# THE DETERMINATION OF THE OPERATING CHARACTERISTICS OF AN 18"-INCH STONEWARE COKE-PACKED GAS ABSORPTION TOWER

by

Billy J. ackson Young III

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Approved:

In Charge of Investigation

Head of Major Department

Dean of Engineering Division

Director of Graduate Studies

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# I. INTRODUCTION

Gas absorption is that unit operation or unit process in which one or more constituents are removed from a gaseous mixture by absorption in a liquid. Since the problem of gas absorption involves the transfer of a soluble gas from the gas phase to the liquid phase, the process is one of diffusion, and whether the purpose be to recover the absorbed constituent or to purify the remaining gas, the largest possible surface of contact or interfacial area must be provided for the interaction between the two phases.

The process of absorption finds wide application in industry today, most processes being carried out as continuous processes in towers in which the gas is passed upward countercurrent to the flow of liquid. Yet, because of the complex nature of the mechanism by which the process of absorption is thought to occur, wide variations exist in the interpretation and application of experimental and plant data. Consequently, there has been a persistent tendency to treat gas absorption as an art rather than as a science.

Although the basic principles of gas absorption were postulated in 1885, the "two-film theory" of diffusion upon which present theoretical concepts are based was not advanced until 1925. Much recent experimental work has been done in attempting to correlate the effect of such variables as gas composition, temperature and pressure of the system, the overall pressure drop through the tower, and the apparent mass velocity of the gas and liquid phases through the tower. However, the major portion of this work has been performed on relatively small size equipment and the resulting data cannot be accurately applied to design calculations for industrial equipment.

The purpose of this investigation is to correlate, by means of empirical equations, the operating characteristics of an absorption system in which carbon dioxide is passed upward in countercurrent flow to the downward flow of water. The absorption will be performed in a 18" stoneware tower 21 feet in height, 15 feet of which are random packed with 1 1/2 to 2 inch coke.

# II. LITERATURE REVIEW

## Theory of Diffusion

Gases. Since the process of gas absorption involves the transfer of a soluble gas from the gas phase to the liquid phase, the process may be designated as a diffusional process. According to the kinetic theory, a gas consists of a large number of individual molecules in rapid motion. Since the molecules move at random, if two gases are placed in the same container, diffusion will result spontaneously. In absorption practice it is frequently necessary to deal with a mixture of two or more gases, both or all of which are more or less soluble in the solvent. Sherwood(49) develops the following equation for the steady-state diffusion of both components of a binary mixture

$$\ln \frac{1-\left(1+\frac{N_B}{N_A}\right)\frac{p_{A_2}}{P}}{1-\left(1+\frac{N_B}{N_A}\right)\frac{p_{A_1}}{P}} = \frac{x}{k}(N_A + N_B) \qquad (1)$$

where

$N_A$ = rate of diffusion of gas "A", gm.mols./(sec.)(sq.cm.)

$N_B$ = rate of diffusion of gas "B", gm.mols./(sec.)(sq.cm.)

$P$ = total pressure, atm.

$p_{A_2}$ = partial pressure of the gas "A" after diffusion, atm.

$p_{A_1}$= partial pressure of the gas "A" before diffusion, atm.

$x$ = distance in the direction of diffusion, cm.

$k$ = $\frac{DP}{RT}$ where $D$= diffusion coefficient, cm.$^2$/sec.

$P$= total pressure, atm.

$R$= gas-law constant, (cc.)(atm.)

$T$= absolute temperature, $^{\circ}$K.

However, before the above equation can be solved it is first necessary to define and evaluate the diffusion coefficient. Sherwood$^{(50)}$ derives the following empirical equation

$$D_G = 0.0043 \frac{T^{3/2}}{P(V_A^{1/3} + V_B^{1/3})^2} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}} \qquad (2)$$

where

$D_G$ = diffusion coefficient, cm.$^2$/sec.

$T$ = absolute temperature, $^{\circ}$K.

$M_A, M_B$= molecular weights of components "A" and "B" respectively

$P$ = total pressure, atm.

$V_A, V_B$= molecular volumes

The above equation should be used in estimating values of "D" only in cases where no good experimental data exists. Several methods have been developed for the experimental determination of gaseous diffusion coefficients$^{(51)}$.

Liquids. Because of the greater density of the liquid phase, the resistance to diffusion is much greater; therefore, diffusion takes place more slowly. The mechanism of molecular diffusion is similar in both liquids and gases; however, in a liquid, because of the closer spacing of the molecules, molecular attraction must be considered. Consequentially, the kinetic theory of liquids has not been fully developed with the result that no theoretical equations for liquid diffusion coefficients have been derived.

If the value of the diffusion coefficient is known from experimental data, then by analogy with gaseous systems, the following relation for the steady-state diffusion of a solute through a stagnant solvent may be developed(51)

$$N_A = \frac{D_L}{x}(C_A + C_B)\ln\frac{C_{B_2}}{C_{B_1}} \qquad (3)$$

where

$N_A$ = rate of diffusion of solvent, gm.mols/(sec.)(sq.cm.)
$D_L$ = diffusion coefficient, cm.$^2$/sec.
$x$ = distance in the direction of diffusion, cm.
$C_A$ = partial molal density of the solute, gm.mols/cc.
$C_B$ = partial molal density of the solvent, gm.mols/cc.
$C_{B_2}$ = partial molal density of the solvent after diffusion, gm.mols/cc.
$C_{B_1}$ = partial molal density of the solvent before diffusion, gm.mols/cc.

The following empirical equation for the determination of liquid diffusivity has been developed(76)

$$D_L = \frac{B\left(\frac{1}{M_A} + \frac{1}{M_C}\right)^{1/2}}{A_A A_C V_C^{1/2}\left[(V'_A)^{1/3} + (V'_C)^{1/3}\right]^2} \qquad (4)$$

where

$D_L$ = liquid diffusivity, ft.$^2$/hr.

$M_A, M_C$ = molecular weight of the solute "A" and the solvent liquid "C" respectively

$V'_A, V'_C$ = molecular volumes of the components "A" and "C" respectively

$A_A, A_C, B$ = constants

$V_C$ = viscosity of the solvent

## Theory of Gas Absorption

Three General Cases of Gas Absorption. The problem of gas absorption in which the concentrations of gas and liquid are in equilibrium with each other and are under definite conditions may be divided into three general cases, which are(43):

1. A chemical reaction occurs between the gas and the liquid, and the gas exerts no appreciable vapor pressure after absorption.
2. A chemical reaction occurs between the gas and the liquid with the formation of an unstable compound, and the gas exerts an appreciable vapor pressure.
3. No chemical reaction occurs, and a vapor pressure proportional to the amount of gas absorbed is exerted.

Solubility of Gases. A solution of a gas in a liquid exerts, at a definite temperature and concentration, a definite partial pressure of the dissolved gas. Different gases will exhibit very great differences in the partial pressures that their solution exerts at equilibrium. The solubility of a gas in a liquid has a limited and definite value dependent upon the nature of the gas and the liquid, and also upon the temperature and pressure. Two coefficients have been employed to express the results of solubility measurements(28);

1. Absorption Coefficient. This coefficient is defined as the volume of gas, reduced to 0°C. and 1 atm., dissolved by unit volume of solvent at the temperature of the experiment under a partial pressure of the gas of 1 atm. Mathematically

$$a = \frac{v_o}{Vp} \qquad (5)$$

where

$a$ = absorption coefficient

$v_o$ = volume of gas dissolved, reduced to S.T.P.

$V$ = volume of solvent

$p$ = partial pressure of the gas, atm.

2. Coefficient of Solubility. This coefficient is defined as the volume of gas, measured under the temperature and pressure at which the gas dissolves, taken up by unit volume of the liquid. Mathematically

$$b = \frac{v}{V} \qquad (6)$$

where

$b$ = coefficient of solubility

$v$ = actual volume of gas dissolved

$V$ = volume of solvent

The effects of temperature and pressure on the solubility of gases in liquids may be summarized as follows:

1. Temperature. Glasstone(28) states that when gases dissolve in water, there is generally a liberation

of heat; it follows, therefore, from the Le Chatelier principle that increases of temperature will result in a decrease of solubility. The relation between absorption coefficients for different temperatures, at constant pressure, may be expressed as

$$\ln \frac{a_2}{a_1} = - \frac{\Delta H}{R} \left( \frac{1}{T_2} - \frac{1}{T_1} \right) \qquad (7)$$

where

$a_1$ = absorption coefficient at temperature $T_1$

$a_2$ = absorption coefficient at temperature $T_2$

$\Delta H$ = differential heat of solution of 1 mole of the gas in a saturated solution (assumed to be independent of temperature)

$R$ = gas-law constant

$T_1$ = original temperature, °K.

$T_2$ = final temperature, °K.

2. Pressure. The most important factor influencing the solubility of a gas is pressure(28). Compression of the gas will tend to increase its solubility. The quantitative relation between solubility and pressure is given by Henry's law, which states that the mass of gas dissolved by a given volume of solvent, at constant temperature, is proportional to the pressure of the gas with which it is in equilibrium. Mathematically

$$p = Hc \tag{8}$$

where

$p$ = partial pressure of the dissolved gas

$H$ = Henry's law constant

$c$ = concentration of the dissolved gas

In general, if a gas absorption process is allowed to reach equilibrium, this will be the point at which the partial pressure of the solute in the gas phase is equal to its partial pressure exerted by the liquid phase(5).

<u>Film Theory</u>. When two separate phases, such as a gas and a liquid, are brought into contact, they tend to approach a state of equilibrium. At equilibrium, the temperature of the two phases will be the same; but the concentration of the gas in solution in the liquid will be less than in the gas phase, and the liquid concentration in the gas phase will be less than in the liquid phase. Sherwood(52) shows that there is a sharp concentration drop across the interface between two phases in contact and in equilibrium. The most successful theory advanced to explain this sharp concentration drop across the interface is the "two-film theory"(74). This theory contends that on the gas phase side of the interface there is a stagnant gas film; on the liquid side of the interface there is a stagnant liquid film. These two films are the principal resistances encountered by a gas diffusing from the gas phase into the liquid phase. Monaweck and Baker(40), in experiment with ammonia and water, obtained data that corroborated

the two-film theory. Although it has been shown that the total resistance encountered by the transfer of material between phases is not wholly offered by a layer of absolute stationary fluid at the interphase boundary, the film concept has been of inestimable service in indicating the physical mechanism of gas absorption(53). Thus, when a mixture of a soluble gas "A" and insoluble gas "B" is brought into contact with a solvent liquid "C", the soluble gas must diffuse in series through a film of the inert gas and a film of the liquid before it can dissolve in the main body of liquid. Therefore, the rate of absorption, after conditions have become constant, is equal to the rate of diffusion through either film. For the gas film(75)

$$N_A = \frac{D_G PA(p_{AG} - p_{Ai})}{RTB_G \; p_{BM}} \qquad (9)$$

where

$N_A$ = rate of diffusion, lb. mols/hr.

$D_G$ = diffusivity of component "A" through the gas film, ft.$^2$/hr.

$P$ = total pressure, atm.

$A$ = interfacial, or absorbing, area, ft.$^2$

$p_{AG}$ = partial pressure of component "A" in the gas phase, atm.

$p_{Ai}$ = partial pressure of component "A" at the gas liquid interface, atm.

$R$ = gas constant, ft.$^3$ atm./(lb.mol)(°R.)

$T$ = absolute temperature, °R.

$B_G$ = equivalent thickness of the gas film, ft.

$p_{BM}$ = log-mean partial pressure of inert component "B" in the gas film, atm.

For the liquid film

$$N_A = \frac{D_L(C_{AL} + C_{CL})(A)(C_{Ai} - C_{AL})}{B_L C_{CM}} \tag{10}$$

where

$D_L$ = diffusivity of component "A" through the liquid film, ft.$^2$/hr.

$C_{AL}$ = concentration of component "A" in the liquid phase, lb.mols/ft.$^3$

$C_{CL}$ = concentration of the solvent "C" in the liquid phase, lb.mols/ft.$^3$

$C_{Ai}$ = concentration of component "A" at the gas-liquid interface, lb.mols/ft.$^3$

$B_L$ = equivalent thickness of the liquid film, ft.

$C_{CM}$ = log-mean concentration of the solvent "C" in the liquid film, lb.mols/ft.$^3$

In the absence of experimental data the values of gas and liquid diffusivities may be estimated from Equations (2) and (4) respectively.

Film Coefficients. The two-film theory permits the use of individual film coefficients in expressing the rate of material transfer(44). Since the stagnant films at the interface are so thin that the amount of solute contained in them at any time is negligible compared to the amount of solute passing through them and all the material passing through one film must also pass through the other, it follows that at any instant the rate of material transfer through one film is the same as the rate through the other, and the two-films constitute two resistances in series. Therefore, it has been shown that(6)

$$\frac{W}{A} = \frac{b_W(p_{ag} - p_{ai})}{(p_b)_m B_g} = \frac{b_{LW}(c_{ai} - c_{aL})}{B_L} \qquad (11)$$

where

$W$ = weight of component "a" transfered per hour, lbs.

$A$ = area measured perpendicular to direction of diffusion of component "a", ft.

$b_W$ = coefficient of diffusion through gas film

$p_{ag}$ = partial pressure of component "a" at one boundary of the gas film, atm.

$p_{ai}$ = partial pressure of component "a" at the other gas film boundary, atm.

$(p_b)_m$ = average partial pressure of component "b" in the gas film, atm.

$B_g$ = thickness of gas film, ft.

$b_{LW}$ = coefficient of diffusion through liquid film

$c_{ai}$ = concentration of diffusing component at one boundary of the liquid film, lbs./ft.$^3$

$B_L$ = thickness of the liquid film, ft.

Data for equivalent film thicknesses are practically nonexistent for the actual conditions under which absorption is carried out. This is due to the fact that film thicknesses depend, in large part, upon the mass velocities of the fluids and the direction of flow. The flow of fluids in an absorption column is extremely complex; therefore, it is convenient to define a gas film coefficient and a liquid film coefficient.

The gas film coefficient may be defined by the equation(7)

$$k_g = \frac{b_W}{(p_b)_m \, B_g} \qquad (12)$$

where

$k_g$ = gas film coefficient

$b_W$ = coefficient of diffusion

$(p_b)_m$ = average partial pressure of component "b" in the gas film, atm.

$B_g$ = thickness of the gas film, ft.

Similarly, the liquid film coefficient may be defined by the equation

$$k_L = \frac{b_{LW}}{B_L} \tag{13}$$

where

$k_L$ = liquid film coefficient

$b_{LW}$ = coefficient of diffusion through the liquid film

$B_L$ = thickness of the liquid film, ft.

Then Equation (10) may be written

$$\frac{W}{A} = k_g(p_{ag}-p_{ai}) = k_L(c_{ai}-c_{aL}) \tag{14}$$

The film coefficients defined above are based upon the assumption that for a given absorption system the effective film thickness is constant.

Gas Film Controlling. If the gas to be absorbed is very soluble, the liquid film resistance is small, and the gas film will be the controlling resistance. Badger and McCabe(8) state: "Physically, this means that the solute gas, when it once gets through the gas film, is sucked in so avidly by the liquid that the liquid film resistance is of negligible importance". Therefore, the rate of absorption depends only upon the gas film coefficient, and Equation (14) may be written

$$\frac{W}{A} = k_g(p_{ag}-p_{ai}) \tag{15}$$

Liquid Film Controlling. If the gas to be absorbed is relatively insoluble, the liquid film will be the controlling resistance. Badger and McCabe(8) state: "Physically this case is the result of the fact that the tendency for the solute gas to move into the liquid is so low, because of its low solubility, that it is this process that is of controlling effect". Therefore, Equation (14) may be written

$$\frac{W}{A} = k_L(c_{ai}-c_{aL}) \tag{16}$$

Overall Coefficients. Since the driving force through the liquid dilm is a concentration difference, and that through the gas film is a partial pressure difference, two overall coefficients can be calculated. These coefficients may be defined by the equations(9)

$$K_g = \frac{W}{A(p_{ag}-p_{aL})} \tag{17}$$

$$K_L = \frac{W}{A(c_{ag}-c_{aL})} \tag{18}$$

where

$K_g$ = overall gas film coefficient

$K_L$ = overall liquid film coefficient

$p_{aL}$ = the equlibrium partial pressure corresponding to the concentration $c_{aL}$

$c_{ag}$ = the equilibrium concentration corresponding to the partial pressure $p_{ag}$

If, for a given system, Henry's law holds, the following equation may be derived from Equations (8), (14), and (17)

$$K_g = \frac{1}{\frac{H}{k_L} + \frac{1}{k_g}} \tag{19}$$

Similarly from equation, (8), (14), and (18)

$$K_L = \frac{1}{\frac{1}{k_L} + \frac{1}{Hk_g}} \tag{20}$$

Also, the following relation may be derived

$$K_L = HK_g \tag{21}$$

In the special case in which the gas film controls

$K_g = k_g$

Conversely, if the liquid film controls, then

$K_L = k_L$

Scheibel$^{(48)}$ states, "Based on the assumption that the gas film coefficient is dependent solely upon the gas rate and the liquid film coefficient is dependent solely upon the liquid rate, the overall transfer coefficient for a given system should correlate to the general formula

$$K_g = \frac{1}{d_g^{-0.8} + a_L^{B}} \tag{22}$$

where

$d, B =$ constants to be evaluated

$a_L$ = effective interfacial area, ft.$^2$/ft.$^3$".

Operating data may be expressed in terms of overall coefficients, even though both gas and liquid film resistances are involved, provided the equilibrium curve is straight over the range of concentrations encountered(56).

Volumetric Coefficients. Zimmerman and Lavine(78) state: "When absorption takes place in packed towers, it is difficult, and frequently impossible, to estimate the effective absorbing area. In such cases, a knowledge of coefficients based on area is of little help. Therefore, it is common practice to express absorption coefficients in terms of volume rather than area. This is done by replacing the area term "A" in the rate equations by the equivalent term "aV", where "a" is the effective area per cubic foot of tower volume".

Under this system Equation (14) becomes

$$W = k_g aV(p_{ag}-p_{ai}) = k_L aV(c_{ai}-c_{aL}) \qquad (23)$$

where

$k_g a, k_L a$ = gas film and liquid film coefficients, respectively, mols/(hr.)(ft.$^3$ of packed volume)(atm. partial pressure difference)

V = packed volume, ft.$^3$

Overall volumetric coefficients may be developed from Equations (17) and (18) in the same manner.

Factors Affecting Film Coefficients. The factors that influence the value of film coefficients may be summarized as follows:

1. Temperature. Temperature affects both the gas film coefficient and the liquid film coefficient.

   (a) Gas film coefficient. Increase of temperature results in a decrease of gas film coefficients, because gas viscosities increase and densities decrease with an increase of temperature(46). From data obtained on the absorption of $NH_3$ in water and $SO_2$ in water the following relations have been derived(31)

$$k_g = C'u^{0.8}T^{-1.4} \qquad (24)$$

$$k_g = C''u^{0.8}\left(\frac{s}{z}\right)^{2/3} \qquad (25)$$

where

$u$ = velocity of the gas

$T$ = absolute temperature

$s$ = specific gravity of the gas mixture

$z$ = the viscosity of the gas mixture

$C', C''$ = constants

Perry(46) states that these equations may be applied with fair accuracy for similar gases, under like conditions of temperature, velocity, and concentration.

(b) Liquid film coefficient. Increase of temperature results in an increase of liquid film coefficients, because of both increased diffusivity and decreased viscosity of liquid(46). Results of the absorption of $SO_2$ in water and $NH_3$ in water indicate that the liquid film coefficient is directly proportional to the fourth power of the absolute temperature However, other experiments involving the desorption of $CO_2$, $O_2$, and $H_2$ from water by air have produced data that seem to indicate that the coefficient increases more rapidly than the fourth power of the absolute temperature(46).

2. Gas Velocity. Changes in gas velocity affects both the gas film coefficient and the liquid film coefficient.

(a) Gas film coefficients. It has been shown that the relation between the gas film coefficient and the gas mass velocity may be expressed as(38)

$$k_g = Cg^n \qquad (26)$$

where

$g$ = mass velocity

$C, n$ = constants

Perry(45) states that in general the constant "n" is equal to approximately 0.8.

(b) Liquid film coefficient. The liquid film coefficient is affected only slightly by gas velocity(30).

3. <u>Liquid Velocity</u>. Liquid velocity affects both the gas film coefficient and the liquid film coefficient.

(a) Gas film coefficient. Data obtained from the absorption of $CO_2$ in carbonate solutions indicate that the gas film coefficient is almost directly proportional to the liquid rate(21).

(b) Liquid film coefficient. The value of the liquid film coefficient depends upon the liquid velocity and relatively little on the nature of the diffusing solute.
Van Arsdel(71) states that an increase of liquid flow relative to gas flow causes an increase in the liquid film coefficient until a critical flow rate is reached. At low liquid rates the increase is greatest.

Factors Affecting the Overall Coefficient. Comstock and Dodge(21), in experiments absorbing $CO_2$ from gaseous mixtures by sodium or potassium carbonate, found that $K_ga$ varies throughout the tower in a given test, because of the changing ratio of bicarbonate to carbonate. Consequently, in comparing results of different tests, it is necessary to have the average percentage conversion approximately the same in the tests to be compared.

Although no rigorous theory has been offered to explain why an increase in liquid rate increases $K_ga$, it has been assumed that the increase in liquid rate increases the thickness of the liquid layer on the packing and makes more liquid available to absorb a given quantity of solute. The effect of gas velocity on $K_ga$ is negligible, but $K_ga$ increases with an increase in temperature.

Sherwood(61) gives the following relation between $K_La$ and the liquid rate

$$K_La = 0.016L^{0.92} \qquad (27)$$

where

L = liquid rate, lb./(hr.)(ft.$^2$) of total cross section

However, other investigators(25), absorbing $CO_2$ by water in a packed tower, found that gas velocity has a large effect and water rate no effect on $K_La$. Musick(41) developed the following equation from the absorption of $CO_2$ in water in a coke-packed tower

$$K_La = 0.0000153L^{1.64} \tag{28}$$

where

$K_La$ = liquid film absorption coefficient, lb./(hr.)(ft.$^3$)(lb./ft.$^3$)

L = liquid flow rate, lb./(hr.)(ft.$^2$) of tower cross section

Boisture(15) using the same system as Musick developed the following relation

$$\log K_La = \frac{L'}{7.966 - 0.544L'} + 0.00242P \tag{29}$$

where $K_La$ = overall liquid film ceefficient, lb. mols $CO_2$/(hr.)(ft.$^3$)(lb. mol $CO_2$/lb. mol $H_2O$)

L' = solvent rate, lb.mols/(hr.)(ft.$^2$)

P = partial pressure of $CO_2$ in inlet gas, mm.Hg.

Donald and Tyson(10) state 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.

One investigator(66) found that the overall coefficents 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.

According to Sherwood(61) the effect of temperature, when the liquid film controls, is so great that an increase, in the temperature over limited range may increase $K_La$ 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 performed. 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.

## Gas Absorption Equipment

All equipment for gas absorption is designed so as to bring the gas and the liquid phases into intimate mutual contact and to provide the largest possible surface of contact or interfacial area for the interaction between the two phases. Perry states(47): "Equipment for gas absorption has never become standardized, nor is there any accepted classification of such apparatus. Equipment for gas absorption may, however, be classified into the following groups:

1. Apparatus in which bubbles of gas are liberated beneath the surface of a liquid.
2. Apparatus in which a spray of liquid is injected into a volume of gas.
3. Apparatus in which gas is caused to pass over pools of liquid held in suitable containers, gas and liquid flow being countercurrent.

4. Absorption towers filled with a suitable packing over which the liquid may flow in films in order to present a large surface of contact to the ascending gas.
5. Absorption towers of the sieve-plate or bubble-cap construction similar to those employed for rectification in the field of distillation.
6. Apparatus containing mechanically driven parts designed to subdivide the liquid and bring it into intimate contact with the gas.

## Packed Towers

This type of gas absorption equipment consists of a tower or chamber packed loosely with any one of a large number of different types of "packing" over which the solvent is allowed to trickle or flow in thin films, without filling the intervening spaces between the individual pieces of packing. With the packings ordinarily obtainable, the interfacial area per unit of volume is much less than can be provided by spray towers or porous-plate equipment, but since both gas and liquid phases are in violent turbulence, packed towers may be used where either the gas or the liquid film is the controlling resistance(55).

Tower Packings. To increase the interfacial area, towers have been filled with packings of various shapes and sizes. Desirable characteristics of a tower packing are(2):

1. Low weight per unit volume. In this connection, the tower walls must be strong enough to support the side force of the packing.
2. Large surface per unit volume. This increases interfacial area.
3. Large free cross section. This permits a low pressure drop due to friction through the tower and therefore reduces the power required for gas circulation.
4. Large free volume. This is especially important in cases in which reactions must occur in the gas phase.
5. Small weight of liquid retained. This decreases the load on the tower and removes the liquid from the tower as rapidly as possible; however, this is a disadvantage if the reaction between the liquid and gas is slow.
6. Mechanical strength and chemical inertness toward material to be handled.

The principal types of tower packings in industrial use are(3):

1. Broken rocks. These have limited use because of their great weight, and they are not always

chemically inert. (Random packed).

2. Coke. This is light in weight and has a large surface per unit weight, but it has a small free section. (Random packed).
3. Stoneware shapes. These find many applications because of the unlimited variety of stoneware and shapes possible. (Both stacked and random packed).
4. Raschig rings. These are the most widely used type of tower packing. One unit consists of cylindrical rings of the same length as the diameter of the cylinder, with the walls as thin as the material will permit. (Random packed).
5. Lessing rings. This type of packing is made of metal with a single internal web. (Random packed).
6. Spiral rings. These are similar to Raschig rings but including an internal helix which may partly or completely fill the cross section of the cylinder. This type of packing is extremely expensive. (Stacked).
7. Berl saddles. These are a specially developed patented packing. They offer greater surface per unit volume and have a low resistance to gas flow. It is claimed that this type of packing gives minimum channeling, reduced side thrust, and increased distribution of solvent as compared to other types of packing. (Random packed).

Liquid Flow in Packed Towers. Regardless of the packing used, one of the most important problems present in a packed tower is the prevention of "channeling", which is the tendency of the liquid to pass through only certain passages of the tower. To prevent channeling several types of distribution plates, baffles, turbines, and spray nozzles have been used; none of which have been completely satisfactory. The qualities which a good distribution plate must have are; strong enough to support the packing, offer the least amount of resistance possible to the flow of both gas and liquid, and equally distribute both gas and liquid over the cross section of the absorption tower. In addition to the type of distribution plate used, the tendency toward channeling is influenced by rates of flow of gas and liquid, size of packing, and arrangement of packing.

Baker, Chilton, and Vernon(11) concluded that in large packed towers there is no tendency for the liquid flow to concentrate near the walls; that uniform distribution, once obtained, continues down through any reasonable depth of packing; that vapor velocity and liquid rate have little effect on distribution. Also, they found that there is little tendency toward channeling where the ratio of tower diameter to packing diameter is equal to or greater than eight to one.

Many tower designers(22) believe that channeling along the walls of the tower may be prevented by arranging the packing so that the largest packing is near the center.

Although uniform liquid distribution over the tower cross section is obtained, it is likely that all the packing surface is not wetted. Mayo, Hunter, and Nash(37) determined 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. They used only one distribution plate at the top of the tower. They arrived at the following conclusions:

1. The packing was practically 100% wetted at the top.
2. The percentage of wetted surface fell to about 40.
3. The tower wall was 60% wetted.
4. The percentage of wetted packing surface was greatest near the tower walls and remained uniform from a few inches below the top of the tower to the bottom.
5. The percentage of total surface wetted increased with the liquor rate up to the flooding point.
6. The gas rate had no appreciable effect upon the percentage of wetted surface.

Also, it was estimated from this investigation, that of the actual wetted surface, 10% may be inactive because of stagnant liquid films at the points of contact of the packing.

Liquid Holdup and Flooding in Packed Towers. In packed towers the gas and liquid rates are limited by the tendency of the column to flood(59). The "loading point" is reached when drops of liquid are mechanically carried up out of the tower by the gas. The "flooding point" is reached when the gas velocity is so high that the liquid cannot penetrate the tower but is held as a layer on top of the packing(4). Elgin and Weiss(26) arrived at the following conclusions concerning liquid holdup and flooding:

1. Gas velocity has little effect on liquid holdup until just before a critical gas velocity is reached, at which, the holdup rises rapidly.
2. Holdup varies linearly with water rate, except at very low rates, until the critical water is reached, then it rises rapidly.
3. All packings show similar behavior.

Pressure Drop Through Packed Towers. Approximately 90% of the pressure drop through the packing in packed towers results from the contraction and expansion in the gas flow through the irregular orifices formed by the packing; the remaining 10% is due to skin friction(18). Sherwood(58) states: "Apart from general maintenance, the power required to force the gas up through the packing frequently represents the principal operating cost of a packed tower. The power cost is proportional to the product of the gas rate and the pressure drop through the tower". Since the pressure drop is the result of contraction losses, expansion losses, and skin friction, and all of these factors are proportional approximately to the square of the gas rate; the following empirical equation may be derived(58)

$$P = \frac{2f' A_N A_p A_L r u_o{}^2 h}{g^{d}p} \qquad (30)$$

$P$ = pressure drop in the height "h"

$f'$= friction factor for gas flow through packing

$A_W$= "wall-effect factor"

$A_p$= a correction factor for hollow packing

$A_L$= a correction for the wetting of the packing by the solvent circulated; unity for dry packing

$r$ = gas density

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

$g$ = acceleration due to gravity

$d_p$= nominal particle size of the packing

Packed Tower Calculations. Sherwood(59) states that the height of an absorption tower determines its absorption efficiency, and the cross section determines the capacity or quantity of gas which can be treated. The following equation has been developed(72) for design calculations of packed towers assuming countercurrent continuous operation and that the vapor dissolved in the solvent follows Henry's law (Equation 8)

$$L(x_1 - x_2) = K_L alS(\Delta x)_{Ave.} \qquad (31)$$

where

$L$ = solute-free solvent, mols./hr.

$x_1$ = concentration of solute in inlet solvent, mols/mol of solvent

$x_2$ = concentration of solute in outlet solvent, mols/mol of solvent

$K_L a$ = overall transfer coefficient, lb.mols/(hr.)(ft.$^3$) (unit conc. difference)

$l$ = height of packed tower, ft.

$S$ = area of cross section, ft.$^2$

$(\Delta x)_{Ave.}$ = logarithmic mean of the overall driving forces at the top and bottom of the tower.

For estimating liquid-film coefficients in packed towers the following relation has been developed(77).

$$\frac{k_L a}{D_L} = C' \left(\frac{L}{A'u}\right)^{1-n'} \left(\frac{u}{pD_L}\right)^{0.5} \qquad (32)$$

where

$k_L a$ = liquid film coefficient combined with area factor, lb./mols/(hr.)(ft.$^3$)(unit conc. difference)

$L$ = solvent rate, lb.mols/hr.

$A'$ = cross-sectional area, ft.$^2$

u = viscosity of the liquid, lb/(ft.)(hr.)

p - density, lb./ft.$^3$

$D_L$ = diffusivity, ft.$^2$/hr.

C',n'= constants, whose values depend upon the type of packing, although for most packing materials, "n" is approximately 0.25

## Industrial Applications of Gas Absorption

Gas absorption has been employed extensively in industry for the following purposes$^{(1)}$:

Recovery of Solvents. Vent gases from condensers, storage tanks, and ventilating gases from solvent recovery systems, are often treated by gas absorption, usually with water as the liquid, although gas adsorption on activated carbon is an alternative process. Benzene and similar products are recovered from coke oven gas by absorption in wash oil. Gasoline is recovered from natural, still, and refinery gases by absorption.

Recovery of Soluble Gases. Ammonia, hydrogen chloride, carbon dioxide are recovered by absorption in water or other agents.

Drying of Gases. Water vapor is removed from air and other gases by absorption in concentrated sulfuric acid, by various salt solutions, and by a saturated solution of calcium chloride on the surface of the solid salt.

Purification of Gases. Hydrogen sulfide and mercaptans are removed from manufactured gas by scrubbing solutions containing sodium carbonate, sodium phenolate, ethanolamine, and similar substances. Fumes are often removed by passing them through absorption towers.

Production of a New Product. The gaseous mixture leaving a coke-oven is passed through a saturator using sulfuric acid as the absorbent medium. The ammonia in the coke-oven gas is absorbed with the formation of solid and crystalline ammonium sulfate(67).

# III. EXPERIMENTAL

## Purpose of Study

The purpose of this investigation was to correlate, by means of empirical equations, certain operating variables of an 18" stoneware absorption tower, 21 feet in height, 15 feet of which were random packed with 1 1/2 to 2 inch coke, using the system $CO_2$-$H_2O$ at approximately 80°F. and 714 mm. of Hg.

## Plan of Investigation

The following is an outline of the work performed during the course of this investigation:

1. Construction and Modification of Apparatus.

   Note: Letters refer to Figure 2, page 46.

   (a) To obtain the solvent rates shown in Table 1, page 36, a 1 1/2 inch iron pipe was installed from the constant head tank (B) to the top of the tower. To regulate the solvent rate, a 1 1/2 inch globe valve was placed in the line with a one inch bypass regulated by means of a one inch needle valve.

   (b) All orifices, manometers, thermometers, and draft gages were calibrated and several modified to ensure more accurate control of the operating variables.

TABLE I

Plan of Operation of the 18" Gas Absorption Tower Using the System $CO_2$-$H_2O$ at Approximately 80°F. and 714 mm. of Hg.

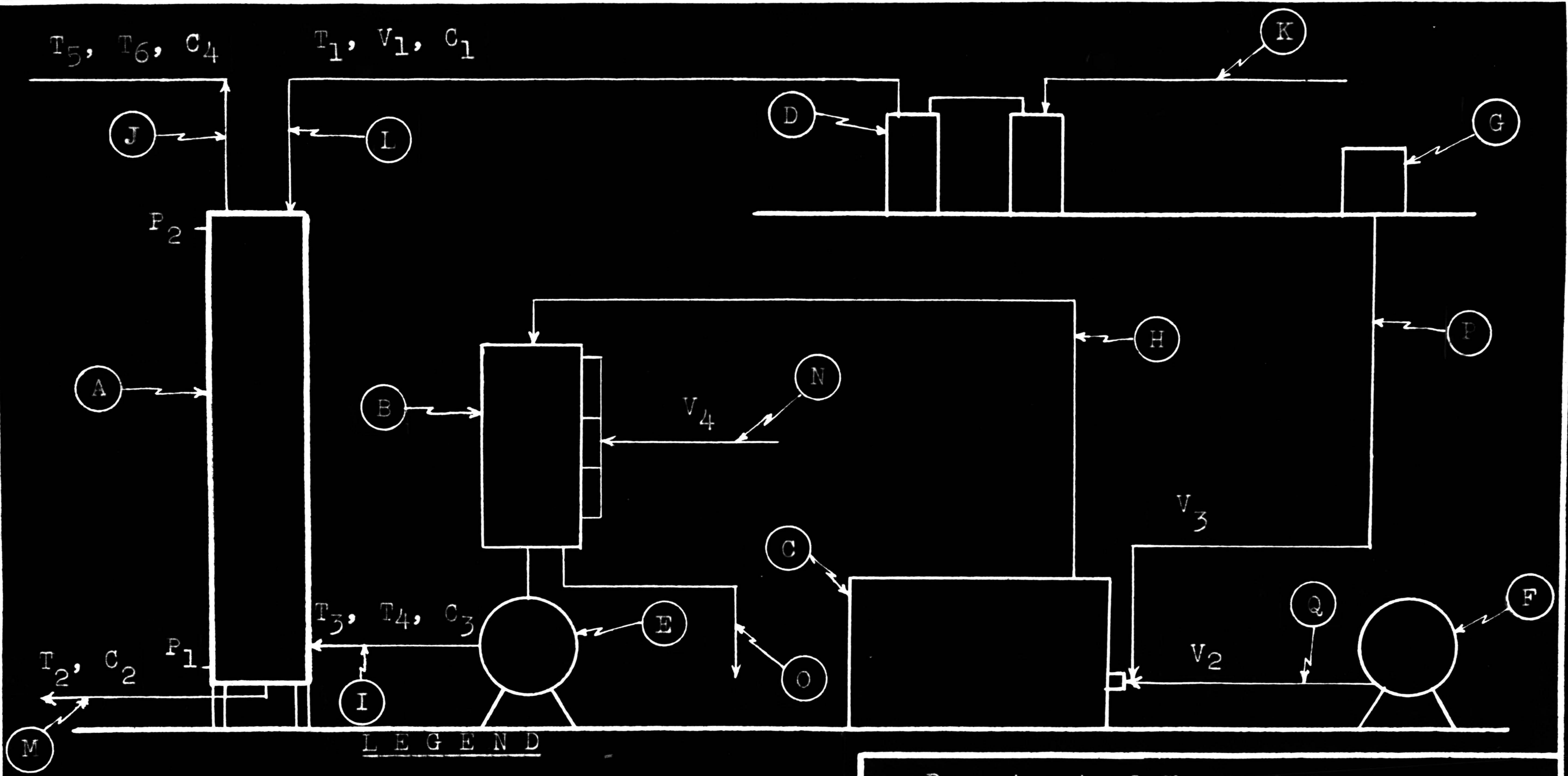
| Test No. | Gas Velocity lb.mols/(hr.)(sq.ft.) | Water Rate lb.mols/(hr.)(sq.ft.) | $CO_2$ in Flue Gas % |
|---|---|---|---|
| 1 | 12.7 | 65 | 3 |
| 2 | 12.7 | 65 | 6 |
| 3 | 12.7 | 65 | 9 |
| 4 | 12.7 | 65 | 12 |
| 5 | 12.7 | 65 | 15 |
| 6 | 12.7 | 75 | 3 |
| 7 | 12.7 | 75 | 6 |
| 8 | 12.7 | 75 | 9 |
| 9 | 12.7 | 75 | 12 |
| 10 | 12.7 | 75 | 15 |
| 11 | 12.7 | 85 | 3 |
| 12 | 12.7 | 85 | 6 |
| 13 | 12.7 | 85 | 9 |
| 14 | 12.7 | 85 | 12 |
| 15 | 12.7 | 85 | 15 |
| 16 | 12.7 | 100 | 3 |
| 17 | 12.7 | 100 | 6 |
| 18 | 12.7 | 100 | 9 |
| 19 | 12.7 | 100 | 12 |
| 20 | 12.7 | 100 | 15 |
| 21 | 2.0 | 100 | 3 |
| 22 | 2.0 | 100 | 6 |
| 23 | 2.0 | 100 | 9 |
| 24 | 2.0 | 100 | 12 |
| 25 | 2.0 | 100 | 15 |
| 26 | 2.0 | 200 | 3 |
| 27 | 2.0 | 200 | 6 |
| 28 | 2.0 | 200 | 9 |
| 29 | 2.0 | 200 | 12 |
| 30 | 2.0 | 200 | 15 |
| 31 | 2.0 | 300 | 3 |
| 32 | 2.0 | 300 | 6 |
| 33 | 2.0 | 300 | 9 |
| 34 | 2.0 | 300 | 12 |
| 35 | 2.0 | 300 | 15 |
| 36 | 2.0 | 400 | 3 |
| 37 | 2.0 | 400 | 6 |
| 38 | 2.0 | 400 | 9 |
| 39 | 2.0 | 400 | 12 |
| 40 | 2.0 | 400 | 15 |
| 41 | 2.0 | 150 | 3 |
| 42 | 2.0 | 150 | 6 |
| 43 | 2.0 | 150 | 9 |
| 44 | 2.0 | 150 | 12 |
| 45 | 2.0 | 150 | 15 |

2. Operation of the Absorption Tower. The plan of operation of the absorption tower is given in Table I, page 36.

3. Data Obtained.

Note: See Figure No. 1, page 38.

- (a) Temperature, °F.
    - (1) Inlet absorbent water, $T_1$
    - (2) Outlet absorbent water, $T_2$
    - (3) Dry bulb temp. of inlet flue gases, $T_3$
    - (4) Wet bulb temp. of inlet flue gases, $T_4$
    - (5) Dry bulb temp. of outlet flue gases, $T_5$
    - (6) Wet bulb temp. of outlet flue gases, $T_6$
    - (7) Room temperature
- (b) Manometer readings, flow rates
    - (1) Inlet absorbing water, $V_1$
    - (2) Compressed air, $V_2$
    - (3) Fuel oil, $V_3$
    - (4) Water to gas cooler, $V_4$
- (c) Draft gage readings
    - (1) Static pressure in base of tower, $P_1$
    - (2) Static pressure in top of tower, $P_2$
    - (3) Atmospheric pressure
- (d) Water samples, 250 ml.
    - (1) Inlet water, $C_1$
    - (2) Outlet water, $C_2$



LEGEND

A. Absorption Tower
B. Gas Cooler
C. Furnace
D. Zeolite Softener
E. Blower
F. Air Compressor
G. Fuel Oil Storage
H. Flue Gas Line
I. Inlet Gas Line
J. Outlet Gas Line
K. Water Main
L. Inlet Water Line
M. Outlet Water Line
N. Inlet Cooling Water
O. Outlet Cooling Water
P. Fuel Oil Line
Q. Compressed Air Line

Department of Chemical Engineering
Virginia Polytechnic Institute
Blacksburg, Virginia

Flow Sheet For The
18" Gas Absorption Tower

Drawn by:
Approved by: FwB.

Figure No.: 1
Date: 1 May 1947

## 4. Calculations.

(a) Calculation of the overall liquid film coefficient of absorption, $K_La$.

(b) Derivation of empirical equations relating the overall liquid film coefficient of absorption, $K_La$, to the following variables:

(1) Gas rate

(2) Solvent rate

(3) Inlet gas composition

## Materials

Potassium Hydroxide, pellets, U.S.P., lot No. 2143. Used in 50% aqueous solution as analytical reagent for $CO_2$ determination. J. T. Baker Co., Phillipsburg, New Jersey.

Sodium Hydroxide, pellets, U.S.P., lot No. 82246. Standardized at 0.0093 N. Used in determination of free $CO_2$ in absorbing water. J. T. Baker Co., Phillipsburg, New Jersey.

Potassium Acid Phthalate, C. P. Used in standardization of 0.0093 NaOH. J. T. Baker Co., Phillipsburg, New Jersey.

Mercury, triple distilled, C. P. Used as displacing fluid in Fisher gas measuring unit. F. W. Berk & Co., Inc., Wood Ridge Division, Wood Ridge, New Jersey.

Meriam Red Oil, sp. gr. 0.0827. Used as indicating fluid in draft gages. The Meriam Company, 1935 West 112th St., Cleveland, Ohio.

Grease, Stopcock, Dow Corning, lot No. 438C25. Used to lubricate all stopcocks on gas analysis apparatus. Dow Corning Corp., Midland, Mich.

Cement, gasket, Permatex No. 1. Used in sealing cooler and stovepipe connections. Permatex Company Inc., Sheepshead Bay, New York.

Salt, kiln dried, evaporated. Used in regenerating zeolite in water softener. Mulkey Salt Co., Detroit, Michigan.

Sodium Hydroxide, flake, commercial grade. Used in preparation of degreasing solution. Diamond Alkali Co., Pittsburgh, Pa.

Phenolphthalein, lot No. 42246. Used in indicator solution in the determination of free $CO_2$ in solvent. J. T. Baker Chemical Co., Phillipsburg, New Jersey.

## Apparatus

Tower, Absorption, consisting of seven 18" (inside diameter) by 33" chemical stoneware sections, packed with 1 1/2 to 2 inch coke. (See Figure No. 2, page 46). Used as an experimental device for absorption studies. Stoneware sections manufactured by United States Stoneware Company, Akron, Ohio.

Burner, Oil, D.F.C., Number C2-3372. Used to burn fuel. Manufactured by the Denver Fire Clay Company, Denver, Colorado.

Furnace, Oil Burning, built of fire brick with an outer shell of common brick. (See Figure No. 4, page 48).

Blower, Centrifugal, 12" diameter, single inlet, type Cl, serial No. 101721, equipped with step cone pulley. Used to force gas through absorption tower. Manufactured by Clarage Fan Company, Kalamazoo, Michigan.

Compressor, Hytor, Nash, size AL-574, 5 1/2" D, 3500 R. P. M., 75 p.s.i. maximum rated pressure. Used to provide compressed air for the operation of oil burner. Manufactured by the Nash Engineering Company, South Norwalk, Connecticut.

Motor, Induction, Western Electric, Type 1824 15-1800, Form C, 15 H. P., 220 volts, 35.9 amperes, speed full load 1740, 60 cycles, 3 phase, A. C., continuous 40° rise. Used to drive compressor. Manufactured by Western Electric Company, Baltimore, Maryland.

Motor, Induction, General Electric, Type K, Model 5KF225A26, Frame 225, 1 H. P., 220/440 volts, 4.2/2.1 amperes, speed full load 335, 60 cycles, 3 phase, A. C., continuous 40° rise. Used to drive blower. Manufactured by General Electric Company, Schnectady, New York.

Motor, Electric, "Companion", 1/4 H. P., Type S.P.H. 110 volts, 60 cycles, 1750 R.P.M. Used to drive oil pump. Purchased from Sears and Roebuck Company, Philadelphia, Penn.

Pump, Oil, Rotary, Sliding Vane; Inlet 3/8 in., Outlet 3/8 in. Used to circulate fuel oil. Manufactured by Brown and Sharpe Manufacturing Company, Providence, Rhode Island.

Softener, Water, zeolite, Number VT-13458, Type HS-18. Used to soften absorbing water. Manufactured by the Permutit Company, New York, N. Y.

Scales, platform type, 500 lb. capacity, No. E571193. Used to weigh discharge water from absorption tower. Purchased from Sears and Roebuck Company, Philadelphia, Penn.

Balance, Analytical, Becker Chainomatic. Used in analytical work. Manufactured by Seederer-Kohlbusch, Inc., Jersey City, N. J.

Pulley, Reeves, Vari-Speed. Used to vary speed of blower. Manufactured by the Reeves Pulley Company, Columbus, Ohio.

Gage, Draft, single tube, Serial No. 106. Used in conjunction with Pitot tube. Manufactured by the Meriam Company, Cleveland, Ohio.

Tube, Pitot, 35" in length. Used to determine gas velocity through absorption tower. Manufactured by the Ellison Draft Gage Company, Chicago, Ill.

Manometers, U-tube, vertical, 28 in., Hg filled. Used to measure rate of flow of water to cooling tower and rate of flow of air to oil burner. Designed and constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Manometer, U-tube, vertical, 28 in., oil over water. Used to measure rate of flow of fuel to oil burner. Designed and constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Gas Analysis Apparatus, Consisting of:

Gas Measuring Unit, Precision Mine-Air Model, Fisher, Specification No. 10-600-34, 72 ml. graduated in 0.2 ml., 22 ml. in 0.1 ml., and 6 ml. in 0.05 ml. divisions.

Gas Absorption Unit, Fisher, Specification No. 10-600-44, Contact Pipette Model.

Gas Sampling Tubes, Fisher, Specification No. 10-920, with stopcocks, 250 ml.

Used for the analytical determination of the per cent of carbon dioxide in inlet flue gas to absorption tower and exit flue gas from absorption tower. Manufactured by the Fisher Scientific Company, St. Louis, Mo.

Anemometer, serial No. 6058. Used to determine gas velocity through absorption tower. Taylor Instrument Company, Rochester, New York.

Thermometer, glass, -40°C. to 50°C., 1° graduations, No. 05005. Used to determine room temperature. Brothcom Co., N. Y.

Thermometer, glass, -40°C. to 50°C., 1° graduations, No. 05004. Used to determine wet bulb temperature of outlet gas from absorption tower. Brothcom Co., N. Y.

Thermometer, glass, -40°C.to 50°C., 1° graduations, No. 05008. Used to determine dry bulb temperature of outlet gas from absorption tower. Brothcom Co., N. Y.

Thermometer, Weston, 0°-250°C., 2° graduations. Used to determine wet and dry bulb temperature of inlet gas to absorption tower. Western Electrical Instrument Corporation, Newark, New Jersey.

Thermometers, Weston, 0°-250°C., 2° graduations. Used to determine temperature of inlet and outlet solvent. Western Electrical Instrument Corporation, Newark, New Jersey.

Analytical Equipment, Miscellaneous:

Pipettes, 50 ml.

Flasks, volumetric 500 ml.

Flasks, volumetric, 1000 ml.

Flasks, Erlenmeyer, 250 ml.

Burette, 50 ml., stopcock.

Burette, 50 ml., bead.

Dishes, evaporating, porcelain, No. 2.

Gages, Draft, single tube, inclined 20 degrees, 20 in. Filled with Meriam Red Oil. Used to determine pressure drop across absorption tower. Designed and constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Barometer, Precision Mercurial, Fortin principal. Manufactured by Henry & Green, New York, N. Y.

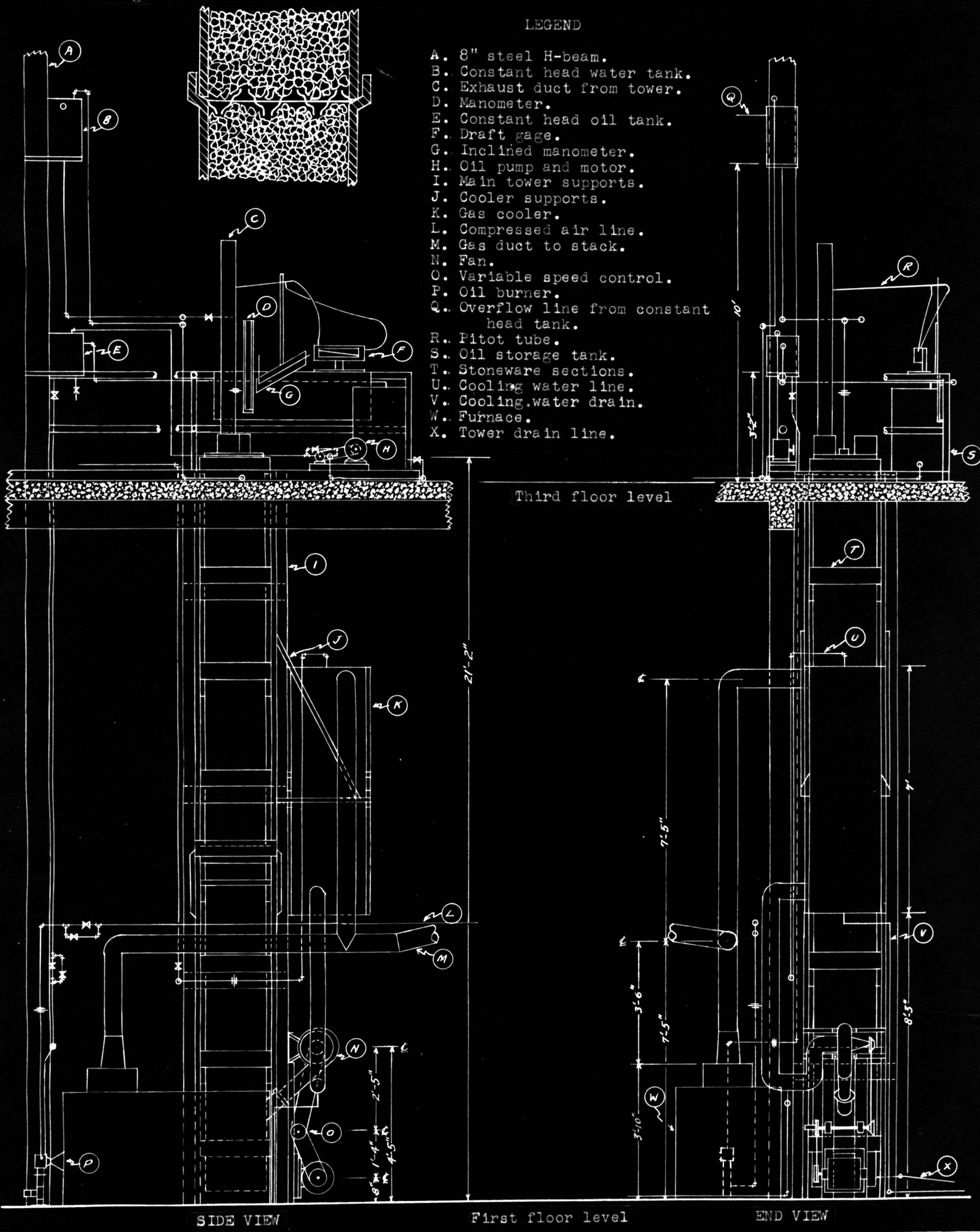
Cooler, Gas, water cooled, heat exchanger. Used to cool flue gas before it enters the absorption tower. Designed and constructed in the Chemical Engineering Department. Virginia Polytechnic Institute, Blacksburg, Virginia. (See Figure No. 3, page 47).

## Method of Procedure

Operation. The operation of the absorption tower may be divided into four distinct phases which are as follows:

1. Furnace Operation. (Letters refer to Figure 2, page 46). In order to insure efficient operation of the oil burner (P), it was necessary to install a cloth filter in the oil line (E) and a 40 mesh wire filter in the compressed air line (L) to prevent solid particles, such as rust

Section view of stoneware pipe showing type of distribution plates used in tower. Distribution plates made from 1" floor plates, joined by welding.



LEGEND

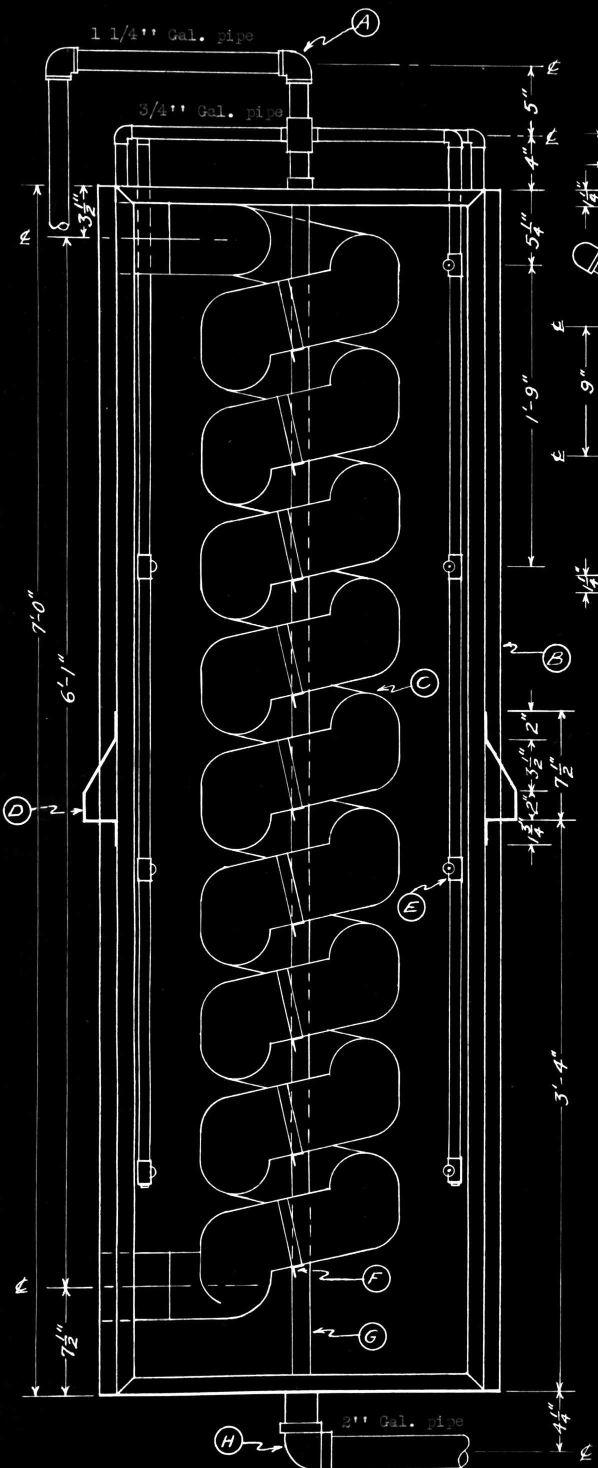
A. 8" steel H-beam.
B. Constant head water tank.
C. Exhaust duct from tower.
D. Manometer.
E. Constant head oil tank.
F. Draft gage.
G. Inclined manometer.
H. Oil pump and motor.
I. Main tower supports.
J. Cooler supports.
K. Gas cooler.
L. Compressed air line.
M. Gas duct to stack.
N. Fan.
O. Variable speed control.
P. Oil burner.
Q. Overflow line from constant head tank.
R. Pitot tube.
S. Oil storage tank.
T. Stoneware sections.
U. Cooling water line.
V. Cooling water drain.
W. Furnace.
X. Tower drain line.

Department of Chemical Engineering
Virginia Polytechnic Institute
Blacksburg, Virginia

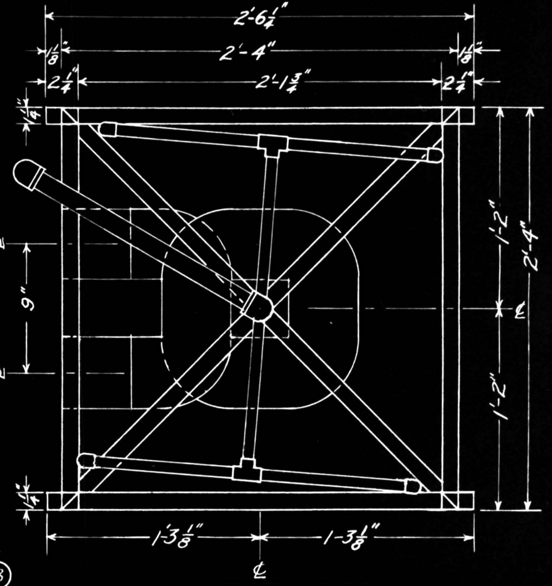
18-INCH STONEWARE
ABSORPTION TOWER AND ACCESSORIES

Drawn by: WWB
Checked by:
Approved by:

Figure No.: 2
Scale: 3/8" = 1'
Date: 8, Jan. '47



SIDE VIEW
Side cover removed



TOP VIEW
Top cover removed

LEGEND

A. Inlet water line.
B. Main frame of cooler.
C. Cooling coil.
D. Cooler support lugs.
E. Spray nozzles.
F. Support arms for coil.
G. Central coil supports.
H. Outlet water line to drain.

NOTES:

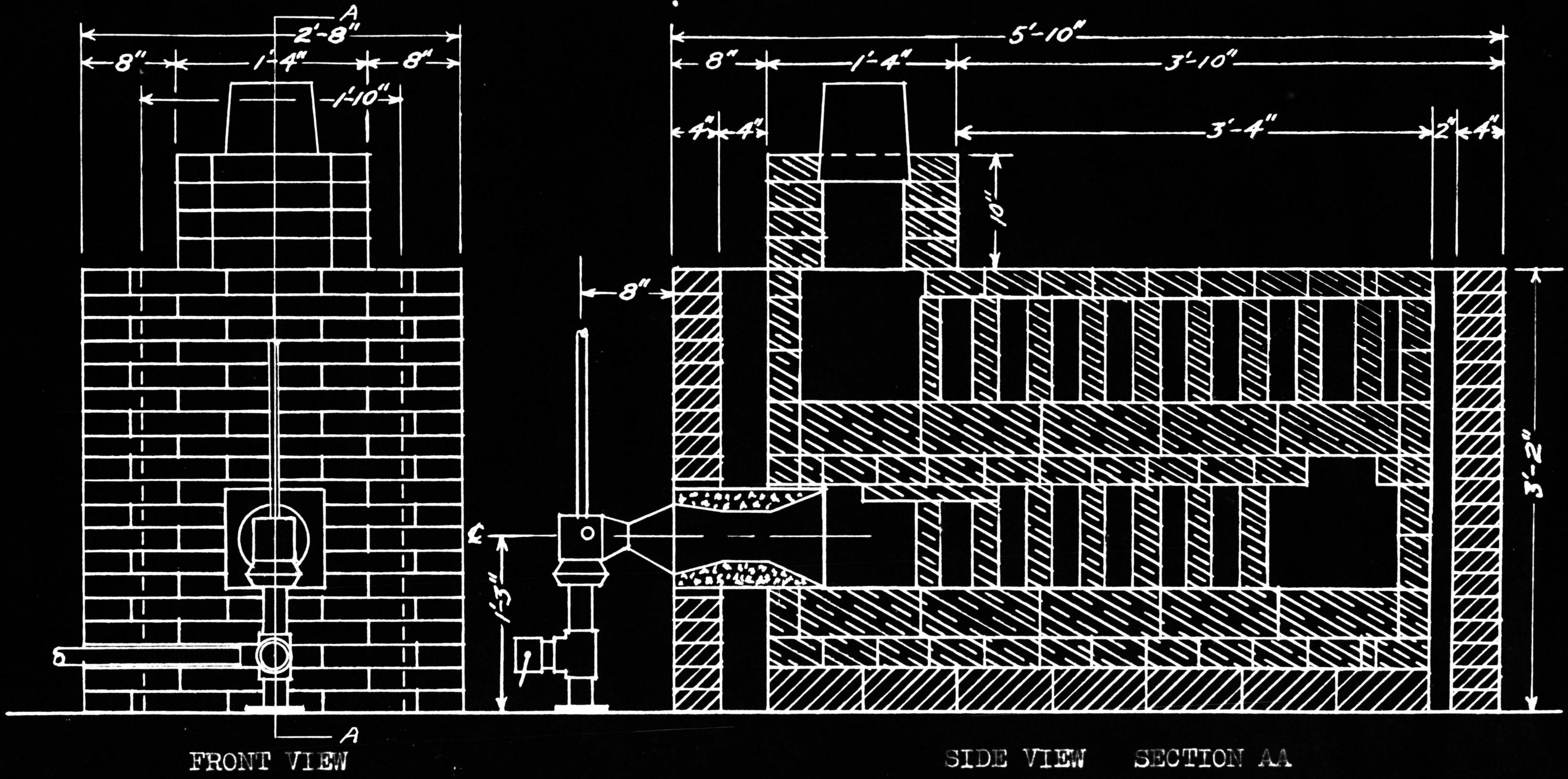
1. Frame of cooler is made of 1 1/4"x 1 1/4" angle iron, welded construction used throughout.
2. Sides of cooler made of 28 gage gal. tin, secured to frame with 1/8"x 3/4" stove bolts, on 6" centers.
3. All spray nozzles on 21" centers.
4. Support lugs made from 1 1/4"x 3/8" bar iron.
5. Cooling coil made from 5" stovepipe elbows, black iron.
6. Pitch of spiral cooling coil, 8".

Department of Chemical Engineering
Virginia Polytechnic Institute
Blacksburg, Virginia

GAS COOLER
FOR
18-INCH GAS ABSORPTION TOWER

Drawn by: wag
Checked by:
Approved by: FWB.

Figure No.: 3
Scale: 1/8"= 1"
Date: 8,Jan.'47



FRONT VIEW

SIDE VIEW SECTION AA

LEGEND

▨ COMMON BRICK

▨ FIRE BRICK

▦ FIRE CLAY

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Virginia Polytechnic Institute
Blacksburg, Virginia

FURNACE
FOR
18-INCH GAS ABSORPTION TOWER

Drawn by: WAB
Checked by: SYY
Approved by: FWB.

Figure No.: 4
Scale: 3/4"= 1'
Date: 1,Jan.'47

and scales, from clogging the atomizing jets on the oil burner (P). Before each period of operation, both filters were removed and cleaned. After the filters were replaced, the oil circulating pump (H) and the Hytor air compressor were started. Small amounts of fuel oil and air were then admitted into the oil burner (P) and the resulting mixture ignited by means of a pilot light. After the mixture was ignited, the amounts of oil and air were gradually increased until the ratio necessary to produce a desired carbon dioxide concentration in the flue gas was obtained. The furnace (W) was operated at a constant air-fuel ratio, with the flue gases bypassing (M) the absorption tower, until a constant temperature was reached.

2. <u>Gas Flow</u>. (Letters refer to Figure 2, page 46). After the furnace (W) had reached a constant temperature, the flow of flue gases was diverted by means of dampers, from the stack (M) to the gas cooler (K). The gas passed through the cooler (K) and was forced through the tower by means of a centrifugal blower (N), which was operated at speeds necessary to give a constant rate of gas flow through the tower.

3. <u>Water Flow</u>. (Letters refer to Figure 2, page 46). Zeolite softened water was passed through a constant head tank (B) and then into the top of the tower

just prior to the introduction of the flue gases into the bottom of the tower. The rate of water flow through the tower was regulated by means of a needle valve.

4. <u>Data Collected</u>. (Letters refer to Figure 1, page 38). After approximately three hours, terminal conditions being constant, the system was assumed to be in equilibrium and the test period begun. Each test was of one hour duration, during which time the following data and samples were taken at the beginning of each test, thirty minutes after the test period had begun, and at the end of the one hour test period:

a. Temperature, $^{o}F$.

    (1) Inlet absorbent water, $T_1$

    (2) Outlet absorbent water, $T_2$

    (3) Dry bulb temp. of inlet flue gases, $T_3$

    (4) Wet bulb temp. of inlet flue gases, $T_4$

    (5) Dry bulb temp. of outlet flue gases, $T_5$

    (6) Wet bulb temp. of outlet flue gases, $T_6$

    (7) Room temperature

b. Manometer readings, flow rates

    (1) Inlet absorbing water, $V_1$

    (2) Compressed air, $V_2$

    (3) Fuel oil, $V_3$

    (4) Water to gas cooler, $V_4$

c. Draft gage readings
    (1) Static pressure in base of tower, $P_1$
    (2) Static pressure in top of tower, $P_2$
d. Pressure
    (1) Atmospheric pressure
e. Velocities, ft./min.
    (1) Outlet gas
f. Water samples, 250 ml.
    (1) Inlet water, $C_1$
    (2) Outlet water, $C_2$
g. Gas samples, approx. 250 ml.
    (1) Inlet gas, $C_3$
    (2) Outlet gas, $C_4$

## Analytical Determinations

1. Free $CO_2$ in Water. Fifty ml. portions from each water sample taken during the test were analyzed for free $CO_2$ content by titrating against 0.0093N. NaOH, using phenolphthalein as the indicator.
2. Per Cent $CO_2$ in Gas. The procedure used in the determination of $CO_2$ in the flue gas was that given by Matuzak(36).

## Data and Results

Experimental Data. The experimental data for this investigation is presented in Table No. II, page 53.

Results. The results of this investigation are shown in Table III, page 54 and are arranged for comparison in Tables IV, V, VI, and VII, pages 55, 56, 57 and 58 respectively. For graphical presentation see Figures No. 5, 6 and 7, pages 65, 69 and 72, respectively.

TABLE NO. II

## Log of Experimental Data for Tests on 18"Stoneware Coke-Packed Gas Absorption Tower Using the System $CO_2$-Water

| Test No. | Date | Water Flow Rate lb./min. | Water Temperature °F | | Concentration Free $CO_2$ in Absorbing Water $\frac{\text{gms. } CO_2}{100 \text{ gms. } H_2O} \times 10^4$ | | Gas Rate Through Tower $\frac{\text{(lb. mols)}}{\text{(hr.)(ft.}^2\text{)}}$ | Gas Temperature °F Inlet Gas | | Gas Temperature °F Outlet Gas | | Concentration of $CO_2$ in gas % by Vol. | | Room Temp. °F | Barometric Pressure mm. Hg | $\Delta$ P Across Tower in. $H_2O$ X $10^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Inlet | Outlet | Inlet | Outlet | | Dry Bulb | Wet Bulb | Dry Bulb | Wet Bulb | Inlet Gas | Outlet Gas | | | |
| 1 | 12 Jun 47 | 35 | 55.4 | 59.0 | 1.87 | 11.50 | 12.7 | 71.6 | 70.2 | 62.6 | 62.6 | 4.14 | 4.12 | 86.4 | 711.4 | 36.1 |
| 2 | 12 Jun 47 | 35 | 54.5 | 59.0 | 2.93 | 6.48 | 12.7 | 71.6 | 70.7 | 63.5 | 62.9 | 2.47 | 2.47 | 87.8 | 711.4 | 33.8 |
| 3 | 17 Jun 47 | 35 | 54.5 | 60.0 | 3.07 | 11.46 | 12.7 | 70.7 | 69.8 | 63.5 | 63.5 | 4.20 | 4.19 | 77.9 | 710.0 | 33.1 |
| 4 | 17 Jun 47 | 35 | 54.5 | 62.6 | 2.87 | 15.35 | 12.7 | 74.3 | 73.4 | 64.1 | 63.5 | 6.21 | 6.15 | 84.2 | 710.0 | 33.1 |
| 5 | 18 Jun 47 | 35 | 54.5 | 64.4 | 2.80 | 18.82 | 12.7 | 77.0 | 75.2 | 64.4 | 64.1 | 7.16 | 7.14 | 84.2 | 710.3 | 33.1 |
| 6 | 18 Jun 47 | 40 | 54.5 | 64.4 | 2.80 | 17.94 | 12.7 | 78.5 | 77.0 | 64.4 | 64.1 | 7.15 | 7.12 | 84.2 | 710.3 | 35.6 |
| 7 | 19 Jun 47 | 40 | 54.5 | 59.0 | 2.19 | 8.45 | 12.7 | 68.3 | 67.4 | 62.9 | 62.6 | 3.88 | 3.90 | 81.5 | 712.6 | 36.8 |
| 8 | 19 Jun 47 | 40 | 59.0 | 60.8 | 2.39 | 17.59 | 12.7 | 74.1 | 73.1 | 63.3 | 62.9 | 6.11 | 6.05 | 83.3 | 712.6 | 33.1 |
| 9 | 20 Jun 47 | 40 | 59.0 | 62.6 | 2.25 | 7.37 | 12.7 | 69.8 | 68.9 | 61.7 | 61.7 | 2.46 | 2.38 | 72.5 | 713.5 | 35.6 |
| 10 | 20 Jun 47 | 40 | 59.0 | 68.0 | 2.31 | 15.49 | 12.7 | 86.0 | 84.5 | 62.6 | 62.6 | 7.51 | 7.37 | 72.5 | 713.5 | 35.6 |
| 11 | 21 Jun 47 | 45 | 59.0 | 62.6 | 2.31 | 7.37 | 12.7 | 70.7 | 69.8 | 61.4 | 61.4 | 2.66 | 2.52 | 72.5 | 716.5 | 36.3 |
| 12 | 21 Jun 47 | 45 | 59.0 | 62.6 | 2.19 | 8.80 | 12.7 | 72.5 | 71.6 | 61.4 | 61.4 | 3.53 | 3.43 | 73.4 | 716.5 | 36.8 |
| 13 | 24 Jun 47 | 45 | 55.4 | 62.6 | 2.19 | 15.55 | 12.7 | 72.2 | 71.3 | 62.1 | 61.7 | 4.80 | 4.79 | 82.4 | 712.8 | 36.8 |
| 14 | 24 Jun 47 | 45 | 55.4 | 62.6 | 2.25 | 21.07 | 12.7 | 75.2 | 73.4 | 62.1 | 61.7 | 5.94 | 5.83 | 86.0 | 712.8 | 36.8 |
| 15 | 25 Jun 47 | 45 | 59.0 | 64.4 | 2.25 | 13.30 | 12.7 | 78.8 | 77.0 | 62.6 | 62.6 | 5.23 | 5.05 | 80.6 | 713.6 | 36.8 |
| 16 | 25 Jun 47 | 53 | 59.0 | 64.4 | 2.13 | 12.62 | 12.7 | 80.6 | 78.8 | 63.3 | 62.9 | 5.02 | 4.79 | 84.2 | 713.6 | 36.8 |
| 17 | 26 Jun 47 | 53 | 57.2 | 62.6 | 2.19 | 8.33 | 12.7 | 64.1 | 63.8 | 62.0 | 61.7 | 2.49 | 2.39 | 82.4 | 712.3 | 37.2 |
| 18 | 26 Jun 47 | 53 | 58.1 | 62.6 | 2.25 | 11.93 | 12.7 | 75.2 | 73.4 | 62.6 | 62.6 | 3.60 | 3.59 | 85.1 | 712.3 | 36.8 |
| 19 | 26 Jun 47 | 53 | 59.0 | 64.4 | 2.20 | 13.03 | 12.7 | 77.0 | 75.2 | 63.5 | 63.5 | 4.75 | 4.66 | 83.3 | 712.3 | 37.2 |
| 20 | 26 Jun 47 | 53 | 59.0 | 64.4 | 2.31 | 16.98 | 12.7 | 79.0 | 77.6 | 64.4 | 64.4 | 6.00 | 5.78 | 84.2 | 712.3 | 37.2 |
| 21 | 27 Jun 47 | 53 | 54.5 | 56.3 | 2.11 | 12.88 | 2.0 | 60.8 | 58.9 | 56.9 | 56.6 | 4.97 | 4.69 | 82.4 | 712.2 | 4.3 |
| 22 | 27 Jun 47 | 53 | 55.4 | 56.3 | 2.19 | 18.00 | 2.0 | 62.6 | 60.0 | 56.9 | 56.6 | 6.89 | 6.42 | 86.1 | 712.2 | 4.2 |
| 23 | 27 Jun 47 | 53 | 55.4 | 56.3 | 2.25 | 26.59 | 2.0 | 64.4 | 62.6 | 59.0 | 59.0 | 10.71 | 10.21 | 90.5 | 712.2 | 4.2 |
| 24 | 28 Jun 47 | 53 | 54.5 | 56.3 | 2.11 | 7.43 | 2.0 | 62.9 | 61.1 | 57.2 | 57.2 | 2.66 | 2.48 | 81.5 | 711.3 | 4.2 |
| 25 | 28 Jun 47 | 53 | 54.5 | 56.3 | 2.19 | 22.09 | 2.0 | 62.9 | 61.4 | 57.5 | 57.2 | 8.84 | 8.56 | 81.5 | 711.3 | 4.2 |
| 26 | 28 Jun 47 | 106 | 54.5 | 56.3 | 2.25 | 23.18 | 2.0 | 62.0 | 60.2 | 58.1 | 57.5 | 9.35 | 8.28 | 84.2 | 711.3 | 6.6 |
| 27 | 29 Jun 47 | 106 | 54.5 | 60.8 | 2.19 | 15.20 | 2.0 | 62.9 | 61.1 | 58.1 | 57.5 | 4.66 | 4.30 | 79.9 | 712.0 | 6.1 |
| 28 | 29 Jun 47 | 106 | 54.5 | 60.2 | 2.25 | 18.82 | 2.0 | 63.8 | 62.0 | 57.5 | 57.5 | 6.68 | 6.00 | 79.7 | 712.0 | 6.7 |
| 29 | 29 Jun 47 | 106 | 54.5 | 60.8 | 2.11 | 33.00 | 2.0 | 63.8 | 61.7 | 57.2 | 57.2 | 10.59 | 9.09 | 84.2 | 712.0 | 6.6 |
| 30 | 29 Jun 47 | 106 | 54.5 | 59.9 | 2.19 | 8.45 | 2.0 | 62.6 | 60.8 | 57.2 | 57.2 | 2.23 | 2.07 | 86.0 | 712.0 | 6.6 |
| 31 | 3 Jul 47 | 159 | 58.1 | 59.0 | 2.05 | 16.74 | 2.0 | 63.5 | 61.7 | 61.7 | 61.7 | 4.65 | 4.17 | 84.2 | 713.9 | 6.6 |
| 32 | 3 Jul 47 | 159 | 58.1 | 59.0 | 2.19 | 23.06 | 2.0 | 63.5 | 61.7 | 61.7 | 61.7 | 6.82 | 6.20 | 87.8 | 713.9 | 7.1 |
| 33 | 3 Jul 47 | 159 | 57.2 | 59.0 | 2.11 | 13.63 | 2.0 | 62.6 | 60.7 | 60.7 | 60.4 | 3.66 | 3.34 | 87.8 | 713.9 | 6.7 |
| 34 | 4 Jul 47 | 159 | 59.0 | 60.2 | 2.25 | 31.30 | 2.0 | 65.3 | 63.5 | 61.7 | 61.7 | 9.73 | 8.47 | 82.4 | 716.2 | 6.7 |
| 35 | 4 Jul 47 | 159 | 59.0 | 59.9 | 2.25 | 20.46 | 2.0 | 63.5 | 62.9 | 62.9 | 62.9 | 5.87 | 5.22 | 84.2 | 716.2 | 7.1 |
| 36 | 4 Jul 47 | 212 | 59.0 | 59.9 | 2.25 | 23.32 | 2.0 | 63.5 | 61.7 | 61.7 | 61.7 | 6.61 | 5.92 | 89.6 | 716.2 | 7.1 |
| 37 | 5 Jul 47 | 212 | 59.0 | 59.9 | 2.25 | 18.07 | 2.0 | 62.6 | 60.7 | 60.7 | 60.7 | 5.49 | 4.90 | 83.3 | 715.4 | 6.7 |
| 38 | 5 Jul 47 | 212 | 59.0 | 59.9 | 2.11 | 8.80 | 2.0 | 62.6 | 60.7 | 60.7 | 60.4 | 2.74 | 2.37 | 84.2 | 715.4 | 7.1 |
| 39 | 5 Jul 47 | 212 | 59.0 | 59.9 | 2.41 | 37.03 | 2.0 | 62.6 | 60.7 | 60.7 | 60.7 | 10.37 | 8.82 | 90.5 | 715.4 | 7.1 |
| 40 | 6 Jul 47 | 212 | 59.9 | 60.8 | 2.25 | 14.38 | 2.0 | 62.6 | 60.7 | 60.7 | 60.4 | 4.35 | 3.80 | 82.4 | 712.0 | 7.1 |
| 41 | 6 Jul 47 | 79.5 | 59.9 | 60.8 | 2.20 | 15.69 | 2.0 | 62.6 | 62.0 | 62.0 | 62.0 | 5.05 | 4.74 | 85.1 | 712.0 | 5.5 |
| 42 | 6 Jul 47 | 79.5 | 59.9 | 60.8 | 2.31 | 29.11 | 2.0 | 62.0 | 61.3 | 61.7 | 61.7 | 10.30 | 9.65 | 86.9 | 712.0 | 5.5 |
| 43 | 7 Jul 47 | 79.5 | 59.9 | 60.8 | 2.32 | 17.94 | 2.0 | 62.6 | 60.7 | 60.4 | 60.4 | 6.11 | 5.76 | 83.3 | 711.1 | 5.7 |
| 44 | 7 Jul 47 | 79.5 | 59.9 | 60.8 | 2.20 | 27.89 | 2.0 | 62.6 | 60.7 | 60.4 | 60.4 | 9.81 | 9.32 | 84.2 | 711.1 | 5.7 |
| 45 | 7 Jul 47 | 79.5 | 59.9 | 60.8 | 2.25 | 11.05 | 2.0 | 62.0 | 60.4 | 60.4 | 60.0 | 3.33 | 3.10 | 86.9 | 711.1 | 5.5 |

# TABLE NO. III

Log of Calculated Results for Tests on 18" Stoneware Coke-Packed Gas Absorption Tower Operated at Approximately 80°F. and 714 mm. of Hg Using the System $CO_2$-Water

| Test No. | L Water Rate To Tower $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | $x_2$ Conc. Free $CO_2$ Inlet $H_2O$ $\frac{\text{mols } CO_2}{\text{mol } H_2O}$ x $10^6$ | $x_1$ Conc. Free $CO_2$ Outlet $H_2O$ $\frac{\text{mols } CO_2}{\text{mol } H_2O}$ x $10^6$ | Per Cent Relative Humidity of Inlet Gas | Partial Pressure Water Vapor DB Temp. Inlet Gas mm. Hg | Partial Pressure Water Vapor Room Temp. mm. Hg | Corrected Partial Pressure $H_2O$ Vapor. Inlet Gas mm. Hg | $P_b$ Corrected pp. $CO_2$ Inlet Gas mm. Hg | $x_{eb}$ $\frac{\text{mols } CO_2}{\text{mol } H_2O}$ X$10^4$ | Per Cent Relative Humidity of Outlet Gas | $P_t$ pp. $CO_2$ in Outlet Gas mm Hg | $x_{et}$ $\frac{\text{mols } CO_2}{\text{mol } H_2O}$ x$10^4$ | $K_La$ Overall Liquid-Film Coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 66.05 | 1.53 | 9.41 | 92.6 | 19.82 | 32.23 | 18.35 | 30.05 | 127.64 | 100 | 29.31 | 131.32 | 0.00268 |
| 2 | 66.05 | 2.93 | 6.49 | 95.5 | 19.82 | 33.69 | 18.93 | 17.95 | 85.50 | 100 | 17.57 | 92.05 | 0.00177 |
| 3 | 66.05 | 2.51 | 9.38 | 95.5 | 19.22 | 24.47 | 18.35 | 30.09 | 128.05 | 100 | 29.75 | 130.91 | 0.00234 |
| 4 | 66.05 | 2.34 | 12.56 | 96.4 | 21.71 | 30.04 | 20.93 | 44.68 | 150.14 | 100 | 43.67 | 154.64 | 0.00295 |
| 5 | 66.05 | 1.12 | 15.40 | 95.0 | 23.75 | 30.04 | 22.56 | 51.41 | 157.91 | 100 | 50.72 | 172.64 | 0.00381 |
| 6 | 75.48 | 2.29 | 14.68 | 93.5 | 24.96 | 30.04 | 23.34 | 51.29 | 157.50 | 100 | 50.57 | 165.28 | 0.00386 |
| 7 | 75.48 | 1.79 | 7.20 | 95.5 | 17.71 | 27.53 | 16.91 | 28.08 | 123.96 | 100 | 27.79 | 126.82 | 0.00244 |
| 8 | 75.48 | 2.51 | 14.13 | 95.1 | 21.56 | 29.18 | 20.50 | 44.09 | 148.91 | 100 | 43.11 | 153.82 | 0.00386 |
| 9 | 75.48 | 1.84 | 6.03 | 95.5 | 18.64 | 20.44 | 17.80 | 17.62 | 85.50 | 100 | 16.98 | 93.27 | 0.00235 |
| 10 | 75.48 | 1.89 | 14.67 | 94.0 | 31.81 | 20.44 | 29.90 | 52.85 | 158.73 | 100 | 52.58 | 168.55 | 0.00332 |
| 11 | 84.92 | 1.89 | 6.03 | 95.5 | 19.22 | 20.44 | 18.35 | 19.12 | 92.05 | 100 | 18.06 | 94.09 | 0.00257 |
| 12 | 84.92 | 1.79 | 7.20 | 95.5 | 20.44 | 21.06 | 19.52 | 25.35 | 112.50 | 100 | 24.58 | 116.59 | 0.00267 |
| 13 | 84.92 | 1.79 | 10.72 | 95.5 | 20.23 | 28.35 | 19.32 | 34.66 | 133.78 | 100 | 34.14 | 142.78 | 0.00366 |
| 14 | 84.92 | 1.84 | 15.24 | 92.0 | 22.37 | 31.82 | 20.58 | 42.91 | 146.05 | 100 | 41.56 | 151.78 | 0.00509 |
| 15 | 84.92 | 1.84 | 10.88 | 92.0 | 25.20 | 26.74 | 23.18 | 37.51 | 134.59 | 100 | 36.04 | 141.96 | 0.00370 |
| 16 | 100.00 | 1.74 | 11.77 | 92.5 | 26.74 | 27.53 | 24.73 | 35.97 | 131.32 | 100 | 34.18 | 138.28 | 0.00508 |
| 17 | 100.00 | 1.79 | 6.81 | 98.5 | 15.31 | 28.35 | 15.08 | 18.08 | 93.27 | 100 | 17.02 | 91.23 | 0.00363 |
| 18 | 100.00 | 1.84 | 9.79 | 96.8 | 22.37 | 30.91 | 21.65 | 26.00 | 107.18 | 100 | 25.57 | 122.73 | 0.00459 |
| 19 | 100.00 | 1.79 | 10.66 | 92.8 | 23.75 | 29.18 | 22.04 | 34.18 | 126.82 | 100 | 33.19 | 135.82 | 0.00450 |
| 20 | 100.00 | 1.89 | 13.89 | 94.0 | 25.37 | 30.04 | 23.85 | 43.12 | 143.59 | 100 | 41.17 | 151.37 | 0.00543 |
| 21 | 100.00 | 1.72 | 10.05 | 89.5 | 13.63 | 28.35 | 12.20 | 36.22 | 143.19 | 100 | 33.40 | 139.91 | 0.00392 |
| 22 | 100.00 | 1.79 | 14.73 | 90.1 | 14.53 | 26.39 | 13.09 | 50.02 | 166.50 | 100 | 45.72 | 162.00 | 0.00525 |
| 23 | 100.00 | 1.84 | 21.76 | 91.0 | 15.47 | 36.68 | 14.08 | 78.33 | 191.05 | 100 | 72.72 | 189.00 | 0.00699 |
| 24 | 100.00 | 1.72 | 6.07 | 90.2 | 14.68 | 27.53 | 13.24 | 19.32 | 98.18 | 100 | 17.64 | 96.14 | 0.00299 |
| 25 | 100.00 | 1.80 | 18.07 | 90.2 | 14.68 | 27.53 | 13.51 | 64.17 | 180.00 | 100 | 60.89 | 179.19 | 0.00604 |
| 26 | 200.00 | 1.84 | 18.97 | 90.0 | 14.22 | 30.04 | 12.80 | 68.19 | 184.10 | 100 | 58.90 | 176.73 | 0.01267 |
| 27 | 200.00 | 1.79 | 12.44 | 90.2 | 14.68 | 24.37 | 13.24 | 33.73 | 137.46 | 100 | 30.62 | 135.00 | 0.01043 |
| 28 | 200.00 | 1.84 | 15.40 | 91.8 | 15.15 | 25.96 | 13.91 | 48.40 | 163.23 | 100 | 42.72 | 156.69 | 0.01130 |
| 29 | 200.00 | 1.72 | 27.00 | 89.2 | 15.15 | 30.04 | 13.51 | 76.78 | 189.82 | 100 | 64.72 | 182.87 | 0.01810 |
| 30 | 200.00 | 1.79 | 6.91 | 90.1 | 14.53 | 31.82 | 13.09 | 16.32 | 85.91 | 100 | 14.74 | 92.05 | 0.00768 |
| 31 | 300.00 | 1.67 | 15.91 | 90.6 | 14.99 | 30.04 | 13.58 | 33.95 | 138.28 | 100 | 29.77 | 134.18 | 0.02091 |
| 32 | 300.00 | 1.79 | 18.87 | 90.6 | 14.99 | 33.69 | 13.58 | 50.13 | 166.50 | 100 | 44.26 | 157.09 | 0.02112 |
| 33 | 300.00 | 1.72 | 11.15 | 89.6 | 14.53 | 33.69 | 13.02 | 26.93 | 125.59 | 100 | 23.84 | 156.28 | 0.01338 |
| 34 | 300.00 | 1.84 | 25.61 | 91.0 | 15.97 | 28.35 | 14.53 | 71.09 | 186.14 | 100 | 60.66 | 181.23 | 0.02589 |
| 35 | 300.00 | 1.84 | 16.74 | 97.0 | 14.99 | 30.04 | 14.54 | 42.99 | 153.41 | 100 | 37.39 | 143.19 | 0.02011 |
| 36 | 400.00 | 1.84 | 19.08 | 90.6 | 14.99 | 35.66 | 13.58 | 48.88 | 163.64 | 100 | 42.40 | 152.19 | 0.02913 |
| 37 | 400.00 | 1.84 | 14.78 | 89.6 | 14.53 | 29.18 | 13.02 | 40.21 | 152.19 | 100 | 35.05 | 140.73 | 0.02357 |
| 38 | 400.00 | 1.72 | 7.20 | 89.6 | 14.53 | 30.04 | 13.02 | 20.09 | 103.09 | 100 | 16.95 | 91.23 | 0.01504 |
| 39 | 400.00 | 1.97 | 30.30 | 89.6 | 14.53 | 36.68 | 13.02 | 76.78 | 190.23 | 100 | 63.10 | 180.00 | 0.04083 |
| 40 | 400.00 | 1.84 | 11.77 | 89.6 | 14.53 | 28.35 | 13.02 | 31.66 | 134.18 | 100 | 27.05 | 125.60 | 0.02040 |
| 41 | 150.00 | 1.79 | 12.84 | 96.7 | 14.53 | 30.91 | 14.05 | 36.85 | 142.37 | 100 | 33.75 | 137.87 | 0.00790 |
| 42 | 150.00 | 1.89 | 23.82 | 95.8 | 14.22 | 32.74 | 13.62 | 75.40 | 189.41 | 100 | 68.71 | 184.50 | 0.01174 |
| 43 | 150.00 | 1.89 | 14.68 | 89.6 | 14.53 | 29.18 | 13.02 | 44.42 | 156.28 | 100 | 40.96 | 151.37 | 0.00832 |
| 44 | 150.00 | 1.80 | 22.82 | 89.6 | 14.53 | 30.04 | 13.02 | 71.50 | 187.78 | 100 | 66.27 | 182.05 | 0.01137 |
| 45 | 150.00 | 1.84 | 9.04 | 91.1 | 14.22 | 32.74 | 12.95 | 24.36 | 118.23 | 100 | 22.04 | 110.46 | 0.00630 |

## TABLE NO. IV

Variation of $K_La$ With Solvent Rate Through the 18" Stoneware Coke-Packed Gas Absorption Tower Operating at Approximately 80°F. and 714 mm. of Hg Using the System $CO_2$-Water

| Test No. | Gas Rate, G $\frac{\text{lb. mols}}{\text{(hr.)(ft.}^2\text{)}}$ | pp. $CO_2$ Inlet Gas mm. of Hg | Solvent Rate, L $\frac{\text{lb. mols}}{\text{(hr.)(ft.}^2\text{)}}$ | $K_La$ $\frac{\text{lb. mols}}{\text{(hr.)(ft.}^3\text{)(Unit conc. diff.)}}$ |
|---|---|---|---|---|
| 2 | 12.7 | 18.0 | 66.1 | 0.00177 |
| 9 | 12.7 | 17.6 | 75.5 | 0.00235 |
| 11 | 12.7 | 19.1 | 84.9 | 0.00267 |
| 17 | 12.7 | 18.1 | 100.0 | 0.00363 |
| 3 | 12.7 | 30.1 | 66.1 | 0.00234 |
| 13 | 12.7 | 34.7 | 84.9 | 0.00366 |
| 19 | 12.7 | 34.2 | 100.0 | 0.00450 |
| 7 | 12.7 | 28.1 | 75.5 | 0.00244 |
| 12 | 12.7 | 25.4 | 84.9 | 0.00267 |
| 18 | 12.7 | 26.0 | 100.0 | 0.00459 |
| 4 | 12.7 | 44.7 | 66.1 | 0.00295 |
| 8 | 12.7 | 44.1 | 75.5 | 0.00386 |
| 14 | 12.7 | 42.9 | 84.9 | 0.00509 |
| 20 | 12.7 | 43.1 | 100.0 | 0.00543 |
| 24 | 2.0 | 19.3 | 100.0 | 0.00299 |
| 45 | 2.0 | 24.4 | 150.0 | 0.00630 |
| 30 | 2.0 | 16.3 | 200.0 | 0.00768 |
| 33 | 2.0 | 26.9 | 300.0 | 0.01338 |
| 38 | 2.0 | 20.1 | 400.0 | 0.01504 |
| 21 | 2.0 | 36.2 | 100.0 | 0.00392 |
| 41 | 2.0 | 36.9 | 150.0 | 0.00790 |
| 27 | 2.0 | 33.7 | 200.0 | 0.01043 |
| 31 | 2.0 | 34.0 | 300.0 | 0.02091 |
| 37 | 2.0 | 40.2 | 400.0 | 0.02357 |
| 22 | 2.0 | 50.0 | 100.0 | 0.00525 |
| 43 | 2.0 | 44.4 | 150.0 | 0.00832 |
| 28 | 2.0 | 48.4 | 200.0 | 0.01130 |
| 32 | 2.0 | 50.1 | 300.0 | 0.02112 |
| 36 | 2.0 | 48.9 | 400.0 | 0.02913 |
| 23 | 2.0 | 78.3 | 100.0 | 0.00699 |
| 42 | 2.0 | 75.4 | 150.0 | 0.01174 |
| 29 | 2.0 | 76.8 | 200.0 | 0.01810 |
| 39 | 2.0 | 76.8 | 400.0 | 0.04083 |

## TABLE NO. V

Variation of $K_La$ With Flue Gas Rate Through the 18" Stoneware Coke-Packed Gas Absorption Tower
Operating at Approximately 80°F. and 714 mm. of Hg Using the System $CO_2$-Water

| Test No. | Solvent Rate, L $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | pp $CO_2$ in Inlet Gas mm. of Hg | Gas Rate, G $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | $K_La$ $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ |
|---|---|---|---|---|
| 17 | 100.0 | 18.1 | 12.7 | 0.00363 |
| 24 | 100.0 | 19.3 | 2.0 | 0.00299 |
| 16 | 100.0 | 36.0 | 12.7 | 0.00508 |
| 21 | 100.0 | 36.2 | 2.0 | 0.00299 |
| 20 | 100.0 | 43.1 | 12.7 | 0.00543 |
| 22 | 100.0 | 50.0 | 2.0 | 0.00525 |

## TABLE NO. VI

Variation of Pressure Drop Across the Tower with Flue Gas Rate Through the 18"
Stoneware Coke-Packed Gas Absorption Tower Operating at Approximately
80°F. and 714 mm. of Hg Using the System $CO_2$-Water

| Test No. | Solvent Rate, L $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | Gas Rate, G $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | Pressure Drop, $\Delta P$ in. of $H_2O \times 10^2$ |
|---|---|---|---|
| 16-20 | 100.0 | 12.7 | 37.0 |
| 21-25 | 100.0 | 2.0 | 4.2 |

## TABLE NO. VII

Variation of $K_La$ With Partial Pressure of $CO_2$ in Inlet Gas to the 18" Stoneware Coke-Packed Gas Absorption Tower Operating at Approximately 80°F. and 714 mm. of Hg Using the System $CO_2$-Water

| Test No. | Gas Rate, G $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | Solvent Rate, L $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | pp of $CO_2$ in Inlet Gas mm. of Hg | $K_La$ $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ |
|---|---|---|---|---|
| 2 | 12.7 | 66.1 | 18.0 | 0.00177 |
| 1 | 12.7 | 66.1 | 30.1 | 0.00268 |
| 3 | 12.7 | 66.1 | 30.1 | 0.00234 |
| 4 | 12.7 | 66.1 | 44.7 | 0.00295 |
| 5 | 12.7 | 66.1 | 51.4 | 0.00381 |
| 9 | 12.7 | 75.5 | 17.6 | 0.00235 |
| 7 | 12.7 | 75.5 | 28.1 | 0.00244 |
| 8 | 12.7 | 75.5 | 44.1 | 0.00386 |
| 6 | 12.7 | 75.5 | 51.3 | 0.00386 |
| 10 | 12.7 | 75.5 | 53.0 | 0.00392 |
| 11 | 12.7 | 84.9 | 19.1 | 0.00257 |
| 12 | 12.7 | 84.9 | 25.4 | 0.00267 |
| 13 | 12.7 | 84.9 | 34.7 | 0.00366 |
| 15 | 12.7 | 84.9 | 37.5 | 0.00370 |
| 14 | 12.7 | 84.9 | 42.9 | 0.00509 |
| 17 | 12.7 | 100.0 | 18.1 | 0.00363 |
| 18 | 12.7 | 100.0 | 26.0 | 0.00459 |
| 19 | 12.7 | 100.0 | 34.2 | 0.00450 |
| 16 | 12.7 | 100.0 | 36.0 | 0.00508 |
| 20 | 12.7 | 100.0 | 43.1 | 0.00543 |
| 24 | 2.0 | 100.0 | 19.3 | 0.00299 |
| 21 | 2.0 | 100.0 | 36.2 | 0.00392 |
| 22 | 2.0 | 100.0 | 50.0 | 0.00525 |
| 25 | 2.0 | 100.0 | 64.2 | 0.00604 |
| 23 | 2.0 | 100.0 | 78.3 | 0.00699 |
| 45 | 2.0 | 150.0 | 24.4 | 0.00630 |
| 41 | 2.0 | 150.0 | 36.9 | 0.00790 |
| 43 | 2.0 | 150.0 | 44.4 | 0.00832 |
| 44 | 2.0 | 150.0 | 71.5 | 0.01134 |
| 42 | 2.0 | 150.0 | 75.4 | 0.01174 |
| 30 | 2.0 | 200.0 | 16.3 | 0.00768 |
| 27 | 2.0 | 200.0 | 33.7 | 0.01043 |
| 28 | 2.0 | 200.0 | 48.4 | 0.01130 |
| 26 | 2.0 | 200.0 | 68.2 | 0.01267 |
| 29 | 2.0 | 200.0 | 76.8 | 0.01810 |
| 33 | 2.0 | 300.0 | 26.9 | 0.01338 |
| 31 | 2.0 | 300.0 | 34.0 | 0.02091 |
| 35 | 2.0 | 300.0 | 43.0 | 0.02011 |
| 32 | 2.0 | 300.0 | 50.1 | 0.02112 |
| 34 | 2.0 | 300.0 | 71.1 | 0.02589 |
| 38 | 2.0 | 400.0 | 20.1 | 0.01504 |
| 40 | 2.0 | 400.0 | 31.7 | 0.02040 |
| 37 | 2.0 | 400.0 | 40.2 | 0.02357 |
| 36 | 2.0 | 400.0 | 48.9 | 0.02913 |
| 39 | 2.0 | 400.0 | 76.8 | 0.04083 |

## Sample Calculations

Note: All data used in sample calculations were taken from test No. 45 (See Table No. II, page 53).

1. Overall Liquid Film Absorption Coefficient, $K_La$. The following equation (see Equation No. 31 page 32), given by Walker, Lewis, McAdams, and Gilliland(72) was used in computing the values of $K_La$

$$(L)(x_1 - x_2) = (K_La)(H)(\triangle x_{av.}) \qquad (33)$$

where

$L$ = lb. mols solute free solvent/(hr.)(ft.$^2$)

$x_1$ = lb. mols solute/lb. mols solvent in outlet water

$x_2$ = lb. mols solute/lb. mols solvent in inlet water

$H$ = height of packing in tower, ft.

$\triangle x_{av.}$ = arithmetic mean overall driving force, lb. mols $CO_2$/(hr.)(ft.$^3$)(Unit conc. difference)

$K_La$ = overall liquid-film coefficient, lb. mols/(hr.)(ft.$^3$)(Unit conc. difference)

The following examples show how the quantities in the above equation were determined

a. (L) Solvent rate, lb. mols/(hr.)(ft.$^2$)

$$L = \frac{(\text{lbs./min.})(60)}{(\text{mol. wt. of } H_2O)(\text{cross sectional area of the 18" diameter tower, ft.}^2)}$$

$$= \frac{(79.5)(60)}{(18)(1.767)}$$

$$= 150.0 \text{ lb. mols/(hr.)(ft.}^2)$$

b. ($x_1$) Conc. of $CO_2$ in outlet water, lb. mols $CO_2$/lb.mol $H_2O$

gm. $CO_2$/50 ml. $H_2O$ = (ml. NaOH)(N. NaOH)(M.E. $CO_2$)

= (5.4)(0.0093)(0.022)

= $11.05 \times 10^{-4}$

Converting this value to lb.mols $CO_2$/lb.mol $H_2O$

$$x_1 = \frac{(11.05 \times 10^{-4})(18)}{(44)(50)}$$

= 0.00000904

= $9.04 \times 10^{-6}$ lb.mols $CO_2$/lb. mol $H_2O$

c. ($x_2$) Conc. of $CO_2$ in inlet water, lb.mols $CO_2$/lb.mols $H_2O$

Calculated in same manner as "b" above

$x_2 = 1.84 \times 10^{-6}$ lb.mols $CO_2$/lb. mol $H_2O$

d. (H) Height of packing in tower, ft.

The packed section of the tower was 15 ft.

e. ($\Delta x_{av.}$) Arithmetic mean overall driving force, lb. mols $CO_2$/lb.mol $H_2O$

$$\Delta x_{av.} = \frac{(x_{et} - x_2) + (x_{eb} - x_1)}{2}$$

where

$x_{et}$ = equilibrium conc. corresponding to the partial pressure of $CO_2$ in the outlet gas.

$x_{eb}$ = equilibrium conc. corresponding to the partial pressure of $CO_2$ in the inlet gas

The values of $x_{et}$ and $x_{eb}$ were obtained from data given by Othmer and Benenati(42). Before this data could be used, however, it was necessary to calculate the exact partial pressure of the $CO_2$ in both the inlet and outlet gas. In order to calculate the exact partial pressures the following assumptions were made:

(1) That the gas samples as analyzed in the Orsat apparatus are 100% saturated with water vapor.

(2) That any changes in per cent relative humidity with small changes in total barometric pressure would be negligible.

Then, since the outlet gas from the tower is 100% saturated

$$P_t\text{, part. pres. } CO_2 \text{ in outlet gas} = \frac{(\%CO_2)(\text{Bar.pres.}, B_p)}{100}$$

$$= \frac{(3.10)(711.1)}{100}$$

$$= 22.04 \text{ mm. of Hg.}$$

Since the inlet gas to the tower is not 100% saturated, the corrected partial pressure of $CO_2$ in the inlet gas may be calculated from the following relation

$$P_b\text{, cor.part.pres.}CO_2 = \frac{(\%CO_2)(B_p - \text{part.pres.}H_2O \text{ at Tower cond.})(B_p)}{(100)(B_p - \text{part.pres.}H_2O \text{ at saturation cond.})}$$

Tower conditions of inlet gas were:

dry bulb temp. = 62.0°F.

Wet bulb temp. = 60.4°F.

% relative humidity = 91.1

part.pres.$H_2O$ at 62.0°F. = 14.22 mm. of Hg

part.pres.$H_2O$ at tower conditions =(% rel.humidity)(part. pres.$H_2O$ at 62.0°F.)

$$=(0.911)(14.22)$$

$$=12.95 \text{ mm. of Hg}$$

sat.part.pres.$H_2O$ at room temp. (86.9°F.)=32.74 mm. of Hg

Barometric pressure = 711.1 mm. of Hg

then

$$P_b, \text{ cor.part.pres.}CO_2 = \frac{(3.33)(711.1-12.95)(711.1)}{(100)(711.1-32.74)}$$

$$=24.36 \text{ mm. of Hg}$$

$x_{et}$, at 22.04 mm. of Hg and 60.4°F., from equilibrium data

$$=2.70 \text{ gms. } CO_2/100 \text{ gms.} H_2O$$

converting this value to lb.mols $CO_2$/lb.mols $H_2O$

$$x_{et} = \frac{(2.70)(18)}{(44)(100)}$$

$$= 100.46 \times 10^{-4} \text{lb.mols } CO_2/\text{lb.mols } H_2O$$

$x_{eb}$, at 24.36 mm. of Hg and 62.0°F., from equilibrium data

$$= 2.89 \text{ gms. } CO_2/100 \text{ gms. } H_2O$$

Converting in the same manner as for "$x_{et}$"

$$x_{eb} = 118.23 \times 10^{-4} \text{lb.mols } CO_2/\text{lb.mol } H_2O$$

then

$$\triangle x_{av} = \frac{(110.46-0.02)(10^{-4}) + (118.23-0.09)(10^{-4})}{2}$$

$$=114.3 \times 10^{-4} \text{ lb.mols } CO_2/\text{lb.mol } H_2O$$

Substituting in the original equation

$$(L)(x_1 - x_2) = K_La\ (H)(\triangle x_{av.})$$

$$(150)(9.04-1.84)(10^{-6}) = (K_La)(15)(114.3)(10^{-4})$$

Solving for $K_La$

$K_La = 0.00630$ lb.mols/(hr.)(ft.$^2$)(unit conc. diff.)

2. <u>Derivation of an Empirical Equation Relating the Overall Liquid-Film Coefficient ($K_La$), Solvent Rate (L), and Partial Pressure of $CO_2$ in the Inlet Gas (p) at a Constant Gas Rate of 12.7 lb.mol/(hr.)(ft.$^2$).</u>

As shown in Figure No. 5, page 65, the plot of log $K_La$ versus the partial pressure of $CO_2$ in the inlet gas results in a series of straight lines. Therefore, the equation relating $K_La$ and the partial pressure is of the general type

$$K_La = 10^{a + bp}$$

where "a" and "b" are constants to be determined. Writing the above Equation in log form

$$\log K_La = a + bp$$

Then by substituting values from Table No. III, page 54, the following equations may be written

For L = 66.1 lb.mols/(hr.)(ft.$^2$)

Test No. 1 - $2.572 = a + 20.0b$

Test No. 2 - $2.752 = a + 18.0b$

Test No. 3 - $2.631 = a + 30.1b$

Test No. 4 - $2.530 = a + 44.7b$

Test No. 5 - $2.419 = a + 51.4b$

Summation of the equations for Test Nos. 1, 2 and 3 and summation of the equations for Test Nos. 4, and 5 uields two equations in "a" and "b" which upon simultaneous solution yield

$$a = -2.859$$

$$b = +0.0080$$

In like manner values of "a" and "b" may be found for L = 75.5, L = 84.9, and L = 100.0.

Summarizing

| L | a | b |
|---|---|---|
| 66.1 | -2.859 | 0.0080 |
| 75.5 | -2.743 | 0.0064 |
| 84.9 | -2.685 | 0.0123 |
| 100.0 | -2.563 | 0.0172 |

The values of L and "a" are most nearly rectified when log L is plotted against "a" as shown in Figure 8(a), page 74. Therefore, the relation between L and "a" is of the type

$$L = 10^{m} + na$$

In log form

$$\log L = m + na$$

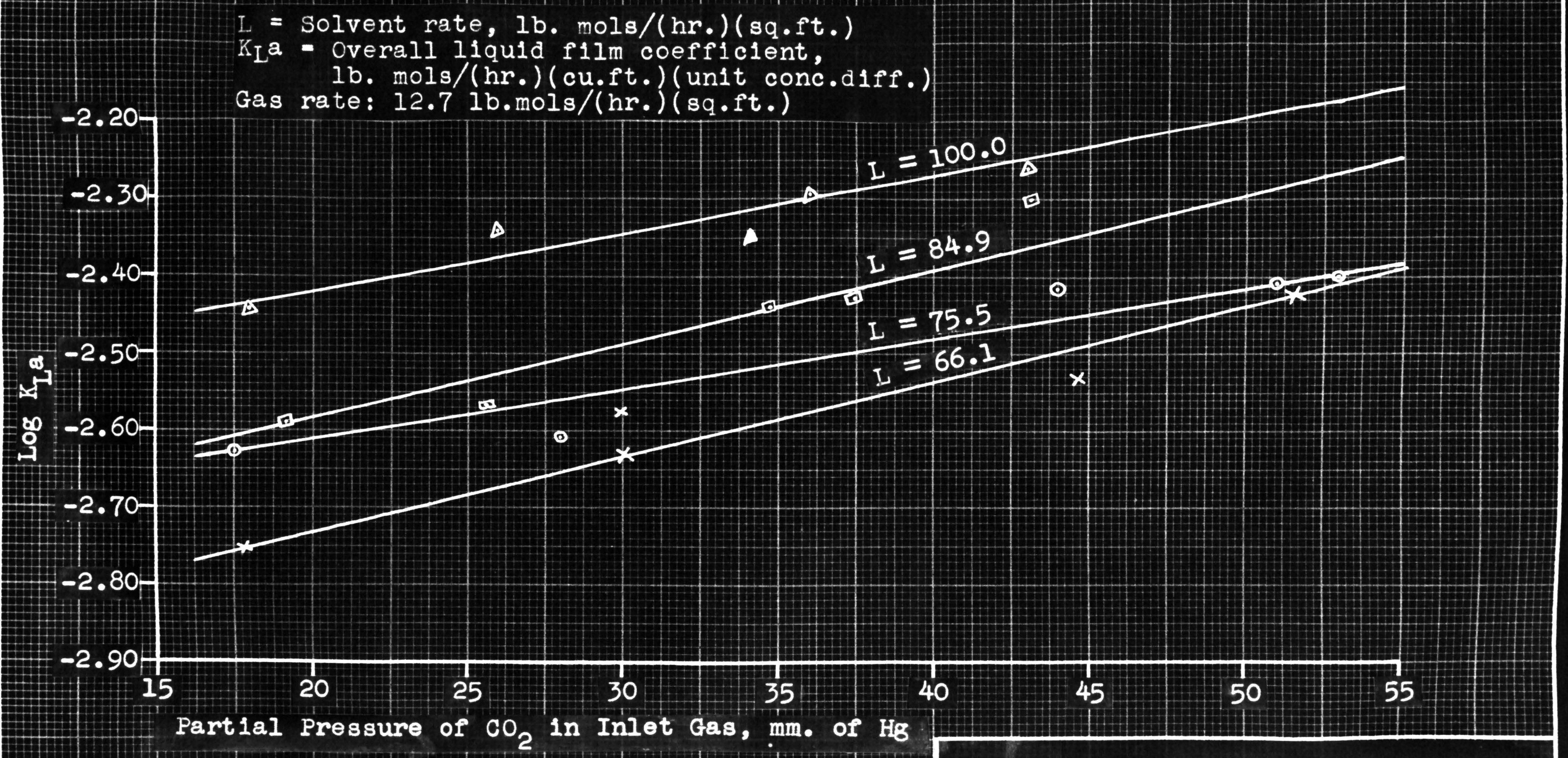
where "m" and "n" are constants to be determined From the previous evaluation of "a" the following equations may be written

For $L = 66.1$ $\quad 1.820 = m - 2.859n$

$L = 75.5$ $\quad 1.878 = m - 2.743n$

$L = 84.9$ $\quad 1.929 = m - 2.685n$

$L = 100.0$ $\quad 2.000 = m - 2.563n$



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Virginia Polytechnic Institute
Blacksburg, Virginia

**Partial Pressure of $CO_2$ in Inlet Gas**
**vs.**
**Log $K_La$**

**Drawn by:**
**Checked by:**

**Figure No.:** 5
**Date:** 9 Oct 47

Summation of the first two equations and the last two equations and simultaneous solution of the resulting two equations yields

$$m = 5.385$$

$$n = 1.260$$

Substituting in the equation

$$\log L = m + na$$

gives

$$\log L = 5.385 + 1.26\ a$$

Thus

$$a = \frac{\log L - 5.385}{1.26}$$

The values of L and "b" are most nearly rectified when L is plotted against "b" as shown in Figure 8(b), page 74. Therefore, the relation between L and "b" is of the type

$$b = f + g\ L$$

where "f" and "g" are constants tobe determined

From the previous evaluation of "b" the following equations may be written

For $L = 66.1$ $\quad 0.0080 = f + 66.1g$

$L = 75.5$ $\quad 0.0064 = f + 75.5g$

$L = 84.9$ $\quad 0.0123 = f + 84.9g$

$L = 100.0$ $\quad 0.0172 = f + 100.0g$

Summation of the first two equations and the last two equations and simultaneous solution of the resulting two equations yields

$$f = -0.00168$$

$$g = 0.000124$$

Therefore

$$b = -0.00168 + 0.000124L$$

Since both "a" and "b" have now been evaluated in terms of L, substitution in the original equation

$$\log K_La = a + bp$$

gives

$$\log K_La = \frac{\log L - 5.385}{1.261} + (0.000124L - 0.00168)p \qquad (34)$$

which may be simplified to

$$\log K_La = 0.793 \log L + (0.000124L - 0.00168)p - 4.27 \qquad (34a)$$

where

$K_La$ = overall liquid-film coefficient, lb.mols/(hr.)(ft.$^3$)(unit conc. diff.)

$L$ = solvent rate, lb.mols/(hr.)(ft.$^2$)

$p$ = partial pressure of $CO_2$ in inlet gas, mm. of Hg

### 3. Derivation of Empirical Equations Relating the Overall Liquid-Film Coefficient ($K_La$), Solvent Rate (L), and Partial Pressure of $CO_2$ in the Inlet Gas (p) at a Constant Gas Rate of 2.0 lb.mols/(hr.)(ft.$^2$).

#### a. Equation Explicit in p.

As shown in Figure No. 6, page 69, the plot log $K_La$ versus the partial pressure of $CO_2$ in the inlet gas results in a series of straight lines. Therefore, the equation relating $K_La$ and the partial pressure is of the general type

$$K_La = 10^{a + bp}$$

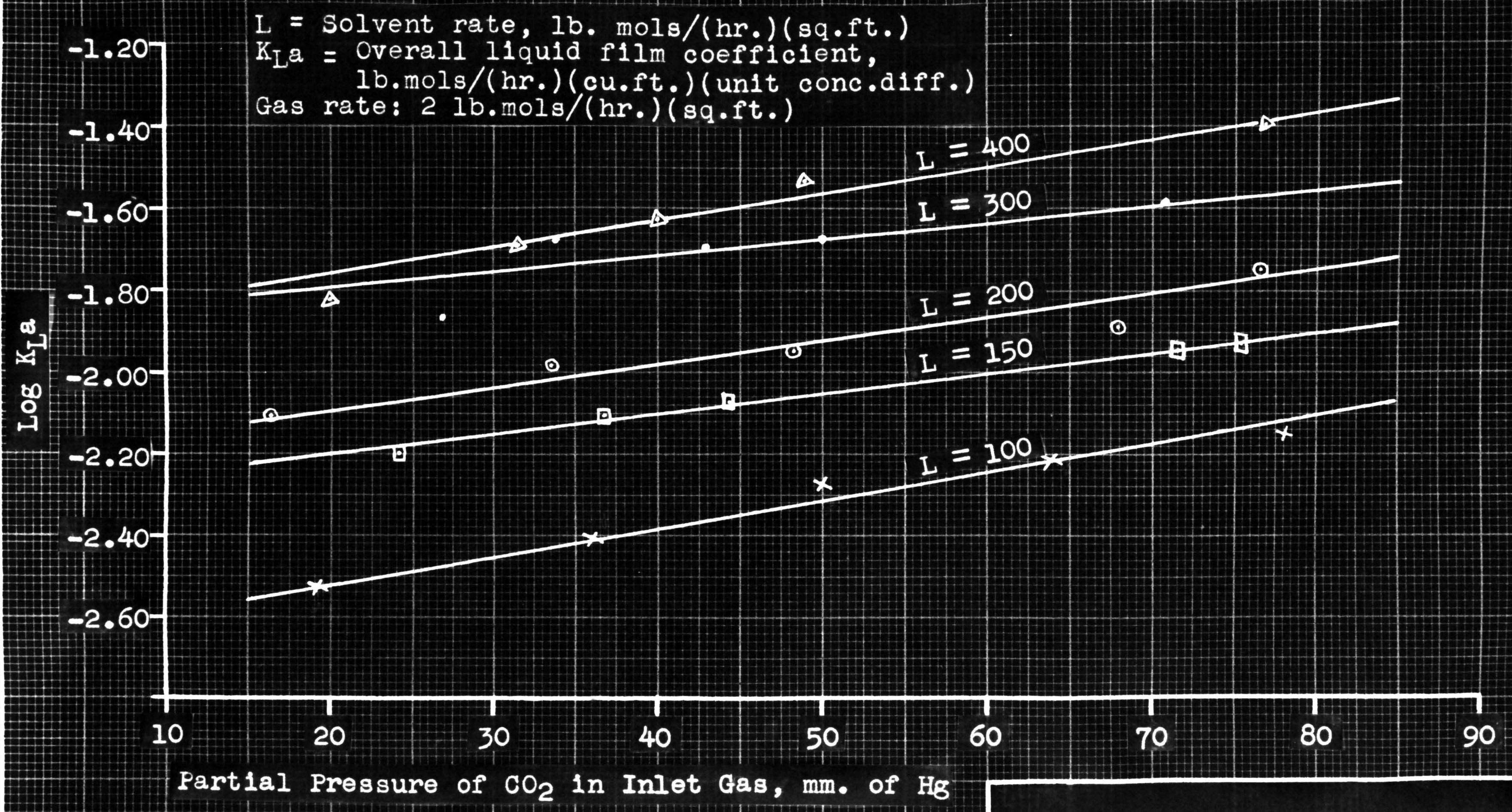
or

$$\log K_La = a + bp$$

In the same manner as in Sample Calculation Number 2, page 63, the following value of "a" and "b" can be determined from Test Numbers 21 through 45.

| L | a | b |
|---|---|---|
| 100.0 | -2.616 | 0.00603 |
| 150.0 | -2.304 | 0.00498 |
| 200.0 | -2.177 | 0.00494 |
| 300.0 | -1.908 | 0.00457 |
| 400.0 | -1.952 | 0.00408 |

The values of L and "a" are most nearly rectified when log L is plotted against "a" as shown in Figure 8(c), page 74. Therefore, the relation between L and "a" is of the general type



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Blacksburg, Virginia

Partial Pressure of $CO_2$ in Inlet Gas
vs.
Log $K_La$

Drawn by:
Checked by:

Figure No: 6
Date: 9 Oct 47

$$L = 10^{m} + na$$

In the same manner as in Sample Calculation Number 2, page 64, the following values of the constants "m" and "n" may be determined

$$m = 5.007$$

$$n = 1.226$$

Therefore

$$a = \frac{\log L - 5.007}{1.226}$$

The values of L and "b" are most nearly rectified when log L is plotted against log "b" as shown in Figure 8(d) page 74. Therefore, the equation relating L and "b" is of the type

$$L = f\,b^{g}$$

or

$$\log L = \log f + g \log b$$

In a manner similar to sample calculation Number 2, page 66, by the following values of the constants "f" and "g" may be determined

$$\log f = 5.881$$

$$g = 1.585$$

Thus

$$\log L = 5.881 + 1.585 \log b$$

Therefore

$$b = 10^{\frac{\log L - 5.881}{1.585}}$$

Substituting in the original equation

$\log K_La = a + bp$

gives

$$\log K_La = \frac{\log L-5.007}{1.226} + (10)\frac{\log L-5.881}{1.585}(p) \qquad (35)$$

which may be simplified to

$$\log K_La = 0.816 \log L + 10^{(0.63 \log L-3.71)}p-4.08 \qquad (35a)$$

where

$K_La$ = overall liquid film coefficient, lb.mols/(hr.)(ft.$^3$)(unit conc. diff.)

$L$ = solvent rate, lb.mols/(hr.)(ft.$^2$)

$p$ = partial pressure of $CO_2$ in inlet gas, mm. of Hg

b. Equation Explicit in L.

As shown in Figure No. 7, page 72, the plot of log $K_La$ versus log of the solvent rate (L), results in a series of straight lines. Therefore, the equation relating $K_La$ and the solvent rate is of the type

$$K_La = aL^b$$

or

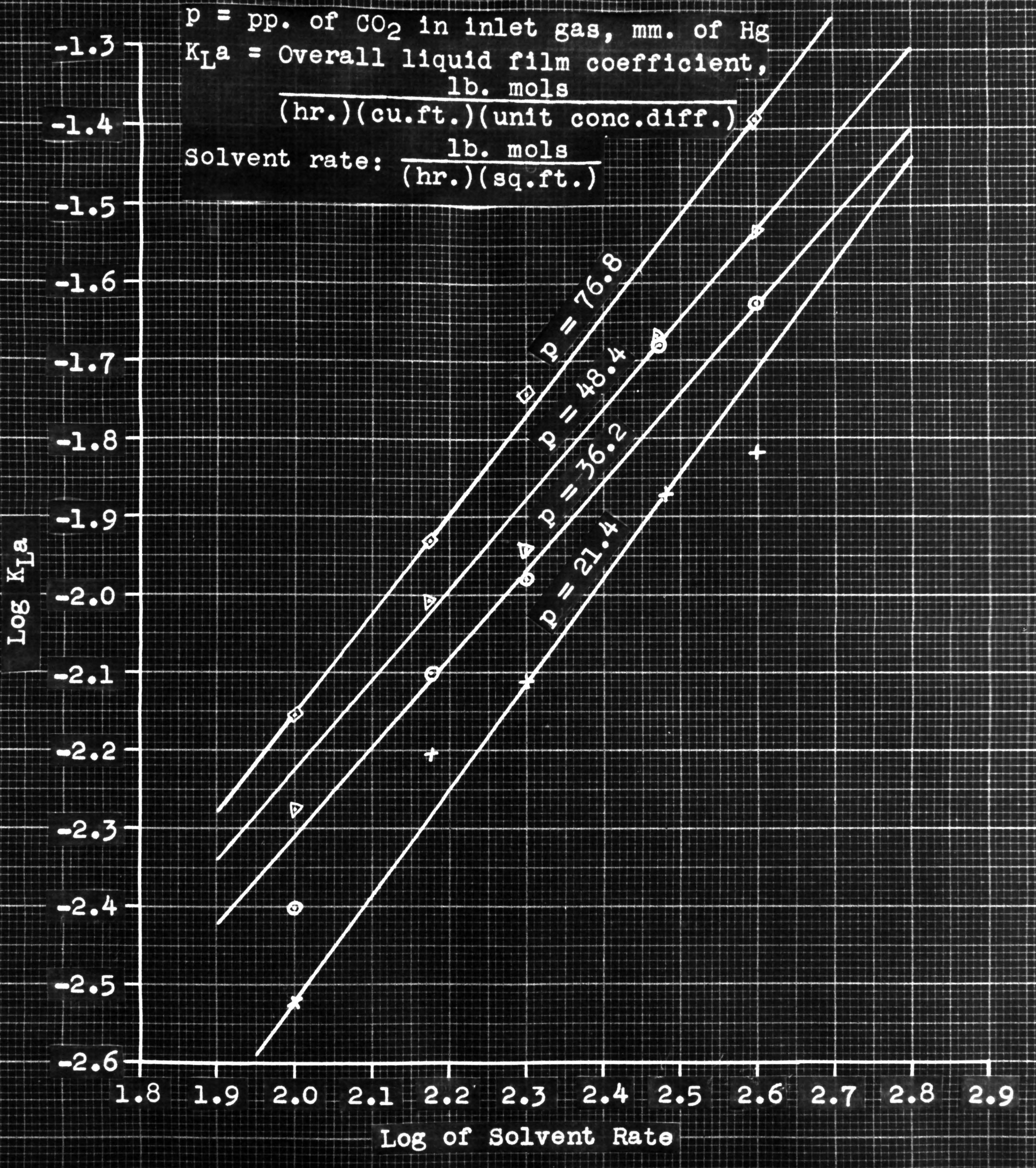
$$\log K_La = \log a + b \log L$$

In a manner similar to Sample Calculation Number 2, page 64, it may be shown that the relation between p and "a" is of the type

$a = m + np$ (See Figure 8(e), page 74).

and that

$$a = 1.357 \times 10^{-5} + (1.942 \times 10^{-8})p$$



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Log of Solvent Rate
vs.
Log $K_La$

Drawn by:
Checked by:

Figure No.: 7
Date: 9 Oct 47

Similarly

$$b = f\ p^g \text{ (See Figure 8(f), page 74).}$$

and

$$b = 1.053p^{0.0478}$$

Therefore

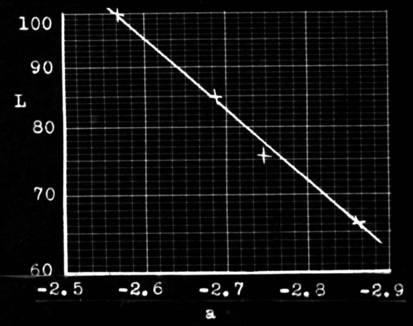
$$K_La = \left[1357\text{x}10^{-8} + (1.942\text{x}10^{-8})p\right] L^{1.053p^{0.0478}} \qquad (36)$$

where

$K_La$ = overall liquid-film coefficient, lb.mols/(hr.) (ft.$^3$)(unit conc. difference)

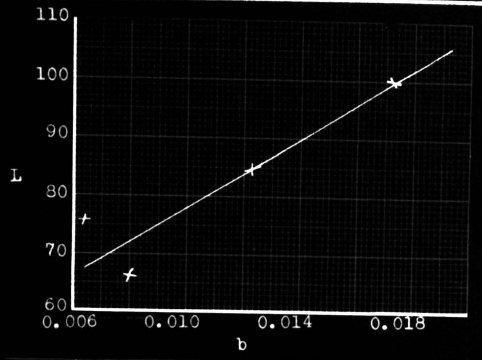
p = partial pressure of $CO_2$ in inlet gas, mm. of Hg

L = solvent rate, lb.mols/(hr.)(ft.$^2$)



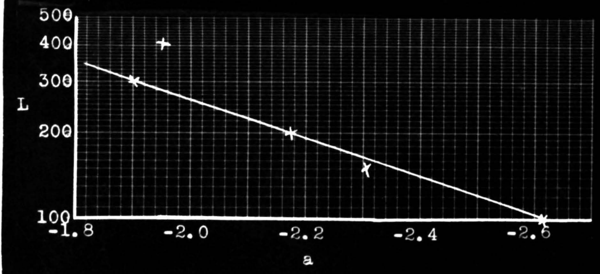
(a)

L vs. "a" in Sample Calculation No. 2, page 64 for Equation No. 34, page 67



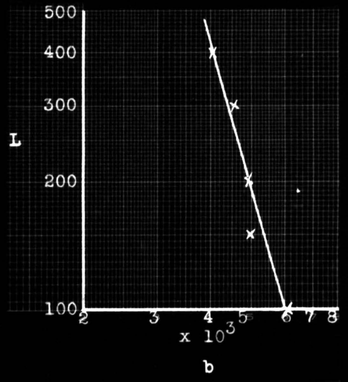
(b)

L vs. "b" in Sample Calculation No. 2, page 66 for Equation No. 34, page 67



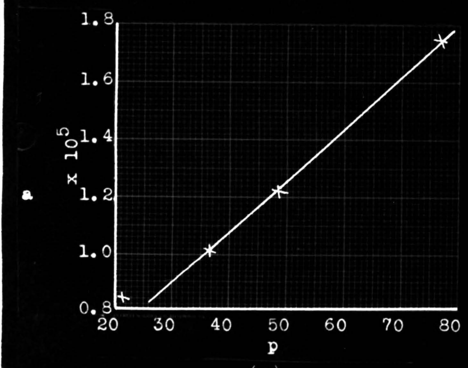
(c)

L vs. "a" in Sample Calculation No. 3a, page 68 for Equation No. 35, page 71



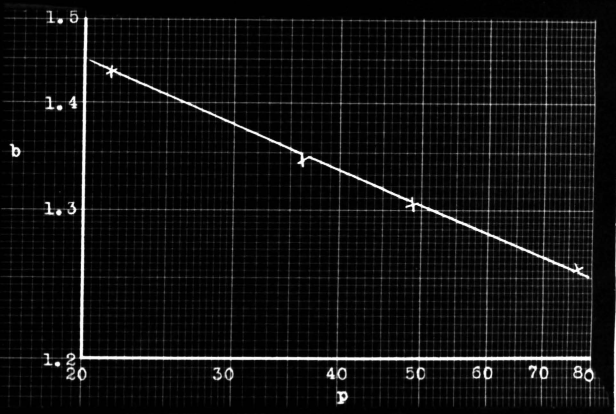
(d)

L vs "b" in Sample Calculation No. 3a, page 70 for Equation No. 35, page 71



(e)

"a" vs. p in Sample Calculation No. 3b, page 71 for Equation No. 36, page 73



(f)

"a" vs. p in Sample Calculation No. 3b, page 73 for Equation No. 36, page 73

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Virginia Polytechnic Institute
Blacksburg, Virginia

Relation of Operating Variables to Constants Used in the Development of Empirical Equations

Drawn by:
Checked by:

Figure No.: 8
Date: 11 Dec 47

# IV. DISCUSSION OF RESULTS

In this investigation experimental data was obtained from the operation of an 18" coke-packed gas absorption tower using the system $CO_2$-$H_2O$, and from this data the overall liquid-film coefficient of absorption ($K_La$), the solvent rate (L), and the partial pressure of $CO_2$ in the inlet (p) were related by means of empirical equations.

## Equipment

**Inlet Water Line.** With a 1 1/2" line from the constant head tank to the top of the tower the maximum rate of flow from the water main could be passed through the tower; however, this maximum rate was only approximately 420 lb.mols/(hr.)(ft.$^2$). Since other investigators(68) investigated solvent rates ranging from 177 to 887 lb.mols/(hr.)(ft.$^2$), the range over which the results of this investigation can be compared is limited.

**Gas Cooler.** The maximum percentage of $CO_2$ in the inlet flue gases during this investigation was 10.71 (see Test No. 23, Table II, page 53); other investigators(15) burning the same fuel (kerosene) and using the same gas cooler obtained an inlet concentration of $CO_2$ to the absorption tower of 12.78%. Water was drained from the cooling coil of the cooler even though no flue gas was passing through the coil, thereby indicating that the presence of water in the cooling coil could not have been the result of condensation of a portion of the flue gas. Since the flue gas is cooled to near its dew point, the cooling coil was probably corroded because of the formation of dilute carbonic acid. The action of water leaking into the cooling coil of the gas cooler was to "strip" out a portion of the $CO_2$ in the flue gas, thereby limiting the range of concentration of $CO_2$ available. Several investigators(17)(68) studied only inlet $CO_2$ concentrations from 15% to 25%; therefore, the comparable results of this investigation are again limited in range.

Furnace. The refractory cement used between the walls of the firebox and the outer furnace shell crumbled each time the furnace cooled after operation. Small particles of the cement would become wedged between the two walls and when the furnace was heated again would cause the walls to warp producing several cracks. This prevented operating the furnace at high enough temperatures to ensure efficient combustion.

Overall Liquid-Film Coefficient, $K_La$. As shown in Table No. III, page 54, results of Test 1 through 20, in which the gas rate was constant at 12.7 lb.mols/(hr.)(ft.$^2$), the solvent rate was varied from 66.1 to 100.0 lb.mols/(hr.)(ft.$^2$) and the inlet gas composition varied from 2.46% $CO_2$ to 7.51% $CO_2$, give values of $K_La$ ranging from 0.00177 to 0.00543 lb.mols/(hr.)(ft.$^3$)(unit conc. diff.) Boisture(15), using the same equipment and system, made absorption studies in which the gas rate was constant at 12.7 lb.mols/(hr.)(ft.$^2$), the solvent rate varied from 63.2 to 115.2 lb.mols/(hr.)(ft.$^2$) and the inlet gas composition varied from 4.06% to 12.78% $CO_2$, obtained values of $K_La$ ranging from 0.00544 to 0.01303 lb. mols/(hr.)(ft.$^3$)(unit conc. diff.). Since this investigation and Boisture's investigation were performed at approximately 80°F. and 714 mm. of Hg, the results should be comparable. However, the values of $K_La$ from this investigation are somewhat lower than those obtained by Boisture. Since the results of this investigation (see Table No. VII, page 58) indicate that an increase in the per cent $CO_2$ in the inlet gas results in a higher value for $K_La$ and Boisture employed higher percentage of $CO_2$ than were used in this investigation, the lower values of $K_La$ are to be expected.

Simmons and Osborn(68) investigated the absorption of $CO_2$ from air by water, at 760 mm. of Hg, in a fiber tube experimental tower 1.6 meters long and 9.1 cm. outside diameter, packed with 0.635 cm. to 1.27 cm. coke. Their data and results over the range of variables comparable to the range of variables in this investigation are summarized in Table No. XIII, page 89. The equation used by Simmons and Osborn to evaluate overall liquid-film absorption coefficient, $(K_La)_1$, was developed by Bennetch and Simmons(13). The units of $(K_La)_1$ are lbs. $CO_2$/(hr.)(ft.$^3$ of operating free volume)(unit conc. diff.), However, both total packed volume and operating free volume were measured by these investigators. If, then, $(K_La)_1$ is multiplied by the ratio of operating free volume to total packed volume and then divided by 44 (converting from lbs. of $CO_2$ to lb.mols), $(K_La)_2$ will have the units of lb.mols/(hr.)(ft.$^3$ of total packed volume)(unit conc. diff.). Therefore, $(K_La)_2$ as shown in the last column of Table XIII, page 89, should be comparable to $K_La$, as computed in this investigation and shown in Table No. III, page 54. It must be remembered that the work of Simmons and Osborn was done at approximately 760 mm. of Hg and the work of this investigation was done at approximately 714 mm. of Hg; consequently, it is to be expected that the higher pressure would produce higher value of $K_La$. However, upon comparison of the two sets of values of $K_La$, the values computed by Simmons and Osborn appear to be somewhat lower than the values of $K_La$ computed from this investigation. According to the results of this investigation (see Table No. V, page 56), $K_La$ decreases with a decrease in gas rate; therefore, since the gas rates of this investigation were 12.7 lb.mols/(hr.)(ft.$^2$) and 2.0 lb.mols/(hr.)(ft.$^2$) and those used by Simmons and Osborn was 0.82 lb.mols/(hr.)(ft.$^2$) or less, their lower values of $K_La$ may be attributed to lower gas rates.

## Factors Affecting $K_La$

**Solvent Rate.** As shown in Table No. IV, page 55, the results of this investigation indicate that the value of $K_La$ increases as the solvent rate increases. This conclusion is corroborated, qualitatively, by the work of both Van Arsdel(71) and Sherwood(61). However, the relation developed by Sherwood relating $K_La$ to liquid rate (see Equation No. 27, page 22) gives values of $K_La$ completely out of the magnitude of the calculated $K_La$'s. However, since Sherwood's equation doesn't take into consideration the effect of inlet gas composition and according to the results of this investigation as shown in Table No. VII, page 58 $K_La$ varies with the inlet gas composition; the equation cannot be expected to apply. However, if Sherwood's equation is written

$$K_La = (C)(0.016\ L^{0.92}) \qquad (37)$$

and the constant "C" is evaluated from known values of $K_La$ and L for a given inlet gas composition and gas rate, the equation may then be used to estimate $K_La$ with an accuracy of approximately plus or minus 14%.

Cantelo, Simmons, Giles, and Brill(17), absorbing $CO_2$ from air by use of water in a glass Raschig ring packed tower 1.6 meters long and 9.1 cm. in diameter, found that $K_La$ decreases "rapidly" with decreasing solvent rate until a critical flow rate is reached whereupon the value of $K_La$

remains substantially constant. From Figure No. 5, page 65, the lines representing different solvent rates are spaced approximately equidistant; therefore, it may be assumed that the critical flow rate for the system used in this investigation lies below 66.1 lb.mols/(hr.)(ft.$^2$).

As shown in Table No. II, page 52 (test Nos. 1 through 20), a 51.3% increase in solvent rate increases the pressure drop across the packed section of the tower 11.0%. Also, from Tests 21 through 45, as shown in Table II, a 300% increase in solvent rate increases the pressure drop across the packed section of the tower by 40.7%. In each of the above cases the gas rate was constant. From equation 30, page 31, it is seen that pressure drop is independent of solvent rate and for a given tower is roughly proportional to the square of the linear gas velocity. However, the above results may be explained by the fact that as the solvent circulates over the packing in the tower it occupies an appreciable fraction of the voids and reduces the mean free cross section open to the passage of the gas. Therefore, as the solvent rate increases the actual linear gas velocity is increased and as shown in Table No. VI, page 57 as gas velocity increases the pressure drop across the packed portion of the tower increases. The above theory is borne out by the work of Chilton and Colburn(18) who found that the pressure drop was influenced both by the gas rate and the free volume of the packing used.

Gas Rate. As shown in Table No. V, page 56, at a solvent rate of 100 lb.mols/(hr.)(ft.$^2$) an 84.3% reduction of the gas rate reduces the value of the overall liquid-film coefficient of absorption by an average of 20%. Moslam, Hershey, and Keen(30) concluded that the liquid-film coefficient is affected only slightly by gas velocity. A possible explanation for the discrepancy between the results of this investigation and those of the above investigators is that a reduction of gas rate from 12.7 to 2.0 lb.mols/(hr.)(ft.$^2$) decreases the turbulence in the liquid stream, with an accompanying decrease in interfacial area between gas and liquid phases. Equation 10, page 12, indicates that the rate of diffusion through a film is proportional to the interfacial area; consequently, if the interfacial area is decreased, the rate of absorption, $K_La$, would decrease.

As shown in Table VI, page 57, at a constant solvent rate of 100 lb.mols/(hr.)(ft.$^2$) an 84.3% reduction of the gas rate reduces the pressure drop across the tower 88.6%. These results are corroborated by other investigators(58).

Composition of Inlet Gas. As shown in Table VII, page 58, $K_La$ increases with an increase in partial pressure of $CO_2$ in the inlet gas. Analysis of Equation 10, page 12, indicates that the driving force through the liquid film, which was the controlling resistance in the system used in this investigation, was a concentration difference over the liquid film; the higher this concentration difference the higher the rate of absorption. Therefore, $K_La$ would be expected to increase with an increase in partial pressure in the inlet gas. This increase of $K_La$ with the partial pressures is also borne out by the empirical equations developed in this investigation. (See Equations Number 34, 35, and 36, pages 67, 71, and 73 respectively.)

Pressure Drop Across Tower. From the results of this investigation there appears to be no relation between the pressure drop through the packed section of the tower and the overall liquid-film coefficient. The random variations of the pressure drop as shown in Table II, page 53 are probably normal variations of replication. Since Chilton and Colburn(18) show that the pressure drop is a function only of the gas rate and free volume of the packing used and that $K_La$ is a function primarily of the solvent rate and the surface-volume ratio of the packing used, no correlation could be expected between the pressure drop and $K_La$.

## Empirical Equations

In the derivation of Equation Number 34, page 67 the relation of the solvent rate (L) to the constant "b" was found to be a straight line (See Figure 8(b), page 74), with "b" increasing as L increased. In the derivation of Equation Number 35, page 71 the relation of the solvent rate (L) to the constant "b" was found to be a straight line where log L was plotted against log "b" (See Figure 8(d), page 74), with "b" decreasing as L increased. Over the range of variables used in this investigation, the amount of the total value of log $K_La$ contributed by the expression found for "b" in either equation is less than 15%. However, as the solvent rate increases, the portion contributed by "b" increases. Therefore, the logarithmic relation, since it covers a wider range of solvent rates, is the more accurate.

The accuracy of the empirical equations developed in this investigation and the conditions under which they were developed are given in Tables No. VIII, IX, and X, pages 84, 85, and 86, respectively. Equation No. 35, page 71, and Equation Number 36, page 73 relate the same variables at a gas rate of 2 lb.mols/(hr.)(ft.$^2$); however, Equation Number 35 is explicit in "p" and Equation Number 36 is explicit in "L".

Table Number XI, page 87 indicates a plus or minus 44.6% deviation when data obtained by Boisture(15), using the same system as used in this investigation, is applied to Equation Number 34, page 67 developed in this investigation. Table No. XII, page 88, indicates a plus or minus 112.2% deviation when the data obtained in this investigation is applied to an equation developed by Boisture using the same system. Since the deviation in the first case is less, it appears that Equation Number 34, page 67 has a wider application.

Substitution of the data of Simmons and Osborn(68) (See Table No. XIII, page 89) in Equation Number 35, page 71 gives positive deviations up to 90%. However, since Equation Number 35

## TABLE NO. VIII

### Deviation of $K_La$ as Computed from an Empirical Equation Developed in this Investigation* from $K_La$ as Computed Directly from Observed Data Obtained by Operating the 18" Stoneware Coke-Packed Gas Absorption Tower at Approximately 80°F. and 714 mm. of Hg Using the System $CO_2$-Water

| Test No. | Gas Rate $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | Solvent Rate L $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | pp. of $CO_2$ in Inlet Gas, p mm. of Hg | $K_La$ (From Obs. Data) $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ | $K_La$ (From Em. Eq.)* $\frac{\text{lb.mols}}{(\text{hr.})(\text{ft.}^3(\text{Unit conc. diff.})}$ | Deviation of $K_La$'s Based on $K_La$ From Obs. Data, % |
|---|---|---|---|---|---|---|
| 1 | 12.7 | 66.1 | 30.1 | 0.00268 | 0.00237 | -11.6 |
| 2 | 12.7 | 66.1 | 18.0 | 0.00177 | 0.00196 | +10.7 |
| 3 | 12.7 | 66.1 | 30.1 | 0.00234 | 0.00234 | 0.0 |
| 4 | 12.7 | 66.1 | 44.7 | 0.00295 | 0.00290 | - 1.7 |
| 5 | 12.7 | 66.1 | 51.4 | 0.00381 | 0.00324 | -14.9 |
| 6 | 12.7 | 75.5 | 51.3 | 0.00386 | 0.00410 | + 6.2 |
| 7 | 12.7 | 75.5 | 28.1 | 0.00244 | 0.00270 | +10.6 |
| 8 | 12.7 | 75.5 | 44.1 | 0.00386 | 0.00365 | - 5.4 |
| 9 | 12.7 | 75.5 | 17.6 | 0.00235 | 0.00229 | - 2.5 |
| 10 | 12.7 | 75.5 | 52.9 | 0.00392 | 0.00423 | + 7.9 |
| 11 | 12.7 | 84.9 | 19.1 | 0.00257 | 0.00267 | + 3.9 |
| 12 | 12.7 | 84.9 | 25.4 | 0.00267 | 0.00303 | +13.4 |
| 13 | 12.7 | 84.9 | 34.7 | 0.00366 | 0.00368 | + 0.5 |
| 14 | 12.7 | 84.9 | 42.9 | 0.00509 | 0.00437 | -14.1 |
| 15 | 12.7 | 84.9 | 37.5 | 0.00370 | 0.00389 | + 5.1 |
| 16 | 12.7 | 100.0 | 36.0 | 0.00508 | 0.00505 | - 0.5 |
| 17 | 12.7 | 100.0 | 18.1 | 0.00363 | 0.00324 | -10.7 |
| 18 | 12.7 | 100.0 | 26.0 | 0.00459 | 0.00395 | -13.9 |
| 19 | 12.7 | 100.0 | 34.2 | 0.00450 | 0.00480 | + 6.7 |
| 20 | 12.7 | 100.0 | 43.1 | 0.00543 | 0.00599 | +10.3 |
| Average percentage deviation (computed without regard to sign): | | | | | | 7.5 |

$$^*\log K_La = \frac{\log L - 5.385}{1.261} + (0.000124L - 0.00168)p$$

where

$K_La$ = overall liquid film coefficient, $\frac{\text{lb.mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$

$L$ = solvent rate, $\frac{\text{lb.mols}}{(\text{hr.})(\text{ft.}^2)}$

$p$ = partial pressure of $CO_2$ in inlet gas, mm. of Hg

## TABLE NO. IX

Deviation of $K_La$ as Computed from an Empirical Equation Developed in this Investigation* from $K_La$ as Computed Directly from Observed Data Obtained by Operating the 18" Stoneware Coke-Packed Gas Absorption Tower at Approximately 80°F. and 714 mm. of Hg. Using the System $CO_2$-Water

| Test No. | Gas Rate $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | Solvent Rate L $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | pp. of $CO_2$ in Inlet Gas, p mm. of Hg | $K_La$ (From Obs. Data) $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ | $K_La$ (From Em. Eq.)* $\frac{\text{lb.mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ | Deviation of $K_La$'s Based on $K_La$ From Obs. Data,% |
|---|---|---|---|---|---|---|
| 24 | 2.0 | 100 | 19.3 | 0.00299 | 0.00405 | +35.4 |
| 21 | 2.0 | 100 | 36.2 | 0.00392 | 0.00470 | +14.8 |
| 22 | 2.0 | 100 | 50.0 | 0.00525 | 0.00527 | + 0.4 |
| 25 | 2.0 | 100 | 64.2 | 0.00604 | 0.00591 | - 2.1 |
| 23 | 2.0 | 100 | 78.3 | 0.00699 | 0.00661 | - 5.4 |
| 45 | 2.0 | 150 | 24.4 | 0.00630 | 0.00660 | + 4.5 |
| 41 | 2.0 | 150 | 36.9 | 0.00790 | 0.00772 | - 2.3 |
| 43 | 2.0 | 150 | 44.4 | 0.00832 | 0.00843 | + 1.3 |
| 44 | 2.0 | 150 | 71.5 | 0.01134 | 0.01178 | + 3.9 |
| 42 | 2.0 | 150 | 75.4 | 0.01174 | 0.01231 | + 4.8 |
| 30 | 2.0 | 200 | 16.3 | 0.00768 | 0.00761 | - 0.9 |
| 27 | 2.0 | 200 | 33.7 | 0.01043 | 0.00940 | - 9.8 |
| 28 | 2.0 | 200 | 48.4 | 0.01130 | 0.01120 | - 0.9 |
| 26 | 2.0 | 200 | 68.2 | 0.01267 | 0.01422 | +12.2 |
| 29 | 2.0 | 200 | 76.8 | 0.01810 | 0.01591 | -12.1 |
| 33 | 2.0 | 300 | 26.9 | 0.01338 | 0.01337 | 0.0 |
| 31 | 2.0 | 300 | 34.0 | 0.02091 | 0.01501 | -28.2 |
| 35 | 2.0 | 300 | 43.0 | 0.02011 | 0.01767 | -12.1 |
| 32 | 2.0 | 300 | 50.1 | 0.02112 | 0.01964 | - 7.4 |
| 34 | 2.0 | 300 | 71.1 | 0.02589 | 0.02717 | + 4.9 |
| 38 | 2.0 | 400 | 20.1 | 0.01504 | 0.01622 | + 7.8 |
| 40 | 2.0 | 400 | 31.7 | 0.02040 | 0.02034 | - 0.1 |
| 37 | 2.0 | 400 | 40.2 | 0.02357 | 0.02393 | + 1.5 |
| 36 | 2.0 | 400 | 48.9 | 0.02913 | 0.02851 | - 2.1 |
| 39 | 2.0 | 400 | 76.8 | 0.04083 | 0.04841 | +18.5 |
| Average percentage deviation (computed without regard to sign) | | | | | | 7.7 |

$$^{*}\log K_La = \frac{\log L - 5.007}{1.226} + (10)^{\frac{\log L - 5.881}{1.585}} (p)$$

where

$K_La$ = overall liquid film coefficient, $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$

L = solvent rate, $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$

p = partial pressure of $CO_2$ in inlet gas, mm. of Hg

## TABLE NO. X

Deviation of $K_La$ as Computed from an Empirical Equation Developed in This Investigation* from $K_La$ as Computed Directly from Observed Data Obtained by Operating the 18" Stoneware Coke-Packed Gas Absorption Tower at Approximately 80°F. and 714 mm. of Hg

Using the System $CO_2$-Water

| Test No. | Gas Rate $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | Solvent Rate L $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | pp. of $CO_2$ in Inlet Gas, p mm. of Hg | $K_La$ (From Obs. Data) $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ | $K_La$ (From Em. Eq.)* $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ | Deviation of $K_La$'s Based on $K_La$ From Obs. Data, % |
|---|---|---|---|---|---|---|
| 24 | 2.0 | 100.0 | 19.3 | 0.00299 | 0.00367 | +22.6 |
| 45 | 2.0 | 150.0 | 24.4 | 0.00630 | 0.00629 | 0.0 |
| 30 | 2.0 | 200.0 | 16.3 | 0.00768 | 0.00875 | +13.9 |
| 33 | 2.0 | 300.0 | 26.9 | 0.01338 | 0.01431 | + 6.5 |
| 38 | 2.0 | 400.0 | 20.1 | 0.01504 | 0.01954 | +29.9 |
| 21 | 2.0 | 100.0 | 36.2 | 0.00392 | 0.00428 | + 9.2 |
| 41 | 2.0 | 150.0 | 36.9 | 0.00790 | 0.00757 | - 4.2 |
| 27 | 2.0 | 200.0 | 33.7 | 0.01043 | 0.01068 | + 2.4 |
| 31 | 2.0 | 300.0 | 34.0 | 0.02091 | 0.01796 | -14.1 |
| 37 | 2.0 | 400.0 | 40.2 | 0.02357 | 0.02563 | + 8.8 |
| 22 | 2.0 | 100.0 | 50.0 | 0.00525 | 0.00507 | - 3.4 |
| 43 | 2.0 | 150.0 | 44.4 | 0.00832 | 0.00843 | + 1.3 |
| 28 | 2.0 | 200.0 | 48.4 | 0.01130 | 0.01220 | + 8.0 |
| 32 | 2.0 | 300.0 | 50.1 | 0.02112 | 0.02069 | - 2.0 |
| 36 | 2.0 | 400.0 | 48.9 | 0.02913 | 0.02938 | + 0.9 |
| 23 | 2.0 | 100.0 | 78.3 | 0.00699 | 0.00601 | -14.0 |
| 42 | 2.0 | 150.0 | 75.4 | 0.01174 | 0.01011 | -13.9 |
| 29 | 2.0 | 200.0 | 76.8 | 0.01810 | 0.01508 | -16.7 |
| 39 | 2.0 | 400.0 | 76.8 | 0.04083 | 0.03623 | -11.3 |
| Average percentage deviation (computed without regard to sign): | | | | | | 9.6 |

$$^{*}\ K_La = \left[1357 \times 10^{-8} + (1.942 \times 10^{-8})p\right] L^{1.053} p^{0.0478}$$

where

$K_La$ = overall liquid film coefficient, $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$

L = solvent rate, $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$

p = partial pressure of $CO_2$ in inlet gas, mm. of Hg

## TABLE NO. XI

Deviation of $K_La$ as Determined by Boisture(15) from $K_La$ as Determined by Applying Boisture's Data to an Empirical Equation Developed in this Investigation* in which the 18" Stoneware Coke-Packed Gas Absorption Tower Was Operated at Approximately 80°F. and 714 mm. of Hg Using the System $CO_2$-Water

| Test No. | Gas Rate $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | Solvent Rate L $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$ | pp. of $CO_2$ in Inlet Gas, p mm. of Hg | $K_La$ (From Obs. Data) $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ | $K_La$ (From Em. Eq.)* $\frac{\text{lb.mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$ | Deviation of $K_La$'s Based on $K_La$ From Obs.Data,% |
|---|---|---|---|---|---|---|
| 3 | 12.7 | 115.17 | 29.4 | 0.00703 | 0.00488 | - 30.6 |
| 4 | 12.7 | 115.17 | 82.4 | 0.01269 | 0.02560 | +102.0 |
| 8 | 12.7 | 115.17 | 88.2 | 0.01303 | 0.03030 | +132.3 |
| 10 | 12.7 | 115.17 | 64.7 | 0.01253 | 0.01534 | + 28.1 |
| 11 | 12.7 | 115.17 | 55.0 | 0.00995 | 0.01156 | + 16.2 |
| 12 | 12.7 | 115.17 | 54.0 | 0.01063 | 0.01123 | + 5.6 |
| 5 | 12.7 | 98.09 | 66.9 | 0.01010 | 0.01650 | + 63.3 |
| 6 | 12.7 | 98.09 | 87.1 | 0.00875 | 0.00677 | - 22.6 |
| 7 | 12.7 | 98.09 | 83.2 | 0.01014 | 0.02430 | +139.4 |
| 16 | 12.7 | 98.09 | 56.1 | 0.00905 | 0.01449 | + 60.1 |
| 13 | 12.7 | 82.06 | 89.4 | 0.00801 | 0.01000 | + 24.8 |
| 14 | 12.7 | 82.06 | 73.6 | 0.00916 | 0.00824 | - 10.0 |
| 18 | 12.7 | 81.06 | 60.1 | 0.00843 | 0.00574 | - 31.9 |
| 19 | 12.7 | 81.06 | 88.5 | 0.01013 | 0.01000 | + 1.3 |
| 9 | 12.7 | 64.08 | 91.6 | 0.00652 | 0.00527 | - 19.1 |
| 15 | 12.7 | 63.19 | 72.8 | 0.00544 | 0.00404 | - 25.7 |
| 17 | 12.7 | 63.19 | 54.6 | 0.00570 | 0.00313 | - 45.0 |
| Average percentage deviation (computed without regard to sign): | | | | | | 44.6 |

$$^*\log K_La = \frac{\log L - 5.385}{1.261} + (0.000124L - 0.00168)p$$

where

$K_La$ = overall liquid film coefficient, $\frac{\text{lb.mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$

L = solvent rate, $\frac{\text{lb.mols}}{(\text{hr.})(\text{ft.}^2)}$

p = partial pressure of $CO_2$ in inlet gas, mm. of Hg

## TABLE NO. XII

Deviation of $K_La$ as Computed Directly from Observed Data Obtained from Operating the 18" Stoneware Coke-Packed Gas Absorption Tower at Approximately 80°F. and 714 mm. of Hg Using the System $CO_2$-Water from $K_La$ as Computed from an Empirical Equation Developed by Boisture(15)*

| Test No. | Gas Rate lb. mols / (hr.)(ft.$^2$) | Solvent Rate L' lb. mols / (hr.)(ft.$^2$) | pp. of $CO_2$ in Inlet Gas, p mm. of Hg | $K_La$ (From Obs. Data) lb. mols / (hr.)(ft.$^3$)(Unit conc. diff.) | $K_La$ (From Em. Eq.)* lb.mols / (hr.)(ft.$^3$)(Unit conc. diff.) | Deviation of $K_La$'s Based on $K_La$ From Obs.Data, % |
|---|---|---|---|---|---|---|
| 1 | 12.7 | 66.1 | 30.1 | 0.00268 | 0.00508 | + 89.5 |
| 2 | 12.7 | 66.1 | 18.0 | 0.00177 | 0.00478 | +170.0 |
| 3 | 12.7 | 66.1 | 30.1 | 0.00234 | 0.00515 | +163.0 |
| 4 | 12.7 | 66.1 | 44.7 | 0.00295 | 0.00554 | + 87.7 |
| 5 | 12.7 | 66.1 | 51.4 | 0.00381 | 0.00575 | + 51.0 |
| Average percentage deviation (computed without regard to sign) | | | | | | 112.2 |

$$^{*}\ \log K_La = \frac{L'}{7.966-0.544L'} + 0.00242p$$

where

$K_La$ = overall liquid film coefficient, $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^3)(\text{Unit conc. diff.})}$

$L'$ = solvent rate, $\frac{\text{lb. mols}}{(\text{hr.})(\text{ft.}^2)}$

p = partial pressure of $CO_2$ in inlet gas, mm of Hg

## TABLE NO. XIII

Recalculation and Summary of the Data and Results Obtained by Simmons and Osborn(68)** from the Operation of a 9.1 cm. Fiber Coke-Packed Gas-Absorption Tower Operated at Approximately 75°F. and 760 mm. of Hg Using the System $CO_2$-$H_2O$

| Test | %$CO_2$ Gas |  | Gas Rate lb.mols/(hr.)(ft.$^2$) | Water Rate lb. mols/(hr.)(ft.$^2$) | Absorption Coefficient |  |
|---|---|---|---|---|---|---|
|  | Inlet | Outlet |  |  | $(K_La)_1$* | $(K_La)_2$* |
| 22 | 16.8 | 14.5 | 0.82 | 111.9 | 0.684 | 0.00665 |
| 23 | 17.0 | 15.1 | 0.81 | 100.5 | 0.663 | 0.00652 |
| 24 | 17.1 | 15.3 | 0.82 | 86.0 | 0.645 | 0.00617 |
| 25 | 17.1 | 15.6 | 0.83 | 385.0 | 0.639 | 0.00534 |
| 31 | 8.5 | 5.1 | 0.28 | 472.8 | 0.924 | 0.00703 |
| 33 | 9.7 | 6.4 | 0.21 | 379.7 | 0.971 | 0.00712 |
| 35 | 15.1 | 12.4 | 0.18 | 385.9 | 1.180 | 0.00986 |

*Units:

$(K_La)_1$: lbs.$CO_2$/(hr.)(ft.$^3$ of operating free volume)(unit conc. diff.)

$(K_La)_2$: lbs.mols/(hr.)(ft.$^3$ of total packed volume)(unit conc. diff.)

**Simmons, C. W. and Osborn, H. B. Tower Absorption Coefficients. Ind. Eng. Chem. <u>26</u>, 531, (1934) was based on a gas rate of 2.0 lb. mols/(hr.)(ft.$^2$) and Simmons and Osborn used gas rates of only 0.82 lb. mols/(hr.)(ft.$^2$) and the results of this investigation indicate that a reduction in gas rate decreases $K_La$ (See Table No. V, page 56), the higher values of $K_La$ from the equation are to be expected. Also, Simmons and Osborn recorded insufficient data to calculate the exact partial pressure of $CO_2$ in the inlet gas.

## Plot of Partial Pressure of $CO_2$ in Inlet Flue Gas vs. Log $K_La$

As shown in Figures No. 5 and 6, pages 65 and 69 respectively, the straight lines representing the average of the points plotted for each of the different solvent rates results in a series of non-parallel straight lines. Since the theory of diffusion offers no explanation as to why the lines are not parallel, a statistical test of significance was made on the slope of each line representing each solvent rate. This test of significance indicated that the slope of the lines did not differ significantly from zero; therefore, as much variability in the slope of the lines as shown in Figures No. 65 and 69 is to be expected.

## Recommendations

On the basis of the results observed in this investigation, the following recommendations are made:

1. Furnace. Before any further work is undertaken, this portion of the equipment should be dismantled and rebuilt. At least 1/2" free space should be allowed between the firebox walls and the outer furnace shell to permit expansion and contraction of these elements. A refractory cement with a coefficient of thermal expansion approximately equal to the coefficient of thermal expansion of the fire bricks should be employed in the construction.
2. Flow Rates. In order to reach solvent flow rates used by other investigators (800 lb. mols/(hr.)(ft.$^2$), a line should be installed directly from the water main line entering the building to the constant head tank.
3. Gas Cooler. One side should be removed from the gas cooler and the cooling coil removed and checked for corrosion due to the formation of dilute carbonic acid. The corroded elements should be replaced by new elements after first being treated with a high temperature resistant silicone varnish. This would permit higher percentages of $CO_2$ in the inlet gas to the tower to be obtained.

4. Calculation of $K_La$. $K_La$ as calculated in this investigation is a volumetric coefficient based upon the total packed volume of the tower. To obtain values of $K_La$ that are more closely related to the interfacial area available for absorption, $K_La$ should be based upon the operating free volume of the tower which is proportional to the interfacial area. To determine the operating free volume, it would first be necessary to determine the drained free volume. This could be done by measuring the amount of solvent that is required to fill the tower. Then, the operating free volume could be determined by passing the gas and solvent through the tower at the desired rate and then closing the inlet and outlet solvent valves simultaneously. The effluent liquid could then be drained off, measured and subtracted from the drained free volume to give the operating free volume.

5. Future Investigations. An investigation should be designed with a statistical approach to ascertain the variation of $K_La$ due to replication. A brief statistical analysis of the curves plotted in Figures No. 5 and 6, pages 65 and 69 respectively, indicated that the slopes of the curves did not differ significantly from zero, which seems to indicate that log $K_La$ does not vary significantly with the partial pressure of $CO_2$. This should be checked by a statistically designed experiment.

## Limitations

On the basis of the data observed in this investigation, the following limitations must be applied to the results:

1. Gas rate-- 2.0 and 12.7 lb.mols air/(hr.)(ft.$^2$)
2. Solvent rate-- 66.1 to 400.0 lb.mols water/(hr.)(ft.$^2$)
3. Partial pressure of $CO_2$ in inlet gas-- 16.3 to 78.3 mm. of Hg
4. Temperature of inlet absorbing water-- 54.5 to 59.9°F.
5. Temperature of inlet gas-- 62.0 to 86.0°F.
6. Room temperature-- 72.5 to 90.5°F.
7. Barometric pressure-- 710.0 to 716.5 mm. of Hg

## V. CONCLUSIONS

In this investigation to relate the operating variables of solvent rate and inlet gas composition to the overall liquid-film coefficient of absorption of an 18" coke-packed absorption tower using the system $CO_2$-$H_2O$, the following limiting conditions were used:

a. Solvent rate-- 66.1 to 400.0 lb.mols water/(hr.)(ft.$^2$)

b. Partial pressure of $CO_2$ in inlet gas-- 16.3 to 78.3 mm. of Hg

c. Temperature of inlet absorbing water-- 54.5 to 59.9°F.

d. Temperature of inlet gas-- 62.0 to 86.5°F.

e. Room temperature-- 72.5 to 90.5°F.

f. Barometric pressure-- 710.0 to 716.5 mm. of Hg

On the basis of the results observed in this investigation, the following conclusions are drawn:

1. The relationship, at a constant gas velocity of 12.7 lb.mols/(hr.)(ft.$^2$) between the overall liquid film absorption coefficient ($K_La$), the solvent rate (L), and the partial pressure (p) of the soluble constituent ($CO_2$) conforms to the equation

$$\log K_La = 0.793 \log L + (0.000124L - 0.00168)p - 4.27$$

The accuracy of this equation when applied to the data of this investigation is plus or minus 7.5%.

2. The relationships, at a constant gas velocity of 2.0 lb.mols/(hr.)(ft.$^2$), between the overall liquid-film absorption coefficient ($K_La$), the solvent rate (L), and the partial pressure (p) of the soluble constituent ($CO_2$) fonforms to the equations

   $$\log K_La = 0.816 \log L + 10^{(0.63 \log L - 3.71)}p - 4.08$$

   $$K_La = \left[1357 x 10^{-8} + (1.942 x 10^{-8})p\right] L^{1.053p^{0.0478}}$$

   The accuracies of these equations when applied to the data of this investigation are 7.7% and 9.6%, respectively.
3. At a solvent rate of 100 lb.mols/(hr.)(ft.$^2$), an 84.3% reduction of the gas rate reduces the values of the overall liquid-film coefficient of absorption by an average of 20%.
4. At a solvent rate of 100 lb.mols/(hr.)(ft.$^2$), an 84.3% reduction of the gas rate reduces the pressure drop across the packed section of the tower 88.6%.
5. At a gas velocity of 12.7 lb.mols/(hr.)(ft.$^2$), a 51.3% increase in solvent rate increases the pressure drop across the packed section of the tower by 11.0%.
6. At a gas velocity of 2.0 lb.mols/(hr.)(ft.$^2$), a 300% increase in solvent rate increase the pressure drop across the packed section of the tower by 40.7%.

7. No correlation exists between the overall liquid-film coefficient ($K_La$) and the pressure drop ($\triangle p$) through the packed section of the tower.

## VI. SUMMARY

This investigation dealt with the determination of the operating characteristics of an 18" stoneware absorption tower twenty-one feet high, fifteen feet of which were random packed with 1 1/2 to 2 inch coke. The tower was located in the Unit Operations Laboratory of the Department of Chemical Engineering, Virginia Polytechnic Institute, Blacksburg, Virginia. Forty-five experiments, using carbon dioxide, in a flue gas mixture, as the solute and water as the solvent, were made to determine and to relate the overall liquid-film coefficient of absorption ($K_La$, lb.mols/(hr.)(cu.ft.)(unit conc. diff.)) to the solvent rate (L, lb.mols/(hr.)(sq.ft.)) and the partial pressure (p, mm. of Hg) of the inlet carbon dioxide. The following relations were developed:

At a constant gas rate of 12.7 lb.mols/(hr.)($ft.^2$)

$$\log K_La = 0.793 \log L + (0.000124L-0.00168)p-4.27$$

At a constant gas rate of 2.0 lb.mols/(hr.)($ft.^2$)

$$\log K_La = 0.816 \log L + 10^{(0.63 \log L-3.71)}p-4.08$$

$$K_La = \left[1357\times10^{-8} + (1.942 \times 10^{-8})p\right] L^{1.053p^{0.0478}}$$

The accuracies of the above equations when applied to the data of this investigation are 7.5%, 7.7%, and 9.6% respectively within the following ranges of conditions:

Solvent rate-- 66.1 to 400.0 lb.mols water/(hr.)($ft.^2$)

Partial pressure of $CO_2$ in inlet gas-- 16.3 to 78.3 mm. of Hg

Temperature of inlet absorbing water-- 54.5 to 59.9°F.

Temperature of inlet gas-- 62.0 to 86.0°F.

Room temperature-- 72.5 to 90.5°F.

Barometric pressure-- 710.0 to 716.5 mm. of Hg

It was found that, at a solvent rate of 100 lb.mols/(hr.)(ft.$^2$), an 84.3% reduction of the gas rate reduced the value of the overall liquid-film coefficient of absorption by an average of 20% and the pressure drop across the packed section of the tower 88.6%.

Results of this investigation indicated that the pressure drop across the tower increases slightly with an increase in solvent rate, but no correlation was found between the pressure drop and the overall liquid-film coefficient of absorption.

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