = R + \delta_f$ where $\delta_f = eR$ so that $aR = (1 + e)R$. Then,

$$Q = \frac{\pi \rho g R^4}{8\mu} \left[4(1 + e)^4 \ln(1 + e) - 3(1 + e)^4 + 4(1 + e)^2 - 1 \right] \dots (5)$$

Using Taylor's theorem for the expansion of $\ln(1 + e)$ and neglecting the terms of fourth and higher powers of e , Q is given by

$$Q = \frac{2\pi\rho g R^4 e^3}{3\mu} \quad (6)$$

In terms of δ_f

$$Q = \frac{2\pi\rho g R \delta_f^3}{3\mu} \quad (7)$$

The liquid film thickness without the cloth covering is therefore,

$$\delta_f = \left[\frac{3\mu Q}{2\pi\rho g R} \right]^{1/3} \quad (8)$$

Sample Calculations

Sample Calculation A-1

Porosity of Cloth Covering

The bulk volume of a section of the cloth was obtained by measuring its length, width and thickness (see sampling procedure). The volume occupied by cotton alone was found by noting the change in volume of water when the piece of cloth completely dipped into a known volume of water contained in a graduated cylinder.

Thickness of eight layers of the cloth = 0.8787 cm.

Average thickness of the cloth = 0.1098 cm.

Length of the cloth = 119.2 cm.

Width of the cloth = 13.4 cm.

Bulk volume of the cloth piece V_B = (119.2)(13.4)(0.1098)
= 174.0 cc.

Initial volume of water before
dipping the cloth piece V_1 = 194.2 cc.

Final volume of water after

$$\text{dipping the cloth piece } V_2 = 227.5 \text{ cc.}$$

$$\text{Volume occupied by cotton alone } (V_2 - V_1) = 33.3 \text{ cc.}$$

$$\text{Void volume of the cloth } V_B - (V_2 - V_1) = 140.7 \text{ cc.}$$

$$\begin{aligned} \text{Porosity of the cloth} &= \frac{\text{Void Volume}}{\text{Bulk Volume}} = \frac{V_B - (V_2 - V_1)}{V_B} \\ &= \frac{140.7}{174.0} = 0.81 \end{aligned}$$

The error introduced in the porosity of the cloth depends upon the accurate measurement of the cloth thickness and of the final volume V_2 since the length and the breadth of the cloth and the initial volume V_1 can be measured accurately. The porosity of the cloth is

$$\epsilon = \frac{V_B - (V_2 - V_1)}{V_B} \quad (1)$$

The differential change in ϵ is corresponding to a differential change in V_B and V_2 is

$$d\epsilon = \frac{1}{V_B^2} (V_2 - V_1) dV_B - \frac{dV_2}{V_B} \quad (2)$$

If the differentials dV_B and dV_2 are replaced by small finite differences, there results as a good approximation for $\Delta\epsilon$ the expression

$$\Delta\epsilon = \frac{1}{V_B^2} (V_2 - V_1) \Delta V_B - \frac{\Delta V_2}{V_B} \quad (3)$$

The quantities ΔV_B and ΔV_2 can be considered as errors in V_B and V_2 and the equation (3) provide a means of computing the resulting

error in the porosity.

If V_B and V_2 can be measured with an accuracy of ± 2 cc., the maximum resulting error in the porosity (taking V_2 as negative) is

$$\begin{aligned}\Delta C &= \frac{1}{174^2} (33.3)^2 + \frac{2}{174} \\ &= 0.0127\end{aligned}$$

The maximum percent error is $\frac{0.0127(100)}{0.81} = 1.57$ percent. Since the maximum error is quite small, the above method of measuring porosity is adequate for the present case.

Sample Calculation A-2

Calculation of Viscosity

The reliability of the viscosity data given in Dow Chemical Company booklet, "Glycols, Properties and Uses", was checked using a standard Ostwald viscometer. The method consists in comparing the viscosity of an unknown component with that of a known component. Water was used as the standard since its viscosity is known with high precision at all temperatures. If t_1 is the time required to empty the bulb of the viscometer containing water of density ρ_1 and viscosity μ_1 and if t_2 is the time taken to empty the same volume for liquid of density ρ_2 and viscosity μ_2 , then

$$\mu_2 = \frac{\rho_2 t_2}{\rho_1 t_1} \mu_1$$

The following results show for 94% propylene glycol.

	<u>water</u>	<u>94% P. glycol</u>
Temperature °F	74.0	83.0
Density g./cc.	0.9976	1.034
Viscosity centipoise	0.919	_____
Time in seconds for emptying the bulb	117.0	3382.0

$$\text{Viscosity of 94\% propylene glycol} = \frac{(1.034)(33.82)(0.919)}{(0.9976)(117)}$$

$$= 27.5 \text{ centipoises.}$$

The following compositions were checked.

<u>Strength</u> %	<u>Temperature</u> °F	<u>Viscosity, centipoises</u>	
		<u>Experiment</u>	<u>Graph</u>
94.0	83.0	27.5	27.5
76.0	77.0	13.38	13.5
44.0	82.0	3.26	3.4
26.0	83.0	1.80	1.85

Sample Calculation A-3-

Calculation of Particle Diameter D_p

The following calculation shows the method of measuring the particle diameter D_p for the cloth of thickness 0.1098 cm. and porosity 0.81. (see PLATE A-2).

Height of the liquid for flow h	= 25.3 cm.
Length of the porous medium L	= 13.3 cm.
Inner radius R_1	= 1.305 cm.
Outer radius R_2	= 1.655 cm.
Area for flow $A = \pi(R_2^2 - R_1^2)$	= 3.26 sq. cm.

Average volume of water collected

$$\text{in 15 min. at } 77^{\circ}\text{F, } Q = 37.0 \text{ cc.}$$

$$\text{Density of water at } 77^{\circ}\text{F} = 1.0 \text{ g./cc.}$$

$$\text{Viscosity of water at } 77^{\circ}\text{F} = 0.0088 \text{ poise}$$

$$\text{Permeability of the porous medium} = k$$

$$= \frac{\mu Q L}{A \rho g h} = 5.94 \times 10^{-8} \text{ sq.cm.}$$

The specific surface S of the particle is defined as the total particle surface divided by the volume of the particle and is related to the permeability of the porous medium as follows:

$$k = \frac{C \epsilon^3}{S^2}$$

$$\text{or } S^2 = \frac{C \epsilon^3}{k}$$

For square geometry the Kozeny constant $C = 0.5619$

$$S^2 = \frac{(0.5619)(0.81)^3}{5.94 \times 10^{-8}} = 5.03 \times 10^{-6}$$

$$S = 2.243 \times 10^3 \text{ sq.cm./cc.}$$

Mean particle diameter $D_p = \frac{6}{S} = 0.002675 \text{ cm.}$

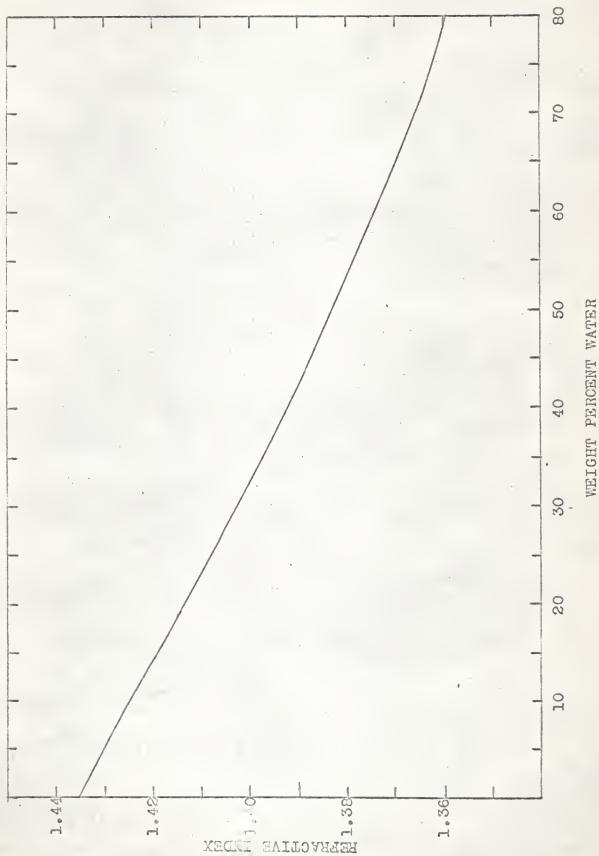
Similarly the particle diameter for other cloths are as follows:

<u>Cloth thickness</u>	<u>Porosity</u>	<u>Particle diameter</u>
0.127 cm.	0.82	0.002675 cm.
0.188 cm.	0.82	0.00248 cm.

EXPLANATION OF PLATE A-1

Refractive index versus percent of water by weight in propylene glycol solutions at 25°C.

PLATE A-1



EXPLANATION OF PLATE A-2

Equipment for finding the particle diameter of the fibres in the cloth packing.

h is the height of the liquid for flow.

L is the length of the porous medium.

$(R_2 - R_1)$ is the thickness of the porous medium.

PLATE A-2

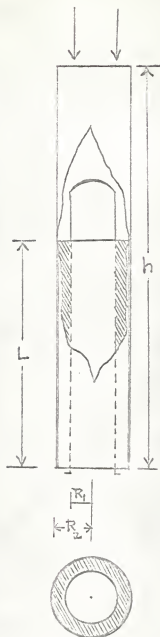


Table A-1. Liquid holdup measurements for water and various concentrations of propylene glycol for different cloth thicknesses. (Physical properties of the liquid and the cloths are also tabulated).

Mean temperature 25°C

S_c	Strength	ρ	μ	σ	Q	Total	H
cm.	% by wt.	g./cc.	poises	dynes/cm.	cc./min.	holdup	g./sq. cm.
	of glycol:					g.	
0.1098	water	1.000	0.0088	72.0	5.4	357	0.0801
					10.2		
					15.4	417	0.0934
					20.0	429	0.0962
					25.2	440	0.0988
					30.0	448	0.1005
					37.0	457	0.1024
					44.5	468	0.1050
					52.5	476	0.1068
0.1098	52.0	1.036	0.055	44.0	5.0	400	0.0897
					10.2	428	0.0960
					15.0	444	0.0995
					19.0	455	0.1020
					25.0	466	0.1042
					31.0	473	0.1060
					39.6	482	0.1080
					49.0	490	0.1099
					58.5	496	0.1111
0.1098	74.0	1.04	0.13	40.0	5.4	424	0.0951
					10.5	455	0.1020
					15.1	469	0.1051
					24.0	483	0.1082
					31.0	495	0.1110
					39.5	506	0.1133
					50.0	516	0.1159
					59.0	523	0.1173
					68.0	529	0.1188
0.1098	82.5	1.039	0.18	38.0	5.0	441	0.0989
					7.3	460	0.1032
					9.8	470	0.1055
					14.6	485	0.1089
					20.2	500	0.1121

Table A-1. (continued)

δ_c	Strength of sol. of glycol:	ρ : g./cc.	μ : poises	σ : dynes/cm.	Q : cc./min.	Total : holdup : %	H : g./sq. cm.
0.1098	82.5	1.039	0.18	38.0	24.7	513	0.1148
					31.0	522	0.1168
					40.0	533	0.1191
					50.0	540	0.1209
					59.0	546	0.1220
					67.5	554	0.1240
0.127	water	1.000	0.0088	72.0	7.5	404	0.0899
					11.1	434	0.0965
					16.7	455	0.1014
					22.2	469	0.1047
					32.0	482	0.1074
					41.5	495	0.1103
					49.0	506	0.1129
					57.0	515	0.1149
70.0	522	0.1163					
0.127	32.2	1.023	0.028	49.0	8.5	508	0.1144
					11.4	523	0.1167
					18.3	541	0.1207
					23.5	550	0.1228
					28.3	558	0.1244
					30.2	561	0.1251
					36.5	564	0.1258
					43.0	567	0.1264
					50.0	572	0.1275
					54.0	576	0.1284
67.0	585	0.1305					
0.127	70.5	1.040	0.105	41.5	8.5	612	0.1364
					13.0	633	0.1412
					21.5	651	0.1451
					28.0	660	0.1472
					35.0	668	0.1491
					46.0	677	0.1501
					51.0	682	0.1521
					61.0	691	0.1542
					66.0	692	0.1544
0.127	90.0	1.037	0.27	37.3	8.7	634	0.1413
					12.4	653	0.1454
					18.5	666	0.1484
					27.6	680	0.1515

Table A-1. (continued)

δ_c	Strength of sol. cm. : % by wt. of glycol:	ρ : g./cc.	μ : poises	σ : dynes : per : cm.	Q : cc./min.	Total : holdup : g.	H : g./sq. cm.
0.127	90.0	1.037	0.2700	37.3	35.5	690	0.1539
					43.0	699	0.1558
					52.0	712	0.1586
					59.0	718	0.1601
					70.5	726	0.1619
0.188	water	1.000	0.0088	72.0	5.3	380	0.0847
					9.5	436	0.0972
					14.1	456	0.1016
					19.7	477	0.1062
					26.5	495	0.1102
					30.1	508	0.1132
					36.2	528	0.1176
					47.0	546	0.1218
					52.0	555	0.1237
60.0	564	0.1257					
70.0	574	0.1278					
0.188	70.5	1.040	0.1050	41.5	10.6	661	0.1473
					18.1	682	0.1520
					30.0	708	0.1578
					40.0	722	0.1609
					46.6	723	0.1611
					50.0	727	0.1620
					58.0	735	0.1639
					64.0	740	0.1649
70.5	747	0.1664					
0.188	83.0	1.038	0.190	38.3	6.7	653	0.1456
					10.4	679	0.1513
					16.3	699	0.1558
					28.6	729	0.1622
					36.0	740	0.1650
					40.0	746	0.1662
					46.0	754	0.1680
					58.0	763	0.1700
67.0	771	0.1719					
0.188	94.0	1.036	0.300	36.7	6.2	743	0.1655
					12.6	767	0.1709
					19.4	785	0.1749
					36.5	820	0.1828
					48.4	832	0.1854

Table A-1. (continued)

δ_c	Strength	ρ	μ	σ	Q	Total	H
cm.	of sol.	:g./cc.	:poises:	dynes:	cc./min.	:holdup:	g./sq.cm.
	of glycol:			per		g.	
	of glycol:			cm.			
0.188	94.0	1.036	0.300	36.7	53.0	844	0.1880
					64.0	852	0.1889
					73.0	859	0.1919
0.2196	water	1.000	0.009	72.0	7.1	589	0.1320
					13.1	638	0.1432
					18.8	655	0.1470
					25.4	679	0.1520
					30.8	685	0.1538
					36.8	697	0.1563
					46.4	715	0.1605
					50.0	720	0.1616
					58.0	728	0.1633
71.0	741	0.1662					
0.2196	70.5	1.040	0.105	41.5	6.3	803	0.1801
					11.6	839	0.1881
					21.0	872	0.1995
					28.4	877	0.1969
					39.0	894	0.2005
					52.0	914	0.2051
					60.0	919	0.2061
					72.0	926	0.2078
0.2196	83.0	1.036	0.190	38.3	8.3	891	0.1999
					13.5	901	0.2020
					21.3	916	0.2057
					28.3	930	0.2085
					38.6	940	0.2109
					45.6	949	0.2128
					54.0	957	0.2145
					62.0	963	0.2160
70.0	968	0.2170					
0.2196	94.0	1.036	0.300	36.7	5.5	877	0.1869
					8.5	898	0.2018
					14.4	918	0.2061
					18.0	920	0.2064
					25.6	938	0.2104
					34.7	954	0.2140
					45.2	974	0.2184
					57.0	989	0.2219
67.0	996	0.2236					

Table A-1 (continued)

δ_c	: Strength :	P	:	μ	:	σ	:	Q	:	Total :	H
cm.	: of sol. :	g./cc.	:	poises:	:	dynes:	:	cc./min.:	:	holdup:	g./sq. cm.
	: % by wt. :		:		:	per :	:		:	g. :	
	: of glycol:		:		:	cm. :	:		:		
0.3294	water	1.000	0.009	72.0	12.4	869	0.1949				
					19.5	892	0.1999				
					25.3	909	0.2039				
					32.5	926	0.2078				
					38.0	937	0.2101				
					44.6	945	0.2119				
					55.0	959	0.2151				
0.3294	32.0	1.023	0.028	49.0	65.0	968	0.2170				
					72.0	974	0.2182				
					9.5	971	0.2178				
					15.2	991	0.2220				
					20.0	1004	0.2249				
					26.0	1014	0.2275				
					33.2	1024	0.2299				
0.3294	70.5	1.040	0.105	41.5	47.7	1041	0.2335				
					52.0	1044	0.2342				
					66.0	1055	0.2364				
					73.0	1060	0.2379				
					10.0	1059	0.2358				
					15.6	1070	0.2400				
					21.0	1081	0.2424				
0.3294	90.0	1.037	0.270	37.3	27.2	1091	0.2448				
					38.5	1107	0.2480				
					46.8	1112	0.2496				
					54.0	1122	0.2518				
					60.0	1126	0.2523				
					71.0	1133	0.2542				
					8.2	1095	0.2458				
16.4	1121	0.2519									
23.0	1133	0.2542									
31.5	1147	0.2570									
37.0	1153	0.2586									
44.5	1162	0.2606									
50.5	1170	0.2622									
60.0	1179	0.2640									
68.0	1187	0.2682									

PREDICTION OF LIQUID HOLDUP IN FALLING FILM
OVER AN EXTERNAL-PACKED POROUS MEDIUM

by

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This work pertains to the prediction of liquid holdup on an externally packed column. The external-packed column is a departure from conventional packed columns in that the liquid flows on the outside of the column rather than through the interior. Characteristics of fluid flow over plane surfaces are well known. When plane surfaces are covered with a porous medium such as cloth for example, the quantity of liquid retained per unit area of surface, i.e., holdup, is changed from that of the uncovered surface.

For this study the liquid flowed on the outside of the tower and the packing selected was a porous medium, corduroy cloth. The packing served to insure a continuous liquid surface and to maintain a constant depth of liquid over all exterior regions of equipment.

Dimensional analysis was employed to formulate the general form for the holdup equation. Experimental liquid holdup measurements were obtained for various concentrations of propylene glycol including pure water, for various flow rates and for different thicknesses of the packing. A digital computer was used to obtain a least square best fit of the experimental data to this general form of the equation.

The correlation coefficient between observed holdup and calculated holdup was ninety percent indicating its high level of significance of the fit of the equation to the data. About nine-tenths of the observed variability among holdups was assignable to multiple linear regression on the five groups considered for the holdup correlation. All the groups, except porosity which was

not varied over wide ranges, were significant. The percent deviation of liquid holdup from the observed data was mainly attributable to the type and method of packing as inferred from the magnitude of the means for the concentration, the flow rates and the packing.

The equation as developed can be used to predict the liquid holdup on any external-packed tower by considering the physical properties of the liquid and the holdup medium. Since the porosity of packing used in taking experimental data varied only over a very narrow range, caution should be exercised in extending this equation to packing having properties which differ appreciably from those used in this work.