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TABLE OF CONTENTS

	Page
I. Introduction.....	1
II. Literature Review.....	3
III. Experimental	
A. Purpose of Study.....	19
B. Plan of Investigation.....	19
C. Materials.....	25
D. Apparatus.....	27
E. Methods of Procedure.....	36
F. Data and Results.....	41
IV. Discussion of Results.....	54
V. Conclusions.....	66
VI. Summary.....	67
VII. Bibliography.....	69
VIII. Acknowledgments.....	73

FIGURES

Figure		Page
I.	Proposed Gas Cooler.....	23
II.	Flow Diagram for 18-inch Stoneware Tower..	24
III.	Gas Cooler for 18-inch Stoneware Tower....	25
IV.	18-inch Stoneware Tower.....	24
V.	Furnace for 18-inch Stoneware Tower.....	25
VI.	Graph, Log K_{LA} vs Partial Pressure of CO_2 .	49

TABLES

Table		
I.	Proposed Plan of Operations.....	21
II.	Table of Experimental Data.....	42
III.	Table of Calculated Results.....	43

I. INTRODUCTION

The process of absorption or desorption finds wide application in industry today as a means of removing a useful or an objectionable constituent from gases or liquids. However, in view of the complex nature of the mechanism by which the process of absorption is thought to occur the data which is available to the engineer for the design of absorption equipment is very limited and, in most instances, may be applied only to specific cases.

The most important contributions to the theoretical considerations involved in absorption processes are those of Whitman (38) and Lewis and McAdams (12). Whitman in 1925 advanced the "two-film theory" of diffusion upon which the present concepts of the mechanism of absorption are based. Lewis and McAdams in 1928 presented graphical methods, based on the "two-film theory" and the theory of equilibrium partial pressure of the solute gas between the gas phase and the liquid phase, for the calculations of gas absorption problems. This method provides a fairly accurate means of computing the required data for the design of absorption equipment but does not take into consideration all of the variables involved in the process.

In recent years a great amount of work has been done by such men as Chilton and Colburn (3), Dodge and Payne (5), and Sherwood (32) based on theories advanced by Whitman, and Lewis and McAdams in an effort to determine the effect of such factors as the temperature

and pressure of the system, the overall pressure drop through the tower, the apparent mass velocity of the gas and liquid phases through the tower, and the concentration of the soluble constituent in the gas phase.

However, the major portion of this work has been done on relatively small size equipment, and consequently the data obtained by these investigators, when applied to design calculations, is subject to limitations. In only a few instances have the investigations been made using what might be classed as pilot plant equipment.

In this investigation it is planned to use an 18 inch stoneware tower with a 15 foot packed section. The packing will consist of 1-1/2 to 2 inch coke dumped at random in the tower. An attempt will be made to remove carbon dioxide from flue gas by absorption in water; prior to use, will be treated with Zeolite to remove any calcium and magnesium present. The effect of such variables as the gas and water velocity, the pressure drop across the column, and the per cent of carbon dioxide in the flue gas on the overall coefficient will be investigated.

II. LITERATURE REVIEW

The basis of all processes involving absorption or desorption lies in the fact that a gas-liquid system not at equilibrium will tend to approach such a condition at a certain rate which is not constant but is dependent upon the degree of saturation of the liquid phase and on the difference in the concentration of the solute in the gas phase and in the liquid phase.

(13)

Lewis and Whitman state that in most cases the "rate of absorption of a solute from a gas by a liquid is limited by processes of diffusion". It is generally assumed that wherever a gas and a liquid are in direct contact there is set up a definite gas-liquid interface bounded on one side by a static liquid film and on the other by a static gas film. In the main bodies of the gas and liquid, mixing, by convection, will be so rapid that the concentration of the solute will be essentially uniform throughout; thus, obviously, any material transfer through the surface films must occur by some diffusional process.

Diffusion through the liquid film proceeds at a rate that is proportional to the concentration difference of the solute in the liquid at the interface and in the main body of the liquid. Likewise, the rate of diffusion through the gas film is controlled by the difference in the concentration of the solute in the main body of the gas and at the interface. From the previous statements it

follows then that the driving force which causes diffusion to take place, in the case of both the gas and the liquid films, is a difference in concentration. This driving force, or difference in concentration, may be termed the specific conductivity of the resisting films. The specific resistance of the gas and liquid films is generally considered a function of the film thickness and the density of the gas or the liquid respectively. As might be expected, the more dense the medium through which diffusion must occur, the greater is the resistance to the process of material transfer. The major factor in determining film thickness under comparable conditions of disturbance is thought to be the ratio of the viscosity to the density. Since this ratio is greater for gases than for liquids, it is apparent that the specific resistance of the gas film would be the greater of the two. However, the greater specific conductivity of the gas film tends to counteract this difference in the resistances, making it necessary to consider the effect of both the liquid and the gas films in most diffusional processes.

Theory of Diffusion

(25)

Sherwood derives a theoretical expression for the rate of diffusion (N_A) of one gas (A) through a second stagnant gas (B) which may be written:

$$N_A = \frac{k}{x} \frac{(P_{A1} - P_{A2})}{P_{BM}}$$

- where N_A = The rate of diffusion of component (A) through the gas film
- k = Constant
- x = Distance in direction of diffusion
- P_{A1} = Partial pressure of gas (A) at point x_1
- P_{A2} = Partial pressure of gas (A) at point x_2
- P_{BM} = Log mean average partial pressure of component (B) at points x_1 and x_2

This equation states that the rate of diffusion is directly proportional to the difference in partial pressure of the diffusing gas (A), and inversely proportional to the length of the path and to the logarithmic mean of the extreme values of the partial pressure of the stagnant or interfering gas (B). This equation is the relation found to be most generally applicable to diffusion processes as encountered in commercial absorption processes.

The rate equation for the steady state diffusion of a solute through a stagnant solvent film is expressed by Sherwood ⁽²⁷⁾ in the following manner:

$$N_A = \frac{D}{x} (C_A + C_B) \frac{(C_{A2} - C_{A1})}{C_{BM}}$$

- where N_A = The rate of diffusion of component (A) through the liquid film
- D = Diffusion coefficient
- x = Distance in direction of diffusion
- C_A = Partial molar density of gas (A) in the main body of the solvent.

- C_B = Partial molar density of gas (B) in the main body of the solvent.
- C_{B2} = Partial molar density of gas (B) at point x_2
- C_{B1} = Partial molar density of gas (B) at point x_1
- C_{BM} = Log mean average partial molar density of gas (B) at points x_1 and x_2
(58)

According to Walker, Lewis and McAdams the correlation of diffusivities in the liquid phase is less satisfactory than for the gas phase. This can probably be attributed to such complicating factors as ionization, association, and dissociation of solute molecules in the liquid phase. Due to relatively large change in the viscosities of liquids with small changes in temperature, the effect to temperature upon diffusion through the liquid phase is much greater than through the gas phase. The data on the diffusion of solutes through stagnant liquid films is limited; but, in general, the rate of diffusion ($\frac{D}{\mu}$) is approximately proportional to the inverse three-halves power of the viscosity.

Film Coefficients

The rate at which the material diffusing is transferred from one phase to another is dependent upon the character of the gas and liquid in question, the conditions of temperature and concentration in the system, and the amount of interphase area available to the diffusional process. Taking these factors into consideration, Badger and McCabe (1)

give the following equation for the rate of diffusion of a gas (A) through a stationary gas film made up principally of an inert component (B):

$$\frac{W}{a} = \frac{b_{Gv} (P_{AG} - P_{Ai})}{(P_B)_{lm} B_G}$$

- where
- W = Weight of component (A) diffusing per unit time
 - a = Interfacial area across which diffusion is occurring
 - b_{Gv} = Diffusion coefficient
 - B_G = Equivalent film thickness
 - P_{AG} = Partial pressure of component (A) in the bulk of the gas stream
 - P_{Ai} = Partial pressure of component (A) at the interface
 - P_{Bi} = Partial pressure of component (B) at the interface
 - P_{Bg} = Partial pressure of component (B) in the gas stream
 - $(P_B)_{lm}$ = Log mean partial pressure of component (B)

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

$$\frac{W}{a} = \frac{b_{lv} (C_{Ai} - C_{Al})}{B_l}$$

- where
- C_{Ai} = Concentration of component (A) at the interface
 - C_{Al} = Concentration of component (A) in the liquid stream

b_{lw} = Diffusion coefficient

B_1 = Equivalent film thickness

Since the surface films are usually very thin, the amount of solute retained in the films would be quite small compared to the amount diffusing through the films and, therefore, the assumption may be made that any material being transferred through one film will, in turn, diffuse through the next. The individual rate equations for the gas and liquid films must then be equal:

$$\frac{W}{s} = \frac{b_{gw} (P_{Ag} - P_{Al})}{(P_B)_m B_g} = \frac{b_{lw} (C_{Al} - C_{Al})}{B_1}$$

A further generalization combining the terms representing the film thickness, the diffusion coefficients, and the partial pressure of the inert gas to give a single coefficient for each film leads to the following equation:

$$\frac{W}{s} = k_g (P_{Ag} - P_{Al}) = k_l (C_{Al} - C_{Al})$$

where $k_g = \frac{b_{gw}}{(P_B)_m B_g}$; gas film coefficient

$k_l = \frac{b_{lw}}{B_1}$; liquid film coefficient

Factors Influencing the Film Coefficients, k_g and k_l

(22)

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

Factors Affecting k_l

(23)

Van Arsdol stated that as the velocity of the liquid relative to that of the gas increased a corresponding increase in the liquid-film coefficient was observed until a certain "critical flow-rate" was reached; after which, further increase had little effect.

(23)

Baker, Harte, and Elgin state that, in general, when the principal resistance is in the liquid film, changes in the liquid flow rate from low to high values will result in significant changes in the absorption coefficient (k_l), the effect being more pronounced the lower the flow rate. Also, the liquid film coefficient is increased by an increase in the temperature because of both increased diffusivity and decreased viscosity.

(10)

Haslam, Hershey, and Keen found that for the systems, NH_3 in water and SO_2 in water, k_l is proportional to T^4 , where T is

the absolute temperature.

(23)
Halloway, in a study on desorption of CO_2 , O_2 , and H_2 from water by air, obtained data which indicated that k_1 is proportional to $e^{-0.023t}$ where t is the water temperature, $^{\circ}\text{C}$, over the range of 5° to 40° C. "This indicates that k_1 increases more rapidly with temperature (at least, over the range 5° to 40° C.) than T^4 ."

(18)
McCormack says that available information tends to show that k_1 is dependent upon the liquor rate, or velocity, but is relatively independent of the nature of the diffusing solute. This statement is perhaps too inclusive in view of the work by Hutchinson and Sherwood (11) in which pure gases, H_2 , He , C_2H_2 , N_2 , O_2 , CO_2 , SO_2 , and Cl_2 were absorbed in water. The liquid was stirred to give a velocity effect and a study of the water-film coefficient variation with stirrer speed was made. Although a general equation,

$$k_1 = 0.0048(\text{RPM})^{0.6}$$

was derived for all the gases, the maximum deviation at like temperatures was 20 per cent.

A generally applicable equation for the liquid-film coefficient in packed towers has been determined by Sherwood and Halloway (33):

$$\frac{k_1 a}{D} = c \left(\frac{l}{u} \right)^{1-n} \left(\frac{u}{D} \right)^{1-s}$$

where u is the liquid viscosity; n , s , and c are constants whose values depend upon the type of packing and equipment used;

(L) is the liquid flow rate; and other symbols are as previously defined.

(25)

Baker, Harte, and Elgin discuss a possible source of error in calculations of k_1 in some of the experimental work on packed towers due to the assumption that the interfacial area is always constant. Actually, "when the rate of liquid flow is low there may be a considerable fraction of the surface of the packing which is not supplied with fresh liquid and, therefore, is not active. Increasing the liquid flow rate will increase the fraction of the surface of the packing which is active and will therefore increase the apparent liquid-film coefficient."

Factors affecting the Gas-Film Coefficient k_g

(26)

Sherwood showed by means of the equation

$$\frac{d}{B^0} = 0.023 \left(\frac{dvp}{\mu}\right)^{0.83} \left(\frac{\mu}{pD}\right)^{0.44}$$

that k_g varies directly as the gas mass velocity to the 0.83 power.

where $\frac{dvp}{\mu}$ = Reynolds number

$\frac{\mu}{pD}$ = Schmidt number

d = Diameter of tower

D = Diffusion coefficient

B⁰ = Effective thickness of gas film in feet

(10)

Haslam, Hershey, and Kean in their work on the absorption of SO_2 and NH_3 in water found that the following empirical equations applied for calculation k_g :

$$k_g = C'' u^{0.8} \left(\frac{s}{z}\right)^{2/5}$$

$$k_g = e' u^{0.8} \frac{1}{T^{1.4}}$$

where u = Gas velocity
 e' = Constant
 C'' = Constant
 s = Specific Gravity
 z = Viscosity of the gas
 T = Absolute temperature

(17)

According to McCormack experiment shows that k_g is proportional to some power of the gas mass velocity; i.e., $k_g = k(g)^n$, the value of the exponent being in most cases 0.8.

(25)

Sherwood lists several factors which effect k_g ; however, these factors are supported only by data on wetted-wall towers:

- (a) Proportional to the 0.56 power of the diffusivity.
- (b) Inversely proportional to approximately the 0.2 power of the tower diameter.
- (c) Independent of the total pressure at a given velocity.
- (d) Proportional to the square root of the absolute temperature at a given Reynold's number.
- (e) Proportional to approximately the 0.8 power of the gas mass velocity.

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

(9)

Hanks and MoAdams found that the gas-film coefficient is inversely proportional to the average partial pressure of the inert gas in the gas film.

Overall Coefficients, K_G and K_L

It is usually more convenient and more accurate to measure the partial pressure and the concentration of the solute gas in the main body of the gas and liquid phases rather than at the interface. For this reason the following equations, based on the assumption that one or the other of the films is the controlling resistance in the diffusion process, have been derived:

$$K_G = \frac{W}{a (P_{Ag} - P_{Al})}$$

$$K_G = \frac{W}{a (C_{Ag} - C_{Al})}$$

where K_G and K_L are the overall coefficients based on the gas and liquid films, respectively, controlling.

It is readily seen that $(P_{Ag} - P_{Al})$ and $(C_{Ag} - C_{Al})$ are the overall driving forces across both the gas and the liquid films.

In the systems which conform to Henry's Law the overall coefficients may be expressed in terms of the individual film

coefficients, k_g and k_l :

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

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

Also, K_L and K_G may be related by the equation:

$$K_L = H (K_G)$$

where (H) is Henry's Law constant.

It is desirable, in most cases where calculations are made on packed towers, to group the overall coefficients, K_G and K_L , with the area factor (A) due to the difficulty in measuring either quantity separately. The factor (A) is defined as the active wetted surface in square feet per cubic feet of packed volume. The active area of the packing varies with both the gas and liquid velocities and is by no means proportional to the actual area of the packing due to several factors, which according to Sherwood are:

- (a) Uneven distribution of liquor over the cross section of the tower.
- (b) Failure of the liquor to wet all of the individual particles.
- (c) Inactive surface at the points of contact of the packing particles, at which the liquor remains stagnant and soon becomes saturated with the solute.

Factors Influencing K_G , K_{GA} , K_L , and K_{LA}

(16)

McCormack says that, in general, the correlation of the

absorption coefficients with the operating variables and physical properties of the system is impossible in view of present knowledge; however, empirical relationships for specific cases are available.

According to Baker, Harte, and Elgin⁽²⁴⁾, considerable error is involved in the calculations of overall coefficients by existing equations, when the gas phase enters the system unsaturated with the solvent vapors and leaves saturated. Use of the usual coefficients may involve an extreme error of 15 per cent. There is no simple method for calculating precise coefficients for this case; however, Sherwood⁽²⁶⁾ offers a diffusion rate equation for such a case which may be applied under certain assumptions.

Donald and Rysen⁽⁶⁾ found that the overall coefficient of absorption in packed towers is dependent upon the density of the gas and is some function of the relative velocity between the gas and the liquid.

Sherwood and Kilgore⁽²⁴⁾ found that the overall coefficients for both absorption and desorption increase with gas velocity and at some critical velocity values of both coefficients are, with experimental error, the same.

According to Sherwood⁽³¹⁾ "it may be noted that the effect of temperature on K_{GA} is different from that on K_{LA} . Since $K_{GA} = H(K_{LA})$ it is possible for K_{GA} to decrease and K_{LA} to increase with an increase in temperature, "because of the fact that (H) is an inverse function of the temperature.

Factors Affecting K_L and K_{LA}

(2)

Cantelo, Simmons, Giles, and Brill, as a result of their studies on the absorption of CO_2 and SO_2 in water, state that the rate of absorption was only slightly affected by gas velocity or gas composition; but was found to decrease rapidly with the liquid flow rate until a critical flow rate was reached, where values of K_L remained constant.

(7)

Drake found that the water velocity had little or no effect upon K_L in the system CO_2 and water in a packed tower; while the gas velocity was found to have a large influence upon the overall liquid-film coefficient.

(30)

Sherwood found that the effect of temperature, in systems where the liquid-film controls, is so large that an increase in temperature over a 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 absorption should be carried out. This optimum may be well above room temperature, so it should not be stated as a general rule, as sometimes given, that absorption processes should always be carried out at temperatures as low as possible."

Factors Affecting K_G and K_{CA}

(8)

Greenwalt offers experimental data on the drying of air with

H_2SO_4 , in a pyrex tube 2 inches in diameter and 32 inches long, which indicates that the overall gas-film coefficient K_G varies as the 0.4 power of the pressure drop across the column.

Although an adequate theory to explain why an increase in the liquor rate increases K_{GD} has never been offered, Comstock and (5) Dodge found that it is commonly assumed that increased turbulence results in a thinner film and, hence, a larger coefficient. However, they say that it is more reasonable to assume that the increased liquor rate increases the amount of liquid available to absorb the solute.

H. E. T. P.

One of the common methods of designing packed towers is to determine the number of theoretical plates that would be required if the operation were carried out in a plate tower, and then to convert to the height of a packed tower, by multiplying the number of theoretical plates by the height of packing equivalent to an (30) theoretical plate. This method is commonly referred to as H. E. T. P., and it is the height of packing that will give the same separation as one theoretical plate. Although this method supposes a stepwise countercurrent operation for a true countercurrent process, the method is fairly accurate if the number of plates is large, and the change in concentration of the solute small.

(15)

According to McCormack the concept of H. E. T. P. is less fundamental than that of overall transfer coefficients and depends upon the relative slopes of the operating line and the equilibrium curve and hence may vary widely over the concentration range in a given column; Correlation of H. E. T. P. with pertinent variables has not been successfully accomplished and this method is primarily empirical.

H. T. U.

Another design method for packed towers is the use of the height of a transfer unit, H. T. U. The H. T. U. is the height of the tower divided by the number of transfer units and is essentially a measure of the difficulty of the diffusional process.

The relationship between the H. T. U. and the overall liquid film coefficient K_{LA} may be expressed by the equation (15)

$$(H. T. U.)_{oL} = \frac{L_M}{K_{LA}(1-x)_{lm}}$$

where $(H.T.U.)_{oL}$ = The height of a theoretical unit in feet, based on the liquid film controlling

L_M = Molar liquid velocity, lb. mols/hr./sq. ft.

K_{LA} = Overall liquid film coefficient, lb. mols/cm. ft./hr./unit conc. difference

$(1-x)_{lm}$ = Log mean concentration difference expressed mols of solute/mol of solvent.

III. EXPERIMENTAL

Purpose of Study

The purpose of this study is:

1. To modify the design of an 18-inch stoneware, coke-packed absorption tower and accessory equipment in such a way as to correct certain inherent difficulties encountered in the operation of the tower, when CO_2 is stripped from flue gas using water as the solvent.
2. To determine the operating characteristics of the tower once the design has been modified.
3. To determine the relationship between the overall absorption coefficient, $K_L a$, and certain operating variables, such as liquid rates and the concentration of the soluble constituent, CO_2 , in the gas stream.

Plan of Investigation

The following is an outline of the work which will be carried out during the course of the investigation:

1. Preliminary Investigation.

- a. Review of the literature with particular emphasis on work by previous investigators who used, basically, the same equipment which is to be used in this study.
- b. Review of possible analytical methods for use in determination of the carbon dioxide content of the flue gas and the

absorbing medium.

2. Preliminary Construction.

- a. Construction and installation of a gas cooling unit of the tubular type to replace present spray cooler. (See Figure 1, page 23.)
- b. Construction and installation of the necessary orifices, manometers, thermometer wells, and draft gages to give more accurate control of the operating variables. (See Figure 2, page 24.)
- c. Construction of a variable-speed drive unit for the blower used to force the flue gas through the tower.
- d. Construction of a venturi meter to measure rate of gas flow from tower.

3. Calibration of Instruments.

- a. Calibration of all orifices.
- b. Calibration of thermometers.
- c. Calibration of venturi meter.

4. Operation of the Absorption Tower.

The proposed plan of operation of the absorption tower is given in Table I, page 21.

5. Data to be Obtained.

Note: See Figure No. 2, page 24.

- a. Temperatures, °F.

T_1 , Inlet gas to tower.

Table No. I

PROPOSED PLAN OF OPERATIONS

Run Number	Gas Velocity ft/min	Water Rate lb/min	% CO ₂ in Blue Gas
1	400	40	8.0
2	"	50	"
3	"	60	"
4	"	70	"
5	"	80	"
6	"	40	10.0
7	"	50	"
8	"	60	"
9	"	70	"
10	"	80	"
11	"	40	12.0
12	"	50	"
13	"	60	"
14	"	70	"
15	"	80	"

Temperatures (Continued), °F.

- T₂. Outlet gas from tower.
- T₃. Inlet water to tower.
- T₄. Outlet water from tower.
- T₅. Inlet gas to cooler
- T₆. Furnace firebox.
- T₇. Inlet cooling water.
- T₈. Outlet cooling water.

b. Pressures.

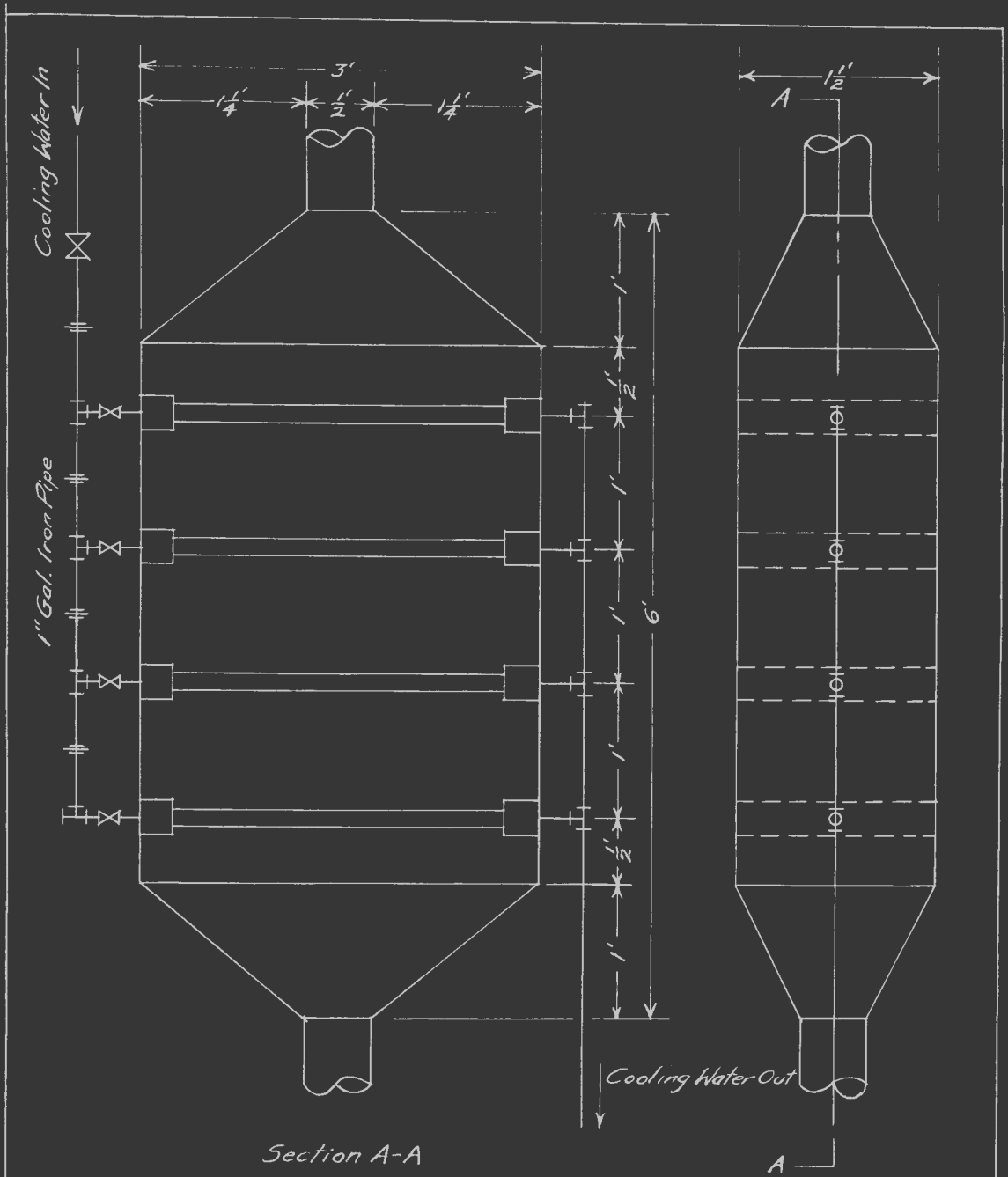
- P₁. Inlet gas.
- P₂. Outlet gas.

c. Concentrations.

- C₁. Carbon dioxide in inlet gas.
- C₂. Carbon dioxide in outlet gas.
- C₃. Free carbon dioxide, carbonates, and bicarbonates in inlet water.
- C₄. Free carbon dioxide, carbonates, and bicarbonates in outlet water.

d. Flow Rates.

- V₂. Outlet gas from tower.
- V₃. Inlet water to tower.
- V₇. Inlet water to cooler.
- V₈. Air to furnace.
- V₉. Fuel oil to furnace.



Section A-A

FIGURE NO. 1

Note: Cooling elements are Standard Flexitube "AEROFIN" Units.

VIRGINIA POLYTECHNIC INSTITUTE
DEPARTMENT OF CHEMICAL ENGINEERING
BLACKSBURG, VIRGINIA

FLUE GAS COOLER FOR THE
18" GAS ABSORPTION TOWER

Scale: 1" = 1'
Date: 6-13-46

Drawn by: WWB
Checked by: fa-13

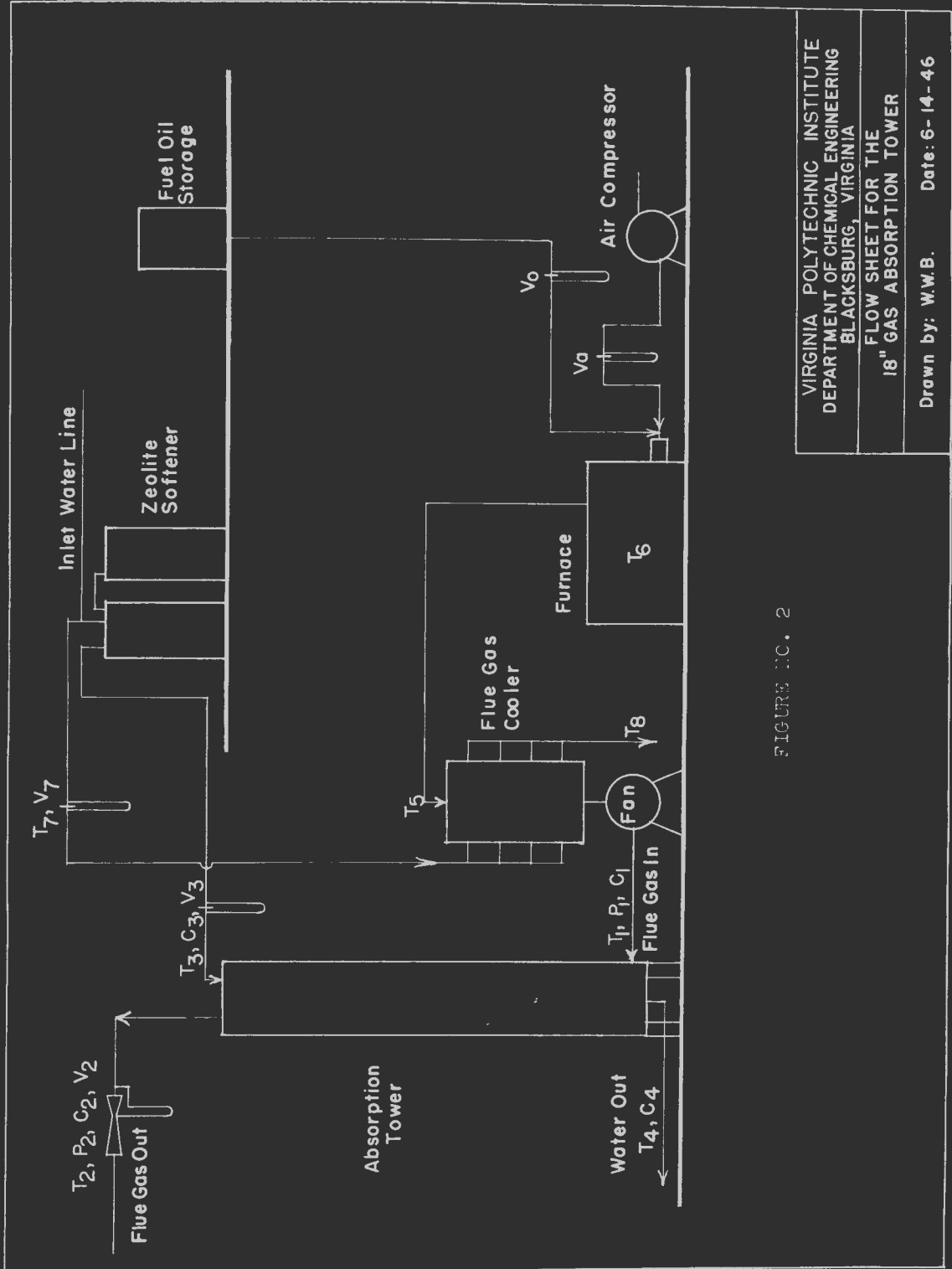


FIGURE NO. 2

VIRGINIA POLYTECHNIC INSTITUTE
DEPARTMENT OF CHEMICAL ENGINEERING
BLACKSBURG, VIRGINIA

FLOW SHEET FOR THE
18" GAS ABSORPTION TOWER

Drawn by: W.W.B. Date: 6-14-46

6. Calculations.

- a. Calculation of overall coefficient of absorption, $K_L a$.
- b. Derivation of empirical equations relating the overall coefficient of absorption, $K_L a$, to such variables as the gas velocity, water velocity, and concentrations of carbon dioxide in the gas and liquid streams.

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 0.0159 N. Used in determination of free CO_2 in absorbing water.

J. T. Baker Co., Phillipsburg, New Jersey.

Cupric Oxide, reagent special, lot No. 29. Used to prepare acid cuprous chloride solution for CO determination. General Chemical Co.,

N. Y., N. Y.

Acid Sulfuric, A.C.S. std., sp. gr. 1.84, lot No. 72648. Used in preparation of pickling solution for descaling stovepipe. J. T.

Baker Co., Phillipsburg, New Jersey.

Acid Hydrochloric, A.C.S. std., sp. gr. 1.19, lot No. 325460. Used to prepare acid cuprous chloride solution for CO determination.

Also as analytical reagent, standardized at 0.0509M, in carbonate and bicarbonate determination. J. T. Baker Co., Phillipsburg, New Jersey.

Potassium Acid Phthalate, C. P. Used in standardisation of 0.0139N 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. 0.827. Used as indicating fluid in draft gases. The Meriam Company, 1955 West 114th St., Cleveland, Ohio.

Grease, Stepcock, Dow Corning, lot No. 458025. Used to lubricate all stepcocks on gas analysis apparatus. Dow Corning Corp., Midland, Mich.

Resin (Silicone), Dow Corning, No. 801, lot No. P-1. Used in compounding resin mixture which was applied to stovepipe to prevent corrosion. Dow Corning Corp., Midland, Mich.

Resin (Silicone), Dow Corning, No. 803, lot No. M-7. Used in compounding resin mixture which was applied to stovepipe to prevent corrosion. 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. Malkey Salt Co., Detroit, Michigan.

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

Apparatus

Tower, Absorption, (one), consisting of seven 18" (inside diameter) by 33" chemical stoneware sections, packed with two-inch coke. Used as an experimental device for absorption studies. Stoneware sections manufactured by United States Stoneware Company, Akron, Ohio. (See Figure No. 4, page 34.)

Burner, Oil, D.F.C., (one), Number G2-3372. Used to burn fuel. Manufactured by the Denver Fire Clay Company, Denver, Colorado.

Furnace, Oil Burning, (one), built of fire brick with an outer shell of common brick. (See Figure No. 5, page 35.)

Blower, Centrifugal, (one), 12" diameter, single inlet, type C1, serial No. 101721, equipped with step cone pulley. Used to force gas through absorption tower. Manufactured by Clarage Fan Company, Kalamazoo, Michigan.

Compressor, Hyter, Mash, (one), size AL-574, 8 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 Mash Engineering Company, South Norwalk, Connecticut.

Motor, Induction, Western Electric, (one), Type 1824 15 1800, Form C, 15 H.P., 220 volts, 36.9 amperes, speed full load 1740, 60 cycles, 3 phase, A. C., continuous 40° rise. Used to drive compressor. Manufactured by Western Electric Company.

Motor, Induction, General Electric, (one), 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, Schenectady, New York.

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

Pump, Oil, Rotary, Sliding Vane, (one), Used to circulate fuel oil. Manufactured by Brown and Sharpe Manufacturing Company, Providence, Rhode Island.

Softener, Water, Zeolite, (one), Humber VT-13458, Type HS-18. Used to soften absorbing water. Manufactured by the Permutit Company, New York, N. Y.

Compressor, Air, Ingersoll-Rand, (one), serial No. 30T-18646, model No. VS402, size 33"x 1 3/4"x 2 3/4". Used to supply compressed air for DeVilbiss, Spray-painting Equipment. Manufactured by the Ingersoll-Rand Company, New York, N. Y.

Scales, platform type, (one), No. 1571193. Used to weigh discharge water from absorption tower. Purchased from Sears, Roebuck and Company, Philadelphia, Penn.

Balance, analytical, Becker Chainomatic, (one), Used in analytical work. Manufactured by Seoderer-Kahlbusch, Inc., Jersey City, N. J.

Painting Equipment, Spray, DeVilbiss, (one), No. 146814, type-MBC. Used in applying silicone resin to stovepipe used in construction of gas cooler. Manufactured by the DeVilbiss Company, Toledo, Ohio.

Oven, Drying, Infra-red, (one). Used to dry silicone coated stovepipe. Designed and constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

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

Gage, Draft, single tube, (one). Used in conjunction with Pitot Tube. Manufactured by the Meriam Company, Cleveland, Ohio.

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

Manometers, U-tube, vertical, Hg filled, (two). 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, oil over water, (one). 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, (one), consisting of:

Measuring Unit, gas, Fisher, (one), Precision Mine-Air

Model, 72 ml. graduated in 0.2 ml., 22 ml. in 0.1 ml., and 6 ml. in 0.05 ml. divisions.

Absorption Unit, gas, Fisher, (one), Valve-Bubbler Model.

Absorption Unit, gas Fisher, (one), Contact Pipette Model.

Sampling Tubes, gas, (six), with stopcocks, 250 ml.

Used for the analytical determination of the percent 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.

Thermometers, glass, (two), 10° - 200° F, 2° graduations. Used to determine the wet and dry bulb temperature of exit gas from absorption tower. Purchased from the Fisher Scientific Company, Pittsburg, Pa.

Thermometers, Weston, (four), 0° - 250° C, 2° graduations. Used to determine wet and dry bulb temperature of inlet gas to absorption tower and exit gas from absorption tower. Manufactured by the Western Electrical Instrument Corporation, Newark, New Jersey.

Thermometer, Weston, (one), 0° - 220° F, 2° graduations. Used to determine temperature of exit liquid from absorption tower. Manufactured by the Weston Electrical Instrument Corporation, Newark, New Jersey.

Thermometer, Weston, (one), 50° - 250° F, 2° graduations. Used

to determine temperature of inlet water to absorption tower.
Manufactured by the Weston Electrical Instrument Corporation,
Newark, N. J.

Analytical Equipment, Miscellaneous:

Pipettes, 50 ml., (two).

Flasks, volumetric, 500 ml., (four).

Flasks, volumetric, 1000 ml., (one).

Flasks, Erlenmeyer, 250 ml., (six).

Burette, 50 ml., stopcock, (one).

Burette, 50 ml., bead, (one).

Dishes, evaporating, porcelain, No. 2, (six).

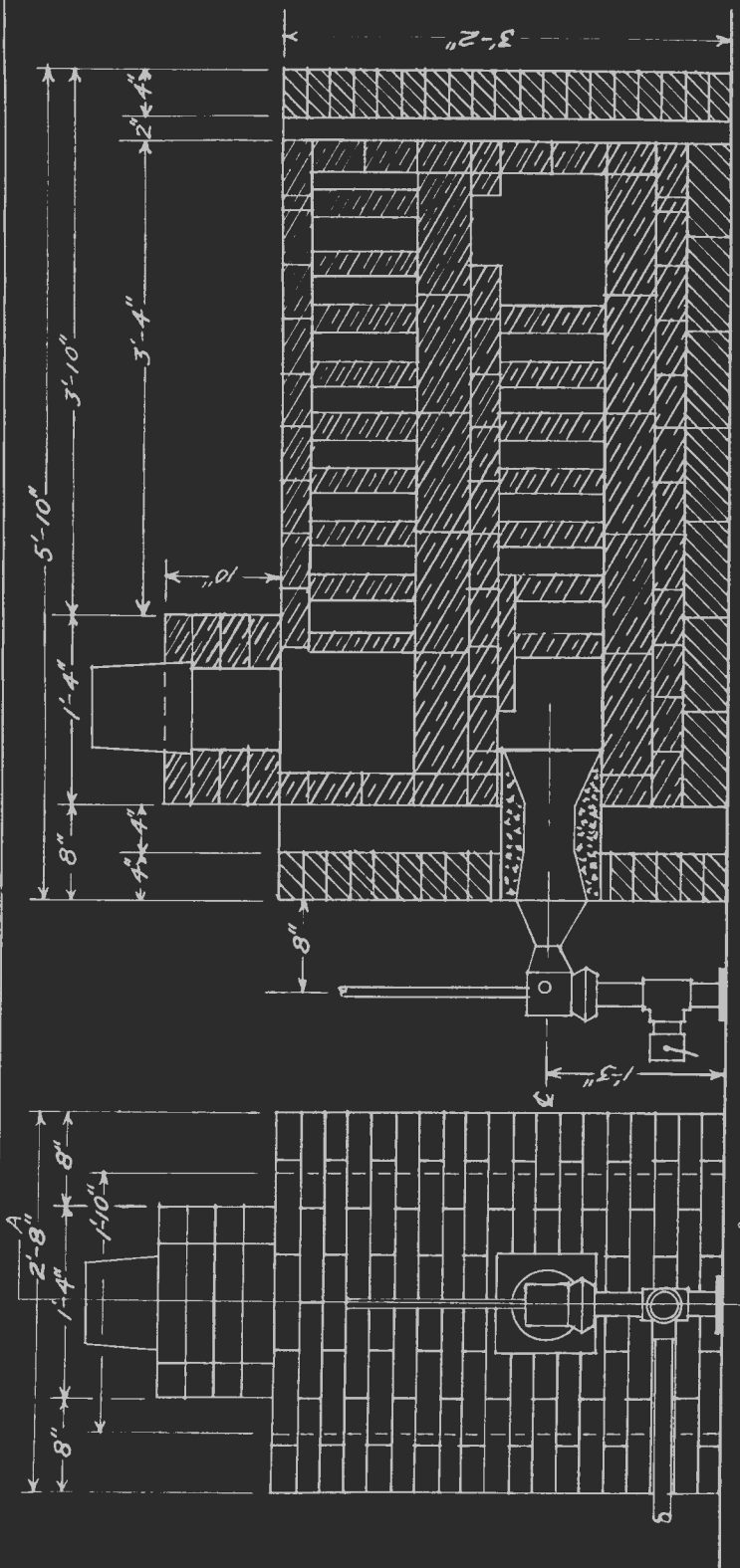
Gages, Draft, (two), single tube, inclined 30 degrees, filled with Merian Red Oil. Used to determine pressure drop across absorption tower. Designed and constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Barometer, Precision Mercurial, (one), Fortin principal.

Manufactured by Henry & Green, New York, N. Y.

Cooler, Gas, (one), 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 33.) The materials used in the construction of this cooler are listed below:

<u>Material</u>	<u>Type</u>	<u>Size</u>	<u>Amount</u>
Stovepipe	St. Section	6" D	14
Stovepipe	Elbow, 90°	6" D	4
Stovepipe	Tee	6" D	1
Stovepipe	Elbow, adjustable	6" D	2
Stovepipe	St. Section	5" D	5
Stovepipe	Elbow, 90°	5" D	42
Stovepipe	Reducer	6"x 5"	1
Dumper		6"	2
Tin	Sheet, galv.	26 gage	85 sq. ft.
Angle Iron	Hot rolled	1-1/4"x 1-1/4"	110 ft.
Screws	Metal holding	1/2" No. 8	1 gr.
Bolts	Stove, round head	1/2"x 1/8"	3 gr.
Bolts	Stove, round head	1"x 1/8"	1 gr.
Pipe	Galv.	2"	22 ft.
Pipe	Galv.	1-1/4"	22 ft.
Pipe	Galv.	1/2"	50 ft.
Elbows	Galv., 90°	2"	4
Elbows	Galv., 90°	1-1/4"	3
Elbows	Galv., 90°	1/2"	4
Elbows, street	Galv., 90°	1/2"	8
Tees	Galv.	2"x 2"x 2"	1
Tees	Galv.	1/2"x 1/2"x 1/2"	16
Unions	Malleable iron	1-1/4"	2
Unions	Malleable iron	1/2"	2
Caps	Galv.	1/2"	2
Cross	Galv.	1/2"x 1/2"x 1-1/4"	1



Department of Chemical Engineering
 Virginia Polytechnic Institute
 Blacksburg, Virginia

FURNACE
 FOR

18-INCH GAS ABSORPTION TOWER

Drawn by: *WAB*
 Checked by: *SKY*
 Approved by: *FWB*

Figure No.:
 Scale: 3/16" = 1'
 Date: 1, Jan, 1947

Methods of Procedure

Construction: On the basis of recommendations made by previous investigators it was deemed necessary that certain modifications and additions to the existing equipment be made, which are as follows:

1. Design and Construction of Gas Cooler. A detail drawing of the cooler is shown in Figure 3, page 33. Previous investigators, Musick (20), and Darwin and Miles (19), used a cooler of the direct contact spray type which allowed intermixing of the flue gas and cooling water, with a resultant loss of a considerable quantity of the carbon dioxide by absorption in the cooling water. Therefore, in order to eliminate this loss, it was necessary that a cooler be designed which would prevent direct contact of the flue gas and coolant.

The main problem encountered in the design of this cooler was the selection of materials which would be suitable and also readily available. A rather serious corrosion problem was encountered in cooling the gas to temperatures at or near its dew point, due to the formation of dilute carbonic acid from the carbon dioxide formed when the fuel oil was burned.

In order to reduce this corrosion to a minimum the stovepipe, which was used in construction of the cooling coil, was coated with a high temperature resistant silicone varnish (60% Dow Corning SC 803, 40% Dow Corning SO 801). Before this was done, however, it was necessary that the pipe be thoroughly degreased and descaled. The degreasing was accomplished by treatment in a 10% NaOH solution at

180° F for approximately ten hours. After degreasing, the stove pipe sections were immediately placed in a pickling bath of 5% H_2SO_4 at 80° F for approximately one hour. The pipes were then washed thoroughly in acid free water. Next, they were dipped in acetone and placed in an atmospheric dryer operating at about 86° F. The acetone was used to decrease the time of drying and thereby retard rust formation. As soon as the pipes were dry, they were sprayed with silicone varnish and allowed to air-dry for about twelve hours. The pipes were then placed in an infra-red drying oven and baked for six hours at 450° F.

The frame for the cooler was constructed of 1-1/4 x 1-1/4" angle iron and was of all welded construction. After completion of the frame, the cooling coil and spray heads were installed. The stove-pipe joints forming the cooling coil were secured by means of metal holding screws and sealed with Permatex gasket sealing compound. The sheet metal sides were then put in place and secured by means of stove bolts and sealed with Permatex to prevent leakage of cooling water. The cooler, as a unit, was then installed (See Figure No. 4, page 34.) and the necessary gas and water lines connected.

2. Construction and Installation of Orifices and Manometers.

In order to provide a more accurate means of controlling the flow rates of air, water, and fuel oil used in operating the absorption tower, metering devices were installed in the following lines: (See Figure 2, page 24.)

- a. Fuel oil: 1/4" orifice with 3/8" globe valve
and 3/8" needle valve control.

- b. Compressed air: 3/4" orifice with 1-1/4" globe valve and 3/4" needle valve control.
- c. Water to tower: 9/16" orifice with 3/4" globe valve and 3/4" needle valve control.
- d. Water to cooler: 3/4" orifice with 1-1/4" globe valve and 3/4" needle valve control.

Standard U-tube manometers (30" long) were installed to measure the pressure drop across all orifices. The orifices were made from No. 16 gage copper plate and placed in the lines between standard pipe flanges.

3. Draft Gages. In order to measure the pressure drop across the tower it was necessary to install two draft gages, one at the bottom and one at the top of the tower. The draft gages were made of 1/8" glass tubing with 1/8" rubber tubing connections leading to the pressure taps in the column. The gages were filled with Meriam Red Oil, sp. gr. 0.827, and were installed at an angle of 30° from horizontal. Each gage was fitted with a scale graduated in 0.05".

4. Installation of Pitot Tube. The gas velocity through the tower was measured by use of a standard Ellison pitot tube. Prior to installation this instrument was calibrated by the Aeronautical Engineering Department, Virginia Polytechnic Institute. Care was taken in installing the tube to make certain that the tip of the tube was placed directly in the center of the gas exhaust line and that it was exactly parallel to the direction of flow, since any error in placement would seriously affect the operation of the tube. A Meriam single tube draft gage, graduated in 1/100 inches of water was used to measure

the pressure differential across the tube.

5. Installation of Constant Head Water Tank. During the first preliminary test runs it was found that the main water line pressure and resulting flow varied considerably when other equipment was in use. In order to eliminate this condition it was necessary to install a constant head tank. This tank was made from a 10 gallon steel barrel and was installed nine feet above the top of the tower.

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

1. Furnace operation. In order to insure efficient operation of the oil burner, it was necessary to install a cloth filter in the oil line and a 40 mesh wire filter in the air line to prevent solid particles, such as rust and scales, from clogging the atomizing jets on the oil burner. Before each period of operation, both filters were removed and cleaned. After the filters were replaced, the oil circulating pump and the Hyter air compressor were started. Small amounts of fuel oil and air were then admitted into the oil burner 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 was operated at a constant air-fuel ratio, with the flue gases bypassing the absorption tower until a constant temperature was reached.

2. ...

2. Gas Flow. After the furnace had reached a constant temperature, the flow of flue gases was diverted, by means of dampers, from the stack to the gas cooler. The gas passed through the cooler and was forced through the tower by means of a centrifugal blower, which was operated at constant conditions.

3. Water flow. Zeolite softened water passed through a constant head tank 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. Data collected. After 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:

a. Temperatures (At ten minute intervals), °F.

1. Inlet absorbent water.
2. Outlet absorbent water.
3. Dry bulb temperature of inlet flue gases.
4. Wet bulb temperature of inlet flue gases.
5. Dry bulb temperature of exit flue gases.
6. Wet bulb temperature of exit flue gases.

b. Manometer readings (At ten minute intervals).

1. Compressed air.
2. Water to cooler.
3. Oil to furnace.

4. Static pressure in base of tower.
5. Static pressure in top of tower.
- c. Draft gage reading (at ten minute intervals).
 1. Pitot tube.
- d. Water samples, 250 ml. (at ten minute intervals).
 1. Inlet water to tower.
 2. Outlet water from tower.
- e. Gas samples, 250 ml. (at twenty minute intervals).
 1. Inlet gas to tower.
 2. Outlet gas from tower.

Analytical Determinations:

1. Free CO₂ in water. Fifty ml. portions from each water sample taken during the test were analysed for free CO₂ content by titrating against 0.0139 N NaOH, using phenolphthalein as the indicator.

2. Per Cent CO₂ in gas. The procedure used in the determination of CO₂ in the fine gas was that given by Matsuzaki (14).

Data and Results

Experimental Data: The experimental data for this investigation is presented in Table No. 2, page 42. All temperatures recorded are the corrected values.

Part 2 of the results of this investigation will be given in Table 3,

TABLE NO 2

LOG OF EXPERIMENTAL DATA FOR TEST RUNS ON 18-INCH GAS ABSORPTION TOWER

TEST NO.	DATE	WATER FLOW RATE TO TOWER $\frac{lb.}{min.}$	WATER TEMPERATURE °F.		CONCENTRATIONS FREE CO ₂ IN ABSORBING WATER $\frac{gm. CO_2}{50 gm. H_2O} \times 10^4$		GAS TEMPERATURE °F.				CONCENTRATION OF CO ₂ IN GAS % BY VOL.		BARO METRIC PRES.	ROOM TEMP. °F.	ΔP FOR PLOT TUBE in. H ₂ O	ΔP ACROSS TOWER in. H ₂ O
			INLET WATER	OUTLET WATER	INLET WATER	OUTLET WATER	INLET GAS		OUTLET GAS		INLET GAS	OUTLET GAS				
							DRY BULB	WET BULB	DRY BULB	WET BULB						
3	11-23-46	61.0	58.1	58.4	3.794	18.85	71.2	69.8	57.0	56.0	4.06	4.98	714.4	82.0	0.025	74.5
4	11-25-46	61.0	58.1	62.6	3.549	42.81	82.0	76.7	52.0	52.0	11.88	12.29	712.7	92.0	0.021	66.2
8	12-14-46	61.0	57.3	61.6	3.639	43.73	76.8	75.4	57.0	56.0	12.53	14.99	710.0	80.0	0.023	74.5
10	12-16-46	61.0	57.3	58.4	4.189	39.45	75.0	72.6	56.0	56.0	3.04	3.65	711.8	77.0	0.020	74.5
11	12-16-46	61.0	57.3	59.4	3.639	30.24	74.8	72.2	54.2	56.0	2.67	2.53	711.8	78.0	0.062	86.2
12	12-6-46	61.0	57.3	59.4	3.945	32.23	72.0	71.2	56.0	56.0	2.51	2.22	711.8	80.0	0.020	70.4
5	11-25-46	52.0	59.0	62.6	3.060	36.72	72.5	72.6	52.0	50.0	3.08	3.33	715.7	92.0	0.021	66.2
6	11-26-46	52.0	59.0	61.6	3.580	26.56	71.2	63.8	53.0	58.0	5.13	5.16	710.4	84.0	0.080	41.4
7	11-27-46	52.0	59.0	63.7	3.780	40.09	79.5	65.4	53.0	58.0	11.52	12.04	714.1	81.0	0.020	51.3
16	12-12-46	52.0	57.5	58.4	3.456	32.10	71.2	69.8	56.0	55.0	2.82	2.87	713.4	74.0	0.030	74.5
13	12-17-46	43.5	57.5	61.6	3.670	43.12	70.6	74.0	53.0	58.0	12.41	12.56	712.4	73.0	0.020	66.2
14	12-17-46	43.5	57.5	61.6	3.050	40.55	75.3	72.6	52.0	58.0	10.24	10.69	712.4	80.0	0.020	74.5
18	12-18-46	43.0	57.3	59.4	3.364	36.79	76.2	69.8	57.0	56.0	8.58	3.35	713.4	74.0	0.030	88.7
19	12-18-46	43.0	57.3	61.6	3.089	47.61	78.0	75.4	58.0	57.0	12.56	12.01	713.4	77.0	0.025	74.5
9	12-14-46	34.0	57.5	63.7	3.870	43.73	81.0	78.0	60.0	58.0	12.78	12.71	712.0	82.0	0.023	66.2
15	12-17-46	33.5	57.8	63.7	3.310	32.11	75.3	72.6	62.0	48.0	10.13	10.12	712.4	73.0	0.025	70.4
17	12-18-46	33.5	67.3	61.6	3.460	31.34	71.2	69.8	57.0	56.0	2.66	2.60	714.4	74.0	0.020	82.7

TABLE NO. 3
 LOG OF CALCULATED RESULTS FOR TEST RUNS ON 18-INCH GAS
 ABSORPTION TOWER

TEST NO	L	L'	X ₂	X ₁	(X ₁ - X ₂)	L(X ₁ - X ₂)	PER CENT RELATIVE HUMIDITY OF INLET GAS	PARTIAL PRESSURE WATER VAPOR AT DB TEMP OF INLET GAS	PARTIAL PRESSURE WATER VAPOR AT ROOM TEMP	CORRECTED PARTIAL PRESSURE WATER VAPOR IN INLET GAS	TOTAL PRESSURE LESS PARTIAL PRESSURE WATER VAPOR IN INLET GAS	TOTAL PRESSURE LESS PARTIAL PRESSURE WATER VAPOR AT ROOM TEMP	P ₀	X _{eb}	X _{eb}	Δx _b	P _f	X _{ef}	X _{ef}	Δx _f	Δx _m	L:G Δx _m	K ₁₀
	16 mols/hr	16 mols/hr x 59 ft	mols CO ₂ /mol H ₂ O x 10 ³	mols CO ₂ /mol H ₂ O x 10 ³	mols CO ₂ /mol H ₂ O x 10 ³			mm Hg	mm Hg	mm Hg	mm Hg	mm Hg	mm Hg	mm Hg	g. CO ₂ /100 g. H ₂ O	mols CO ₂ /mol H ₂ O x 10 ³	mols CO ₂ /mol H ₂ O x 10 ³	mm Hg	g. CO ₂ /100 g. H ₂ O	mols CO ₂ /mol H ₂ O x 10 ³	mols CO ₂ /mol H ₂ O x 10 ³	mols CO ₂ /mol H ₂ O x 10 ³	mols CO ₂ /mol H ₂ O x 10 ³
3	203.23	115.17	3.10	15.42	12.32	2506	93.0	18.8	26.9	17.5	696.9	682.5	29.4	3.04	124.3	184.2	35.6	3.53	144.4	144.4	134.3	3560	0.00723
4	203.33	115.17	2.90	34.37	31.47	6360	75.0	27.7	36.9	20.8	632.9	676.9	82.4	4.52	185.0	184.7	82.7	4.76	194.8	194.8	182.7	5090	0.01263
8	203.33	115.17	2.90	35.34	32.96	6700	95.0	22.5	25.2	21.4	682.6	694.8	82.2	4.68	191.5	191.1	83.0	4.80	196.4	196.4	193.7	5140	0.01303
10	203.33	115.17	3.43	52.28	28.85	5860	93.4	20.6	22.8	19.2	692.8	689.0	64.7	4.26	174.0	173.7	61.5	4.37	178.8	178.8	176.3	4605	0.01253
11	203.33	115.17	2.98	24.74	21.76	4420	93.4	20.6	25.8	18.2	632.6	689.0	56.0	4.03	165.0	164.8	53.5	4.18	171.1	171.1	167.9	4445	0.00885
12	203.33	115.17	3.23	26.42	23.19	4710	93.8	19.6	25.0	18.4	632.4	686.6	54.0	4.02	164.7	164.4	52.2	4.15	168.9	168.9	167.2	4480	0.01063
5	173.23	98.09	2.50	30.04	27.54	4760	71.5	20.6	36.3	14.2	632.4	676.6	66.8	4.26	73.9	173.6	66.6	4.44	181.9	181.9	177.8	4918	0.01012
6	173.23	98.09	2.93	21.73	18.80	3258	93.1	18.0	28.7	16.7	693.7	681.7	97.1	3.83	136.2	186.0	36.7	3.55	145.2	145.2	140.5	3725	0.00875
7	173.23	98.09	3.10	22.80	29.70	5140	87.6	22.5	26.0	18.6	695.5	688.1	83.2	4.86	186.3	186.0	85.9	4.80	196.4	196.4	191.2	5090	0.01014
16	173.23	98.09	2.83	26.26	23.43	4060	93.1	18.0	20.6	16.7	686.7	692.8	56.1	4.08	169.1	166.8	54.6	4.20	171.9	171.9	163.4	4480	0.00905
13	145.00	82.06	3.00	34.27	31.27	4135	88.6	20.6	34.4	16.2	694.2	682.0	82.4	4.70	192.2	191.9	83.3	4.83	197.7	197.7	194.8	5160	0.00901
14	145.00	82.06	2.50	33.20	30.70	4450	89.6	20.6	25.2	18.9	693.9	687.2	73.6	4.42	180.7	180.4	71.8	4.54	186.0	186.0	182.2	4655	0.00916
18	143.33	81.06	2.75	29.17	27.02	3879	93.1	18.0	20.6	16.7	696.7	692.8	60.1	4.18	171.1	170.8	59.4	4.31	176.1	176.1	173.5	4600	0.00843
19	143.33	81.06	2.63	38.95	36.42	5220	88.6	22.5	22.8	22.0	693.4	690.6	88.5	4.67	181.0	180.8	88.0	4.85	198.4	198.4	194.5	5150	0.00913
9	113.22	64.08	3.00	32.80	29.80	3779	67.6	26.0	26.9	27.8	687.2	683.1	91.6	4.90	192.2	191.8	90.4	4.26	198.8	198.8	195.4	5150	0.00682
15	111.66	63.19	2.63	26.27	23.64	2675	89.6	20.6	24.4	18.5	693.9	688.0	72.8	4.40	180.0	179.7	72.1	4.54	186.0	186.0	182.9	4650	0.00544
17	111.66	63.19	2.93	26.64	22.81	2540	93.1	18.0	20.6	16.7	693.4	692.8	54.8	4.05	165.3	165.5	54.2	4.18	171.1	171.1	168.3	4460	0.00570

mols CO₂
 mol H₂O
 mol difference

Results: The results of this investigation are shown in Table 3, page 43. For graphical presentation see Figure No. 6, page 49.

Sample Calculations:

Note: All data used in sample calculations were taken from test No. 19 (See Table No. 2, page 42).

1. Overall Liquid Film Absorption Coefficient, (K_{LA}): The following equation given by Walker, Lewis, Maidams, and Gilliland was used in computing the values of (K_{LA}):

$$(L)(x_1 - x_2) = (K_{LA})(H)(S)(\Delta x_{av})$$

where L = lb. mols solute free solvent/hr.

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

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

H = height of packing in tower, ft.

S = cross sectional area of tower, sq. ft.

Δx_{av} = arithmetic mean overall driving force, lb. mols CO_2 /hr./cu. ft./unit conc. difference.

K_{LA} = overall liquid film coefficient, lb. mols lb. mols CO_2 /hr./cu. ft./unit conc. difference.

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

(1) Solvent Rate, lb. mols/hr.:

$$L = \frac{(\text{lbs./min.})(60)}{\text{mol. wt. of } H_2O}$$

$$= \frac{45 \times 60}{18}$$

$$= 145.55 \text{ lb. mols/hr.}$$

(x₁) Conc. of CO₂ in inlet water, lb. mols CO₂/lb. mol H₂O:

$$\text{gm. CO}_2 / 50 \text{ ml. H}_2\text{O} = (\text{ml. NaOH})(\text{normality NaOH})(\text{N.E. CO}_2)$$

$$= (15.57)(0.0139)(0.022)$$

$$= 0.004761$$

$$= (47.61)(10^{-6})$$

Converting this value to lb. mols CO₂/lb. mol H₂O

$$x_1 = \frac{(47.61)(18)(10^{-6})}{(44)(50)}$$

$$= 0.000003815$$

$$= (32.15)(10^{-6}) \frac{\text{lb. mols CO}_2}{\text{lb. mol H}_2\text{O}}$$

(x₂) Conc. of CO₂ in inlet water, lb. mols CO₂/lb. mol H₂O:

Calculated in same manner as (x₁)

$$x_2 = (2.55)(10^{-6}) \frac{\text{lb. mols CO}_2}{\text{lb. mol H}_2\text{O}}$$

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

The packed section of the tower was 15 ft.

(S) Cross sectional area of tower, sq. ft.:

The diameter of the tower was 18".

$$S = \frac{3.1416 \times D^2}{4}$$

$$= \frac{3.1416 \times 1.5^2}{4}$$

$$= 1.767 \text{ sq. ft.}$$

(Δx_{av}) Arithmetic mean overall driving force,

lb. moles CO₂/lb. mol H₂O:

Δx_{av} may be calculated by means of the following equation:

$$\Delta x_{av} = \frac{(x_{ot} - x_g) - (x_{oh} - x_l)}{3}$$

where x_{ot} , x_{oh} = equilibrium conc. corresponding to the partial pressure of CO₂ in the outlet and inlet gas, respectively.

The values of x_{ot} and x_{oh} were obtained from the data given by Othmer and Benenati (21). Before this data could be used, however, it was necessary to calculate the exact partial pressure of the CO₂ in both the inlet and outlet gas. In order to calculate the partial pressures the following assumptions must be made:

1. That the gas samples as analyzed in the Great 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 so small as to be negligible.
3. That the partial pressure exerted by water vapor in air is directly proportional to the per cent relative humidity.

partial pressure CO₂ in outlet gas = $\frac{(\%CO_2)(\text{total pres., } P_p)}{100}$

$$= \frac{(12.41)(715.6)}{100}$$

= 88.6 mm. Hg.

On the basis of the assumptions given above, the corrected partial pressure of CO₂ in inlet gas, mm. Hg., may be calculated from the following relation:

$$\text{cor. partial pres. CO}_2 = \frac{(\% \text{CO}_2)(P_p - \text{partial pres. H}_2\text{O at tower cond.})(P_s)}{(100)(P_p - \text{partial pres. H}_2\text{O at saturation cond.})}$$

The partial pressure of water vapor at tower conditions, i.e., dry bulb temp., 78°F, wet bulb temp., 75.4°F, per cent relative humidity, 88.6, was calculated as follows:

$$\text{partial pres. H}_2\text{O at 78°F} = 23.58 \text{ mm. Hg.}$$

$$\begin{aligned} \text{partial pres. H}_2\text{O at tower conditions} &= (\% \text{ Rel. humidity}) \\ &\quad (\text{partial pres. H}_2\text{O at 78°F}) \\ &= 0.886 \times 23.58 \\ &= 20.89 \text{ mm. Hg.} \end{aligned}$$

The partial pressure of water vapor at saturation conditions and at room temperature:

$$\text{partial pres. H}_2\text{O at 77°F} = 22.81 \text{ mm. Hg.}$$

$$\begin{aligned} \text{cor. partial pres. CO}_2 &= \frac{(12.56)(713.40 - 20.89)(713.40)}{(100)(713.40 - 22.81)} \\ &= \frac{(12.56)(692.51)(713.40)}{(100)(690.59)} \\ &= 90.3 \text{ mm. Hg.} \end{aligned}$$

(x_{gt}) equilibrium conc. corresponding to the partial pressure of CO₂ in the outlet gas. (From equilibrium data.)

equilibrium conc., gas $\text{CO}_2/100$ gas $\text{H}_2\text{O} \approx 4.85$

converting this value to lb. mols $\text{CO}_2/\text{lb. mol H}_2\text{O}$

$$x_{0a} = \frac{(4.85)(18)}{(44)(100)}$$

$$\approx 0.01984$$

$$\approx (198.4)(10^{-6}) \frac{\text{lb. mols CO}_2}{\text{lb. mol H}_2\text{O}}$$

(x_{0b}) equilibrium conc. corresponding to the partial pressure of CO_2 in the inlet gas. Calculated in the same manner as (x_{0a}).

$$x_{0b} = (191.0)(10^{-6}) \frac{\text{lb. mols CO}_2}{\text{lb. mol H}_2\text{O}}$$

$$\Delta x_{av} \frac{\text{lb. mols CO}_2}{\text{lb. mol H}_2\text{O}} = \frac{(198.4 - 0.0255)(10^{-6}) + (191.0 - .3015)(10^{-6})}{2}$$

$$\approx \frac{(198.4 + 190.6)(10^{-6})}{2}$$

$$\approx 194.5(10^{-6}) \frac{\text{lb. mols CO}_2}{\text{lb. mol H}_2\text{O}}$$

Solving the original equation for K_{LA} :

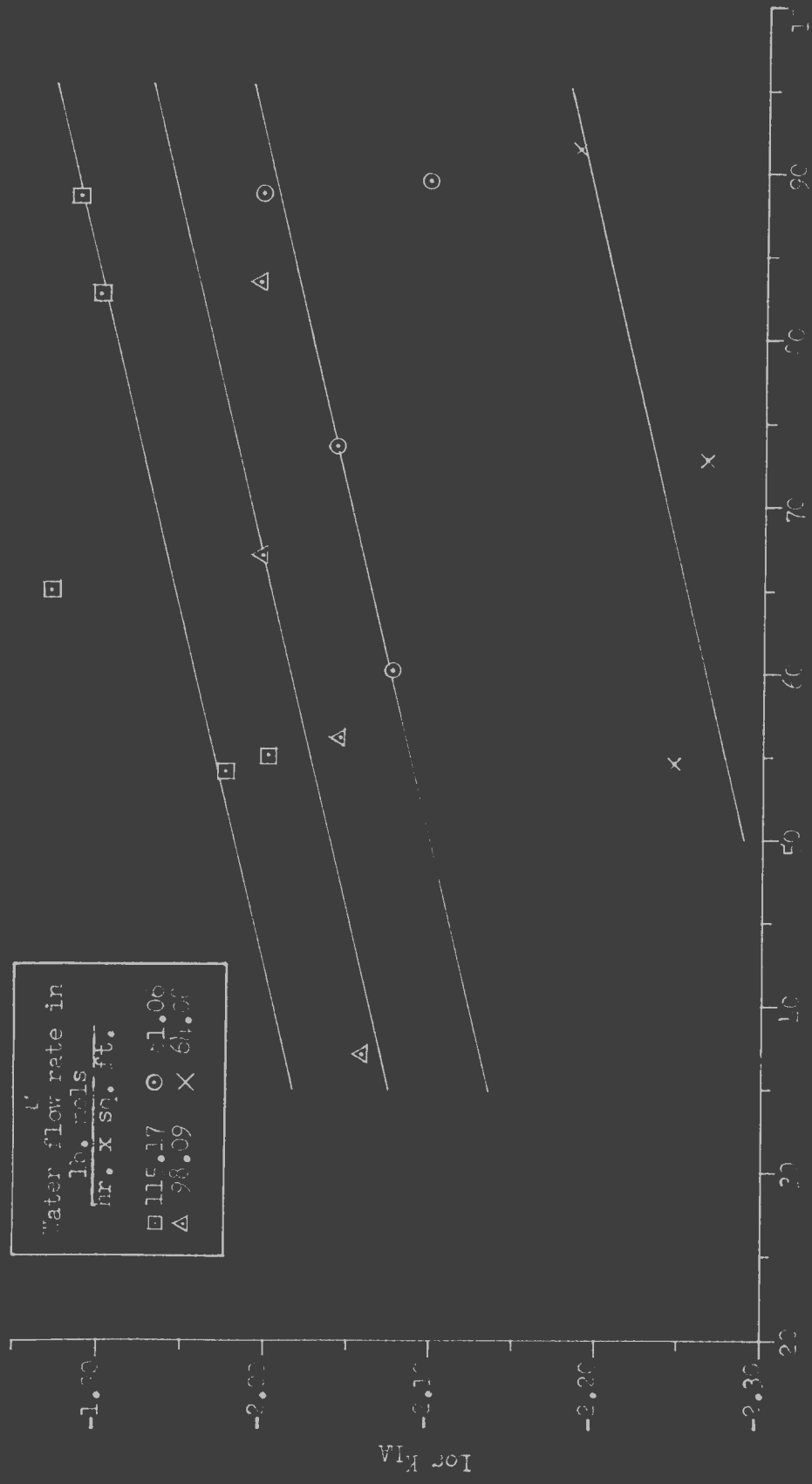
$$K_{LA} = \frac{L(x_1 - x_2)}{(H)(S)(x_{av})}$$

$$= \frac{(143.55)(38.15 - 2.53)(10^{-6})}{(15)(1.767)(194.5)(10^{-6})}$$

$$= \frac{(143.55)(35.62)(10^{-6})}{(15)(1.767)(194.5)}$$

$$K_{LA} = 0.01015 \text{ lb. mols CO}_2/\text{hr.}/\text{cu.ft.}/\text{unit conc difference.}$$

Water flow rate in
 $\frac{\text{lb. mols}}{\text{hr.} \times \text{sq. ft.}}$
 □ 115.17 ○ 51.06
 △ 98.09 X 64.50



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 Blacksburg, Virginia

Partial Pressure of CO₂ in Inlet Gas
 VS
 Log K_{1A}

Drawn by: *WWS* Figure No.:
 Checked by: Date: 4 Jan 47

2. Derivation of empirical equation relating the Overall Coefficient (K_{LA}), Solvent Rate (L'), and Partial Pressure of $CO_2(P)$. The following table was compiled using values taken from Figure 6, page .

L' Flow Rate*	Log K_{LA}	P Partial Pressure CO_2^{**}	Log K_{LA}	P Partial Pressure CO_2^{**}	a	b
115.17	-2.010	37.50	-1.895	85.00	-2.101	0.00242
98.09	-2.050	45.00	-1.935	92.50	-2.159	0.00242
81.04	-2.120	41.00	-2.025	76.00	-2.219	0.00242
64.08	-2.220	53.50	-2.155	93.00	-2.409	0.00240

Note: * lb. mols/hr./sq.ft
 ** mm. Hg .

As may be seen in Figure 6, the plot of $\log K_{LA}$ versus the partial pressure of CO_2 in the inlet gas results in a series of straight, parallel lines. The equations relating K_{LA} and the partial pressure must therefore be of the type $K_{LA} = 10^a + bp$, where (a) and (b) are constants to be determined. Writing the equation in log form

$$\log K_{LA} = a + bp,$$

then substituting values from the table for a flow rate of 115.17 in the above equation gives two equations

$$-1.895 = a + 85.00b$$

$$-2.010 = a + 37.50b;$$

which when solved simultaneously for (a) and (b) give the following values

$$a = -2.101$$

$$b = 0.00242 .$$

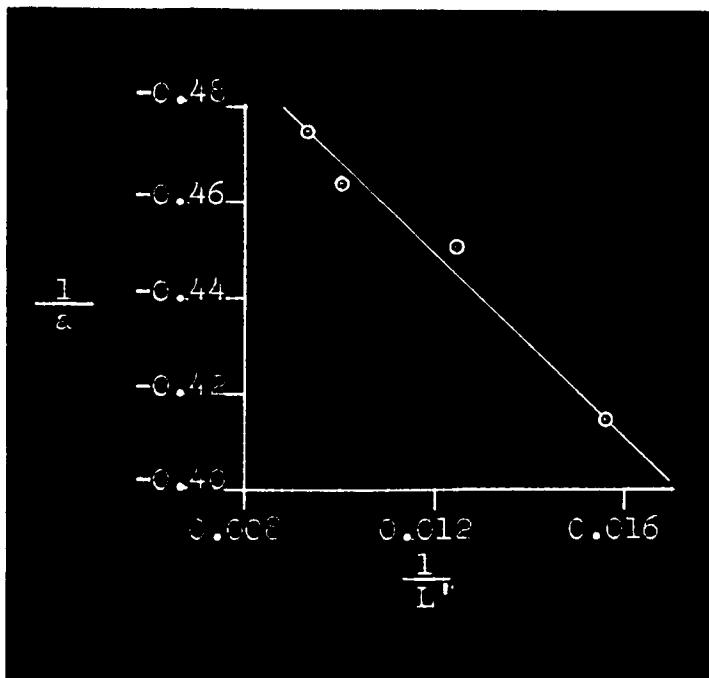
The constants (a) and (b) were determined in like manner for each of the remaining groups of data.

From the above table it is obvious that the constant (b) does not vary with changes in solvent rate (L'); however, (a) varies as the solvent rate changes. Thus, it becomes necessary to express the constant (a) in terms of the solvent rate (L'). Following is a tabulation of values used in correlating the relationship between (a) and (L'):

L'	a	$\frac{1}{L'}$	$\frac{1}{a}$	c	d
115.17	-2.101	0.008688	-0.478	-0.544	7.966
98.09	-2.159	0.010195	-0.464	-0.544	7.966
81.06	-2.219	0.012456	-0.451	-0.544	7.966
64.08	-2.409	0.015606	- .415	-0.544	7.966

Note: c = lb. mols/hr/sq.ft.

When $\frac{1}{L'}$ is plotted against $\frac{1}{a}$ the data is rectified and a straight line results as shown in the following figure.



The equation of the resulting straight line is of the type

$$\frac{1}{a} = c - \frac{d}{L^2}$$

where (c) and (d) are constants to be evaluated. Substituting the values of $\frac{1}{a}$ and $\frac{1}{L^2}$ in the above equation results in the four equations given below.

$$-0.475 = c - 0.008683 d,$$

$$-0.464 = c - 0.010195 d,$$

$$-0.451 = c - 0.012436 d,$$

$$-0.415 = c - 0.015606 d.$$

which when solved simultaneously give the following values for (c) and (d):

$$c = -0.544,$$

$$d = 7.966.$$

Rewriting the equation and substituting the values of (c) and (d) gives

$$\frac{1}{a} = -0.544 - \frac{7.966}{L'} .$$

Solving for (a)

$$a = \frac{L'}{7.966 - 0.544 L'} .$$

Rewriting the original equation and substituting the values for (a) and (b)

$$\text{Log } K_{LA} = \frac{L'}{7.966 - 0.544 L'} - 0.00242 P .$$

The average percent deviation of calculated values of (K_{LA}) from those observed is 2.2 percent computed without regard to sign.

IV. DISCUSSION OF RESULTS

The purpose of this investigation was to correct certain inherent difficulties in the operation of the tower. In order to accomplish this objective several modifications of and additions to the existing equipment were made. A further objective was to obtain sufficient experimental data to permit correlation of such variables as the overall coefficient (K_{LA}), the solvent rate (L'), the partial pressure (P) of the soluble constituent (CO_2) in the gas stream, and the pressure drop (ΔP) across the packed section of the tower.

Equipment Modifications

Gas Cooler: Test runs made after the new cooler was installed show that it is decidedly more efficient than the spray cooler used in previous investigations. The new cooler is capable of cooling 650 lb./hr. of dry air from approximately $700^{\circ} F$ to $70^{\circ} F$, whereas the old spray type cooler had a capacity of 500 lb./hr. of dry air reduced from $700^{\circ} F$ to $100^{\circ} F$. This increase in efficiency may be attributed to several factors:

1. The increase in the length of the mean free path of the gas in the cooler from 7.5' in the old cooler to 21.5' in the new cooler.
2. The increased turbulence of the gas due to the resistance offered by the rough walls of the stovepipe used to fabricate the spiral cooling coil would, obviously, tend

to reduce the effect of the stagnant gas film and thereby increase the rate of heat transfer.

3. An increase in the amount of cooling water used from approximately 3600 lb./hr. used by the old cooler to 15,000 lb./hr. in the case of the new.

(80)

According to Sherwood⁽⁸⁰⁾, "In systems where the liquid film controls, the effect of temperature is so large that an increase in temperature over a 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 absorption should be carried out." The results of this study would seem to indicate that the lower inlet gas temperatures (70° to 80°F) made possible by the installation of the new cooler were somewhat nearer the optimum operating conditions for this particular system of carbon dioxide and water than were the gas temperatures (100° to 190°F) used by Musick⁽²⁰⁾, and Harwin and Miles⁽¹⁹⁾.

Orifices, Manometers, and Regulating Valves: As a result of the installation of orifices and needle control valves in the water, oil, and compressed air lines, the constancy of flow in these lines was greatly increased. This also made it possible to reproduce, with ease, any given set of operating conditions. The operation of the manometers used in conjunction with the orifices was not, in all cases, satisfactory, and could perhaps be corrected.

The manometer on the oil line was placed in such a position that it was necessary for the lead lines to pass about one foot from

the furnace. Even though these lines were lagged with 1" of 80% magnesia insulating material, it was observed that when the furnace reached maximum operating temperature of approximately 2500° F, the pressure differential indicated by the manometer would gradually decrease and after about 1 to 1-1/2 hours time would reach zero reading. This condition was probably due to the formation of vapor in both lead lines under sufficient pressure to counterbalance the small difference in pressure, from 3 to 4 in. of water, which should have been indicated by the manometer.

The orifice which was installed in the inlet water line to the tower gave inconsistent readings, which seemed to indicate that for the low rate of flow (from 2000 to 3600 lb./hr.) and low head (10ft.) in this line, the orifice was placed too near the open end of the line.

Orsat Apparatus and Accessories: The Precision Mine-Air model Orsat apparatus which was used in this investigation made possible more accurate analysis of the gas samples and, thereby, added to the accuracy of the final results. With this apparatus it was possible to detect changes in CO₂ content as small as 0.1 percent; whereas, with the Technical Fine-Gas model used by previous investigators (19)(20), it was difficult to detect changes as great as 0.5 percent.

Another factor contributing to the accuracy of the final results was the use of gas sampling bottles in conjunction with the Orsat apparatus. In previous investigations one or the other of the

following methods were used to obtain gas samples:

1. Location of the Orsat apparatus at either the top or bottom of the tower with sampling tubes to the apparatus from the terminals of the tower. This arrangement resulted in one sampling line about 21 feet long which was very difficult to purge of stagnant gas and would, therefore, increase the possibility of errors occurring in analysis.
2. The use of short sampling lines (1 to 3 ft.) at either end of the tower and movement of the Orsat apparatus each time a sample was to be analyzed. Although this procedure may have eliminated or materially reduced any error resulting from the insufficient purging of a long sampling line as described in the first method, it, obviously, augmented the actual physical effort required on the part of the operator, and greatly increased the amount of time required to perform an analysis.

The use of 250 ml. ground glass stoppered sampling bottles for collecting gas samples eliminated not only the unsatisfactory conditions described above and greatly increased the ease with which the analysis could be made, but also made possible the use of sampling lines about 1-1/2 ft. in length. A further advantage was the fact that it was possible, using these sample bottles, to collect a large enough volume of gas to make two analyses on each sample. The methods used previously did not provide for this and hence if a mistake in

analysis occurred no means of checking this error was available.

Pitot Tube: The installation of this instrument provided a much more convenient means of checking the velocity of the gas through the tower than the anemometer heretofore used. However, even though this instrument was calibrated prior to installation, it is doubtful if it gave any more accurate results than would have been possible using an anemometer since a pitot tube of this type is not particularly adapted to such low gas velocities (1000 ft./min) as were used in this investigation. The principal advantage of this instrument when compared with the anemometer is the fact that very little time is required to make an observation, whereas the anemometer must be timed for a period of one minute.

Furnace: The furnace used to produce the flue gas was not modified in any way; however, it was necessary to make some repairs in order to insure efficient operation. After about eight test runs had been completed a large crack developed in the top of the firebox and made it impossible to operate the furnace at sufficiently high temperatures to give efficient combustion. Investigation showed that a refractory cement used between the walls of the firebox and the outer furnace shell had failed and begun to crumble. As this disintegration continued with alternate heating and cooling of the furnace, the small particles settled toward the bottom of the space between the two walls and caused a permanent displacement or warping to take place.

During the course of the investigation several minor adjustments were

difficulty was encountered in maintaining continuous burner performance. This faulty operation was corrected when the compressed air line and the oil lines to the burner were equipped with filters to remove any small dirt particles which might clog the atomising jets in the burner.

Calculated results

The following equation was derived from the data obtained in this investigation and may be applied with a maximum of 2.2 percent deviation:

$$\text{Log } K_{LA} = \frac{L'}{7.966 - 0.544 L'} + 0.00242 P$$

where K_{LA} = lb. mols CO_2 /hr./cu. ft./ (lb. mol CO_2 /lb. mol H_2O)
 L' = solvent rate in lb. mols/hr./sq. ft.
 P = partial pressure of CO_2 in inlet gas in mm. Hg .

The limits within which this equation is accurate are listed below:

- a. Gas velocity.....12.7 lb. mols air/hr./sq. ft.
- b. Solvent rate.....65 to 115 lb. mols water/hr./sq. ft.
- c. Partial pressure of CO_257 to 90 mm. Hg .
- d. Temperature of water.....57.8 to 66.7° F .
- e. Temperature of gas.....56.0 to 65.0° F .

In Figure 6, page 49, the curves showing Log K_{LA} plotted versus the partial pressure of CO_2 in the gas stream at constant solvent rates are parallel but are not equidistant. Although these curves represent

solvent rates decreasing in equal amounts of 17 lb. mols/hr./sq.ft., note that the interval between the curves for 118.17, 98.09, and 81.06 lb. mols/hr./sq. ft. is practically constant whereas the interval between the curves representing 81.06 and 64.08 lb. mols/hr./sq. ft. is a little more than twice as large. This condition would seem to indicate that between these two flow rates, i.e., 81.06 and 64.06 lb. mols/hr./sq. ft., some critical flow is reached where any further reduction in the liquid rate would greatly decrease the active wetted surface of the packing, thereby reducing the surface area available to the diffusion process. This condition would tend to reduce (K_{LA}) since this term is a function not only of the amount of material transferred but also of the actual area over which this transfer takes place. This theory may be substantiated by the work of Baker, Marto, and Elgin⁽²³⁾ who found that "when the rate of liquid flow is low there may be a considerable fraction of the surface of the packing which is not supplied with fresh liquid and, therefore, is not active. Increasing the liquid flow rate will increase the fraction of the surface of the packing which is active and will therefore increase the apparent liquid-film coefficient."

⁽²⁴⁾
According to Sherwood this change in the actual active surface area per unit volume of packing may be attributed to several factors:

1. Uneven distribution of solvent over the cross section of the tower.
2. Failure of the solvent to wet all of the individual particles.

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

The values of (K_{LA}) calculated from the experimental data obtained in this investigation do not show very close agreement with those obtained by Cantale, Simmons, Giles, and Brill⁽²⁾ or Simmons and Osborne⁽²²⁾. These investigators give values of (K_{LA}) for the system CO_2 and water ranging from 10 to 40 lb. mols/hr./cu.ft./ (lb. mols CO_2 /cu.ft. H_2O) under conditions where the solvent rate (L') varied from 110 to 1100 lb. mols/hr./sq.ft. and the gas rate ranged from 0.2 to 1 lb. mols/hr./sq.ft. Values of (K_{LA}) determined in this investigation when calculated in units of lb. mols/hr./cu.ft./ (lb. mols CO_2 /cu.ft. H_2O) range from 0.0015 to 0.0037. The solvent rate (L') varied from 64 to 115 lb. mols/hr./sq. ft. with the gas rate (G) remaining essentially constant at 12.7 lb. mols/hr./sq.ft. through all of the test runs.

In both of the investigations mentioned above the towers and the tower packing used were "very small"; the equipment of Simmons and Osborne is described⁽²²⁾ as a "small" tower packed with 0.75 in. glass spheres, Cantale and coworkers⁽²⁾ used a tower 3.5 in. in diameter packed with small glass rings to a height of 35 in. It is estimated from data given by Perry⁽²²⁾, that the packing used by these investigators would have a surface area approximately 200 sq.ft./cu.ft. whereas the coke packing used in this investigation has a surface-volume ratio of approximately 18 sq.ft./cu.ft.

The fact that these investigations were conducted using comparatively high solvent rates and tower packings with extremely high surface-volume ratios would tend to increase the values of (K_{LA}) obtained. Likewise, the use of very low gas velocities would also tend to increase the amount of solute transferred by allowing a longer period of contact between the gas and liquid phases. This condition, obviously, would tend to give larger values for (K_{LA}) .

On the basis of this discussion it is clear that the conditions of the test by Simmons and Osborne, and Cantale and co-workers are hardly comparable to those used in this investigation and could not be expected to yield like results.

An attempt was made to correlate the pressure drop (P) through the packed section of the tower with the overall liquid film coefficient (K_{LA}) ; however, there seems to be no relationship between these variables. According to Chilton and Colburn⁽³⁾, the pressure drop is dependent upon the gas velocity and the free volume of the packing used, whereas the value of (K_{LA}) is influenced primarily by the solvent rate and also the surface-volume ratio of the packing. It could hardly be expected then that these two variables should give any correlation, dependent as they are, upon entirely different factors.

Recommendations

The following recommendations listed are based on observations

made during the operation of the tower:

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, thereby eliminating the detrimental effect caused by the disintegration of the refractory cement used at the present time.
2. Orifices: The orifice used to measure the inlet water to the tower should either be relocated about 3' from where this line enters the constant head tank or the constant head tank be replaced with a closed tank, acting as a surge basin to eliminate the fluctuations in line pressure caused by the inconsistent resistance encountered in the Zeolite water softener.
3. Pitot Tube: It is recommended that the pitot tube be replaced by a Velometer. This instrument is more sensitive than the Pitot tube at low velocities. It is also especially adapted for measurement of gas flow under turbulent conditions, whereas the accuracy of the pitot tube is affected somewhat when used under conditions other than stream line flow.
4. Manometers: The lead lines and possibly the manometer for the orifice on the fuel oil line to the burner should be located in a position where they would not be affected by the heat from the furnace. A likely position would be on the south side of the 8" H-beam near the furnace.

5. Flow Rates: It is recommended that, should further investigations be made using this same equipment, the solvent rate be increased to between 300 to 500 lb. mols/hr./sq.ft. and the gas velocity be reduced to 3 to 5 lb. mols/hr./sq.ft. These changes would tend to increase the amount of absorption taking place by increasing the surface area available to the diffusional process as well as providing for longer time of contact between the gas and liquid phase.
6. Tower Packing: The maximum amount of absorption possible with this particular equipment could probably be increased if the tower packing now in use were replaced by some packing having essentially the same free volume ratio but a higher surface-volume ratio than does the 1-1/8 to 2 inch coke. A suitable packing material in this case would be H. H. spiral rings 3 x 3 inches, this packing would have the same free volume ratio but would have a surface-volume ratio approximately fifty percent greater than the 1-1/8 to 2 inch coke now in use.

Limitations

This investigation of the absorption of CO₂ in water was carried out using an 18-inch stoneware absorption tower packed with 1-1/8 - 2 inch coke. The water used as a solvent was softened in a Zeolite water softener and contained 435 p.p.m. bicarbonates as sodium

bicarbonate. The equation derived from the data may be applied with a maximum error of 2.2 percent within the following limits:

1. Gas Velocity.....12.7 lb. moles air/hr./sq.ft.
2. solvent rate.....65 to 115 lb. moles water/hr./sq.ft.
3. Partial pressure of CO_237 to 90 mm. Hg .
4. Temperature of water.....57.3 to 65.7° F .
5. Temperature of gas.....56.0 to 63.0° F .

V. CONCLUSIONS

In this investigation to determine the operating characteristics of an 18-inch coke-packed stoneware absorption tower employing water to "strip" carbon dioxide from flue gas the following limiting conditions were used;

- a. Gas velocity 12.7 lb. mols air/hr./sq.ft.
- b. Solvent rate 65 to 115 lb. mols water/hr./sq.ft.
- c. Partial pres. of CO₂ 37 to 90 mm. Hg .
- d. Temperature of water 55.3 to 65.7° F .
- e. Temperature of gas 56 to 86° F .

The conclusions which may be drawn from the results of this study are listed below;

1. The relationship between the overall liquid film absorption coefficient (K_{LA}), the solvent rate (L'), and the partial pressure (P) of the soluble constituent (CO₂) conforms to the equation

$$\text{Log } K_{LA} = \frac{L'}{7.966 - 0.546 L'} + 0.00242 P .$$

The accuracy of this equation, within the limiting conditions as given above, is plus or minus 2.2%.

2. No correlation could be made between the overall liquid film absorption coefficient (K_{LA}) and the pressure drop (ΔP) through the packed section of the tower.

3. The flue gas cooler which was designed and built during the course of this investigation (See Figure 3, Page 35) is capable of cooling 650 lb./hr. of dry air from approximately 700°F. to 70°F. using 15,000 lb./hr. of cooling water at an inlet temperature of 50°F.

VI. SUMMARY

The 18-inch coke-packed absorption tower used in this investigation was located in the Unit Operations Laboratory of the Department of Chemical Engineering, Virginia Polytechnic Institute, Blacksburg, Virginia. During the course of this work a number of changes and additions to existing equipment were made in an effort to improve the operation of the tower. Nineteen experiments, using carbon dioxide, in a flue gas mixture, as the solute and water as the solvent, were made to determine some of the operating characteristics of the tower.

A new gas cooler was designed and constructed using a spiral cooling unit made from 5 inch stove pipe elbows. The elbows were coated with silicone resin in an effort to reduce corrosion. The capacity of this unit was approximately 50% greater than the open-spray type cooler used previously.

The anemometer used heretofore to measure gas velocities through the tower was replaced by a pitot tube and draft gage in an effort to facilitate this determination.

A Precision Mine-Air model Orsat apparatus was installed to replace the Technical Flue-Gas model used in previous experimental work. Gas samples were taken for analysis by means of gas sampling bottles which permitted the use of short sampling tubes. These two changes in equipment and procedure greatly simplified the accurate determination of CO₂ in the gas stream.

Orifices, metering control valves, and manometers were installed in all pipe lines conveying materials to the tower in order to increase

the ease and accuracy of controlling the flow of these various materials.

After the above changes had been completed, a series of nineteen test runs was made. As a result of the data collected the following conclusions were drawn:

1. The relation between the overall liquid film coefficient (K_{LA}), the solvent rate (L'), and the partial pressure (P) of the CO_2 in the gas stream may be expressed by the equation

$$\text{Log } K_{LA} = \frac{L'}{7.966 - 0.544 L'} + 0.000242 P$$

within the limits as listed below:

- a. Gas velocity 12.7 lb. moles air/hr./sq.ft.
 - b. Solvent rate 68 to 115 lb. moles water/hr./sq.ft.
 - c. Partial pres. of CO_2 .. 57 to 90 mm. Hg .
 - d. Temperature of water .. 53.5 to 55.7° F .
 - e. Temperature of gas 56 to 56° F .
2. No correlation could be made between the overall liquid film coefficient (K_{LA}) and the pressure drop (ΔP) through the packed section of the tower.
 3. The flue gas cooler which was designed and built during the course of this investigation (See Figure 3, Page 38) is capable of cooling 650 lb./hr. of dry air from approximately 700°F. to 70°F. using 18,000 lb./hr. of cooling water at an inlet temperature of 58°F.

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