DETERMINATION OF THE OPERATING CHARACTERISTICS OF AN ABSORPTION TOWER

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I. INTRODUCTION

The process of gas absorption consists of the transfer of a soluble gas from the gas phase to the liquid phase. This is brought about by mixing the gas and liquid, usually in such a way as to have a large interfacial area of contact and to have the fluid streams in counterflow. The largest possible surface should be provided for the interaction between the phases because the rate at which a soluble constituent of a gas passes into solution is ordinarily rather slow.

The chief purpose of absorption equipment is to provide for this large interfacial area between gas and liquid at a low cost. Commercial gas absorption apparatus has never become standardized and there are no specific types characteristic of individual makers. As a matter of fact, absorption towers are usually designed and built by engineers connected with the plant in which they are to be used, and for this reason there are hardly two units alike.

Four major types of absorption apparatus are in general use.(22)

a. The wetted-wall tower. This tower is most useful for experimental work since it has a definite measurable area of contact.

b. Spray towers. These towers are most used where the gas film is the controlling resistance because the drops of liquid from the sprays have a

high velocity relative to the gas and thus cause the gas film resistance to be lowered.

c. Bubble towers. Bubble towers are opposite in principle to the spray towers. In this case the liquid film resistance is lowered by the motion of the bubble through the liquid; while within the bubble the gas is relatively stationary and the material transfer is, for the most part, by true diffusion.

d. Packed columns. The packed column consists of a tower packed loosely with any one of a large number of different types of packing, over which the solvent trickles or flows in thin films, while the gas passes upward through the intervening spaces countercurrent to the flow of the liquid. The packings ordinarily used give a much smaller area of contact between the phases per unit volume than does either the spray tower or the bubble tower. Since both gas and liquid are in violent turbulence, packed towers may be used where either gas or liquid film controls.

Although the basic principles of gas absorption were laid down by Hurter[19] more than fifty years ago, their application for

many years continued to be qualitative rather than quantitative. This was true, according to Van Arsdel[48], partly because of the apparent complexity of the events and partly because of doubt as to whether any pertinent constants could be sorted out of the mass of variables.

Theoretical equations for the diffusion of gases have been developed, but due to the nature of the absorption apparatus and to the fact that there are no theoretical equations for the diffusion coefficients of liquids, all gas absorption calculations depend on experimentally determined coefficients. The values of these coefficients are valid only for the particular unit and, to a great extent, for the particular set of conditions for which they were determined. If it were desired to know the capacity of an absorption tower, the amount of material transferred from the gas to the liquid phase under certain conditions of operation, or the required height of a tower to perform a given absorption, then the absorption coefficients must be known or determined by experiment.

The purpose of this investigation is to modify the design of the 18-inch laboratory stoneware absorption tower in order to correct certain inherent defects of operation, and to determine the operating characteristics of the tower after the design has been modified. The absorption coefficients of the tower for a system in which the liquid film is the controlling resistance, specifically carbon dioxide in water, are to be determined. Also, an attempt will be made

to determine the relationship between the absorption coefficients and certain operating variables. Liquid and gas rates of flow and concentration and partial pressure of the soluble constituent, carbon dioxide, in the liquid and gas phases respectively are the variables to be used.

II. LITERATURE REVIEW

Monaweck and Baker[27], in experiments with ammonia and water, gave a very good proof of the validity of the film theory which is much used to explain the mechanism of gas absorption. When ammonia was accompanied by an inert gas, they found that the value of K, the overall absorption coefficient, decreased considerably with the passage of time from the moment that the gas and liquid phases were brought into contact. This decrease in the value of K could be explained by either an increase in resistance with time, a decrease in the effective value of the driving force, or both. It could not be accounted for by any phenomenon occurring within the liquid because, when the gas phase was composed of only pure ammonia and water vapor, the value of K remained constant. The decrease must then be related to the inert gas. It is conceivable, however, that there may have been a more concentrated solution at the surface of the liquid, which would exert a correspondingly higher vapor pressure and thus lower K. Also, it might be that the rapid rate of absorption of the ammonia with the consequent liberation of the heat of solution may have raised the temperature of the body of the liquid phase which in turn would result in a higher vapor pressure and a lower K. If either of these possibilities were responsible for the decrease in K, then the decrease should have been most marked in the

experiments in which there was no inert gas in the gas phase.

The explanation for the decrease in K must then be in some change which takes place in the gas. Since the value of K was found to be the same for all concentrations of the gas phase at the instant the two phases were brought into contact, it follows that the decrease of K with time was to be accounted for by the building up of a resistance to the passage of the ammonia molecules from the body of the gas to the liquid surface. It is assumed that this resistance is caused by a gas film consisting of a layer of inert and non-absorbed gas at and near the liquid surface.

Sherwood(35) says, ''the film concept has been of inestimable service in providing a mental picture of the surface resistances encountered in interphase transfer of momentum, of materials and of heat.... The word 'film' is somewhat misleading, however, since it is frequently erroneously inferred that the resistance is offered wholly by a layer of absolutely stationary fluid at the interfacial boundary.... It is possible, however, to imagine a purely stagnant film of such thickness that it would offer the same resistance as is usually encountered in transfer between the phases. The thickness of such a 'fictitious film' is best termed the 'effective film thickness'.''

Theory of Diffusion

The diffusion coefficient, D, is useful in comparison of different solutes in the same apparatus. For gas diffusion coefficients, Gilliland[15] and Sherwood[44] derived the semi-empirical formula,

$$D = 0.0166 \frac{T^{3/2}}{P\,(V_A^{1/3} + V_B^{1/3})^2} \left(\frac{1}{M_A} + \frac{1}{M_B}\right)^{1/2}$$

where

D	=	diffusion coefficient in ft.^{2}/hr.
V_A and V_B	=	molecular volumes.
M_A and M_B	=	molecular weights.
T	=	absolute temperature (°K).
P	=	pressure (atm.).

Although reliable experimental values of D are preferable to those calculated by the above equation, the equation shows how D varies with the temperature and pressure.

According to Perry[28], no definite correlation is available for liquid diffusion coefficients.

Film Coefficients

Badger and McCabe[2] give the following equation for the rate of diffusion of component (a) through a stationary gas film made up mainly of an inert component (b):

$$\frac{W}{A} = \frac{b_{gw}\,(P_{ag} - P_{ai})}{(P_b)_m\, B_g}$$

where

w	=	lb. of component (a) per hr.
A	=	area measured perpendicular to direction of diffusion of (a) in sq. ft.
B_g	=	film thickness in ft.
$(P_b)_m$	=	logarithmic mean of P_{bg} and P_{bi}.
P_{bi}	=	partial pressure of component (b) in gas stream in atmospheres.
P_{ag}	=	partial pressure of component (a) in gas stream in atmospheres.
P_{ai}	=	partial pressure of component (a) at interface in atmospheres.
b_{gw}	=	coefficient of diffusion in (lb.) (ft.)/(hr.) (sq. ft.)

The corresponding equation for the diffusion of a single component through a liquid film is:

$$\frac{W}{A} = \frac{b_{lw}\,(C_{ai} - C_{al})}{B_l}$$

where

C_{ai} = concentration of (a) at the interface in (lb.)/(cu. ft.).

C_{al} = concentration of (a) in liquid in (lb.)/(cu.ft.).

b_{lw} = diffusion coefficient in (sq.ft.)/(hr.)

B_l = equivalent film thickness in (ft.)

P_{ai} and C_{ai} are coordinates on the solubility curve of component (a) in the liquid and at the temperature of the absorption.

The amount of material transferred through the liquid film is equal to that transferred through the gas film. Also, the terms representing the film thicknesses, partial pressure of the inert gas, and diffusion coefficients can be combined to give a single coefficient for each film. The equation then becomes, according to Badger and McCabe[1],

$$\frac{W}{A} = k_g (P_{ag} - P_{ai}) = k_l (C_{ai} - C_{al})$$

where

$$k_g = \frac{b_{gw}}{(P_b)_m B_g}$$

$$k_l = \frac{b_{lw}}{B_l}$$

It is convenient to combine the two film coefficients in to a single overall coefficient which may be defined by the equation,

$$K_g = \frac{W}{A(P_{ag} - P_{al})}$$

when based on the gas film and by the equation,

$$K_l = \frac{W}{A(C_{ag} - C_{al})}$$

when based on the liquid film.

P_{al} = equilibrium partial pressure corresponding to concentration C_{al}.

C_{ag} = equilibrium concentration corresponding to partial pressure P_{ag}.

The overall coefficient can be expressed in terms of the individual film coefficients k_g and k_l as follows:

$$K_g = \frac{1}{\frac{1}{k_g} + \frac{H}{k_l}}$$

$$K_l = \frac{1}{\frac{1}{Hk_g} + \frac{1}{k_l}}$$

where

H = Henry's law constant.

Also

$$K_l = H K_g$$

H. E. T. P.[49]

Since the equilibrium curve and operating line are identical for given conditions of operation in both plate and packed towers, a common method of designing packed towers has been to determine the number of theoretical plates that would be required to carry out the operation in a plate tower and to multiply this number by the H.E.T.P. The H.E.T.P. is the height of packing equivalent to one theoretical plate. This value is experimentally determined by calculating the number of theoretical plates necessary to be equivalent to some packed tower and then dividing the number into the height of the tower. Theoretically, the use of the H.E.T.P. is unsound because it substitutes a stepwise countercurrent for a true countercurrent operation. However, the method is fairly accurate if the number of theoretical plates is large and the change in concentration per plate small.

H. T. U.

Another design method for packed towers is the height of a transfer unit, H.T.U. The number of transfer units is defined by Walker, Lewis, McAdams and Gilliland[49] as equal to

$$\int_{Y_2}^{Y_1} \frac{d_y}{(Y - Y^+)} = \frac{k_y a S l}{G}$$

or in terms of X as equal to

$$\int_{X_2}^{X_1} \frac{d_X}{(X^+ - X)} = \frac{k_1 a S l}{L}$$

X = concentration of solute in liquid in mols/mol solvent.

X^+ = equilibrium value of X corresponding to Y.

Y = concentration of solute in gas in mols/mol solute-free gas.

Y^+ = equilibrium value of Y corresponding to X.

k_y = gas-phase transfer coefficient in lb.-mols/(hr) (sq.ft.) (unit Y).

k_1 = liquid-phase transfer coefficient in lb.-mols/(hr) (sq.ft.) (unit X).

a = interfacial surface area per unit volume in (sq.ft.)/ (cu.ft.).

s = area of cross section in sq. ft.

l = height of packed tower in ft.

G = mols solute-free gas per hr.

L = mols solute-free absorbent per hr.

1 and 2 = conditions at gas inlet and outlet, respectively, or the limits of integration of X and Y.

Walker, Lewis, McAdams, and Gilliland[49] say, "The H.T.U. is then the height of the tower divided by the number of transfer units. It's advantage over the H.E.T.P. is that it is defined on the basis of the true differential countercurrent process rather than the incorrect stepwise countercurrent process."

Factors Affecting the Film Coefficients, k_g and k_l

According to Perry[29], complete information as to the variation of the individual film coefficients with changes in conditions of operation is not available. It has been shown that k_g and k_l vary with the effective film thickness, with the specific diffusion coefficient, with the average concentration of inert gas in the gas film (for k_g), and with the average concentration of solvent in the liquid film (for k_l).

Factors Affecting k_g

Hanks and McAdams[17], in experiments with ammonia and water, found that the gas film coefficient is inversely proportional to the average partial pressure of the inert gas in the film. Experimental evidence on the effect the kind of carrier gas used in gas absorption has on the gas film coefficient is lacking, although several authorities have stated that the nature of the carrier gas used should affect it.

Sherwood[39] lists the factors which affect k_g for wetted -wall towers as follows:

(a) Proportional to 0.56 power of the diffusivity.

(b) Proportional inversely to approximately the 0.2 power of the tower diameter.

(c) Independent of the total pressure at a given mass velocity.

(d) Proportional to the square root of the absolute temperature at a given Reynold's number.

(e) Proportional to approximately the 0.8 power of the gas mass velocity.

(f) Inversely proportional to the mean partial pressure of the inert gas.

According to McCormack[23], experiment shows that k_g is proportional to some power of the gas mass velocity, $k_g = \gamma g^n$, the value of the exponent, n, in most cases being approximately 0.8. g = mass velocity = (linear velocity) (density). Substituting the above value of k in the equation for K_g, the overall coefficient, the following equation is obtained:

$$\frac{1}{K_g} = \frac{1}{\gamma g^{0.8}} + \frac{H}{k_1}$$

If $\frac{1}{K_g}$ for a series of runs at different gas velocities be plotted vs. $\frac{1}{g^{0.8}}$, a straight line with intercept $\frac{H}{k_1}$ and slope $\frac{1}{\gamma}$ should result, since k_1 may be assumed independent of gas velocity.

According to Perry[32], an increase in temperature results in a decrease in gas-film coefficients, since gas viscosities increase and gas densities decrease with an increase in temperature.

As a result of their studies on the absorption of SO_2 in water and of NH_3 in water, Haslam, Hershey, and Kean[18] give the formulas,

$$k_g = C'' u^{0.8} \left(\frac{S}{Z}\right)^{2/3}$$

$$k_g = C' u^{0.8} (T)^{-1.4}$$

where u is the gas velocity, c'' and c' are constants, S the specific gravity and Z the viscosity of the gas, and T is the absolute temperature.

Colburn[9,10] and Colburn and Chilton[8] have shown that in similar apparatus values of gas-film absorption coefficients can be predicted from observed values of the surface coefficients of heat transfer.

Sherwood[41] showed by means of the equation,

$$\frac{d}{B'} = 0.023 \left(\frac{du\rho}{\mu}\right)^{0.83} \left(\frac{\mu}{\rho D}\right)^{0.44}$$

that k_g varies directly as the mass velocity of the gas to the 0.83 power for wetted-wall towers. The Schmidt number depends only on the system and $\frac{1}{B'}$ varies as the 0.83 power of the mass velocity.

$\frac{du\rho}{\mu}$ = Reynold's number

$\frac{\mu}{\rho D}$ = Schmidt number

d = diameter of tower

D = diffusion coefficient

B' = effective thickness of gas film in ft.

Factors Affecting k_l

Van Arsdel[48] found that increase of liquid flow relative

to gas flow caused an increase in the liquid-film coefficient until a ''critical flow rate'' was reached, after which, further increase had little effect. The effect was the more pronounced, the lower the liquid rate.

Haslam, Hershey, and Kean[18] found that for the systems, SO_2 in water and NH_3 in water, k_l is proportional to T^4, where T is the absolute temperature.

McCormack[24] says that available information indicates that k_l depends on the liquor velocity and relatively little on the nature of the diffusing solute.

Perry[32] shows that an increase in temperature increases the liquid-film coefficients because of both increased diffusivity and decreased viscosity of the liquid.

Hutchinson and Sherwood[20] summarized the work on liquid -film coefficients in stirred apparatus and gave the results of their own experiments, in which the pure gases, H_2, He, C_2H_2, N_2, O_2, CO_2, SO_2 and Cl_2 were absorbed in water. Below stirrer speeds of 100 r.p.m. no effect was measurable but at speeds above 100 r.p.m. and at a temperature of 25° C., the data were all represented, with a maximum deviation of 20 percent, by the following equation:

$$k_l = 0.0048\ (\text{r.p.m.})^{0.6}$$

A generally applicable equation for the liquid-film coefficient in packed towers has been determined by Sherwood and

Holloway(46)

$$\frac{k_l a}{D} = \alpha \left(\frac{L}{\mu}\right)^{1-n} \left(\frac{\mu}{\rho D}\right)^{1-S}$$

α, n and S are constants whose values depend on the type of packing and units used, L is the liquid rate of flow and other symbols are as previously defined. ''No generally applicable equation has yet been determined for the gas-film coefficient.''

According to Perry(32), a distinction must be made between the exposed surface of a tower and the active exposed surface, which is the actual area of contact between the gas and liquid phases. Increase in liquid flow rates will increase the active fraction of the packing and will therefore increase the apparent liquid-film coefficient if the area is assumed constant as is usually done.

Factors Affecting the Overall Coefficients, K_g and K_l

As explained by Sherwood(37), the grouping of the overall coefficients with the area factor is convenient in the case of packed towers because of the difficulty of measuring either quantity separately. The factor (a) is defined as the active wetted surface in square feet per cubic feet of packing. It must be an average value because the wet area varies from point to point in the tower and by no means is proportional to the surface area of the dry packing. This lack of proportionality is due primarily to three causes as

given by Sherwood[37]:

a. Uneven distribution of liquor over the cross section of the column.

b. Failure of the liquid to wet all of the individual particles.

c. Inactive surface at the points of contact of packing particles, at which the liquor remains stagnant and soon becomes saturated with the solute.

McCormack[25] says that as yet no general correlation of the absorption coefficients with the operating variables and physical properties of the system is possible, but empirical equations and data for various types of equipment may be found in the literature.

According to Perry[30], the presence of solvent vapors in the gas phase has no effect on the absorption coefficients of H.T.U. if the gas phase enters saturated with the solvent and remains saturated. However, if the gas enters free from solvent vapors and leaves saturated, use of the usual coefficients may involve an extreme error of 15 percent and an error under usual conditions of less than 5 percent. There is no simple method for calculating precise coefficients for this case.

The theory of Davis and Crandall on the absorption of gases in systems involving irreversible chemical reactions is explained in Perry's Handbook[31]. However, data on the coefficients for calculating the rate of absorption are not sufficiently available to allow the ready application of this theory.

In England, Donald and Tyson[3], found that the overall coefficient of absorption in a tower depends on the density of the gas and is some function of the relative velocity between gas and liquid.

Kowalke, Hougen, and Watson[21], on the basis of experimental work, advanced the theory that the rate of absorption of NH_3 and similar gases is controlled by a diffusion factor and a water distribution factor. This factor is a function of the packing and the rates of gas and water flow. They state that the total surface of the tower packing is of less importance than the position of the surfaces and that the best packing is that which produces the greatest agitation of gas in direct contact with the water surface.

Sherwood and Kilgore[47] found that the overall coefficients for both absorption and desorption increase with gas velocity and at a given gas velocity the values of both coefficients are, within experimental error, the same.

Bennetch and Simmons[5] observe that at elevated mol-flow ratios the absorption coefficients increase and explain it by the fact that the free volume of the tower is diminished and that the solvent flow rate is increased.

According to Sherwood[42] the effect of temperature on $K_g a$ is different than on $K_g a$. Since $K_g a = HK_l a$, it is possible for for $K_g a$ to decrease and $K_l a$ to increase with temperature (H decreases with increased temperature.) HP is equal to C in this case.

Factors Affecting K_g and K_ga

Greenewalt[16], using a tower which consisted of a 32-inch pyrex glass tube with an inlet nozzle permitting different pressure drops through the tower, found that the overall gas-film coefficient varied as the 0.4 power of the frictional drop of the gas through the apparatus. The pressure drop of a gas through a conduit varies directly as the square of the velocity of the gas and, therefore, the pressure drop would vary as the 0.8 power of the gas velocity. Also, according to the above author, the degree of turbulence and velocity effects of countercurrent flow in absorption towers can be expressed as a single function of the resistance to flow of the tower itself.

Comstock and Dodge[11] made a study of the absorption of CO_2 from gaseous mixtures by sodium or potassium carbonate. They found that K_ga changes markedly throughout the tower in a given run, due to the changing ratio of bicarbonate to carbonate. Therefore, in comparing results of different runs, it is necessary to have the average percentage conversion about the same in the runs under comparison. A narrow range of conversion is also desirable.

The above authors also found that K_ga increased greatly with an increase in pH (8-10.5) of the carbonate solution. The pH used was the arithmetic mean of the two terminal values.

Although an adequate theory to explain why an increase in liquor rate increases K_ga has never been offered, Comstock and Dodge[11]

say that it is commonly assumed that increased turbulence results in a thinner film and hence a larger coefficient. However, they say that it is more reasonable to assume that the increased liquor rate increases the thickness of the liquid layer and makes more liquid available to absorb a given quantity of carbon dioxide. The effect of gas velocity on $K_g a$ they found to be negligible, while an increased temperature had an accelerating effect on the absorption rate.

Factors Affecting K_l and $K_l a$

Cantelo, Simmons, Giles and Brill[6] studied the absorption of CO_2 and SO_2 in a tower and reported that the rate of gas removal was only slightly affected by gas velocity and gas composition, but decreased rapidly with the liquid flow rate until a critical flow was reached, where the value of K_l remained constant.

According to the data of Draemel and Ruckman, as given by Sherwood[40], $K_l a$ is a function of L.

L = liquid rate, lb/(hr) (sq. ft. of total cross section). Using a tower of 10 inches diameter, dumped-packed to a height of 56 inches with one-inch carbon Raschig rings and absorbing CO_2 in water they found that

$$K_l a = 0.016 L^{0.92}$$

Gas and liquid temperatures were between 69° and 79° F. in all runs.

Drane[13] found that gas velocity had a large effect and water rate had no effect on the absorption of CO_2 by water in a packed

tower. These results contradict those of Draemel and Ruckman.

According to Sherwood[36], the effect of temperature, when the liquid film controls, is so large that an increase in temperature over a limited range may increase K_1a sufficiently to offset the increased vapor pressure of the solute over the solution. Under such conditions there is an optimum operating temperature at which the absorption should be carried out. This optimum may be well above room temperature, so it should not be stated as a general rule, as sometimes given, that absorption processes should always be carried out at temperatures as low as are practical.

Temperature in Gas Absorption

According to Perry[33], application of the Gibbs phase rule to gas absorption shows that there are three degrees of freedom, which is to say that temperature, pressure, and the composition of one phase may all be independently varied. If the heat of reaction is significant, the process takes place in a manner that is neither isothermal or adiabatic. The rate of heat transfer is slow and considerable temperature differences may exist between the apparatus and the environment and also between the liquid and gas phases in a single small portion of the system. Under such conditions, the calculation of temperatures is unsatisfactory if not impossible; yet these temperatures determine the vapor pressure of the soluble gas from the liquid phase and, therefore, the driving force causing absorption and determining

the capacity of the system.

Pressure Drop in Packed Towers

Chilton and Colburn[7] used data on pressure drop and heat transfer to get a friction factor plot which gave a method for predicting pressure drops in packed towers.

They pointed out that most of the pressure drop was due to contraction and expansion in the gas flow through the irregular orifices formed by the packing, and estimated that only 10 percent of the drop was due to skin friction.

According to Sherwood[38], either increased turbulence or increased skin friction tends to thin the surface-air film and promote interphase diffusion. A given energy loss due to skin friction is more efficient in promoting heat transfer than is the same loss due to turbulence in the main body of the gas. By analogy, it appears that the best packings would be those in which the pressure drop due to skin friction is large compared to that due to turbulence. This is not true in streamline sections, in which the gas does not change direction, and high coefficients are obtained by using high gas velocities. A packing meeting these conditions is a bundle of vertical tubes without headers and with spacers to maintain passages between the tubes having the same hydraulic radius as the interior of the tubes. Sherwood found this packing to give excellent capacity coefficients with very low pressure drop.

Sherwood[43] gives an empirical equation for the pressure drop in packed towers which is based on the Fanning equation for friction in pipes.

$$\Delta P = \frac{2f'(A_w)(A_p)(A_e)(\rho)(u_o)^2(h)}{g(d_p)}$$

ΔP = pressure drop in height h.

u_o = linear velocity of gas based on total cross section of the tower.

ρ = gas density.

A_w = wall effect factor.

A_p = correction for hollow packing.

A_e = correction for wetting of packing.

g = acceleration of gravity.

d_p = nominal particle size of packing.

Loading and Flooding Points

As explained by Sherwood[45], the gas and liquor rates in a tower are limited by the tendency to flood. Increased gas velocity results in more liquid holdup and higher pressure drop through the tower until finally the gas bubbles violently through the liquid, the pressure drop rises sharply with a slight increase in gas velocity and liquid is carried from the tower mechanically by the leaving gas. This is known as the flood point. The loading point is sometimes used synonymously with flooding point, but has been defined as the point

above which the pressure drop becomes proportional to an exponent greater than 2 on the gas rate.

Elgin and Weiss[14] found that on log-log plots of pressure drop vs. gas velocity at fixed liquor rates, at a certain gas velocity, a more or less abrupt break occurred in the curve, above which the pressure rose almost vertically. Simultaneously with the attainment of this point spraying of the liquor from the tower top was observed. This point was called the ''flooding point''. A lower break on the P-gas velocity plot, above which its slope was more than 2.0, was called the ''leading point''. Plotting the square root of the gas velocity vs. the square root of the liquid velocity at flooding on rectangular coordinates gives a straight line.

Course of Liquor Flow in Packed Towers

The tendency of the liquid to channel through certain parts of the tower rather than to spread uniformly over the packing constitutes one of the main difficulties of operation of a packed tower. Channeling also prevents the making of reliable calculations on the tower operation because it lowers the rates of absorption and consequently the tower coefficients.

Deutsche[12] says that many tower designers believe that packing should be largest near the center of the tower in order to reduce resistance there and prevent the liquid from flowing to the walls.

An experimental study of liquor distribution over various packings has been reported by Baker, Chilton and Vernon[4]. They passed air and water through a number of common packing materials and collected the water draining from the bottom at several small cross-sectional areas of the column. By using different heights of packing they obtained data on the liquor distribution over the tower cross-section at different distances from the top. With packing particles large compared to tower diameter, they found a tendency for the liquor to concentrate near the walls and for the center of the column to run dry. With large ratios of tower diameter to packing size, this tendency was negligible. With 1/2-inch broken stone packing in a 6-inch column, the water assumed a fairly uniform distribution at a point 4 feet from the top and the distribution remained fairly constant to a point 15 feet from the top. When the same packing was used in a 3-inch column more than 70 per cent of the water was found to be in the 25 per cent of the cross-section next to the tower wall.

Baker, Chilton, and Vernon concluded that reasonably uniform liquor distribution is obtained if the ratio of tower diameter to packing diameter is greater than 8 to 1. If this ratio is less than 8 to 1, the liquor tends to flow to the tower walls. In 3-inch and 6-inch columns and using a tower to packing size ratio of more than 8, liquor distribution at the top improved the uniformity of flow only in the top 4 feet of packing. In a 12-inch tower, using the same conditions,

uniform distribution was not attained until a depth of nearly 10 feet was reached. This indicates that initial distributors are necessary in large towers.

Changes in liquor rates over the ordinary range had little effect on the uniformity of distribution.

Variations in gas velocity were also found to have little effect on the liquor distribution, except as the flooding point was approached, when more even distribution was obtained.

Even when the liquor flows with uniform distribution over the tower cross-section, it is likely that all the packing surface is not wetted. Mayo, Hunter, and Nash[26] made a study of the extent to which packing is wetted by using water containing a red dye in a tower having paper walls and containing paper Raschig rings. The rings were made of double thicknesses of paper so they could be divided and the dyed areas on both inner and outer surfaces measured. Since a distributor was used, the packing was almost perfectly wetted at the top of the tower but the percentage of wetted surface fell to about 40, being approximately the same for both inner and outer surfaces of the rings. At the same point, the tower wall was 60 percent wetted. In the packing the percentage of wetted surface was greatest near the walls, but this nonuniformity did not increase below a point a few inches from the top. The percentage of total surface wetted increased with the liquor rate up to the flooding point. The gas rate had no measurable effect on the wetted surface up to the flooding point.

The above authors estimate that 10 percent of the actual wetted surface may be inactive because of stagnant liquid films at the points of contact of the packing.

Tower Packings

Desirable characteristics of a good tower packing as listed by Badger and McCabe(1) are as follows:

a. Low weight per unit volume.

b. Large surface per unit volume.

c. Large free-cross-section. This gives a low friction drop through the tower and therefore requires less power for gas circulation.

d. Large free volume. This is especially important where time must be allowed for reactions in the gas phase.

e. Small weight of liquid retained. This decreases the load on the tower and removes the liquid from the tower as rapidly as possible. If the reaction between the gas and liquid is slow or if the solubility of the gas in the liquid is low, this may be a disadvantage.

In addition to these are the obvious requirements that the packing must be cheap, must have a reasonable mechanical strength, and must be chemically inert towards the materials to be handled. Minimum side thrust on the tower is also desirable.

The chief types of tower packings as classified by Perry(34) are as follows:

a. Broken rock: -- This packing has great weight, small surface per unit volume and small free cross-section.

b. Coke: -- Coke is light in weight and has large surface per unit weight but has small free cross section.

c. Stoneware shapes: -- Specially-made brick of ordinary brick stacked in various arrangements are examples of this type of packing.

d. Raschig rings: -- This packing offers the best combination of low weight per unit volume, free volume, free cross section, and total surface of any type of packing.

e. Lessing rings: -- These are rings of metal with a single internal web.

f. Spiral rings: -- These rings have the general dimensions of Raschig rings but with an internal helix which increases the surface without greatly decreasing either free cross section or free volume.

g. Berl saddles: -- These are a specially-developed patented packing which consists of saddle-shaped porcelain units that are piled in the tower at random. They offer great surface per unit volume have low resistance to gas flow, and are said to give minimum channeling, reduced side thrust, and increased distribution compared to other types of packing.

III. EXPERIMENTAL

A. Purpose of Study

The purpose of this investigation is to correct certain inherent defects of operation of the 18-inch stoneware absorption tower in the Unit Operations Laboratory of Virginia Polytechnic Institute. These corrections are to be made by modifying the design of the tower. After the modifications of design are made, the operating characteristics of the tower, for the particular system of the absorption of carbon dioxide by water, are to be determined. The absorption coefficients and the relationships between these coefficients and certain operating variables, such as liquid and gas rates of flow, are the operating characteristics to be determined. Due to the fact that in this system, carbon dioxide and water, the carbon dioxide is slightly soluble in the water and the liquid film is the controlling resistance to absorption, emphasis will be placed on the determination of the liquid film coefficient, k_1a, and on the relationship between k_1a and the liquid rate of flow, L.

B. Plan of Investigation

Tower Platform: -- Construct a platform adjacent to the third floor balcony of the laboratory and around the tower top because, in the present condition, it is both difficult and dangerous to take ex-

perimental readings at the top of the tower.

Distribution Plates: -- Design a new type of distribution plate in order to secure a more thorough mixing of the gas and liquid phases. This plate is to be constructed of 18-gage galvanized sheet metal and will consist of the frustums of two cones, soldered together at their small bases. This shape will force the gas and liquid from the tower walls toward the center and should tend to reduce channeling.

Sampling System: -- Design sampling system to obtain representative samples of gas for analysis.

Cooler: -- Re-design and rebuild the spray cooler for cooling the flue gas, in order to reduce entrainment of water from the cooler to the tower and to eliminate leakage of the cooler.

Furnace: -- Rebuild the furnace for the production of the flue gas.

Tower: -- Dismantle the tower, clean and repack the coke by hand, and install the plates and sampling system. In order to lessen the tendency of the water to channel near the tower walls, the coke is to be packed with the larger pieces which offer lower resistance to fluid flow near the center.

Orsat Apparatus: -- Design a modified Orsat apparatus to give a more accurate analysis of the carbon dioxide content of the flue gas. The burette of the available apparatus has a volume of 100 ml, the lower 50 ml of which is graduated in 1/5-ml divisions.

The burette of the modified apparatus is to have a volume of approximately 314 ml and a 50-ml section graduated in 1/10 ml divisions.

Operating Characteristics: -- Determine the operating characteristics of the tower by means of the following steps:

a. Make a series of runs on the tower using liquid flow rates of 5 to 37 pounds per minute and gas flow rates of 24 to 42 cubic feet per minute of gas out of the tower. Other variables, particularly temperatures of the gas and liquid in different parts of the apparatus, will be held to as limited a range of variation as possible in order to determine the real effect the variables under consideration have on the absorption coefficients of the tower. The liquid and gas rates of flow cannot be varied independently.

b. During each run the following data are to be taken at 10 to 15 minute intervals:

1. Liquid rates through the tower and cooler, (lbs./min.).

2. Gas velocity through the tower, (ft./min.).

3. Carbon dioxide content of the flue gas entering and leaving the tower, by means of both the standard Orsat apparatus and the Orsat of modified

design, (per cent by volume of total gas).

4. Temperatures of the water and flue gas entering and leaving the tower and of the flue gas entering the cooler.

5. Quantitative analysis of the water entering and leaving the tower and cooler for carbonate, bicarbonate and free carbon dioxide content.

6. Wet bulb temperature of the flue gas entering the tower (exit gas is assumed to be saturated).

c. After obtaining the necessary data mentioned in Part b above, k_1a will be calculated from the data taken after the constancy of the readings indicate that the tower was operating under conditions of equilibrium.

d. The calculated values of k_1a will be plotted versus the experimentally measured liquid rates on logarithmic coordinate paper.

e. An equation showing the relationship of the liquid rate, (L), to k_1a will be derived, using the method of averages for the determination of the constants.

C. Materials

City Water: -- This water was used, as taken from the main, both to cool the flue gas before it entered the tower and as the absorbing medium in the tower. It was also used in connection with the operation of the Hytor.

Kerosene: -- This material was obtained from the Standard Oil Company of New Jersey, Christiansburg, Virginia, and was used in the oil burner to produce the flue gas.

Coke: -- The coke was of the metallurgical type and was obtained from the foundry of Virginia Polytechnic Institute. The size range was 2-1/2 to 3-1/2 inches.

Hydrochloric Acid: -- Standard laboratory reagent, obtained from the General Chemical Company, New York, New York, was standardized at 0.0058 N.

Sodium Hydroxide: -- Standard laboratory reagent, obtained from Phipps and Bird, Inc., Richmond, Virginia, was standardized at 0.0021 N.

Potassium Hydroxide (50% solution): -- Standard laboratory reagent obtained from Phipps and Bird, Inc., Richmond, Virginia.

Standard Phenolphthalein and Methyl Orange Indicator Solutions: -- Standard indicators obtained from Eastman Kodak Company, Rochester, New York.

Bricks: -- These bricks were common red building brick and were made by the Roanoke-Webster Brick Company, Roanoke, Virginia.

Fire Bricks: -- High alumina refractory type made by the Harbison-Walker Refractories Company, Pittsburgh, Pennsylvania.

Fire Clay: -- Ohio refractory clay found immediately below coal seams, obtained from the Cedar Heights Clay and Coal Company, Oak Hill, Ohio.

Pitch: -- The melting point of this material was approximately 95° C. At this temperature the pitch softened but was too viscous to flow freely.

Galvanized Sheet Metal: -- Standard 18-gauge material obtained from the New River Lumber Company, Blacksburg, Virginia.

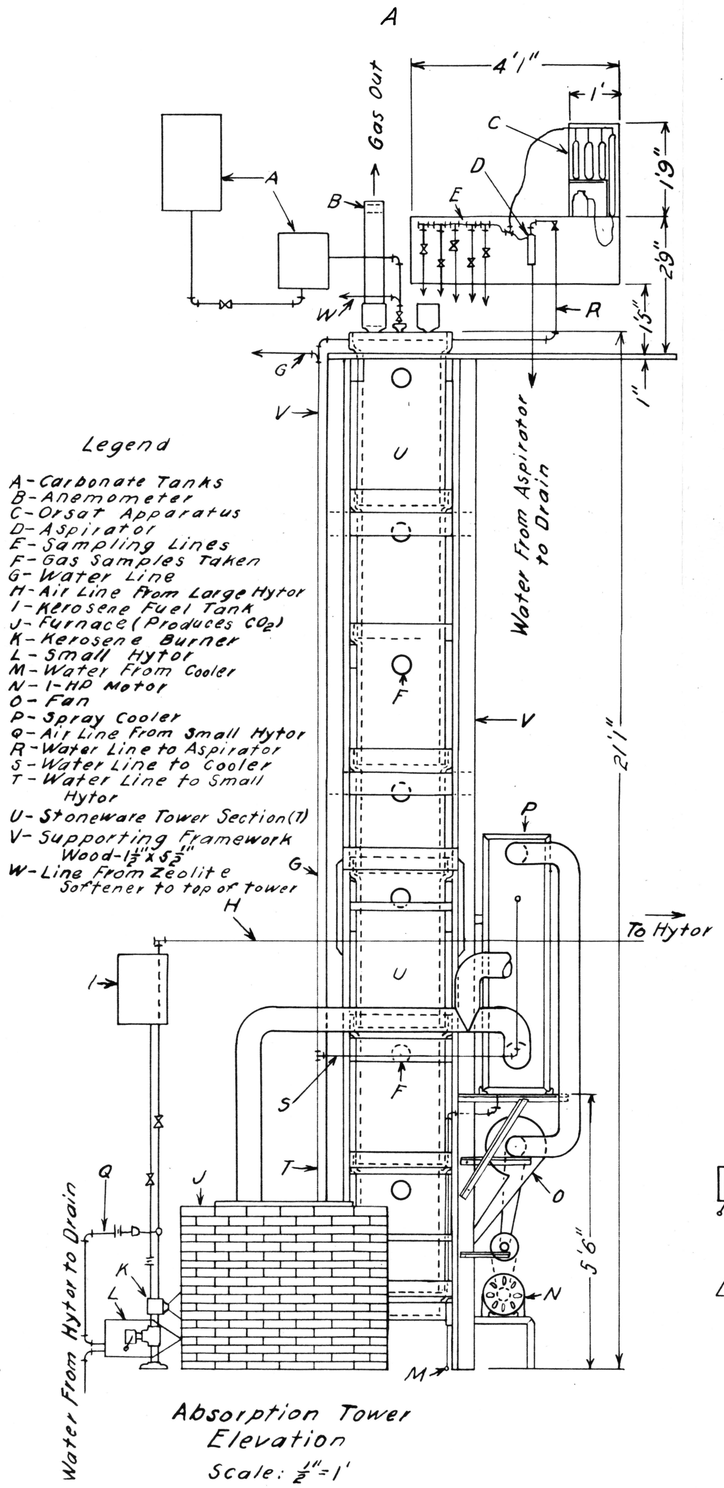
Galvanized Wire: -- Standard 26-gauge material obtained from the New River Lumber Company, Blacksburg, Virginia.

D. Apparatus

Stoneware Absorption Tower consisting of seven sections of chemical stoneware, 18'' I.D. x 33'' in length, made by the United States Stoneware Company, Akron, Ohio. (See Figures I-A and I-B and Photograph No. 1).

Nash Hytor Compressor, size AL-574, 5-1/2'' D, 3500 R.P.M., 75 lb. per square inch maximum pressure, Nash Engineering Company, South Norwalk, Connecticut. (See Photograph No. 2).

Spray Cooler, constructed of 18-gauge galvanized sheet metal, water-proofed with pitch. Gas travels countercurrent to water spray produced by eight nozzles. (See Figure I-C and Photograph No. 3).



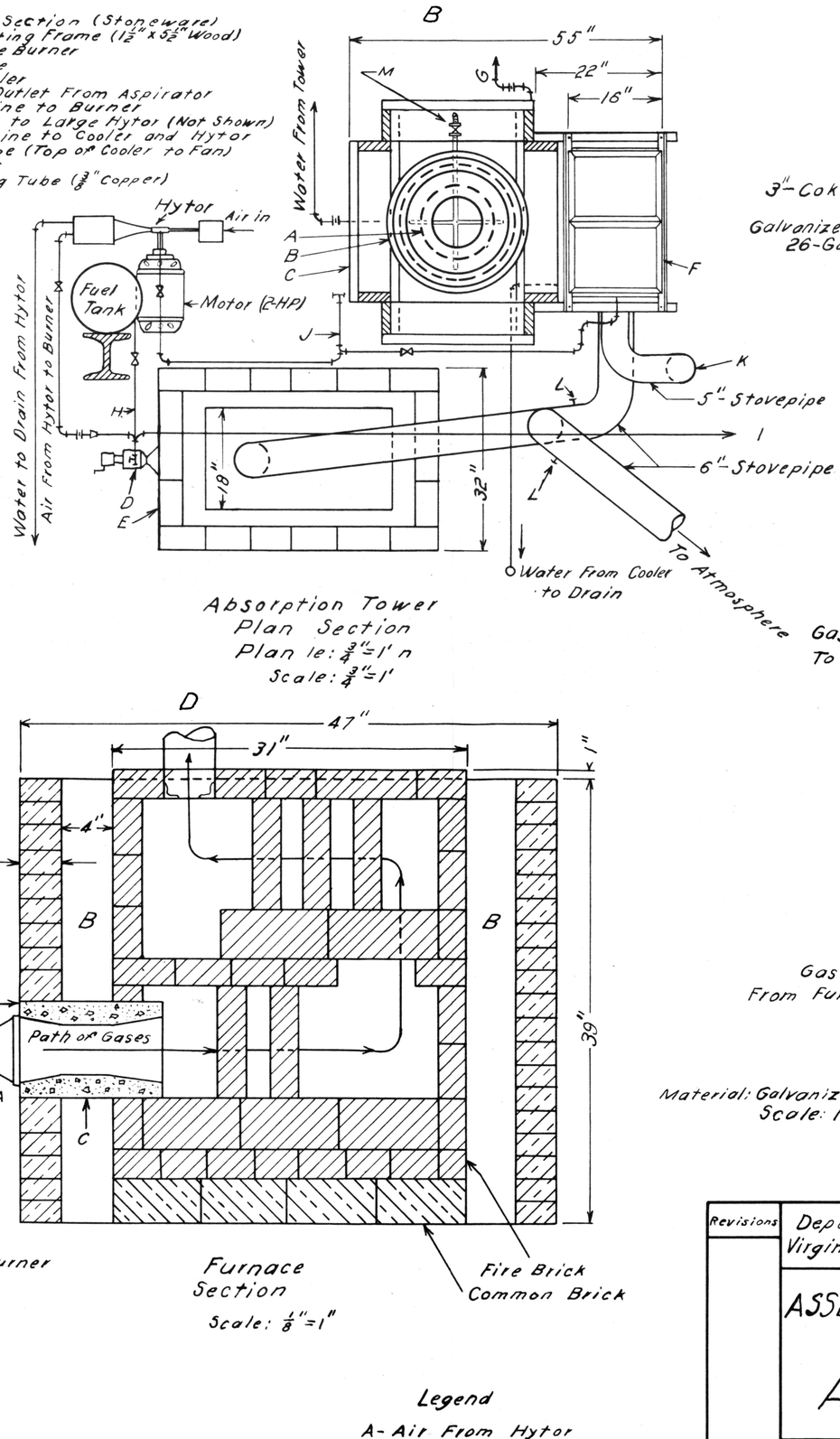
Legend

A-Carbonate Tanks
B-Anemometer
C-Orsat Apparatus
D-Aspirator
E-Sampling Lines
F-Gas Samples Taken
G-Water Line
H-Air Line From Large Hytor
I-Kerosene Fuel Tank
J-Furnace (Produces CO_2)
K-Kerosene Burner
L-Small Hytor
M-Water From Cooler
N-1-HP Motor
O-Fan
P-Spray Cooler
Q-Air Line From Small Hytor
R-Water Line to Aspirator
S-Water Line to Cooler
T-Water Line to Small Hytor
U-Stoneware Tower Section(7)
V-Supporting Framework Wood-$1\frac{1}{2}$"x$5\frac{1}{2}$"
W-Line From Zeolite Softener to top of tower

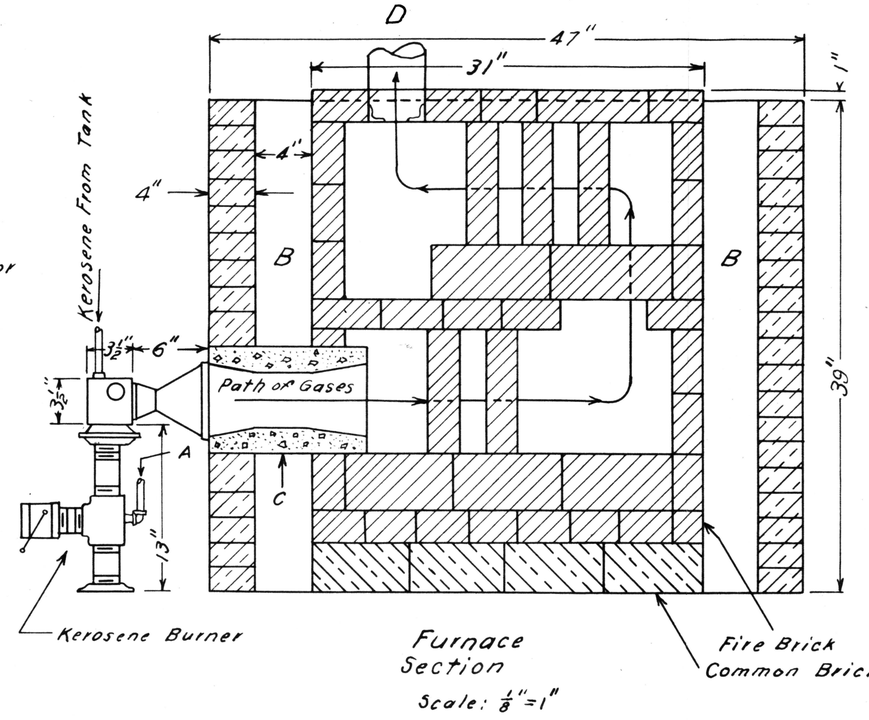
Absorption Tower
Elevation
Scale: $\frac{1}{2}$"=1'

Legend

Plate
Tower Section (Stoneware)
Supporting Frame ($1\frac{1}{2}$"x$5\frac{1}{2}$" Wood)
D-Kerosene Burner
E-Furnace
F-Gas Cooler
G-Water Outlet From Aspirator
H-Fuel Line to Burner
I-Air Line to Large Hytor (Not Shown)
J-Water Line to Cooler and Hytor
K-Gas Pipe (Top of Cooler to Fan)
L-Dampers
M-Sampling Tube ($\frac{3}{8}$" Copper)



Absorption Tower
Plan Section
Plan le: $\frac{3}{4}$"=1' n
Scale: $\frac{3}{4}$"=1'



Furnace
Section
Scale: $\frac{1}{8}$"=1"

Legend

A-Air From Hytor
B-Air Space
C-Cement

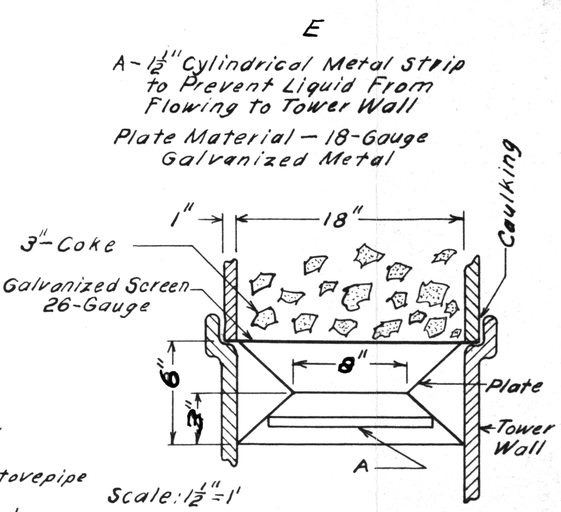
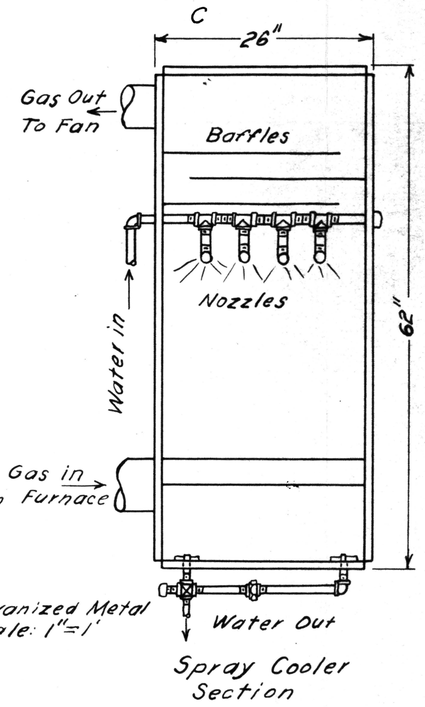


Plate Detail
Section
New Type
New Type



Spray Cooler
Section

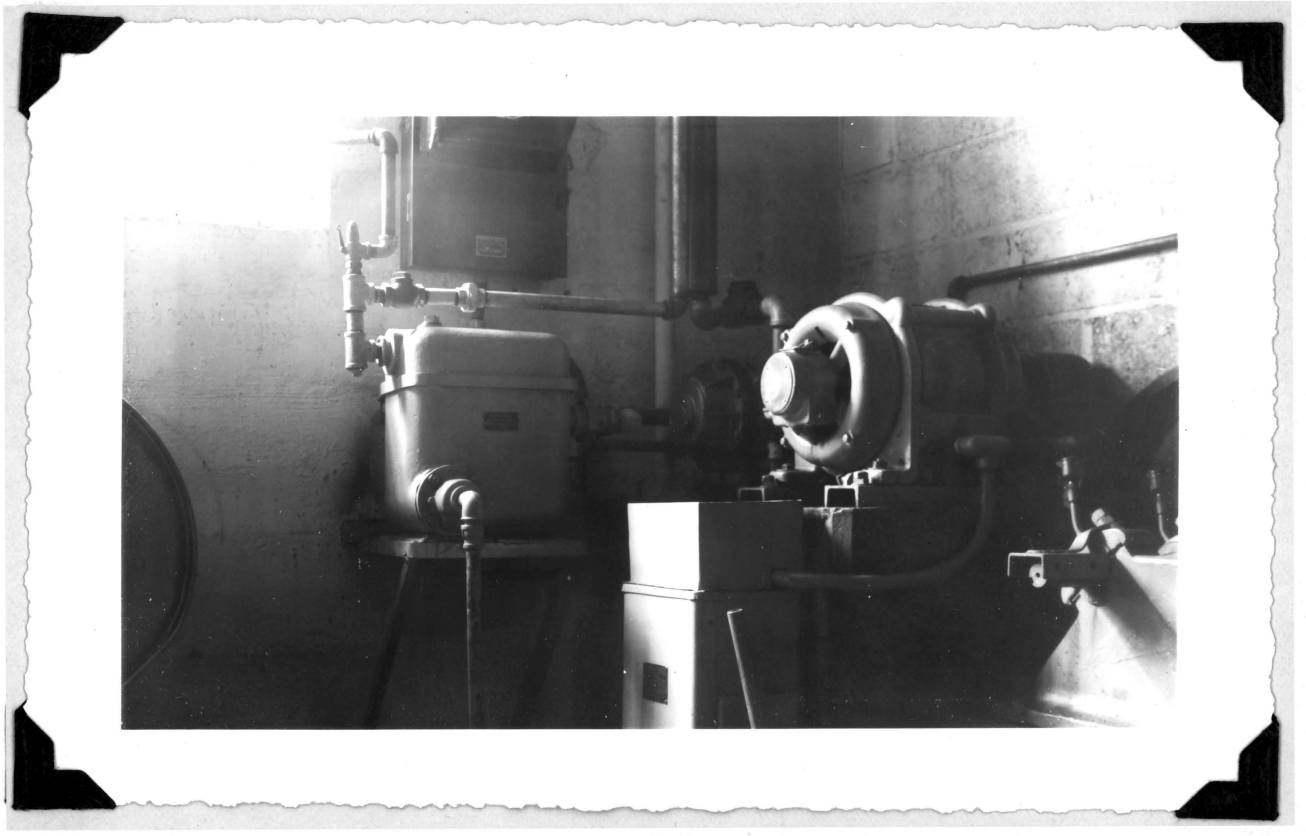
Figure I

Revisions	Department of Chemical Engineering Virginia Polytechnic Institute, Blacksburg, Va.
	ASSEMBLY AND DETAIL DRAWING OF AN 18-INCH STONEWARE ABSORPTION TOWER
	Drawn – J.K.M. Traced – J.K.M. Checked – ✓ Approved – Fuls Case – 539 File – THESIS Drawing – 1 Date – 4-4-42



Photograph No. 1

Overall View of 18-Inch Stoneware Absorption Tower



Photograph No. 2

Nash Hytor Compressor Used to Compress Air for Kerosene Burner Shown in Photograph No. 3

Oil Burning Furnace, constructed of fire bricks with an outer shell of common bricks (see Figure I-D and Photograph No. 4).

D.F.C. Oil Burner, No. C2-3372, Denver Fire Clay Company, Denver, Colorado (see Figure I-D and Photograph No. 4).

General Electric Induction Motor, 1 H.P., 60 cycles, a.c., 3-phase, continuous 40° C. rise, General Electric Company, Schnectady, New York (see Photograph No. 3).

Western Electric Induction Motor, 15 H.P., 60 cycles, a.c., 3-phase, continuous 40° C. rise, Western Electric Company, (see Photograph No. 2).

Orsat Gas Analysis Apparatus, 100-ml burette with 50-ml section graduated in 1/5 ml divisions and having Schellbach blue-and-white back, three absorption pipettes of two-compartment type and with rubber expansion bags, absorbing compartment filled with glass tubes, Fisher Scientific Company, Pittsburgh, Pennsylvania, (see Photograph No. 5).

Modified Orsat Gas Analysis Apparatus, 314-ml burette with 50-ml section graduated in 1/10 ml divisions (see Photograph No. 6).

Anemometer, Biram type, 4-inch aluminum fan, revolutions are recorded on three dials which read up to 10,000 feet, Julien P. Friez and Sons, Inc., Baltimore, Maryland.

One 3/4-inch Filter Pump, having air entraining tube of cast brass at bottom, Fisher Scientific Company, Pittsburgh, Pennsylvania.

Ball Mill, 12-1/2'' inside diameter, 18-1/2'' long, porcelain lined, Patterson Foundry and Machine Company, East Liverpool, Ohio.

One 12'' Centrifugal Glower, type C1, single inlet, size 5, serial No. 101721, equipped with step pulley, Clarage Fan Company, Kalamazoo, Michigan (See Photograph No. 3).

Mercury Column Barometer, Chemistry Department, Virginia Polytechnic Institute.

Crosby Pressure Gage, 0 to 100 lb. per sq. in., 5 lb. per sq. in. graduations, 3'' diameter, Crosby Gage Company, Boston, Massachusetts.

Two timers, Eastman Kodak Company, Rochester, New York.

Glass Thermometer, 0 to 100° C.

Weston Thermometer, 50 to 300° F.

Weston Thermometer, 50 to 250° F.

Weston Thermometer, 50 to 500° F.

Weston Thermometer, 0 to 220° F.

Weston Thermometer, 200 to 1000° F.

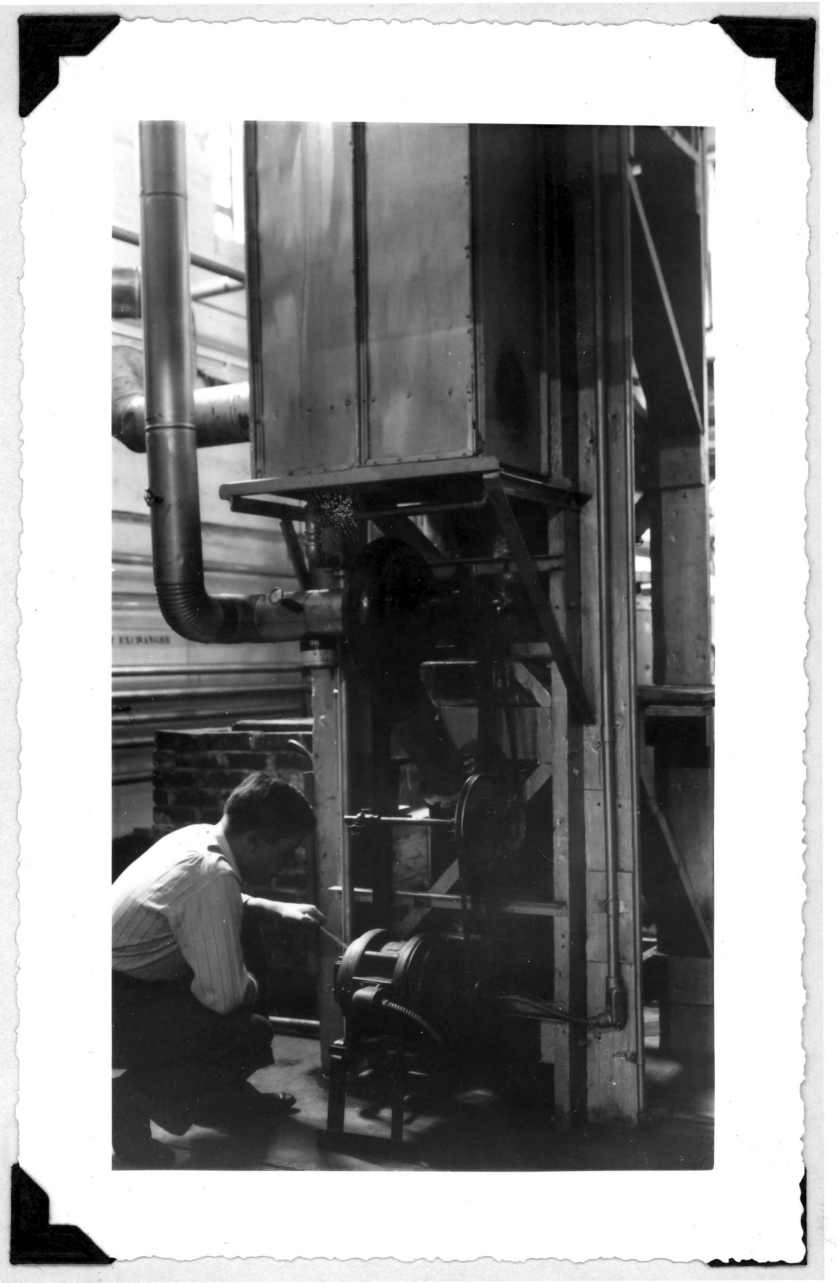
Platform Spring Scales, 0 to 25 lb., one ounce graduations, adjustable, 8'' high, 6 x 6-inch platform, 6-3/8-inch slanted dial, Catalog No. 11F7164, Sears Roebuck and Company, Chicago, Illinois.

Six Distributing Plates, constructed of 18-gauge galvanized metal, (see Figure I-E).

Five Sampling Tubes, constructed of 3/8-inch copper tubing (See Figure II).

Kerosene Feed Tank, 5 gallons capacity, gravity feed.

Three 5-liter Reagent Bottles.



Photograph No. 3

View of Bottom of 18-Inch Stoneware Absorption Tower
Showing Spray Cooler and Blower to Force Gases Through Tower



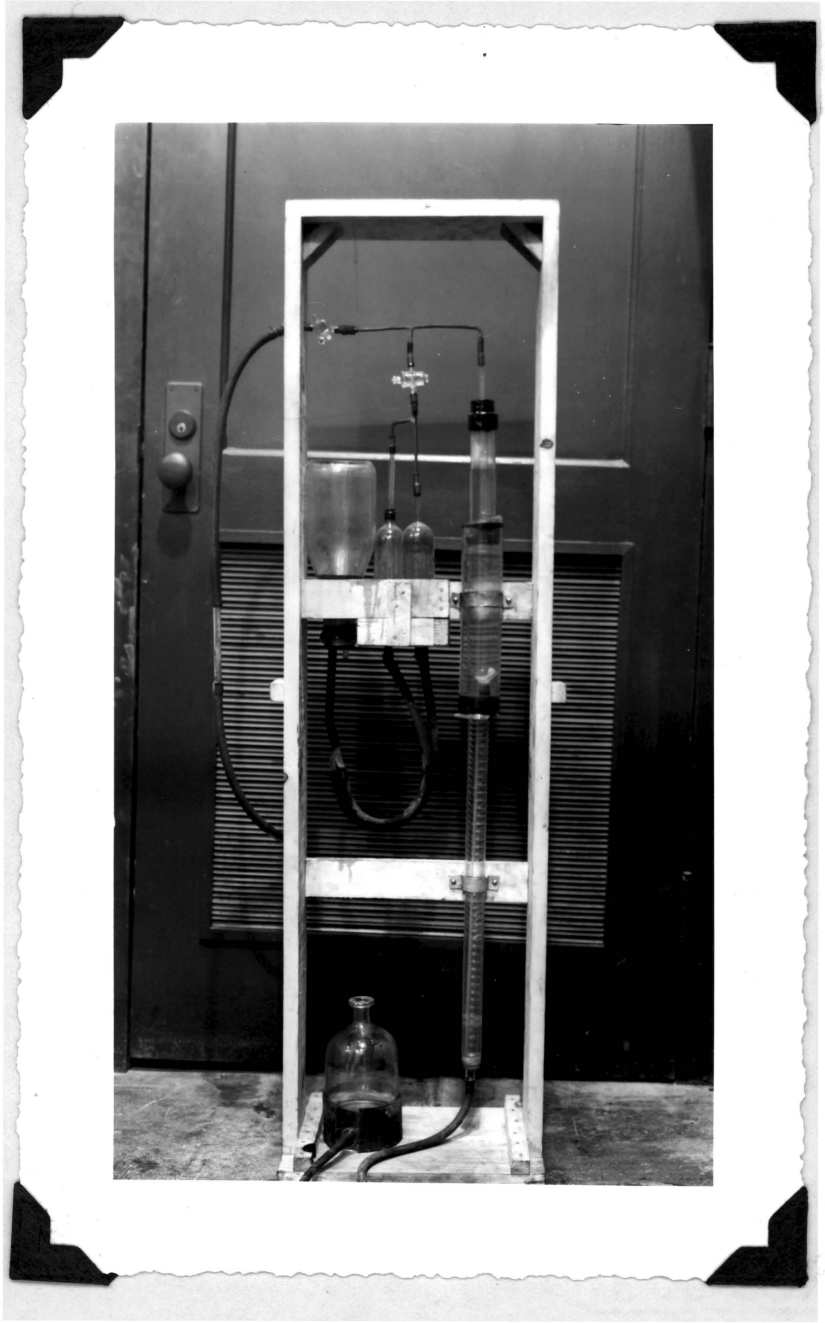
Photograph No. 4

Kerosene Burner and Furnace for Production of Flue Gas Used In Absorption Experiments With CO_2 and Water in 18-Inch Stoneware Tower



Photograph No. 5

Analyzing Exit Tower Gas for Carbon Dioxide with Standard Orsat Apparatus



Photograph No. 6

Modified Orsat Apparatus Used In Analyzing Tower Gas For Carbon Dioxide (314 ml Burette, 1/10 ml Graduations)

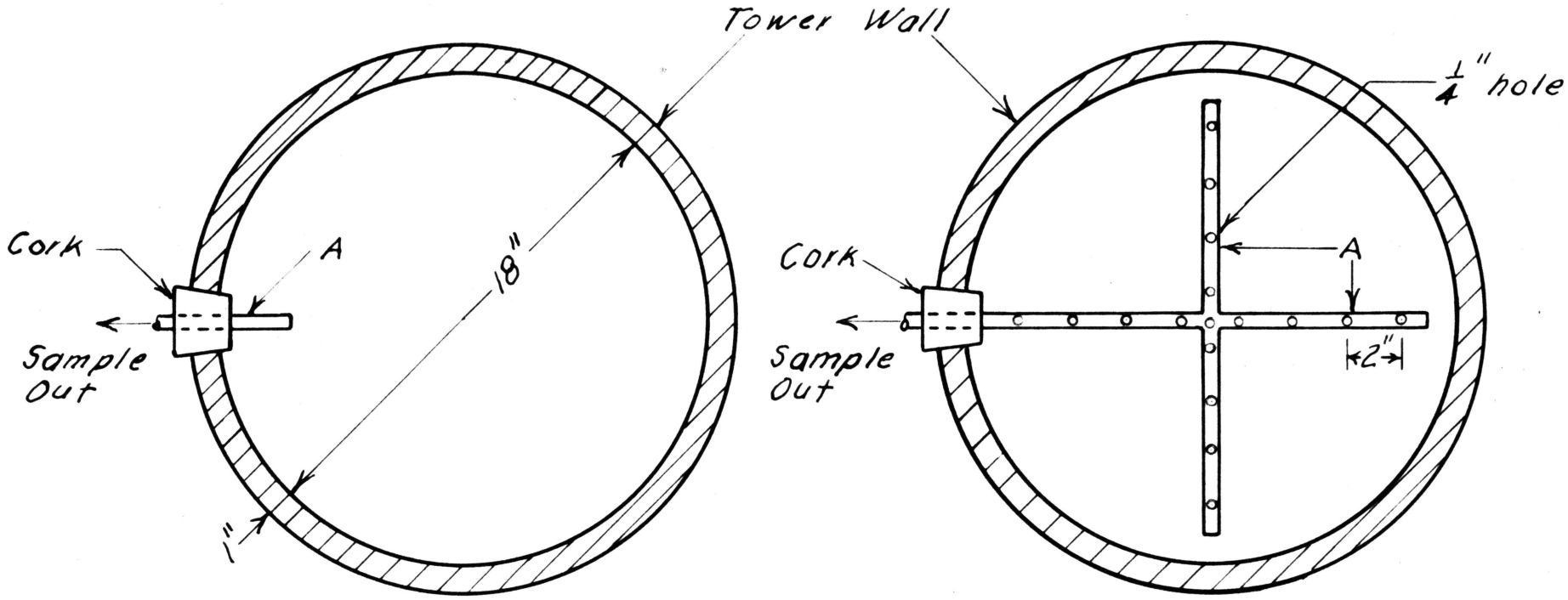
Two 50-ml Burettes, Fisher Scientific Company, Pittsburgh, Pennsylvania.

Two 250-ml Erlenmeyer Flasks, Pyrex.

Two 250-ml Beakers, Pyrex.

Four 250-ml Sample Bottles.

One 25-ml Pipette.



Gas Sampling Tubes

Figure II

A - 3/8" Copper Tubing

Department of Chemical Engineering	
Virginia Polytechnic Institute	
Detail of Sampling Tubes	
Drawn by: J.K.M.	Date: 5/6/42
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Approved by F.W.B.	5/6/42

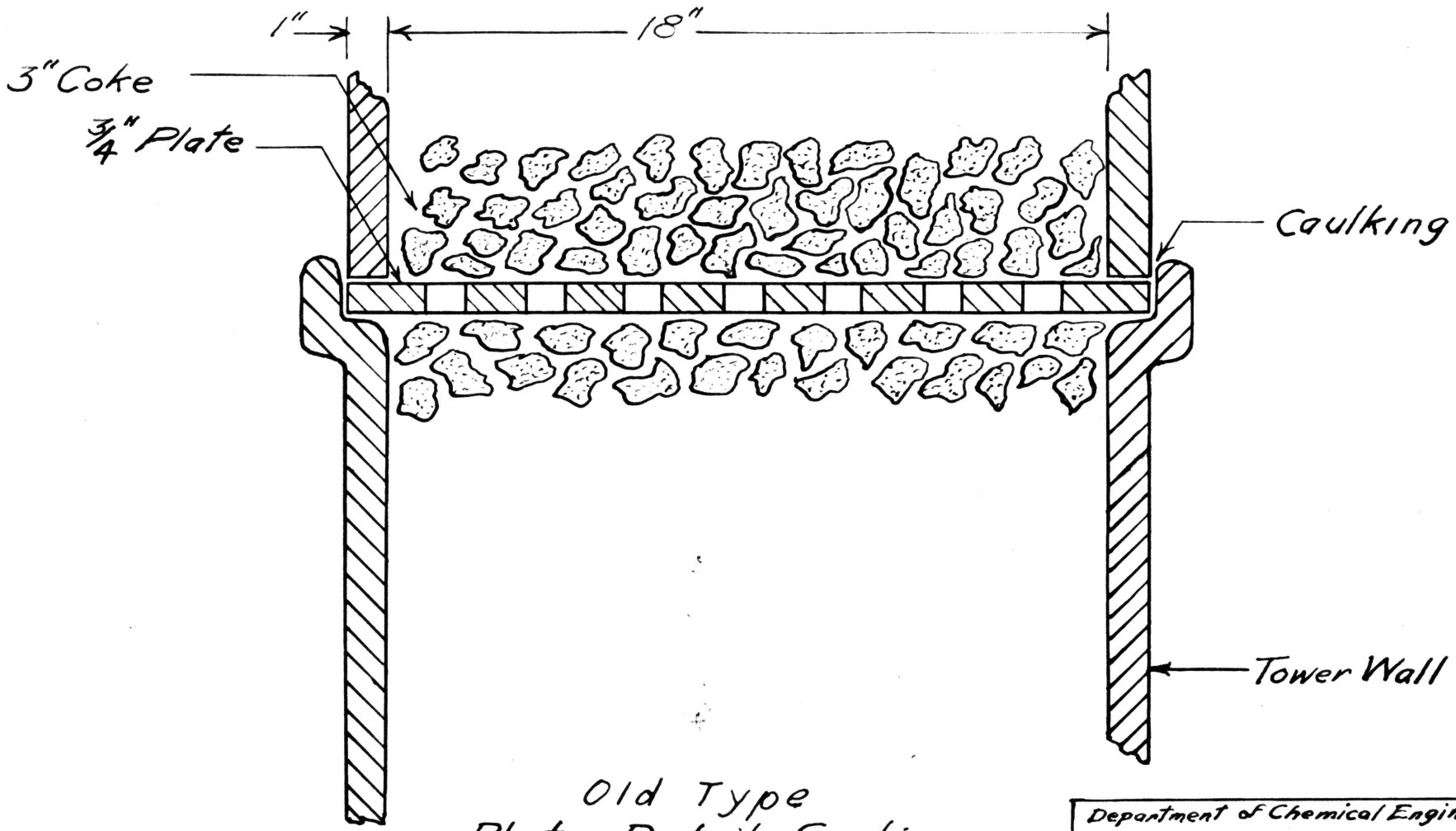
E. Methods of Procedure

Construction of the Platform:--The platform was constructed of 3/4-inch dressed pine adjacent to the third floor balcony. A guard rail of 1-1/2-inch pipe of welded construction was built around the platform to insure safety to workers. A wooden panel was constructed to support the header of the sampling system, the aspirator, and the Orsat apparatus and was bolted to 1-1/4-inch angle irons which were welded to the guard rail.

Design of Distributing Plate:-- The new plates, replacing the stoneware discs originally in the tower, consisted of two parts; i.e., the redistributing plate proper and the wire meshed screen for supporting the packing. The redistributor was made of 18-gauge galvanized sheet metal and consisted of the frustums of two cones, soldered together at their small bases whose diameters were eight inches. The large diameter of the plate was equal to the tower diameter and the depth of the entire plate was equal to the six inches. The upper frustum of the plate had the large base on the upper side and served to bring the liquid from the tower wall to the center, while the lower frustum had the small base on the upper side and directed the gas to the middle portion of the tower. To the lower cone of the plate there was soldered a circular ring of 18-gauge metal 1-1/2 inches in width. This formed a short cylindrical surface, the axis of which coincided with the axis of the tower and the function of

which was to cause the liquid to fall on the packing rather than to cling to the plate and flow back to the tower wall. The coke was packed to such a height that it touched the bottom of the next higher plate. Immediately above, and resing on the redistributor was a circular piece of 26-gauge galvanized wire screen. This was fitted between the tower sections and served to support the coke in the next higher section. A section drawing of the new plate is shown in Figure I-E and one of the old plate is shown in Figure III.

Sampling System: -- A sampling system was designed in order to permit the obtaining of a more representative sample, and to permit all the gas sampling and analyzing operations to be performed on the platform at the top of the tower. In the new system, the gas was drawn through a sampler of 3/8-inch copper tubing which had the form of a cross and which had 17 symmetrically placed holes on the bottom side of the tubing for the actual sampling, while in the old system, the entire sample was taken from a point near the tower wall. Drawings of the two samplers are shown in Figure II. Samplers were located on the first, second, fourth, sixth and seventh sections of the tower which is composed of seven sections. Lines of 1/4-inch pipe, leading from each sampler to a common header on the platform at the top of the tower were installed. By means of the system of valves as shown in Figure I-A, a sample may be taken from any sampler to the top of the tower and analyzed there, thus eliminating the difficulty of obtaining samples from the different parts of the tower. The aspirator



Old Type
Plate Detail Section

FIGURE III

Department of Chemical Engineering VIRGINIA POLYTECHNIC INSTITUTE	
PLATE DETAIL SECTION	
Drawn by R.E.S. Traced by W.W.B. Approved by F.W.B	Date: 5/6/42 5/6/42 5/6/42

shown in the drawing was used to draw stale gas from the lines so as to insure the obtaining of a fresh sample for analysis.

Spray Cooler: -- A drawing of the rebuilt spray cooler is shown in Figure I-C. Originally, it rested with its long axis in a horizontal position and the flue gas passed from one end to the other, cross-current to the water spray. Due to the unusually large amount of entrainment of water with the gases leaving the cooler and entering the tower, a change in design was necessary.

Furnace: -- After the furnace was destroyed by an explosion, it was rebuilt with an explosion door on each side in order to minimize the probability of a repetition of the accident. However, it was found that the steel doors did not give satisfactory service with the high temperatures of the furnace and consequently became the source of much heat loss. Due to the failure of the mortar, under conditions of repeated heating and cooling, the furnace had to rebuilt a second time. This time the explosion doors were omitted. A drawing showing a section of the furnace may be found in Figure I-D.

Dismantling of Tower: -- The tower was dismantled and the coke packing removed and washed in a jet of water. As the tower was reassembled, the new plates and samplers were installed. The tower was repacked by hand with coke of approximately 3-inch particle size. The smaller pieces of coke, approximately 2-1/2 to 2-3/4 inches particle size, because of the greater resistance they offer to liquid flow, were packed nearer the walls of the tower in order to lessen the

tendency of the water to channel near the tower walls.

Modified Orsat Apparatus: -- Due to the low solubility of carbon dioxide in water, the difference in carbon dioxide content of the flue gas entering the tower and that of the same gas when leaving the tower was necessarily rather small. The maximum possible difference, under the conditions of operation used in these experiments, was approximately 0.2 per cent of the total volume of the gas. The standard Orsat apparatus available for this work had a burette of 100-ml capacity and 1/5-ml graduations. The 1/5-ml graduation was equivalent to 0.2 per cent of the total volume of the gas, which was approximately the maximum per cent absorption of the total quantity of gas to be measured. Also, since the per cent absorption was obtained by determining the difference between the Orsat analyses, the magnitude of the possible accidental error, even though remaining within the limits of accuracy of the apparatus and of the operator, was increased by the mere process of subtraction.

In an attempt to obtain more accurate analyses, a modified Orsat apparatus having a burette capacity of 314.4 ml and burette graduations of 1/10-ml was designed (See Photograph No. 6). This burette consisted of an ordinary 50-ml burette attached to a glass cylinder by means of a short piece of rubber tubing. The volume of the burette was determined by weighing the quantity of water required to fill the portion between the lowest graduation and a point on the capillary tube leading from its top.

In most of the experimental runs, analyses were made with both the standard and modified apparatus, in order to check, to some extent, the modified apparatus. The amounts of absorption determined by each apparatus agreed fairly well with each other, although the modified apparatus usually indicated lower percentages of carbon dioxide at the entrance and exit of the tower, Since the modified apparatus was not used in all the experiments and in order to have all the calculations of the same basis, the data obtained by means of the standard apparatus were used in making the calculations. The development of leaks in the burette of the modified apparatus prevented its being used in some of the experiments.

Operating Characteristics: -- In controlling the operating variables of the tower, the rate of flow of water through the tower was controlled by means of a valve located at the top and was measured by weighing on spring scales the amount discharged from the tower in a definite time.

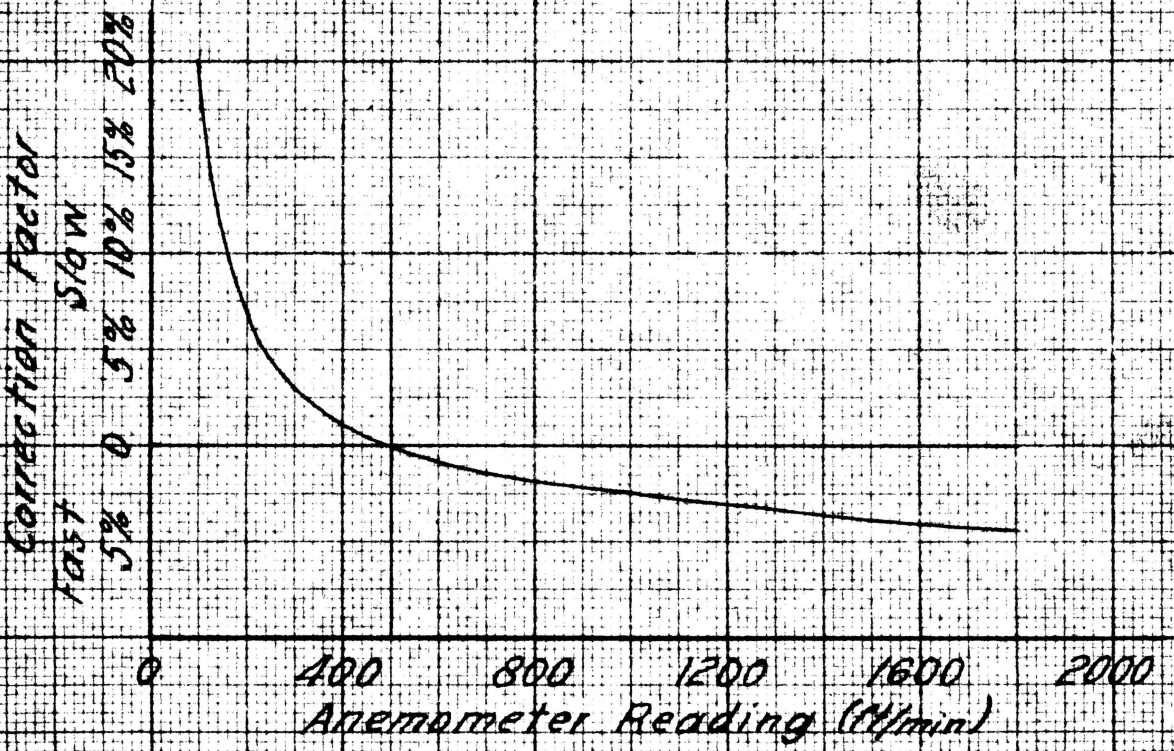
The rate of flow of the gas was measured by means of an anemometer, which was so placed that all the gas was forced to pass through the anemometer. The observed readings were corrected according to the calibration curve furnished by the manufacturer. A copy of the calibration curve is shown in Graph No. 1.

The Orsat measurements were taken at the top and bottom of the tower so as to eliminate any possible error that might have been introduced by the use of the long sampling lines. Also, samples

of gas for analysis were taken only from the terminal sections of the tower, no data at all being taken on the conditions in the intermediate tower sections. A sample of the flue gas was drawn into the burette of the Orsat apparatus and then expelled to the atmosphere immediately before the sample to be analyzed was drawn in. This was done in order to remove stagnant gas from the sampling lines.

The thermometers used in taking the various temperatures were placed in constant temperature baths at room temperature and at the boiling point of water, in order to determine any apparent differences in temperature they might show where no real difference existed. The temperatures used in the calculations were corrected to a common basis by the addition of the correction factor thus determined to an average of the observed readings. The temperature of the exit gas was used to determine the humidity of the air leaving the tower and the other temperatures were taken, primarily, in order to make it possible to ascertain when the tower was operating under conditions of equilibrium. According to Sherwood(36), the temperature of the absorbing water has great effect on the liquid film coefficient, and the temperatures of the tower water were examined in order to determine whether any such effect was apparent in this case. It was assumed that the gas samples analyzed were brought to a common base of temperature and humidity in the Orsat apparatus before analysis, thus eliminating errors in the analyses due to changing temperatures and humidities.

CALIBRATION CURVE FOR ANEMOMETER USED TO MEASURE GAS RATE OF FLOW IN 18-INCH STONEWARE ABSORPTION TOWER



Graph No. 1

J.H.M. 9-23-42

The water entering and leaving the tower and cooler was analyzed for carbonate, bicarbonate and free carbon dioxide content. The carbonate and bicarbonate contents were determined by titrating a 25-ml sample of the water with 0.0058 N hydrochloric acid, using phenolphthalein and methyl orange indicators (See Photograph No. 7). The free carbon dioxide was determined by titrating another 25-ml sample of the same water with 0.0021 N sodium hydroxide. Weak solutions were used because of the low concentrations of carbonates, bicarbonates and free carbon dioxide in the water.

F. Sample Calculations

Equilibrium Curve: -- An equilibrium curve for carbon dioxide and water at 20° C was calculated from Henry's law,

$$p = Hc$$

where

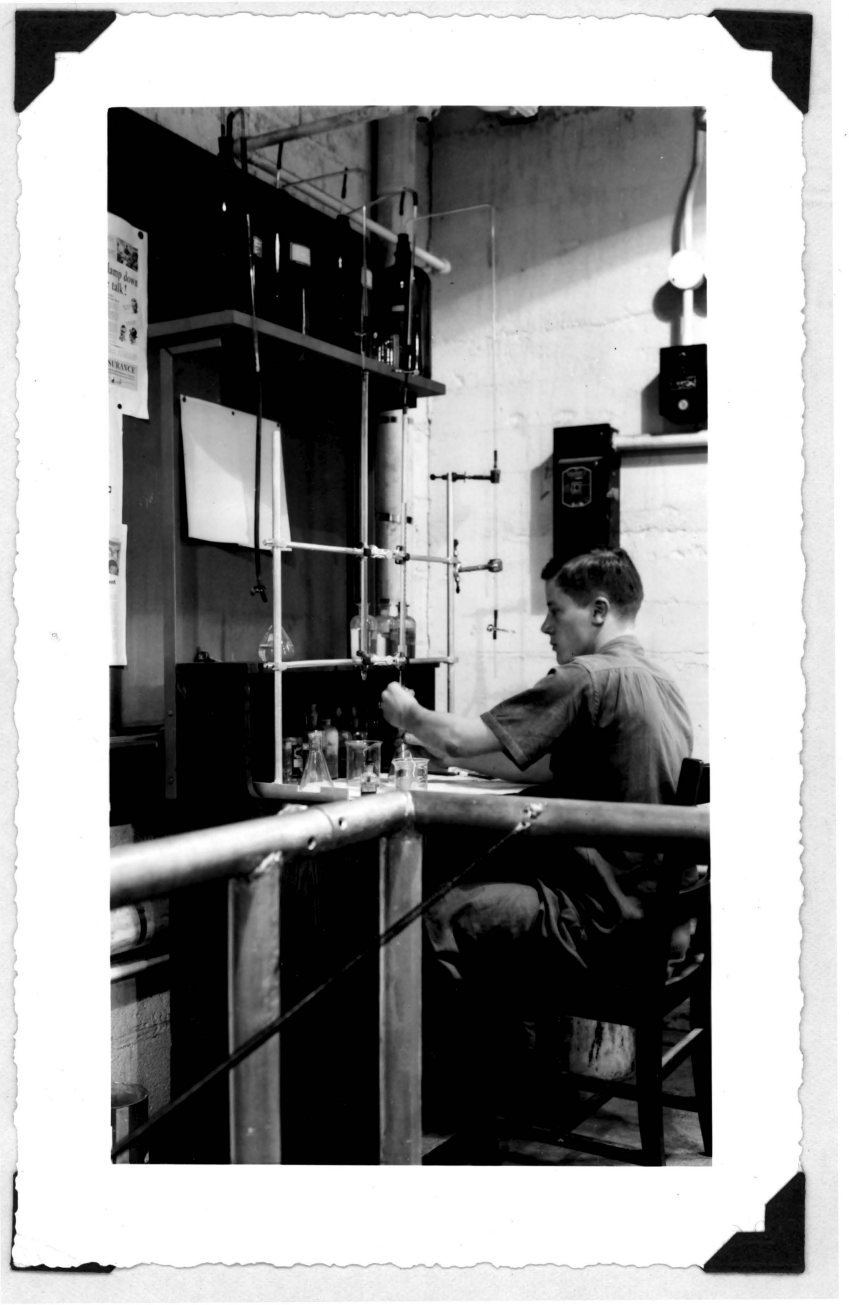
p = partial pressure of dissolved gas (mm Hg).

c = concentration of dissolved gas in liquid (mols CO_2/mol solution).

H = Henry's law constant (1420).

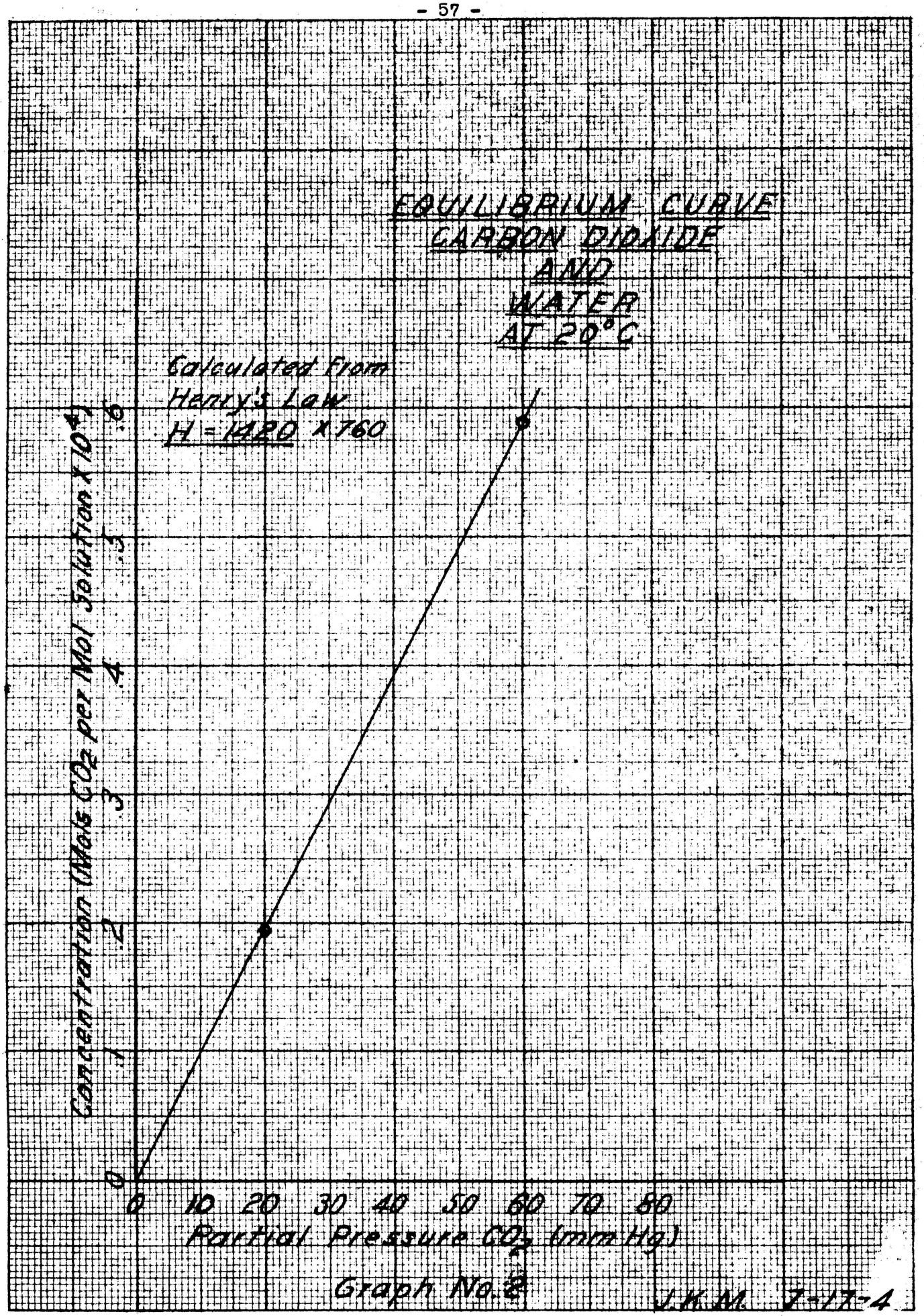
Points on the line were determined by assuming partial pressures of the carbon dioxide and calculating the corresponding concentrations (See Graph No. 2).

Equilibrium Distribution Curve: -- In gas absorption calculations, it is convenient to change the units of the equilibrium



Photograph No. 7

Titrating Absorbing Tower Water to Determine Carbon Dioxide Content



Graph No. 2

J.K.M. 7-17-4

curve from partial pressures and concentrations to x and y units, where,

x = pounds of absorbable material in the liquid per pound of pure absorbing liquid.

y = pounds of absorbable material in the gas per pound of inert gas.

Values of x and y at one particular partial pressure of the absorbable gas locate one point on the x-y diagram or the equilibrium distribution curve. A curve was plotted from calculated values of x and y at various partial pressures of the carbon dioxide covering the range of partial pressures used in the experiments.

Entrance and exit compositions of the flue gas and water in the tower were converted to x-y units, locating the ends of the operating lines which were then drawn on the same graph as was the equilibrium distribution curve (See Graph No. 3).

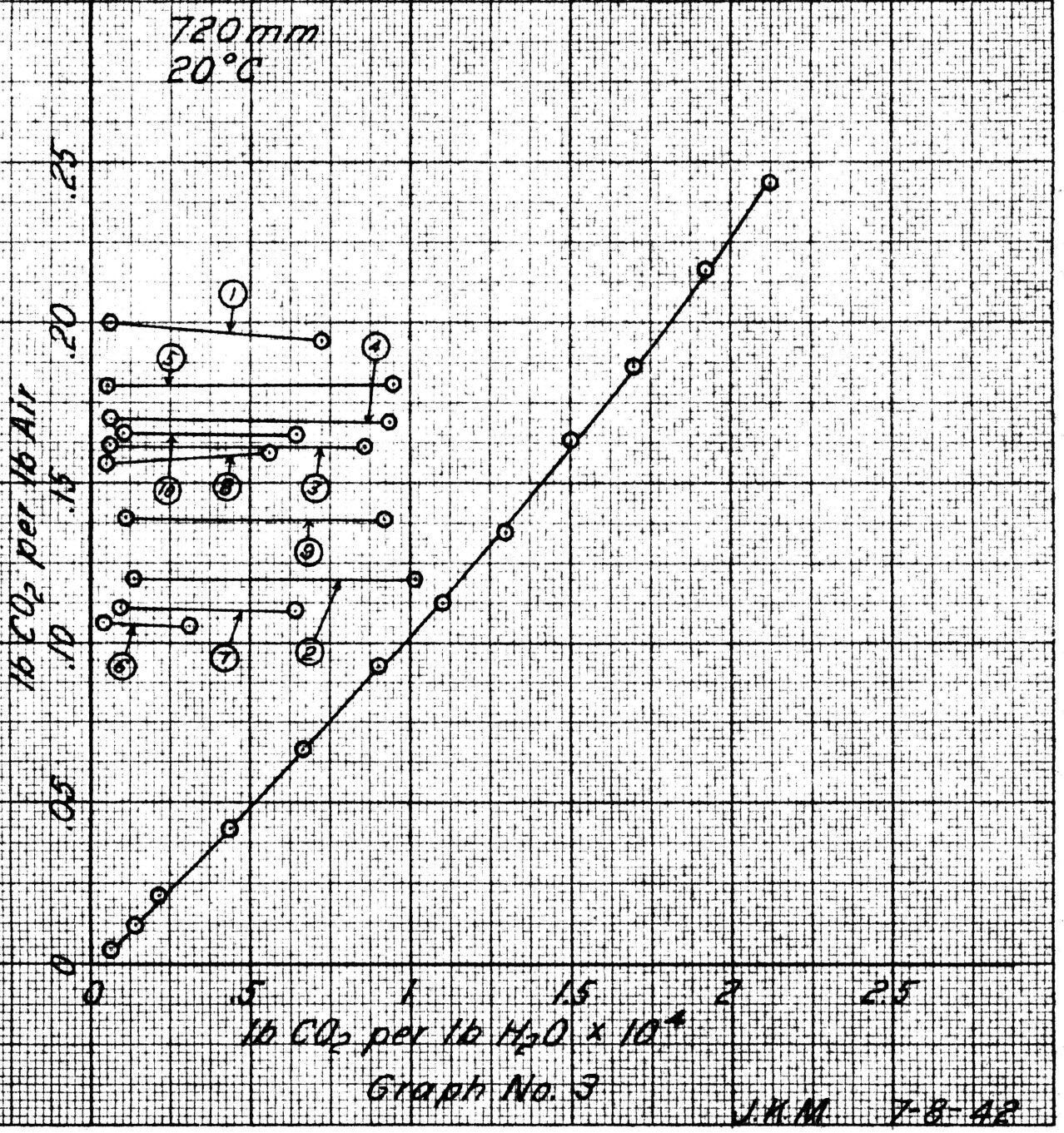
Location of Operating Lines: -- The data used to calculate the entrance and exit compositions of the water and flue gas in the tower were averages of corrected values or readings. These readings were obtained during the experimental runs after the tower appeared to be operating under conditions of equilibrium as observed from the readings of the various instruments used in the experiments.

The weights of carbon dioxide leaving and entering the tower per unit time were calculated by determining the pounds of carbon dioxide per pound of dry air, in the entering and exit flue gases, from the Orsat analyses. These values, multiplied by the pounds of

dry air passing through the tower per unit time gave the weight rate of flow of carbon dioxide in and out of the tower. The weight rate of flow of the dry air was calculated on the assumption that the exit air was saturated with water vapor, since it had been in thorough contact with water throughout its passage through the cooler and tower. Assuming the flue gas to be composed only of carbon dioxide, water and air (except carbon dioxide), the volume of humid air leaving the tower per unit time was calculated from the Orsat analysis and anemometer reading by subtracting the volume of carbon dioxide from the total volume of the flue gas. In order to determine the pounds of dry air per minute passing through the tower, this calculated value of the volume of humid air (cu. ft.) was divided by the humid volumes of the same air (cu. ft. per lb. dry air). Humidities and humid volumes were calculated from the partial pressures of water vapor obtained from handbooks and the experimentally determined temperatures and atmospheric pressures.

The weight rates of absorption, as determined above, were compared with those determined by means of the titration data in an attempt to obtain a material balance of the carbon dioxide transferred between the gas and liquid phases. The carbon dioxide contents of the flue gases entering and leaving the tower, as determined by the above method, were combined with the carbon dioxide contents of the water entering and leaving the tower as determined by titrations, to locate the terminal points of the operating line. Any point on

EQUILIBRIUM DISTRIBUTION CURVE FOR CARBON DIOXIDE BETWEEN THE PHASES CO_2 SOLUTION AND AIR WITH OPERATING LINES



Graph No. 3

J.H.M. 7-8-42

this operating line represents the compositions of the gas and liquid at some particular point in the tower. The coordinates of the operating line are in x-y units and the line is drawn on the same graph as is the equilibrium distribution curve (Graph No. 3). It is necessary, in order to perform the graphical integration described below, that the operating line and the equilibrium distribution curve be plotted on the same graph.

The numbers on the operating lines correspond to those on the graphs showing the integration for that particular operating line.

Integration of Rate Equation: -- The liquid film coefficient, k_1a, was calculated by means of the rate equation. According to Badger and McCabe[1], this equation may be written,

$$\int_{x_2}^{x_1} \frac{dx}{x_i - x} = \frac{(k_1a)\ (\rho_{av})\ (V_1)}{L}$$

where,

x_1 = lb. CO_2/lb. exit water.

x_2 = lb. CO_2/lb. entering water.

x_i = equilibrium value of x.

k_1a = film coefficient (lb./hr.) (cu.ft.) (lb./cu.ft.)

ρ_{av} = density of water (lb./cu.ft.).

V_1 = packed volume of tower (cu.ft.).

L = rate of water flow through tower (lb./hr.).

if x_i and x are small in comparison to one. In this case, x_i and x had no values greater than 0.0002 and the numerical values of the liquid film coefficients were determined by the solution of the above equation. The equation was solved by graphically evaluating the integral and substituting the value obtained in the equation, which then contained but one unknown, k_1a. The unit of x is lb. carbon dioxide per lb. of absorbing water and that of y is lb. carbon dioxide per lb. dry air. The operating line represents the liquid and gas compositions in x-y units at the different points in the tower, the end points of the operating line representing the terminal conditions in the tower. The equilibrium value of x, x_i, for a particular value of x was found by drawing a line parallel to the x-axis and intersecting the operating line at x. The intersection of the drawn line with the equilibrium distribution curve located x_i.

Inspection of Graph No. 3 shows that all values of x on the operating line gave very nearly the same value of x_i, since the operating line is almost parallel to the x-axis. In the evaluation of the above integral, the same value of x_i was used with the different values of x selected from the operating line for a particular experiment. A plot was made of x versus $1/(x_i-x)$ for various values of x, ranging in value from that representing the carbon dioxide content of the liquid entering the tower to that representing the composition of the exit liquid. The area inclosed by the plotted curve, x-axis and the ordinates, x_1 and x_2 was the value of the integral.

Equation Relating k_1a to L: -- Equations of the form,

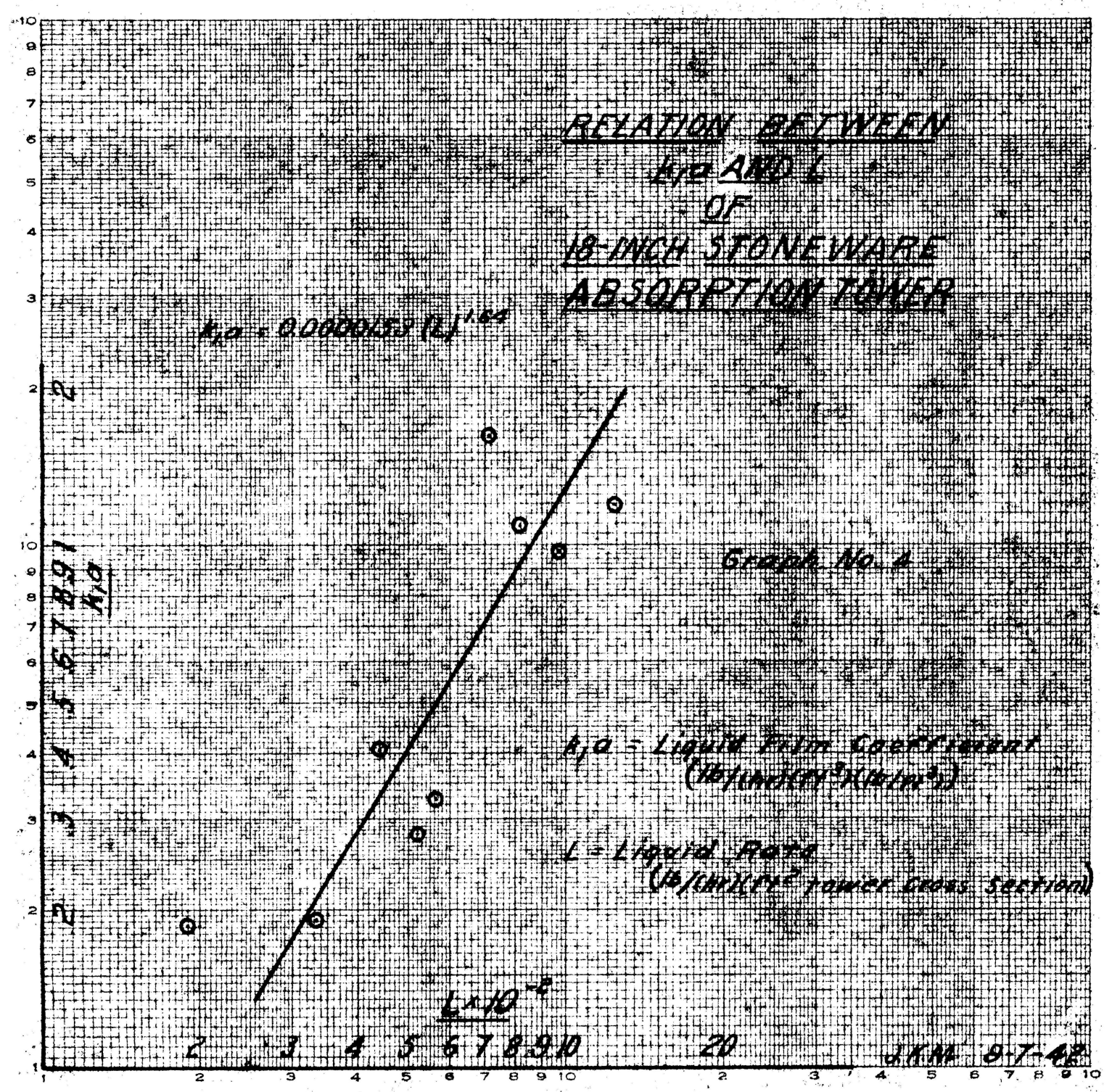
$$K_1a = (a') (L)^n,$$

for the absorption and desorption of carbon dioxide in water have been developed and some are given by Sherwood(40). Since the liquid film is the controlling resistance in the absorption of carbon dioxide by water, k_1a is almost equal to K_1a. It was assumed that, in this case, a relation of the above type between k_1a and L existed. Although the data was rather scattered in the plot of k_1a versus L on logarithmic coordinate paper, as shown in Graph No. 4, an equation of the straight line assumed was derived. The constants were determined by the method of averages and the equation found to be

$$k_1a = 0.0000153 (L)^{1.64}$$

A detailed calculation following the above procedure is described on subsequent pages.

Equilibrium Distribution Curve Calculations: -- From the equilibrium curve calculated as shown above (Graph No. 2), corresponding partial pressures and concentrations are selected and changed from the units of mm Hg and mols per mol solution to x-y units. The x-y units are defined above and each point selected from the equilibrium curve results in a point on the equilibrium distribution curve, upon a change of units. Values of partial pressures up to 100 mm Hg


RELATION BETWEEN
k_1a AND L
OF
18-INCH STONEWARE
ABSORPTION TOWER
$k_1a = 0.0000455\,(L)^{1.64}$
Graph No. 4
k_1a = Liquid Film Coefficient
(lb/(hr)(cu ft))/(lb/(hr)(sq ft))
L = Liquid Rate
(lb/(hr)(sq ft tower cross section))
$\frac{L \times 10^{-2}}{k_1a}$
$L \times 10^{-2}$
JAM 9-7-48

are used in the calculation of the equilibrium distribution curve. (Graph No. 3). The curve is plotted for 20° C, which temperature was taken as the average temperature in the tower.

10 mm Hg taken as partial pressure of CO_2

$$y = \frac{44}{29} \times \frac{10}{710} = 0.02135 \text{ lb. } CO_2 \text{ per lb. air}$$

From Graph No. 2, the concentration of carbon dioxide in water at 10 mm partial pressure and 20° C is 0.0000097 mols carbon dioxide per mol solution.

$$x = \frac{0.0000097 \times 44}{0.9999 \times 18} = 0.0000237 \text{ lb. } CO_2/\text{lb. } H_2O$$

Location of Operating Lines: -- (Calculation for operating line No. 7 shown on Graph No. 3).

Carbon Dioxide Content of Exit Gas: --

Average room temperature was recorded as 25° C.

23.52 mm Hg = vapor pressure of water at 25° C.

720 mm Hg = average atmospheric pressure.

23.5/720 = 3.3 per cent of flue gas in burette, of Orsat apparatus, was water vapor.

6.7 per cent carbon dioxide shown by Orsat analysis.

100 - (3.3 + 6.7) = 90 per cent inert gas in exit flue gas.

(6.7 x 44)/(90 x 29) = 0.1130 lb. CO_2/lb: dry air in exit gas = y_2.

Carbon Dioxide Content of Entering Air, y_1: -- Calculated in the same manner as was y_2.

Concentration of Carbon Dioxide in Inlet and Exit Tower Water: --

17.5 cc 0.0021 N NaOH required to titrate the CO_2 in 25 cc of exit tower water.

$$\frac{17.5 \times 0.0021 \times 0.044}{25} = 0.0000648 \text{ lb. } CO_2/\text{lb. } H_2O = x_1$$

Concentration in inlet water, x_2, is calculated in a similar manner.

The points, x_1, y_1 and x_2, y_2, locate the operating line on Graph No. 3.

Absorption Rates: -- The absorption rates are not used to determine the location of the operating line but are affected by the position of the line and were calculated as shown below.

Humidity of Exit Air:

The exit air was assumed to be saturated at 18° C.

15.77 mm Hg vapor pressure of water at 18° C.

$$H = \frac{18 \times 15.77}{29 \times (717 - 15.77)} = 0.01395$$

Humid Volume of Exit Air: -- The humid volume was calculated from the formula given by Badger and McCabe(2).

$$V = (0.73t + 335.7)\left(\frac{1}{29} + \frac{H}{18}\right)\frac{760}{P}$$

t = temperature (° F.)
H = humidity
P = total pressure

$$V = (0.73 \times 65 + 335.7)\left(\frac{1}{29} + \frac{0.01395}{18}\right)\left(\frac{760}{717}\right) =$$

14.3 cu. ft. per lb. dry air.

Total Volume of Exit Air Per Unit Time:

44.5 cu. ft. gas per minute = gas flow rate calculated from anemometer reading.

44.5 x 0.933 = 41.52 cu. ft. wet air per minute leaving tower.

Rate of Flow of Dry Air Through Tower:

$\frac{41.52}{14.3}$ = 2.90 lb./min.

Rate of CO_2 Absorption Based on Orsat Analysis:

2.90 x (0.1120 - 0.1130) = -0.0029 lb./min.

Rate of Carbon Dioxide Absorption Based on Titration Data:

15 ml 0.0021 N NaOH required to titrate the CO_2 absorbed by 25 ml of tower water.

Water rate through the tower was 5.6 lb./min.

$\frac{15 \times 0.0021 \times 0.044 \times 5.6}{25}$ = 0.000312 lb/min.

Graphical Integration of the Rate Equation: -- (Calculation for Operating Line No. 9).

$$\int_{x_2}^{x_1} \frac{dx}{x_i - x} = \frac{(k_1 a)\ (\rho_{av})\ (V_1)}{L}$$

From the equilibrium curve, x_i is found to be equal to 0.000133 for all values of x. x_i is the point at which a line parallel to the

x-axis and passing through the point, x, on the operating line, intersects the equilibrium curve. Since, in this case, the operating line was almost parallel to the x-axis, a common value of x_i was taken.

$0.368 \div 2.642 = 0.1391$ lb. CO_2/lb. air out = y_2.

$0.374 \div 2642 = 0.1415$ lb. CO_2/lb. air in = y_1.

$\frac{3.08 \times 0.0021 \times 0.044}{25} = 0.0000114$ lb. CO_2/lb. H_2O in x_2.

$\frac{25.28 \times 0.0021 \times 0.044}{25} = 0.0000936$ lb. CO_2/lb. H_2O out = x_1.

x_1, y_1 and x_2, y_2 are coordinates of the end points of the operating line.

Below is given in Table I the values of x and of $1/(x_i-x)$ for operating line No. 9. A plot was made of x as abscissae and $1/(x_i-x)$ as ordinates and is shown in Graph No. 5. The area inclosed by the curve, the x-axis and the ordinates, x_1 and x_2 was determined by counting the squares on the graph and in that area. The value of this area or the value of the integral in the rate equation was substituted in the equation which was then solved for k_1a.

Table I.

Values Used in Integration of Rate Equation

For Operating Line No. 9

x	$x_i - x$	$\frac{1}{x_i - x}$
0.0000114	0.0001216	8,230
0.00002	0.000113	8,850
0.00003	0.000103	9,710
0.00004	0.000093	10,750
0.00005	0.000083	12,050
0.00006	0.000073	13,700
0.00007	0.000063	15,880
0.00008	0.000053	18,870
0.00009	0.000043	23,250
0.0000936	0.0000394	25,370

1.12 = value of integral.

62.3 lb./cu.ft. = density of water leaving tower which is equivalent to the density of the solution since the solution is very dilute.

23.65 cu. ft. = packed volume of the tower, V_i.

816 lb./(hr.)(sq.ft. tower cross section) = liquid rate, L.

$$1.12 = \frac{(k_1a)(62.3)(23.65)}{816}$$

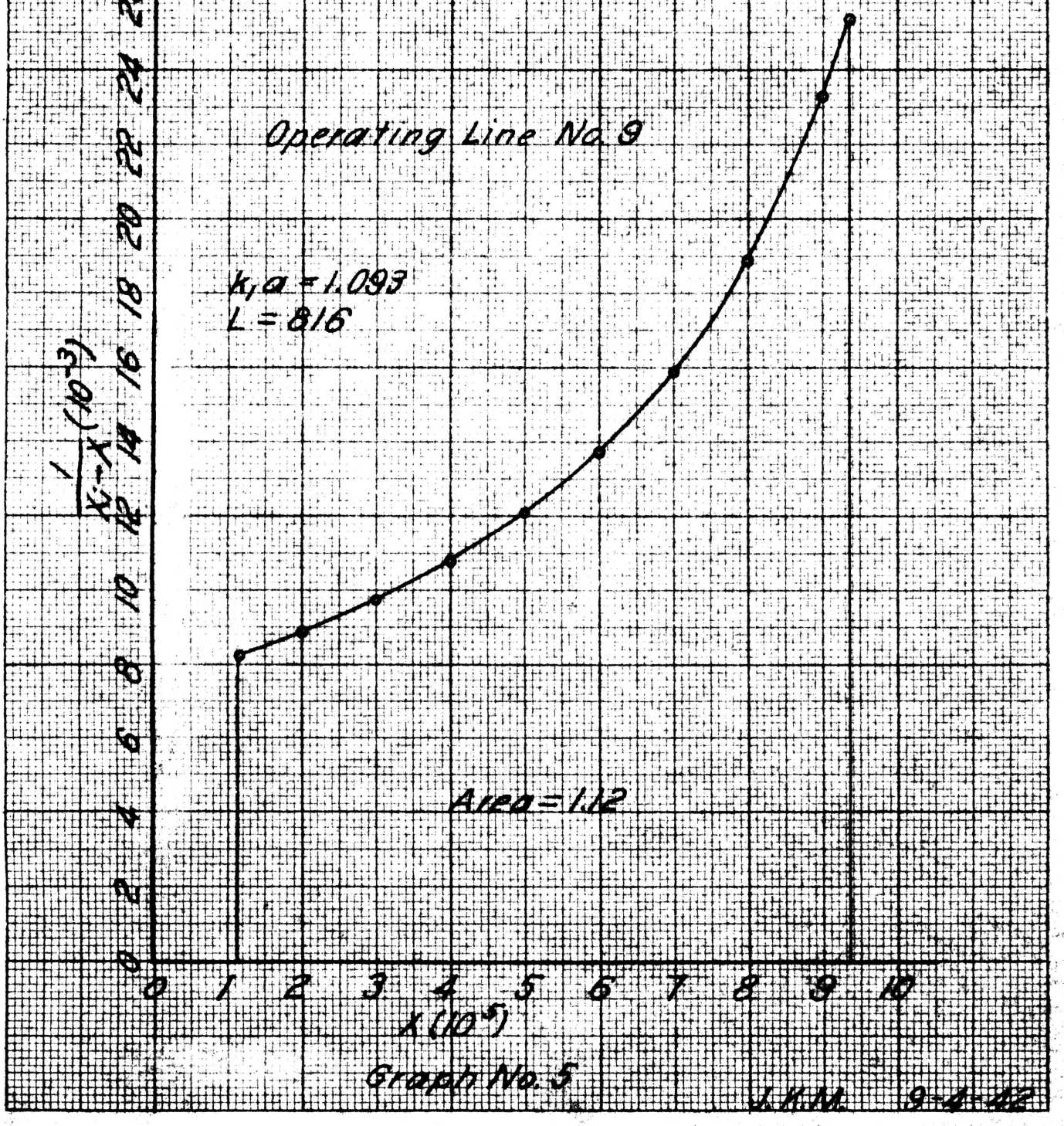
$$k_1a = 1.09 \text{ lb./(hr.)(cu.ft.)(lb./cu. ft.)}$$

Equation Relating k_1a to L: -- The values of k_1a as calculated by the above method are tabulated in the Table II with the corresponding liquid rates. The number of the operating line is also

Data Taken 9-3-42
Run No. 1

CALCULATION OF k_1a OF ABSORPTION TOWER

Graphical Integration of Rate Equation



Graph No. 5

J.H.M. 9-4-42

given in order that reference can be made to the graphs showing the integrations and the operating lines.

Table II.

Calculated Values of k_1a for Various Water Flow Rates

Operating Line No.	L (lb./min.)	L (lb./(hr.)(sq.ft.)	k_1a (lb./(hr.)(cu.ft.)(lb./cu.ft.)
7	5.6	191	0.186
10	9.8	334	0.189
5	13.0	443	0.413
8	15.4	523	0.281
1	16.7	566	0.325
2	21.0	714	1.60
9	24.0	816	1.093
4	28.5	970	0.97
3	36.5	1240	1.185

The results of the calculations based on Operating Line No. 6 were omitted from the calculation of the equation, because the titration data differed so markedly from that of the other experiments as to indicate that a mistake had been made.

It was assumed that a relation between k_1a and L of the form,

$$k_1a = a' (L)^n$$

existed. The constants, a' and n, in the equation were then evaluated by the method of averages. In this method, an equation representing the difference between the calculated value of k_1a and the experimental value of k_1a is written for each experimentally determined

point. Since there are two constants to be determined, the nine equations were divided into two groups. Each group of equations was added to form one equation for the sum of the residuals for that particular group of points. Since the equation to be determined was that for which the sum of the residuals was zero, the two equations obtained by the above method were equated to zero and solved simultaneously for the two unknowns, a' and n.

$$R_1 = a'(191)^n - 0.186$$
$$R_2 = a'(334)^n - 0.189$$
$$R_3 = a'(442)^n - 0.413$$
$$R_4 = a'(523)^n - 0.281$$

$$\Sigma R = a'\left[191^n + 334^n + 442^n + 523^n\right] - 1.069 = 0$$

$$R_5 = a'(566)^n - 0.325$$
$$R_6 = a'(714)^n - 1.60$$
$$R_7 = a'(816)^n - 1.093$$
$$R_8 = a'(970)^n - 0.97$$
$$R_9 = a'(1240)^n - 1.185$$

$$\Sigma R = a'\left[566^n + 714^n + 816^n + 970^n + 1240^n\right] - 5.173 = 0$$

a' was eliminated from the above equations and n found to be 1.64 by solving the following equation by trial and error:

$$\left[566^n + 714^n + 816^n + 970^n + 1240^n\right] = 4.85\left[191^n + 334^n + 442^n + 523^n\right]$$

a' was then determined by substitution and the equation found to be

$$k_1a = 0.0000153\ (L)^{1.64}$$

G. Results of Absorption Experiments With Carbon Dioxide and Water in a Coke-packed 18-inch Stoneware Absorption Tower

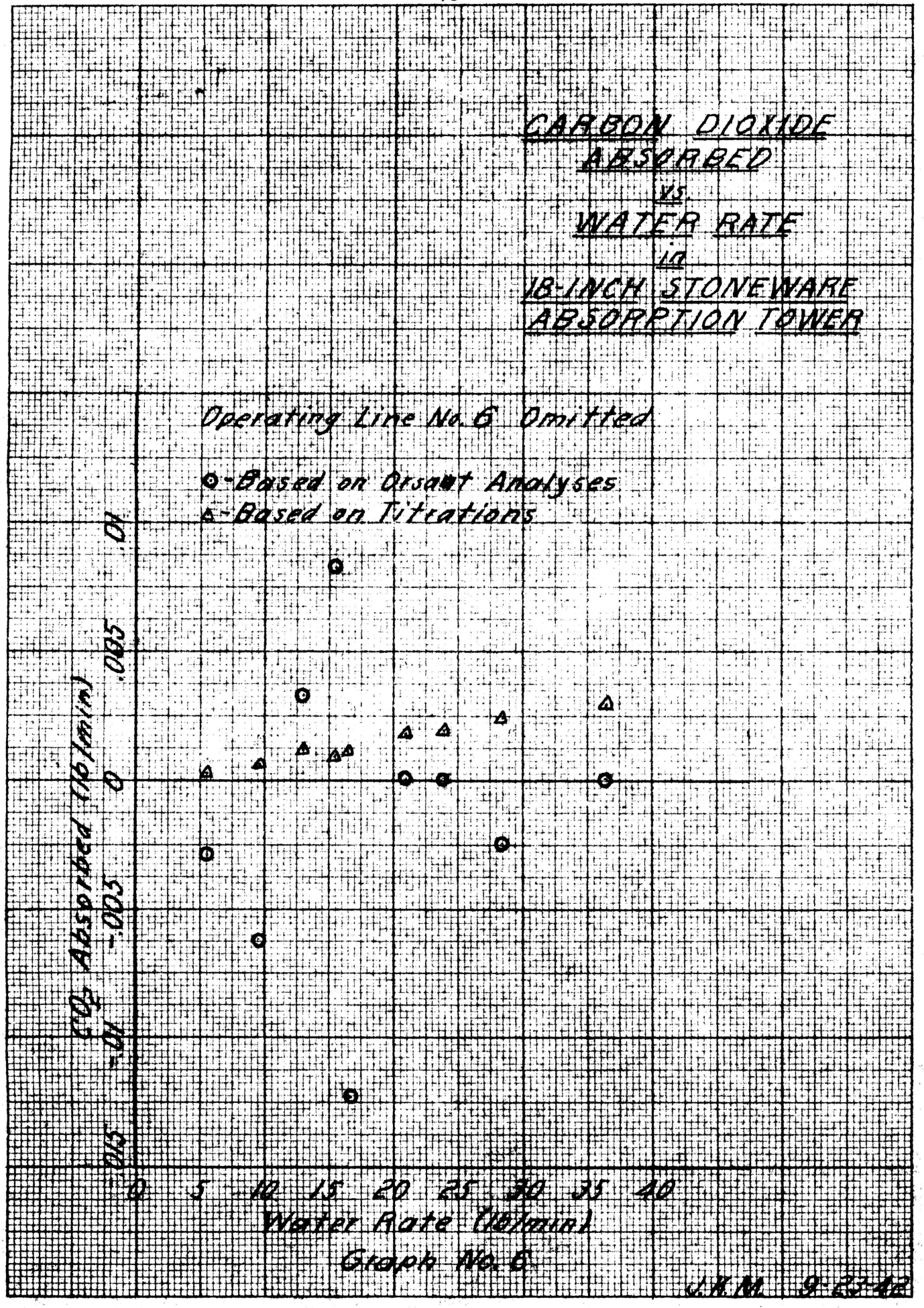
Table III gives a comparison of the rates of absorption of carbon dioxide in water with the rate of water flow through the tower (See Graph No. 6). Reference is made to the operating lines which are drawn on the equilibrium distribution curve (Graph No. 3). Average Orsat analyses are also given. (Table III is shown on the following page).

The results based on Operating Line No. 6 are not shown on Graph No. 6 or used in the derivation of the equation relating k_1a to L, because the wide variation of the titration data in this case indicated that a mistake had been made.

Table III.

Experimentally Determined Absorption Rates for Various Liquid Rates of Flow

Orsat Analysis (% CO_2)		Water Rate (L)	Operating Line	Carbon Dioxide Absorbed (lb./min.)	
in	out	lb./min.	No.	Based on Orsat	Based on Titration
6.65	6.70	5.6	7	-0.00290	0.000312
9.37	9.47	9.8	10	-0.00619	0.000635
10.55	10.50	13.0	5	0.00334	0.001150
9.3	9.1	15.4	8	0.00831	0.000894
11.05	11.45	16.7	1	-0.0123	0.001106
7.1	7.1	21.0	2	0	0.001860
8.2	8.2	24.0	9	0	0.001970
9.8	9.85	28.5	4	-0.00249	0.002480
6.3	6.4	29.4	6	-0.00401	0.000788
9.4	9.4	36.5	3	0	0.002920



Graph No. 6

J.K.M. 9-23-42

In Table II are given the values of the liquid film coefficients, k_1a, for the absorption of carbon dioxide by water in the 18-inch stoneware tower, as compared to the rate of water flow through the tower. Reference is made to the operating line on Graph No. 3 by means of which the coefficients were calculated from experimental data.

Omitting calculations based on operating line No. 6 and assuming that a plot of k_1a versus L on logarithmic coordinates can be represented by a straight line, the equation,

$$k_1a = 0.0000153\ (L)^{1.64}$$

was derived. The unit of L is lb./(hr.)(sq.ft. tower cross section).

The following graphs show the graphical integrations by means of which the values of k_1a given in Table II were calculated.

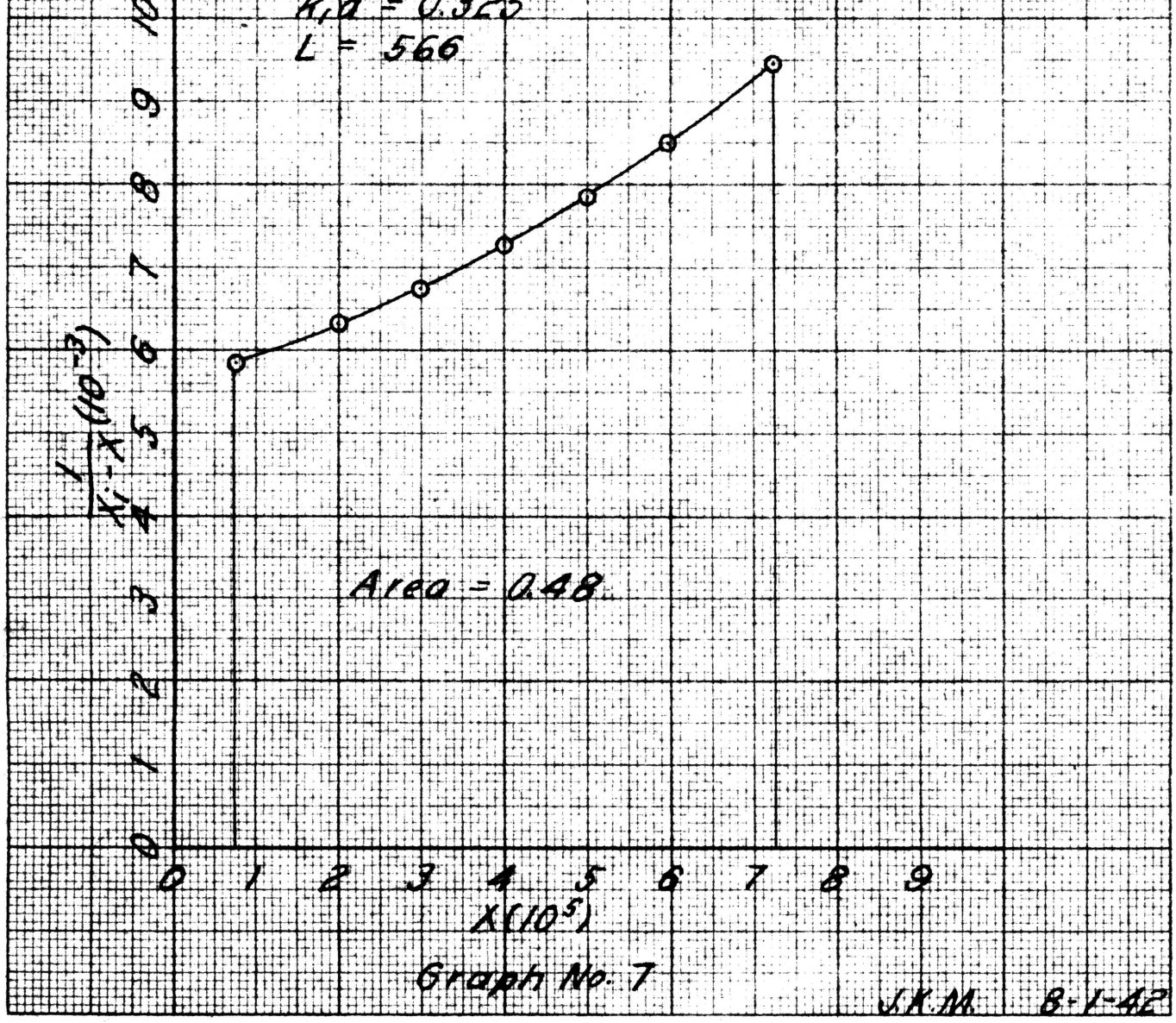
Data Taken 7-30-42
Run No. 2

CALCULATION OF K,a OF ABSORPTION TOWER

Graphical Integration of Rate Equation

Operating Line No. 1

$K_1a = 0.325$
$L = 566$



Graph No. 7

J.K.M. 8-1-42

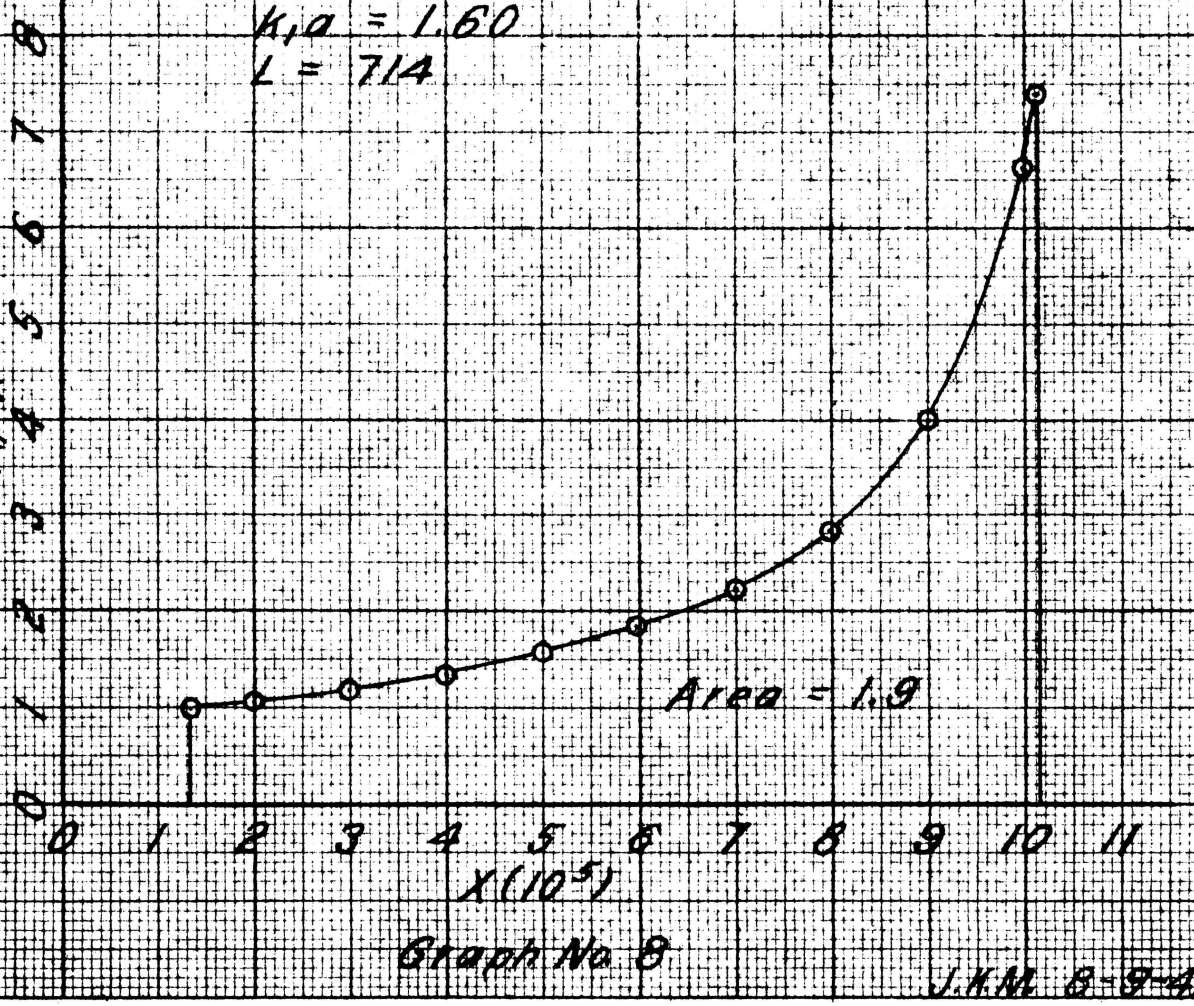
Data Taken 8-8-42

CALCULATION OF K,a OF ABSORPTION TOWER

Graphical Integration of Rate Equation

Operating Line No 2

K,a = 1.60
L = 714



Graph No 8

J.K.M. 8-9-42

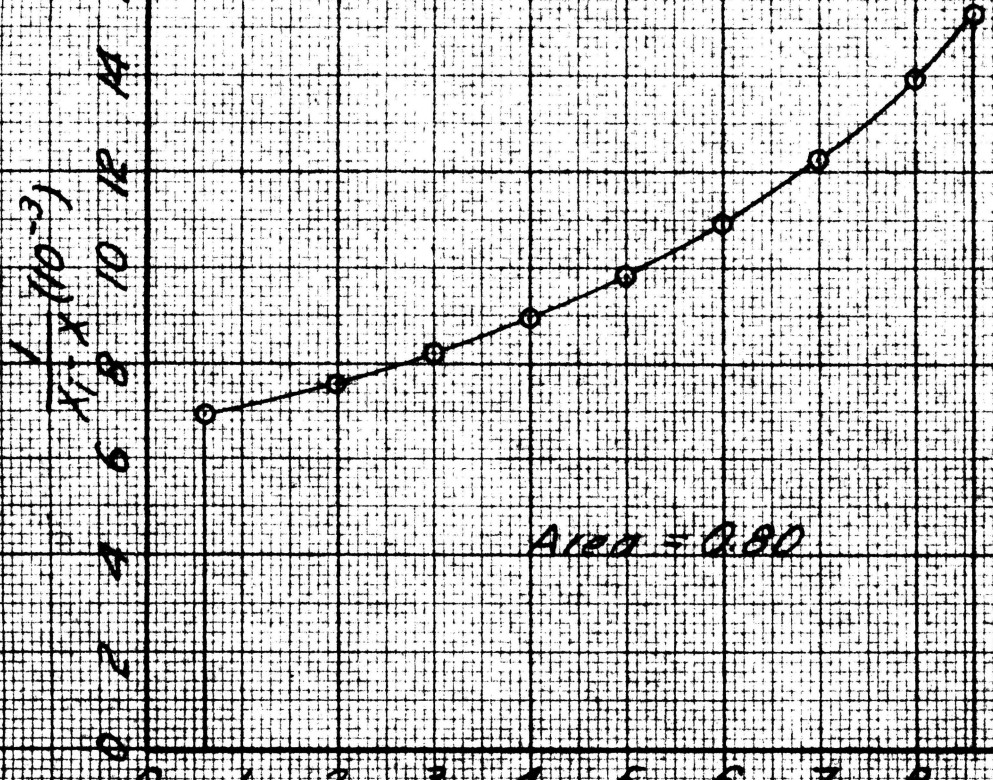
Data Taken 8-12-42
Run No. 1

CALCULATION OF $K_y a$ OF ABSORPTION TOWER

Graphical Integration of Rate Equation

Operating Line No. 3

$K_y a = 1.185$
$L = 1240$



Graph No. 9

J.K.M. 8-16-42

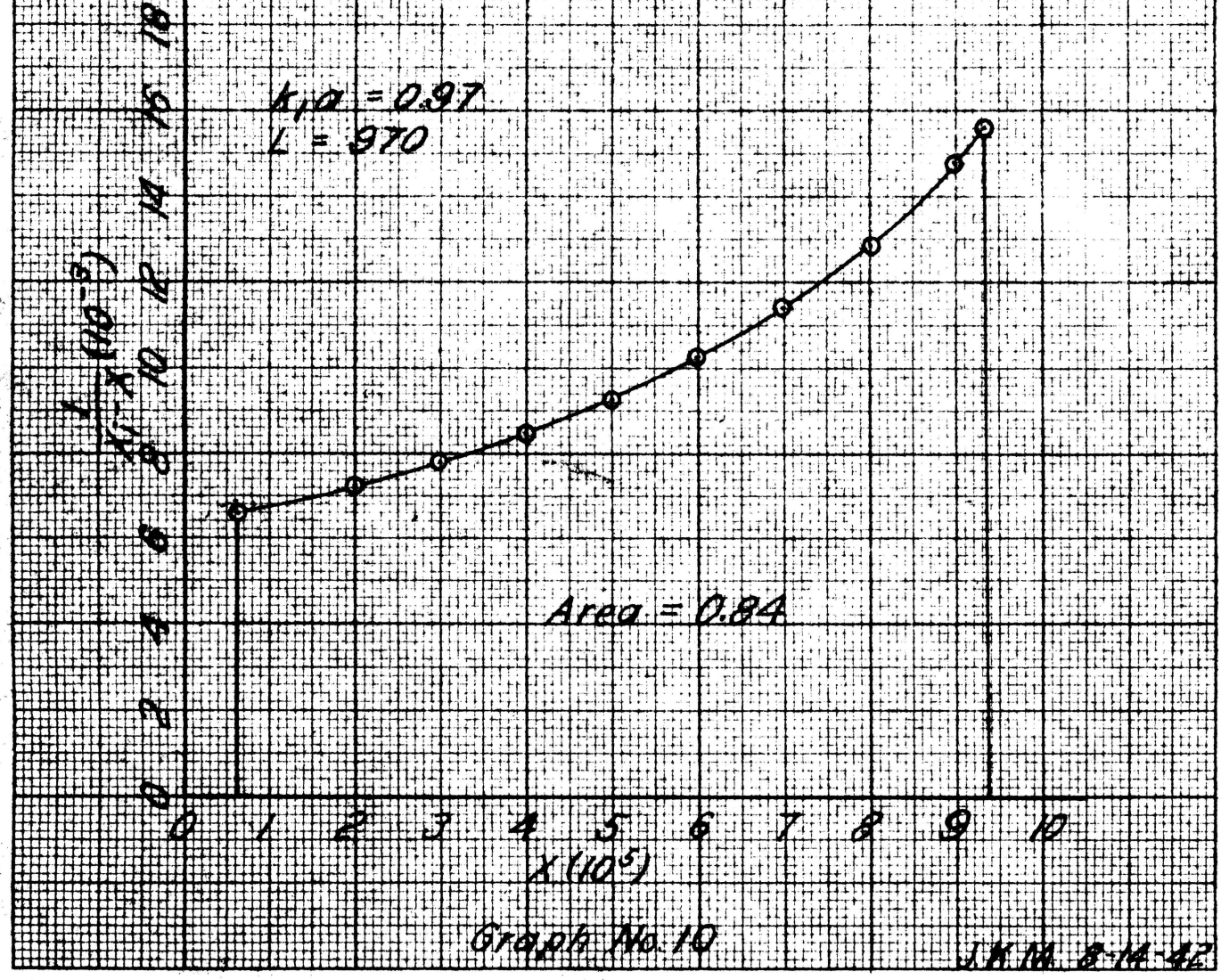
Data Taken 8-12-42
Run No. 2

CALCULATION OF K_1a OF ABSORPTION TOWER

Graphical Integration of Rate Equation

Operating Line No. 4

$K_1a = 0.97$
$L = 970$



Graph No. 10

JKM 8-14-42

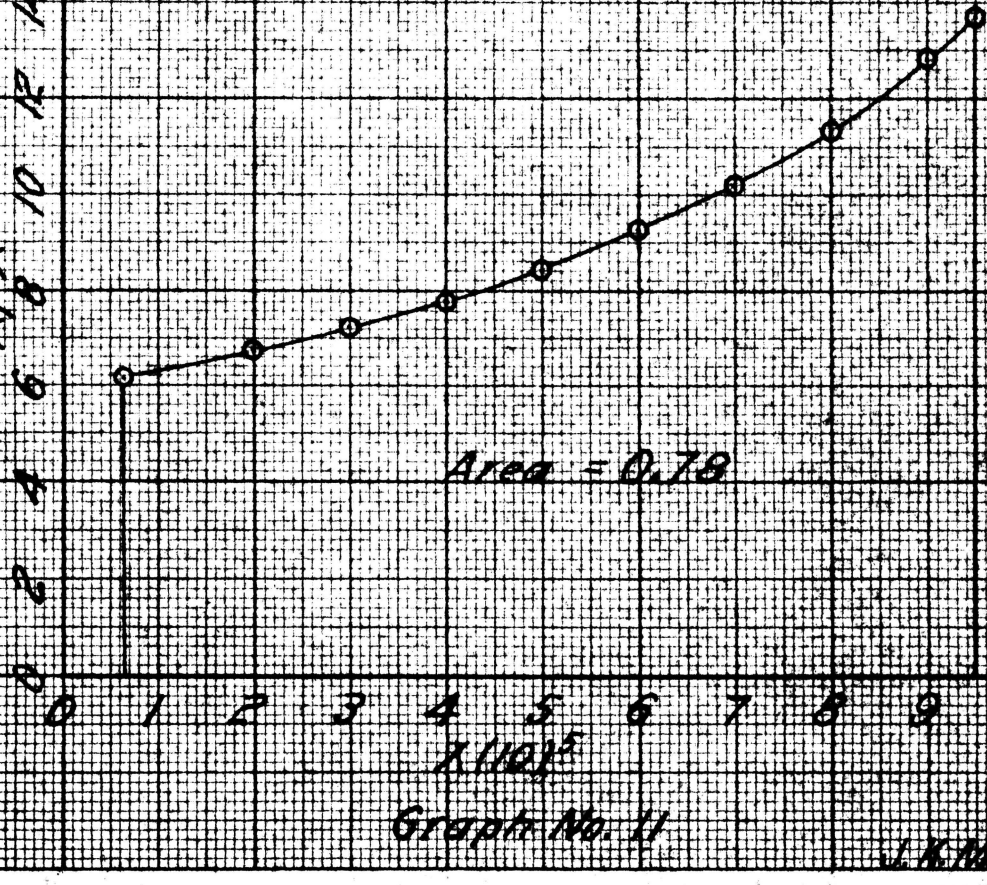
Data Taken 8-12-42
Run No. 3

CALCULATION OF $K_x a$ OF ABSORPTION TOWER

Graphical Integration of Rate Equation

Operating Line No. 5

$K_x a = 0.413$
$L = 442$



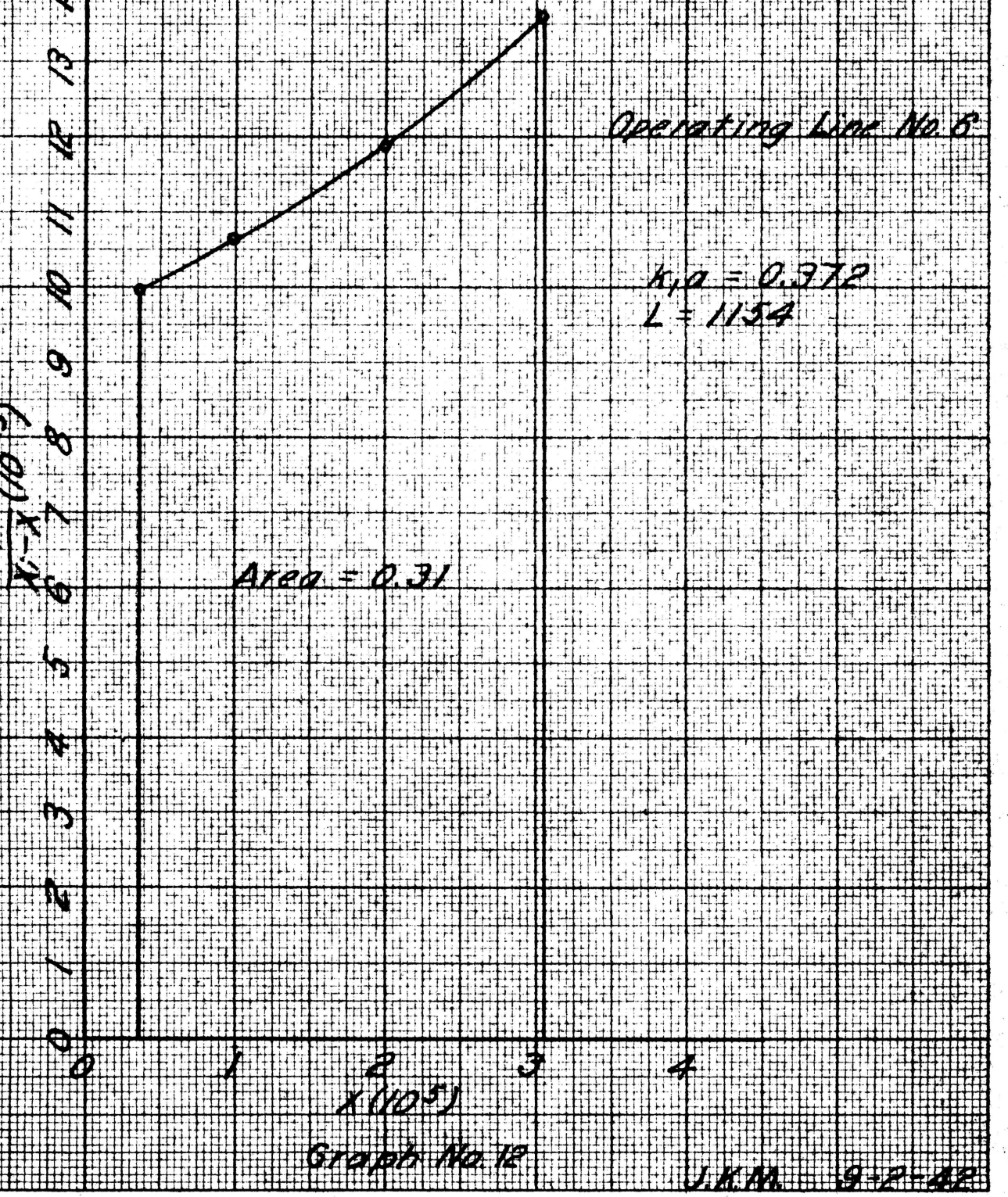
Graph No. 11

J.K.M. 8-12-42

Data Taken 9-1-42
Run No. 1

CALCULATION of K,a OF ABSORPTION TOWER

Graphical Integration of Rate Equation



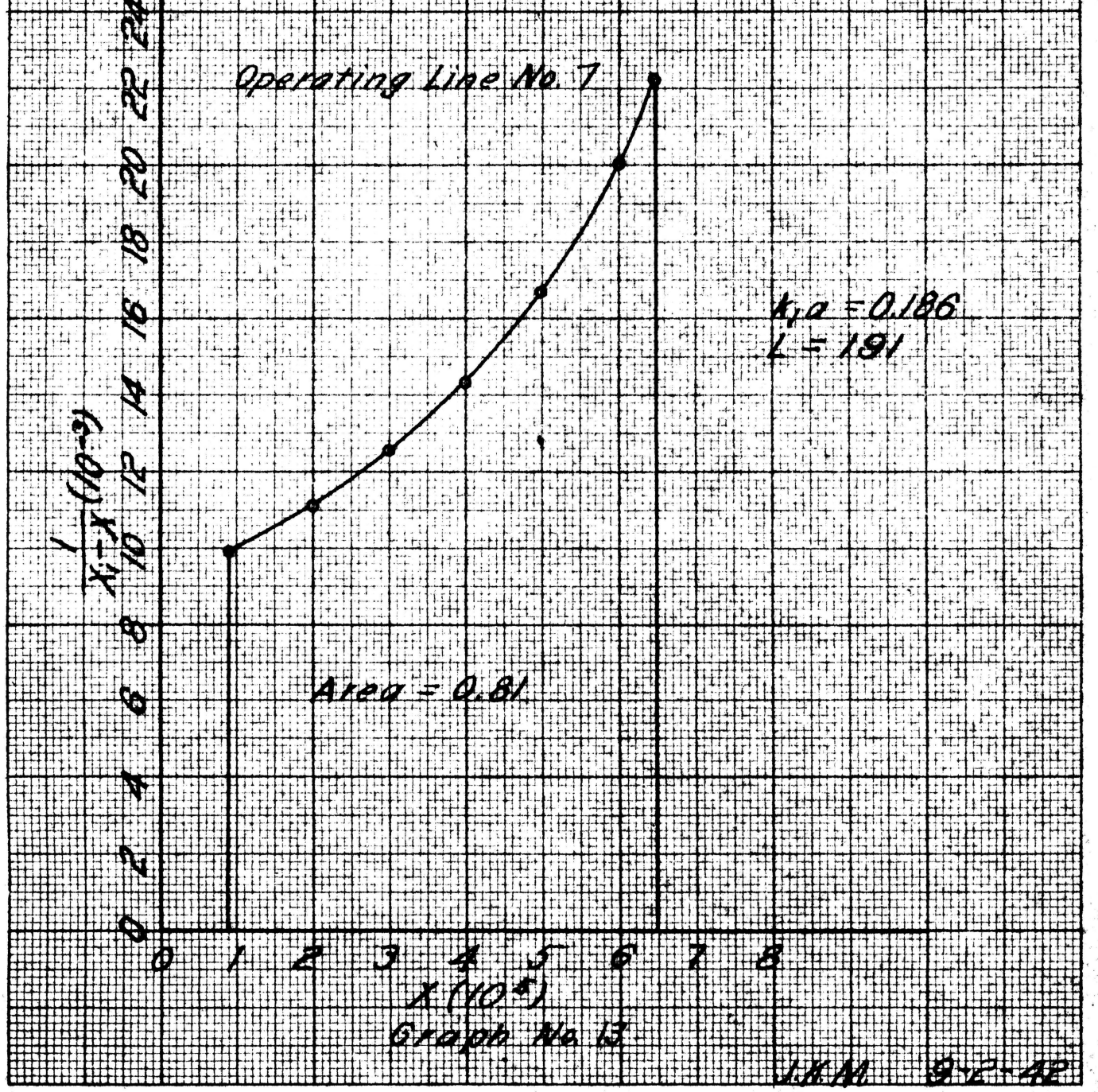
Graph No. 12

J.K.M. 9-2-42

Data Taken 9-1-42
Run No. 2

CALCULATION OF K_1a OF ABSORPTION TOWER

Graphical Integration of Rate Equation



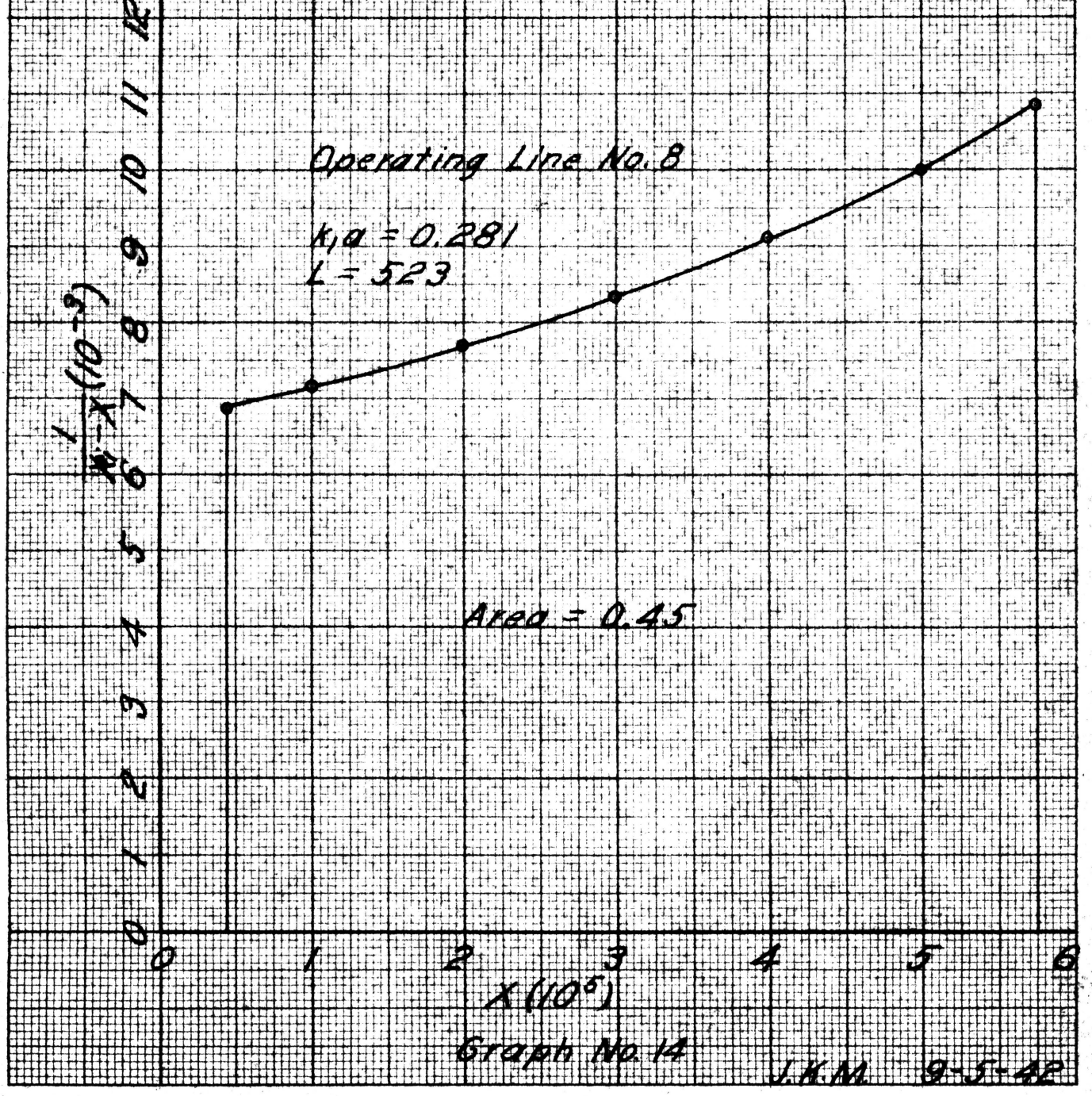
Graph No. 13

J.K.M. 9-2-42

Data Taken 9-2-42

CALCULATION OF K,a OF ABSORPTION TOWER

Graphical Integration of Rate Equation



Graph No. 14

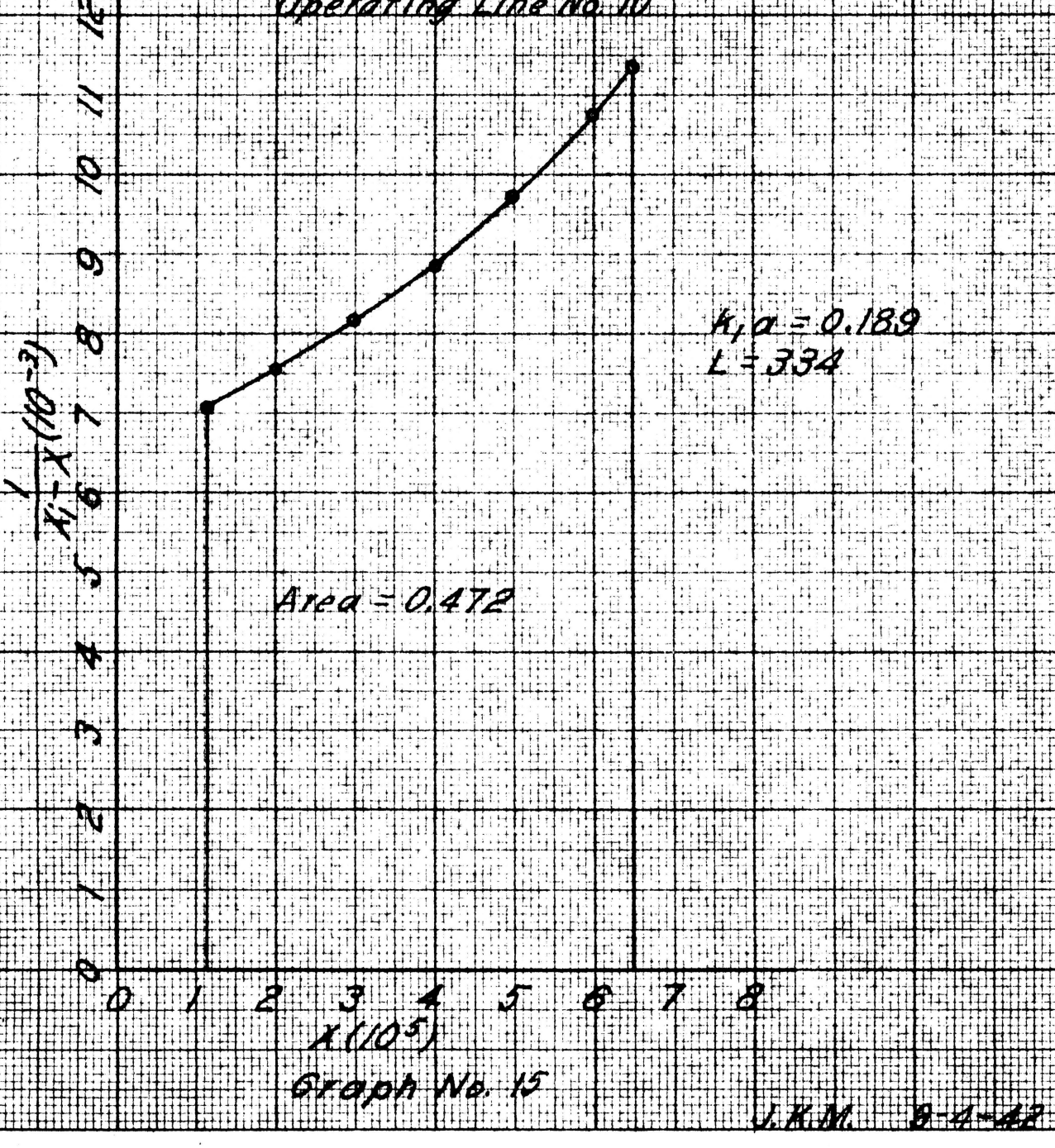
J.K.M. 9-5-42

Data Taken 9-3-42
Run No. 2

CALCULATION OF K_1a OF ABSORPTION TOWER

Graphical Integration of Rate Equation

Operating Line No. 10



Graph No. 15

J.K.M. 9-4-42

IV. DISCUSSION OF RESULTS

Distributing Plates: -- The new distributing plates installed in the 18-inch stoneware tower appeared to have reduced the extent of channeling of the absorbing water near the tower walls. This is shown by the fact that the experimentally determined values of the coefficient, k_1a, increases with the liquid rate, (L). Channeling, because of its tendency to decrease the surface available for material transfer between the phases, tends to lower the value of k_1a.

Sampling Device: -- For the system, carbon dioxide and water, the new sampling device obtains samples of tower gas for analysis that show very nearly the same carbon dioxide content at both the top and bottom of the tower. In the experimental runs on the tower, a maximum difference in carbon dioxide content between the entrance and exit tower gases of 0.4 per cent of the volume of the total gas was obtained from analyses using the standard Orsat apparatus. The above statement applies only to average differences in gas compositions for the different experimental runs and, in one case, a difference between the carbon dioxide contents of the entrance and that of the exit tower gas, was found to be 0.8 per cent of the total gas volume.

Both the 0.8 and the 0.4 per cents carbon dioxide absorbed from the flue gas were more than could be accounted for by the ab-

sorption of carbon dioxide in the tower water as determined by the titrations, and in some cases the Orsat analyses showed negative absorption, which also could not be accounted for by desorption of the carbon dioxide from the water, which would have been shown by the titrations. In this case, the discrepancy was small and was probably due to lack of a high degree of sensitivity of the Orsat apparatus.

The old sampling system, however, in practically every test obtained samples of gas which, on analysis, showed 5 to 10 per cent more of the absorbable constituent in the exit than in the entering gas. The data on some of these analyses may be found in the Unit Operations Laboratory Reports of Virginia Polytechnic Institute, 1941. Probably the most reasonable explanation for this obvious error is that representative samples of gas for analysis were not obtained from the tower. Non-representative sampling may have due to both the method of packing and to the sampling device. The coke was merely dumped in the tower, but it was found that the smaller pieces were in the central portion of the tower. This tended to cause channeling near the tower walls because of the greater resistance the smaller pieces of packing offered to fluid flow. As seen in Figure II, the old sampling device was a straight piece of copper tubing entering the tower at right angles to the direction of gas flow and obtaining the gas sample from one point in the tower near the wall.

Modified Orsat Apparatus: -- The modified apparatus, although having a volume approximately three times as great and a burette graduation of one-half the size, gave practically the same results as did the standard apparatus.

The carbon dioxide compositions determined by the modified apparatus were, on the average, lower by 0.49 per cent of the total gas volume than were those determined by the standard apparatus on the same experimental run, but the data did not indicate that one was more accurate than was the other.

Analysis of Data: -- The absorption of carbon dioxide by water in the 18-inch stoneware tower, when calculated quantitatively on the basis of the Orsat analyses of the entering and exit flue gases, did not indicate that any relationship existed between the rate of absorption and the rate of flow of the water through the tower. However, when the rate of absorption was calculated on the basis of the titrations of the entering and exit absorbing water, a relationship between the rate of absorption and the rate of liquid flow was indicated (See Graph No. 6). Even though the titrations were performed with weak solutions, in which a sharp end point was unobtainable, the evidence indicated that the Orsat analyses were the real source of error and that the titrations gave more reliable results.

As may be seen from the experimental data, given in Table IV, the carbon dioxide content of the flue gas at a particular point

in the tower, as determined by the Orsat apparatus, often varied 0.2 per cent or more in consecutive readings, at 10-minute intervals. In some experiments, the Orsat apparatus showed a carbon dioxide content in the flue gas entering the tower of 0.4 per cent more than that in the exit gas, while in other experiments the greater concentration was observed in the exit gas. In still other experiments, the gas analysis showed the same carbon dioxide content of the flue gas at both the entrance and exit of the tower. Since the maximum possible absorption of carbon dioxide by the water under the conditions of operation of the tower in these experiments did not account for more than 0.2 per cent decrease (based on total per cent by volume) in the carbon dioxide content of the flue gas passing through the tower, it is obvious that little reliance can be placed on the determination of the absorption rate from the Orsat analyses.

It was found, as shown below, that the difference in carbon dioxide content between the gases entering the tower and the same gases when leaving the tower could be expected to be less than 0.2 per cent of the total gas:

> The equilibrium distribution curve for carbon dioxide, between the phases, carbon dioxide solution and air at 20° C and 720 mm pressure, shows that the maximum concentration of carbon dioxide in the water that could possibly leave the tower was 0.00018 lb. carbon dioxide

TABLE IV

LOG OF EXPERIMENTAL DATA FOR ABSORPTION OF CARBON DIOXIDE BY WATER IN COKE-PACKED 18-INCH STONEWARE ABSORPTION TOWER

Run No	Date	Reading	Time	Water Analysis: Inlet Water cc 0.0058 N HCl to Phenol	Inlet Water cc 0.0058 N HCl to M.O.	Inlet Water cc 0.0021 N NaOH	Exit Water cc 0.0058 N HCl to Phenol	Exit Water cc 0.0058 N HCl to M.O.	Exit Water cc 0.0021 N NaOH	Cooler Water (out) cc 0.0058 N HCl to Phenol	Cooler Water (out) cc 0.0058 N HCl to MO	Cooler Water (out) cc 0.0021 N NaOH	Gas Analysis (% CO_2) Modified Apparatus In	Modified Apparatus Out	Standard Apparatus In	Standard Apparatus Out	Liquid Rate lb/min Tower	Liquid Rate lb/min Cooler	Gas Velocity ft/min	Water Temp. In (°F)	Water Temp. Out (°C)	Gas Temperatures (°F) In Tower Wet Bulb	In Tower Dry Bulb	Out of Tower	On First Tower Section	In Cooler	Barometer mm Hg
1	7-30-42	1	2:35	0	23.4	2.1	0	19.9	15.8	0	17.6	9.0	10.9	10.35	—	—	15	37	290	68	23	105	113	74	74	690	
		2	2:45	0	23.5	2.2	0	20.7	24.1	0	16.3	15.9	11.77	11.77	—	—	17	37.5	285	68	23	105	114	74	72	700	719
		3	2:55	0	19.2	1.9	0	21.6	18.9	0	18.5	19.1	—	—	11.0	11.8	17	36.5	280	68	23	107	115	74	72	700	
		4	3:05	0	—	2.0	0	22.2	13.2	0	18.8	19.2	—	—	11.1	11.1	16	35	280	68	23	108	115	74	72	700	
2	8-8-42	1	10:50	0	16.65	3.65	0	16.70	28.35	0	16.65	28.4	8.10	8.71	—	—	21	48	500	56	21	85	94	62	74	640	
		2	11:00	0	16.70	3.60	0	16.75	27.15	0	16.25	27.15	6.90	6.94	—	—	22	51	496	56	20	86	95	62	75	660	
		3	11:10	0	16.60	3.75	0	16.25	27.20	0	16.30	27.20	—	—	7.0	7.0	22	49	496	57	20	86	95	63	75	672	728
		4	11:20	0	16.80	—	0	16.30	27.50	0	—	27.50	—	—	7.2	7.2	21	48	494	57	20	86	98	63	75	718	
		5	11:30	—	—	—	—	—	—	—	—	—	—	—	—	—	21	48	494	57	20.5	87	100	63	76	730	
3	8-12-42	1	11:00	0	16.5	2.4	0	23.0	24.6	0	18.0	22.7	8.16	8.63	—	—	36.5	43	466	62	24	88	100	67	64	660	
		2	11:10	0	16.6	3.0	0	22.8	24.4	0	18.0	27.0	7.90	8.79	—	—	36	45	466	62	24	88	100	65	64	685	713
		3	11:20	0	17.1	1.9	0	21.7	20.4	0	17.3	24.1	—	—	9.4	9.4	37	44	474	62	24	88	100	65	64	680	
		4	11:30	0	16.9	2.1	0	21.4	26.2	—	—	—	—	—	9.4	9.4	36.5	42	474	62	23	88	100	65	64	690	
4	8-12-42	1	2:20	0	19.9	1.7	0	18.0	27.0	0	19.3	22.1	9.3	8.64	—	—	22.5	38	477	62	19	88	102	68	68	660	
		2	2:30	0	19.7	1.9	0	18.2	25.0	0	19.4	24.1	9.3	9.1	—	—	27.7	38	477	62	19	88	102	68	68	660	713
		3	2:40	0	19.8	1.4	0	18.7	22.7	0	19.9	21.1	—	—	9.9	9.8	28	38	477	62	19	88	103	68	68	670	
		4	2:50	0	18.8	1.8	0	18.7	26.3	0	—	—	—	—	9.8	9.8	29	38	477	62	19	88	103	68	68	675	
5	8-12-42	1	3:30	0	19.7	1.9	0	18.5	26.2	0	17.3	22.0	9.24	10.5	—	—	14	36	488	62	21	90	108	70	72	735	
		2	3:40	0	18.6	1.5	0	18.3	25.2	0	17.7	24.0	9.5	9.5	—	—	12	36	489	62	21	94	110	70	76	735	713
		3	3:50	0	17.7	1.6	0	18.7	25.6	0	17.3	21.9	—	—	10.5	10.5	13	38	489	62	22	93	113	70	75	735	
		4	4:00	0	17.5	1.4	0	18.2	26.4	0	—	—	—	—	10.6	10.5	13	40	489	62	83	93	114	70	76	740	
6	9-1-42	1	3:00	0	18.0	1.0	0	18.3	7.60	0	18.1	5.40	—	—	6.8	7.0	30½	51	539	61	18	82	89	63	63	538.5	
		2	3:10	0	18.2	1.0	0	18.3	7.95	0	17.8	7.2	—	—	6.3	6.7	29	57	534	60	18	81	87	62	61	534	
		3	3:20	0	18.4	1.1	0	17.55	9.12	—	—	—	—	—	6.4	6.4	29¼	57	551	60	17.5	81	87	64	61	551	
		4	3:30	0	17.9	1.1	0	17.6	8.60	0	18.2	7.1	—	—	6.2	6.4	29¼	57	550	60	17.5	81	87	64	61	550	717
		5	3:40	—	—	—	0	17.8	7.8	—	—	—	—	—	6.3	6.4	30	57	546	60	17.5	81	87	64	62	546	
		6	3:50	—	—	—	0	17.9	8.9	—	—	—	—	—	6.9	6.7	29	60	547	60	17.5	82	89	64	62	547	
		7	4:00	—	—	—	0	18.0	8.6	0	18.4	6.3	—	—	—	—	29¼	58	548	60	17.5	82	89	64	62	548	
7	9-1-42	1	4:35	0	17.6	2.7	0	17.60	16.7	0	18.9	6.7	—	—	6.9	6.7	5¾	57	548	60	23	83	91	64.5	68	610	
		2	4:45	0	17.88	2.4	0	17.88	17.5	0	19.1	5.9	—	—	6.5	6.8	5¾	59	548.5	60	21	84	91	65.0	68	610	
		3	4:55	0	18.1	2.5	0	17.5	17.1	—	—	—	—	—	6.5	6.6	5¾	59	547	60	21	84	91	65.5	68	610	717
		4	5:05	—	—	—	0	19.1	17.8	—	—	—	—	—	6.8	6.8	5½	58	546	60	21	83	92	65.0	68	610	
		5	5:15	—	—	—	0	19.6	18.0	0	19.3	4.9	—	—	6.7	6.7	5¾	59	548	60	20	84	92	65.0	69	610	
8	9-2-42	1	2:15	0	19.9	1.2	0	21.0	13.0	0	22.0	10.6	—	—	10.2	10.2	15½	60	526	63	25	83	88	69	72	550	
		2	2:30	0	20.2	1.5	0	23.5	9.7	0	17.9	16.8	9.5	9.97	—	—	15½	60	523	63	23	83	90	67	70	580	
		3	2:45	0	18.9	1.6	0	23.2	14.7	0	18.15	16.35	—	—	9.2	9.6	15½	—	523	63	21	82	90	66	68	595	717
		4	3:00	—	—	—	0	19.8	14.4	—	—	—	8.87	8.90	—	—	15	59	520	63	21	83	90	66	68	605	
		5	3:15	—	—	—	0	19.1	19.5	—	—	—	—	—	9.4	8.6	15½	—	518	61	21	82	90	66	67	610	
		6	3:30	—	—	—	0	20.2	16.6	0	19.3	17.1	8.11	7.16	—	—	15½	58	536	61	20	82	90	66	66	605	
9	9-3-42	1	9:45	0	17.5	3.05	0	17.95	56.55	0	17.10	24.6	—	—	7.0	7.0	25	63	486	64	18	78	84	65	62	510	
		2	10:00	0	18.0	3.10	0	18.2	22.5	—	—	—	—	—	8.2	8.2	24¾	54	502	65	18	80	84	64	62	540	
		3	10:15	0	17.3	3.09	0	18.8	22.3	0	18.0	27.2	—	—	8.0	8.8	24	57	503	61	18	80	85	63	62	540	
		4	10:30	—	—	—	0	19.0	23.5	0	17.6	21.8	—	—	8.4	8.0	24	63	504	62	18	80	86	63	62	545	715
		5	10:45	—	—	—	0	19.2	23.0	0	18.3	22.2	—	—	8.4	8.2	25	57	504	62	18	80	85	64	62	555	
		6	11:00	—	—	—	0	19.5	24.2	—	—	—	—	—	8.4	8.4	24	60	504	62	18	81	86	63	62	565	
		7	11:15	—	—	—	0	19.3	26.14	—	—	—	—	—	8.2	8.2	24	57	503	62	18	81	87.5	63	62	570	
		8	11:30	—	—	—	0	19.8	25.5	—	—	—	—	—	8.0	8.0	24	63	506	62	18	81	88	63	62	570	
10	9-3-42	1	2:15	0	17.6	3.21	0	18.8	17.7	0	19.4	25.9	—	—	8.6	10.2	10½	60	506	61	21	81	85	71	69	570	
		2	2:30	0	18.7	3.1	0	19.4	16.9	0	18.7	22.0	—	—	10.4	10.2	10	68	501	63	22	81	90	69	69	580	
		3	2:45	0	19.1	3.3	0	19.3	17.2	0	19.8	23.8	—	—	9.9	9.7	10	68	495	63	22	81	90	68	70	590	
		4	3:00	—	—	—	0	18.4	17.35	—	—	—	—	—	9.8	9.8	10	64	493.5	63	22	81	90	68	70	599	715
		5	3:15	—	—	—	0	18.15	18.1	—	—	—	—	—	9.9	9.8	10	65	501	63	22	81	90	68	70	605	
		6	3:30	—	—	—	0	17.20	10.12	—	—	—	—	—	9.3	9.6	9½	64	495.5	63	22	81.3	90	67	70	610	
		7	3:45	—	—	—	0	16.80	6.9	—	—	—	—	—	9.3	9.4	10	64	501	63	22	81.5	90	68	70	611	
		8	4:00	—	—	—	0	16.90	9.8	—	—	—	—	—	9.3	9.4	10	61	499	63	22	81.5	90	67	71	620	

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per lb. water, if the solution were in equilibrium with air containing not more than 0.2 lb. carbon dioxide per lb. of air. Since no concentration of carbon dioxide in air greater than 0.2 lb. carbon dioxide per lb. of air was used in any of the experiments performed and since no liquid rates greater than 37 lb. per minute were used, the carbon dioxide could not have been absorbed at a greater rate than 0.0067 lb. per minute in any of the experiments performed. When the rate of carbon dioxide absorption was calculated from the Orsat analyses, it was found that, on the average, an exit gas containing 0.2 per cent less of carbon dioxide than the entering gas, more than accounted for this maximum amount of carbon dioxide that the water could have taken from the gas. This is too low a percentage of absorption to be measured with an Orsat apparatus, particularly when the figure is obtained from the difference between the Orsat readings. The differences may not have as high a degree of accuracy as does either of the two readings subtracted.

In some of the experiments, negative amounts of absorption were shown by the Orsat analyses. This negative absorption did not actually take place because the operating lines show, by their location above the equilibrium distribution curve, that the partial

pressures in the gas phase, in all the experiments, were at all times greater than the equilibrium partial pressures. This indicates that the limits of accuracy of the Orsat apparatus are too limited to permit the measurement of the amount of carbon dioxide absorbed by the water in this particular tower and under these particular conditions of operation.

Calculation of k_1a: -- The calculation of the liquid film coefficient, k_1a, from the experimental data was performed by graphically evaluating the integral,

$$\int_{x_2}^{x_1} \frac{dx}{x_i - x}$$

and substituting the value obtained in the rate equation,

$$\int_{x_2}^{x_1} \frac{dx}{x_i - x} = \frac{(k_1a)(\rho_{av})(V_1)}{L}$$

The values of x are selected from the operating line (Graph No. 3) and the corresponding values of x_i are the x-coordinates of the points on the equilibrium distribution curve, drawn on the same graph, which have the same ordinates or same values of y (lb. CO_2/lb. dry air) as do the particular values of x selected.

The slope of the equilibrium line is so great that the same value of x_i was used for all points on the operating line. Thus, the

changes in the values of y in the tower, as determined from the Orsat analyses and as shown by the slopes of the operating lines, had little effect on the values of the integrals and consequently little effect on the calculated values of the liquid film coefficient, k_1a. However, the overall value of y, which determines both the distance the operating line lies above the x-axis and location of the operating line relative to the equilibrium distribution curve, has a much greater effect on the value of x_i.

The overall values of y were calculated from Orsat analyses of flue gases containing from 6 to 11 per cent carbon dioxide and for this reason should be relatively much more accurate than are the amounts of absorption calculated from differences in y corresponding to differences in Orsat analyses of approximately 0.2 per cent of the total volume of the gas analyzed.

Therefore, the inability to measure accurately, by means of the Orsat apparatus, the decrease in carbon dioxide content of the flue gases passing through the tower should have small effect on the accuracy of the calculated values of k_1a.

Derivation of Equation Relating k_1a to L: -- Empirical equations showing the relationship of k_1a to L, the water rate of flow, for the absorption or desorption of carbon dioxide by water in various types of towers and using various packings have been developed and are discussed by Sherwood[40]. The equations are of the form,

$$K_1a = a' (L)^n$$

where a' and n are constants. If a relation of this type exists in the case under consideration, and assuming k_1a to be equal to K_1a, since the liquid film is the controlling resistance, then a plot of k_1a versus L on logarithmic coordinates should give a straight line. Such a plot was made and, although the data was rather scattered, a definite trend in the same direction as that of the data given in the literature was obtained.

Assuming that the data could be represented by a straight line and omitting the point calculated from operating line No. 6, an equation relating k_1a to L was derived. This point was omitted because the titration data from which it was calculated differed so markedly from that of the other nine experiments as to indicate a mistake had been made. The constants were determined by the method of averages and the equation found to be,

$$k_1a = 0.0000153\ (L)^{1.64}$$

Sherwood gives the equation,

$$K_1a = 0.016\ (L)^{0.92}$$

for the desorption of carbon dioxide from water to air in a 10-inch tower, dumped-packed with 1-inch Raschig rings. According to the same author, this equation should apply to absorption also.

Sherwood[42] also says that preliminary data indicate the k_1 for a water-solute system does not vary appreciably with the

solute. If this is true, k_1a for other solutes in water may be taken directly from the data on carbon dioxide absorption or calculated from the above equation.

Relation of k_1a to Other Variables: -- No relationship between the absorption coefficients and any of the other operating variables, i.e., gas flow rate, gas temperature, water temperature, and concentrations of the carbon dioxide in the water and gas respectively, were observed. However, according to Sherwood[36], the temperature of the absorbing liquid has great effect on the value of the liquid film coefficient, k_1a. The temperatures of the absorbing water in these experiments varied from approximately 14 to 21° C., but no relationship was found between the temperatures and coefficients. However, the scattering of the points on the logarithmic plot of k_1a versus L may be partly explained by these temperature variations.

Recommendations: -- It is recommended that the Bureau of Mines modification of the Orsat apparatus, using a compensating tube and manometer for temperature and pressure corrections and mercury as the confining liquid, be used if this work is to be continued or enlarged upon.

Limitations: -- This study was limited to experimental data on the absorption of carbon dioxide from flue gas by hard water in an 18-inch stoneware tower packed with 3-inch coke. The carbon dioxide content of the flue gas used varied only from 6 to 11 per cent by volume. Also, an attempt was made to eliminate the effects

of temperature by keeping the gas and water temperatures within a small range of variation, 15 to 25° C. Practically all of the temperatures taken within the tower were in this range, but the flue gas usually had temperatures 4 to 20° C. above this range, immediately before entering the first section of the tower.

V. CONCLUSIONS

As a result of the modifications made in the design and of the experiments performed with carbon dioxide and water in the 18-inch, coke-packed, stoneware absorption tower in the Unit Operations Laboratory of Virginia Polytechnic Institute, it is concluded that:

1. The maximum absorption of carbon dioxide by water, possible under the conditions of operation used in these experiments, was less than 0.2 per cent of the volume of the flue gas passing through the tower. The conditions of operation used in the experiments were as follows:

   a. Water flow rate through tower - (5-37) lb./min.

   b. Gas flow rate through tower - (24-45) cu.ft./min.

   c. Tower water temperature - (14-23) ° C.

   d. Tower gas temperature - (17-46) ° C.

   e. Carbon dioxide content of flue gas - (6-11) per cent carbon dioxide.

2. The definite increase of the absorption coefficient, k_1a, with the liquid rate of flow, L, as shown by the equation,

$$k_1a = 0.0000153\ (L)^{1.64}$$

indicates that channeling of the liquid in the tower has been materially reduced by the new plates.

3. The relationship between the experimentally determined values of the absorption coefficient, k_1a, and the liquid flow rate, L, for the absorption of carbon dioxide by water in the tower, may be expressed as

$$k_1a = 0.0000153\ (L)^{1.64}$$

L = lb./(hr.)(sq.ft. tower cross section), varied from 191 to 1240.

k_1a = lb./(hr.)(cu.ft.)(lb./cu.ft.)

4. The new sampling device obtains more representative samples of gas than did the old system. The new sampling device obtained gas samples which, when analyzed, showed the same carbon dioxide content for both inlet and exit gas, with a maximum variation of 0.4 per cent on the total gas basis. The old sampling device often showed 5 to 10 per cent more absorbable component in the exit gas than in the entering gas.

5. The modified Orsat apparatus, having a burette capacity of 314.4 ml and burette graduations of 1/10 ml, on the average, gave a lower reading of total carbon dioxide content in the flue gas of 0.49 per cent than did the standard apparatus, but the accuracy of the analysis was not improved.

VI. SUMMARY

Certain modifications in the design of an 18-inch stoneware absorption tower, packed with 3-inch coke and located in the Unit Operations Laboratory of Virginia Polytechnic Institute, were made and experiments to determine the operating characteristics of the tower in the absorption of carbon dioxide by water were performed, after the changes in design were made.

A distribution plate to reduce channeling, a sampling system to insure the obtaining of representative samples, and a modified Orsat apparatus to permit greater accuracy of gas analyses, were designed. Channeling appeared to be somewhat reduced by the new plate and the data showed that the new sampling system obtained more representative gas samples for analysis. The modified Orsat apparatus did not appear to give more accurate gas analyses.

The liquid film coefficient was calculated from data on nine experimental runs at water flow rates varying from approximately 5 to 36 pounds per minute. Temperatures of gas and water, gas flow rate, and carbon dioxide content of the flue gas were held to as limited a range of variation as possible and the data used in the calculations were taken after the tower was operating under conditions of equilibrium, as shown by the constancy of the readings.

The equation,

$$k_1a = 0.0000153\ (L)^{1.64}$$

where

k_1a = liquid film absorption coefficient (lb./(hr.)(cu.ft.)(lb./cu.ft.)

L = liquid flow rate (lb./(hr.)(sq.ft. tower cross section).

was derived from the experimental data. It was assumed that the relation was a power equation of the form set forth in the literature by Sherwood.

No relationship between the absorption coefficients and either the gas rate of flow, temperature of the gas, temperature of the water or carbon dioxide content of the flue gas was observed.

VII. BIBLIOGRAPHY

1. Badger, W.L. and McCabe, W.L. ''Elements of Chemical Engineering''. p. 376-409. McGraw-Hill Book Company, Inc., New York. 1936. 2nd ed.

2. Ibid. p. 243-249.

3. Baker, E.M. Absorption and Adsorption. Chem. and Met. Eng. 35, 578 (1928) (Chem. Trade J., 73, 577-578 (1923)). Original not seen.

4. Baker, T., Chilton, T.H. and Vernon, H.C. The Course of Liquor Flow in Packed Towers. Trans. Am. Inst. Chem. Engrs., 31, 296 (1935).

5. Bennetch, L.M. and Simmons, C.W. Tower Absorption Coefficients. Ind. Eng. Chem., 24, 301 (1932).

6. Cantelo, R.C., Simmons, C.W., Giles, E.M. and Brill, F.A. Tower Absorption Coefficients. Ind. Eng. Chem., 19, 989-992 (1927).

7. Chilton, T.H. and Colburn, A.P. Pressure Drop in Packed Tubes. Trans. Am. Inst. Chem. Engrs., 26, 178 (1931). (Ind. Eng. Chem., 23, 913 (1931)).

8. Chilton, T.H. and Colburn, A.P. Mass Transfer (Absorption) Coefficients. Ind. Eng. Chem., 26, 1183 (1934).

9. Colburn, A.P. A Method of Correlating Forced Convection Heat Transfer Data and a Comparison with Fluid Friction. Trans. Am. Inst. Chem. Engrs., 29, 174 (1932).

10. Colburn, A.P. Relation Between Mass Transfer (Absorption) and Fluid Friction, Ind. Eng. Chem., 22, 967 (1932).

11. Comstock, C.S. and Dodge, B.F. Rate of Carbon Dioxide Absorption by Carbonate Solutions in a Packed Tower. Ind. Eng. Chem., 29, 520 (1937).

12. Deutsch, Z. G. Packed and Spray Type Contactors. Chem. and Met. Eng., 46, 318 (1939).

13. Drane, H.D.H. The Design and Operation of Gas Scrubbing Towers. J. Soc. Chem. Ind., 43, 329 T (1924).

14. Elgin, J.C. and Weiss, F.B. Liquid Holdup and Flooding in Packed Towers. Ind. Eng. Chem., 31, 435 (1939).

15. Gilliland, E.R. and Sherwood, T.K. Diffusion of Vapors into Air Streams. Ind. Eng. Chem., 26, 516 (1934).

16. Greenewalt, C.H. Absorption of Water Vapor by Sulfuric Acid Solutions. Ind. Eng. Chem., 18, 1291 (1926).

17. Hanks, W.V. and McAdams, W.H. Studies in Absorption. Ind. Eng. Chem., 21, 1034 (1929).

18. Haslam, R.T., Hershey, R.L. and Keen, R.H. Effect of Gas Velocity and Temperature on Rate of Absorption. Ind. Eng. Chem., 16, 1225 (1924).

19. Hurter, F. The Comparative Efficiency of Various Modes of Treating Liquids With Gases. J. Soc. Chem. Ind., 4, 639 (1885).

20. Hutchinson, M.H. and Sherwood, T.K. Liquid Film in Gas Absorption. Ind. Eng. Chem., 29, 836 (1937).

21. Kowalke, O.L., Hougen, O.A. and Watson, K.M. Absorption of Ammonia in Towers. Chem. and Met. Eng., 32, 443-446, 506-510 (1925).

22. McCormack, H. ''The Applications of Chemical Engineering''. p. 302-347. D. Van Nostrand Book Company, New York. 1940.

23. Ibid. Page 309.

24. Ibid. Page 308.

25. Ibid. Page 307.

26. Mayo, F., Hunter, T.G. and Nash, A.W. Wetted Surface in Ring -Packed Towers. J. Soc. Chem. Ind., 54, 375T (1935).

27. Monaweck, J.H. and Baker, E.M. A Study of the Mechanism of Film Formation in Gas Absorption. Trans. Am. Inst. Chem. Engrs., 22, 171 (1929).

28. Perry, H.H. ''Chemical Engineers' Handbook''. p. 1169. McGraw-Hill Book Company, New York. 1941. 2nd ed.

29. Ibid. Page 1147.

30. Ibid, Page 1156.

31. Ibid. Page 1152.

32. Ibid. Pages 1170-1171.

33. Ibid. Page 1157.

34. Ibid. Page 1198.

35. Sherwood, T.K. ''Absorption and Extraction''. p. 28. McGraw-Hill Book Company, New York. 1937. 1st ed.

36. Ibid. Page 183.

37. Ibid. Page 135.

38. Ibid. Page 134.

39. Ibid. Page 167.

40. Ibid. Page 181.

41. Ibid. Page 40.

42. Ibid. Page 189.

43. Ibid. Page 138.

44. Ibid. Page 16.

45. Ibid. Page 146.

46. Sherwood, T.K. and Holloway, F.A.L. Performance of Packed Towers. Trans. Am. Inst. Chem. Engr., 36, 39 (1940).

47. Sherwood, T.K. and Kilgore, A.J. Absorption and Desorption of Ammonia in a Coke-Packed Column. Ind. Eng. Chem., 18, 744 (1926).

48. Van Arsdel, W.B. An Extension of the Theory of Gas-Absorption Towers. Trans. Am. Inst. Chem. Engrs., 14, 391 (1921-22).

49. Walker, W.H., Lewis, W.K., McAdams, W.H. and Gilliland, E.R. "Principles of Chemical Engineering". p. 489-490. McGraw-Hill Book Company, New York. 1937. 3rd ed.

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