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Absorption of Carbon Dioxide by Water under Pressure in a Packed Tower (II)

Influence of Operating Factors upon Over-all Capacity Coefficient

By

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In the previous papers^(1),2) the author reported the results of preliminary experiments on pressure absorption of carbon dioxide by a packed tower, and also of an experimental study of water distribution in the same tower. In the present report data are presented on the overall capacity coefficient $K_L a$ under various operating conditions, obtained in a continued study on the pressure absorption of carbon dioxide.

I. Review of Previous Experimental Work

On the absorption of CO_2 by water in packed towers, several studies have been made.^(3),4),5),6) However, these studies were almost all made under the ordinary pressure, and moreover those using large scale experimental towers are a few.

Sherwood, Draemel and Ruckman⁷⁾ studied on the desorption of CO_2 using a 7 foot-tower of 10 inches in diameter, dumped-packed to a height of 54–56 inches with 1-inch carbon Raschig rings (free space: 74%), by uniformly distributing the water dissolving CO_2 from the top of the tower and by sending air from the bottom. As the result, the gas rate did not influence $K_L a$ within the range of 57–314 lbs/hr·ft², although slight variations in water temperature and change of liquid rate L_s exerted remarkable influence. Therefore, they reported that liquid-film resistance was controlling in this case; the relation of $K_L a$ vs. L_s was expressed as the following empirical equation:—

$$K_L a = 0.021 L_s^{0.88} \dots\dots\dots (1)$$

provided $K_L a$: $\frac{\text{lbs}}{(\text{hr})(\text{ft}^3)(\text{lb}/\text{ft}^3)}$

L_s : 800–9,000 lbs/hr·ft²

t : 24°C

Sherwood and Holloway⁸⁾ studied on the desorption of gases having small solubility in a tower of 20 inches diameter, packed to a depth of 8 inches with 1.5 inch Raschig rings. First series of experiments on the desorption of CO_2 , O_2 and H_2 from water by air was carried out under the experimental conditions of t : 5–40°C, gas rate: 30–1,300 lbs/hr·ft², and water rate: 200–32,000 lbs/hr·ft². For liquid rates below the incipient loading, the data were correlated by the expression

$$\frac{k_L a}{D_L} = \alpha \left(\frac{L_s}{\mu'} \right)^{1-\pi} \left(\frac{\mu'}{\rho' D_L} \right)^{1-\pi} \dots\dots\dots (2)$$

or the corresponding form

$$(\text{H. T. U.})_L = \frac{1}{\alpha} \left(\frac{L_s}{\mu'} \right)^n \left(\frac{\mu'}{\rho' D_L} \right)^s \dots\dots\dots (2')$$

where D_L : diffusion coefficient in liquid, μ' , ρ' : viscosity and density of liquid, respectively.

Values of the exponents n and s were found to be 0.25 and 0.50 respectively for these data. The equation is not dimensionless and the proportionality constant α may be expected to vary with the nature of the packing material and with the units employed.

Then, additional data were obtained on desorption of O_2 from water in the same tower, with various kinds of packing and with different heights of packed bed, over a similar range of gas and liquid rates as in the first series. According to the results, a relatively small variation of $k_L a$ or $(\text{H.T.U.})_L$ was shown with size and type of packing, liquid distribution at the top of the tower and manner of placing the packing in the tower. Also no variation was shown with packed height, gas rate or solute gas concentration, although liquid rate and liquid temperature influenced $k_L a$ or $(\text{H.T.U.})_L$ remarkably.

The solubility of acetylene in water is slightly larger than that of CO_2 . Sanka⁽⁹⁾ separated acetylene from mixture of 20% acetylene and 80% H_2 by using a packed tower, and studied the mass transfer and the influence of operating factors upon $K_L a$. The towers used were as follows mainly:—

(a) Small tower of inside diameter: 11.45 cm, and height of packed bed: 158.5 cm, packed with 15 mm ceramic Raschig rings (free space: 75%); and

(b) Large tower of inside diameter: 40 cm, and height of packed bed: 156 cm, packed with 35 mm ceramic Raschig rings (free space: 76.3%).

Moreover, the case where bamboo Raschig rings of three different sizes within the range of 36 mm–21 mm, were packed irregularly at three stages, was experimented for comparison purpose.

Sanka obtained following results on the absorption of acetylene by water under ordinary pressure.

(1) $K_L a$ was not affected by gas rate and the resistance of liquid film was controlling.

(2) The relation of $K_L a$ to water rate in the case of large tower (b) was expressed as the following equation:—

$$K_L a = 3.3 L_s^{0.63} \dots\dots\dots (3)$$

provided L_s : 5.0–16.3 m³/m²·hr.

t : 11.2–12.0°C

(3) $K_L a$ increased with increasing water temperature, showing its maximum value at 25–30°C, and then decreased at 35–45°C. One had better use low temperature water in practice.

Sanka also reported the result on the pressure absorption of acetylene and a generalized experimental equation concerning the absorption of gases having small solubility in water in packed tower. This will be mentioned later.

Studies on pressure absorption in packed tower have been extremely few, and two reports, those of Yushkevich et al. and Sanka are to be found. Yushkevich, Zhavoronkov and Zel'venskii⁽¹⁰⁾ studied on the pressure absorption under 1–10 atm., using a small-scale tower, inside diameter of which was 10.4 cm. Iron Raschig rings of 21 mm were packed randomly to a height of 271 cm (free space: 72.5%), and mixture of 20% CO₂ and 80% air was used as the raw gas. The influences of the operating factors on $K_L a$ were studied, and the results they obtained are as follows:—

(1) $K_L a$ increases with L_s within the experimental range of L_s : 36–170 m³/m²·hr.*, but its gradient is lowered by the increase of pressure**.

(2) $K_L a$ is lowered with the increasing pressure, when the other conditions (temperature, gas and water rates) are constant. The decreasing of $K_L a$ accompanied with the increasing pressure is remarkable in the case of great water rate.

(3) $K_L a$ is increased with the increasing velocity of solute-free gas under the working pressure of 5 atm. and within the range of L_s : 58–130 m³/m²·hr.* and G_s : 247–890 m³/m²·hr.***

(4) The experiments with the CO₂ concentrations of raw gas of 10% and 20%, under the conditions of pressure of 5 atm., G_s : 705 m³/m²·hr.* and L_s : 58–130 m³/m²·hr.* showed that the variation of gas composition had no effect upon $K_L a$.

(5) The results as above mentioned, show that resistances of both

* Yushkevich and others have expressed the water rate and gas velocity as the value to space area in their original paper, and $K_L a$ was obtained as the value based on free space volume of packed bed. But as to the sign *, the author converted to the value for total sectional area of tower.

** Cf. Fig. 13.

*** Cf. Fig. 20.

gas and liquid films are effective. Assuming that the liquid film resistance is inversely proportional to the water rate and the gas film resistance is proportional to the pressure, Yushkevich, Zhavoronkov and Zel'venskii calculated the percentage of resistances of both films in the over-all resistance.

(6) Data of industrial absorption towers in Bereznikovskiy Factory and Stalinogorskiy Factory were presented.

(7) The experimental results coincide with the theory of gas absorption based on the double film theory.

The report of Yushkevich, Zhavoronkov and Zel'venskii is the only report on the pressure absorption of CO_2 over a large extent of water rate; the influence of pressure was reported for the first time. However, their apparatus was a small experimental tower, and the ratio of the tower diameter d_t to the nominal diameter of packings d was small ($d_t/d < 5$). In view of the studies by Uchida and Fujita,¹¹⁾ and others¹²⁾ about this fact, influence may be exerted by tower wall and channeling in such a tower.

Sanka¹³⁾ packed Raschig rings of 21 mm irregularly to a height of 200 cm (free space: 70.4%) in the tower of inside diameter 22.35 cm, and observed the influence of pressure by changing it within the range of 4–13 kgs/cm² under the possible constant conditions of liquid rate 0.97–1.22 m³/m²·hr., raw gas rate 105–132 m³/m²·hr. and temperature 18.9–20.5°C, using a mixture of 17.3–26.7% acetylene and H_2 as raw gas. The experimental results were as graphed Figure 1, and in this case $K_L a$ was shown to be not influenced by the pressure.

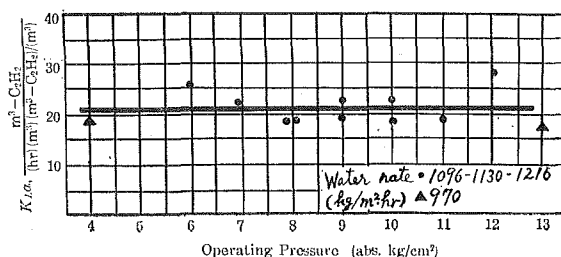


Fig. 1 Influence of Operating Pressure in Absorption of C_2H_2 (by Sanka)

Then, arranging data on the absorption and desorption by packed towers of gases having small solubility (O_2 , H_2 , CO_2 , C_2H_2 , Cl_2) Sanka gives the following equation:—

$$(K_L a d^2 / D) = 0.00023 (u'^2 / 2gd)^{-0.4} (du' \rho' / \mu')^{1.5} (\mu' / \rho' D_L)^{0.8} \quad \dots (4)$$

where d : nominal diameter of packings (cm), u' : superficial liquid velocity (cm/sec), μ' : viscosity of liquid (g/cm·sec), ρ' : density of liquid (g/cm³), D_L : diffusion coefficient in liquid (cm²/sec) and g : acceleration of gravity, 980 (cm/sec²).

In the case of water $\rho' = 1$, therefore, Eq. (4) is written as follows:—

$$K_L a [1/\text{sec}] = 0.00465 d^{-0.1} u'^{0.7} \mu'^{-0.7} D_L^{0.3} \quad \dots (4')$$

Fujita,¹⁴⁾ studying the relation between $[\text{H.T.U.}]_{OL}$ and many factors, and utilizing data in the literatures for absorption, desorption, humidification of air and his own experimental data of ordinary pressure absorption of CO₂ in packed tower, obtained the following generalized equation:—

$$[\text{H.T.U.}]_{OL} = \left(\frac{d}{26} \right)^{0.1} \left(\frac{G_W}{500} \right)^{0.2} (l^2 d_i)^{0.1} \left(\frac{\nu'}{D_L} \right)^n \\ \times \left\{ 0.306 \left(\frac{m G_M}{L_M} \right)^{-0.23} + 0.128 \left(\frac{m G_M}{L_M} \right)^{-1.30} \right\} \quad \dots (5)$$

where d : nominal diameter of packings, (mm).
 d_i : inside diameter of tower, (m).
 D_L : diffusion coefficient of solute gas in liquid, (cm²/sec).
 G_M : total gas rate in tower, (kg-mol/m²·hr).
 G_W : total gas rate in tower, (kg/m²·hr).
 L_M : liquid rate in tower, (kg-mol/m²·hr).
 l : height of packed bed, (m).
 m : gradient of equilibrium curve, $(N_{OL})(L_M)/(N_{OG})(G_M)$.
 n : function of m obtained from figure.
 ν' : kinematic viscosity of liquid, (cm²/sec).

A part of author's absorptional experiments* at 20 atm and several data in industrial absorption towers are included in the used data; all data are within the accuracy of ± 40 –60% to the Eq. (5). Fujita's equation (5) is applicable to physical absorption of gas in packed tower in spite of the magnitude of solubility.

II. Influence of Operating Factors upon Over-all Capacity Coefficient

The over-all capacity coefficient $K_L a$ is the mean value of the entire

* Kurokawa and Takeya's report at the annual meeting of Soc. Ind. Chem. (Japan), 1941; data of the preliminary experiments¹⁾.

column expressed by the product of over-all coefficient K_L and the gas-liquid contact area a . It is hard to calculate the numerical value of K_L and a separately. However, as several kinds of factors act upon K_L and a , the author has examined them individually according to the literatures.

1. Gas-liquid Contact Area.

The total area of packings in a dry packed bed is invariable, provided the kinds of packings, the packing method and the number of packings are constant. The gas-liquid contact area (effective wetted area per unit volume = a (m^2/m^3)) in the packed bed, which is available for gas absorption, is disproportional to the over-all area of the packings. It is generally presumed that the area a varies according to the sorts of packings, the packing method, the dimension of the column, the method of the liquid feeding and the operating conditions of absorption (especially to the sorts of gas and liquid, and their flow rates). Moreover, as a is supposed to be variable according to the position in the packed bed (even in case of particular absorption condition), so a would be regarded as the mean value of the entire packed bed.

According to Sherwood, the principal reasons why the effective wetted surface of a packed bed is disproportional to the total area of the packings are⁽⁶⁾:—

(a) Uneven distribution of the liquid over the cross section of the column. (b) The failure of the liquid to wet all of the individual particles. (c) Inactive surface at the points of contact of the packing particles, where the liquid remains stagnant and is saturated by solute.

As for the distribution of water, some deviation (it differs by position of packed bed) from the ideal state is noticed. If proper care is taken, for the feeding and flowing methods and increasing of the liquid rate properly, the distribution is much improved, and hence a is increased.^{(2),(6)} The experiments indicating (b) and (c), were made by Mayo, Hunter and Nash⁽⁵⁾ using comparatively small scale experimental columns. They used three kinds of column (inside diameter $\times$ height was respectively 3×48 , 6×24 and 2×36 inches), fitted with paper liner and packed with paper Raschig rings (d : 0.5 and 1 inch) at random. After the feeding with water containing red dye from perforated plate distributor in steady state within constant time (10–15 minutes), they took out and dried the packings and paper liner, and measured the percentages of the total dyed area (a').

- (1) The value of α' of the column surface was considerably greater than that of the packings. Of the surface of the packings, the outside was a little more wet than the inside.
- (2) The value of α' increased steadily as the liquid rate was increased up to the flooding point (Figures 2, 3 and Table 1).

TABLE 1 Percentage of Total Surface Wetted at Various Water Rates, α' (by Mayo, Hunter & Nash)

l/d_t \ L_s	1.52	21.0	23.0	39.0	47.0
2	44.5	50.9	65.0	68.5	72.0
4	36.1	39.6	51.0	54.5	57.6
6	—	36.2	46.0	48.3	52.8
8	—	34.1	43.1	47.1	49.7
10	28.1	32.6	42.0	45.5	48.0

Remarks: L_s : water rate ($t/m^2 \cdot hr$)
 l : height of packed bed (inch)
 d_t : tower diameter ($=3$ inch)
 d : diameter of packing ($=1/2$ inch)

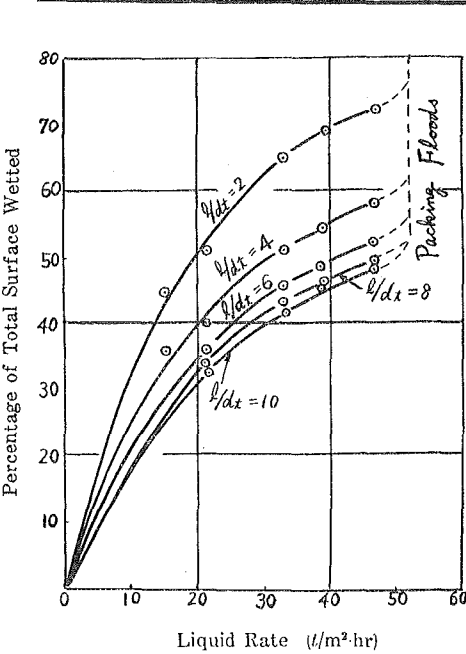


Fig. 2 Variation of Total Surface Wetted with Water Rate (by Mayo, Hunter & Nash.)

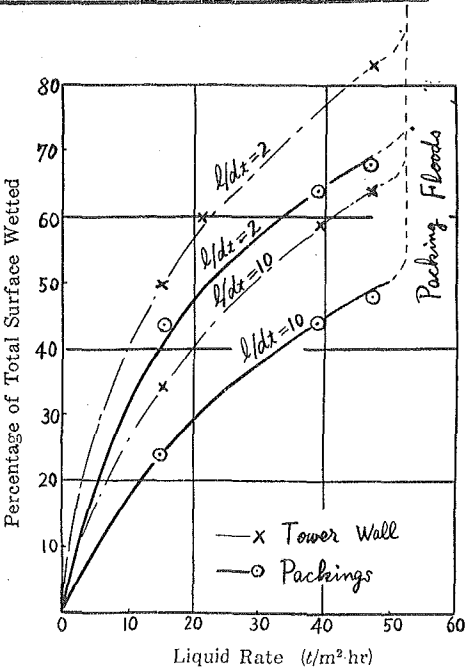


Fig. 3 Variation of Total Surface Wetted with Water Rate (by Mayo, Hunter & Nash.)

(3) The value of a' varied according to the height of the packed bed (l): greatest on the top of the packings just under the water distributor and becoming smaller as the water descended; that is, a tendency for the liquid to concentrate to the wall from the center of the tower with flowing-down and a channeling were noticed.

(4) Comparing the two cases where the packings big and small, were packed in two corresponding columns in each size (cases of $d: 1$ in., $d_t: 6$ in., and $l: 12$ in., and $d: 0.5$ in., $d_t: 3$ in., and $l: 6$ in.), so that d_t/d and l/d_t became equal, it was found that total surface of the bigger packings was greater, and the value of a' became smaller. For instance: the value in the case of $L_s: 40$ t/m²·hr. indicated the difference as $a'_{d=1}: 45\%$ and $a'_{d=0.5}: 70\%$.

(5) The rate of air sent from the bottom of tower had no measurable influence upon a' up to the flooding point.

(6) Under various liquid feed rates and air rates (in the steady flowing state), the rate of the hold-up existing in the column was measured and divided by the wetted surface, with a view to find the average thickness of liquid stream*. The results are as follows. The hold-up increased with the increasing liquid rate. Any change of the thickness of stream was not noticed within the range of $L_s: 9.4$ – 39.0 t/m²·hr., nor within the range of the air rate 128 – 225 m³/m²·hr. (when $L_s: 21$ t/m²·hr.), and the average thickness was 0.7 mm.

(7) The inactive surface in the case of gas absorption, though being not quantitative measurement, is presumed to correspond to 10% or so of the actual wetted surface.

Whether or not these results are directly applicable to the present author's intermediate scaled experiments remains uncertain. At any rate, the fact that the wetted area $a'\%$ does not indicate any noticeable value in the experiments by Mayo, Hunter and Nash, is worthy of note.

In fine, from the above, a conclusion is drawn to the effect that a uniform distribution and the increasing water rate to certain extent, are essential in order to increase the gas-liquid contact area in gas absorption tower.

2. Factors of the Film Coefficients.

There exist the following relations⁶⁾ among the over-all coefficient

* Observing the flowing of liquid in glass tower, Mayo et al. acknowledged that it flowed down on the surface of packings and did not become drops.

of mass transfer K_L and the gas and liquid film coefficients, k_G and k_L :—

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{H}{k_G} \quad \dots\dots\dots (6)$$

$$k_G = \frac{1}{t_G} \cdot \frac{DP}{RTp_{BM}} \quad \dots\dots\dots (7)$$

$$k_L = \frac{1}{t_L} \cdot \frac{D_L(C_A + C_B)}{C_{BM}} \quad \dots\dots\dots (8)$$

where H : Henry's law constant.

t_G : effective thickness of gas film.

t_L : effective thickness of liquid film.

D : diffusion coefficient for gas.

D_L : diffusion coefficient in liquid phase.

R : gas law constant.

T : absolute temperature.

P : total pressure.

p_{BM} : logarithmic mean of inert gas pressures at film boundaries.

C_A : concentration of solute in liquid phase.

C_B : concentration of solvent in liquid phase.

C_{BM} : logarithmic mean of C_B at film boundaries.

Therefore all conditions which have influence upon Henry's law constant, the diffusion coefficients, and the effective thickness of the films, have influence upon K_L also.

1) Diffusion coefficients D , D_L .

When gas A is diffusing in gas B , the diffusion coefficient D is expressed as the following equation theoretically⁶⁾.

$$D = \frac{R^2 T^2}{\alpha' P} \quad \dots\dots\dots (9)$$

Maxwell derived the following equation theoretically, considering the gas molecule as elastic solid sphere⁶⁾.

$$D = \left(\frac{R^{3/2}}{\sqrt{8\pi} A} \right) \frac{T^{3/2}}{PZ^2} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}} \quad \dots\dots\dots (10)$$

where, A : Avogadro's number.

Z : distance between the centers of two unlike molecules at collision.

M_A, M_B : molecular weight of gases A and B , respectively.

α' : proportionality constant.

Gilliland¹⁶⁾ obtained the following experimental equation for convenience sake.

$$D = 0.0043 \frac{T^{3/2}}{P(V_A^{1/3} + V_B^{1/3})^2} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}} \quad [\text{cm}^2/\text{sec}] \quad \dots\dots (11)$$

V_A, V_B : molecular volume of A and B gases, respectively. According to the measured value of actual gases, change of D caused by the temperature T is a little greater than the above mentioned, and it shows $n=1.75$ in the case of a gas system akin to the permanent gas, and $n=2$ in the case of a condensable gas system in the equation $D \propto T^n$ ¹⁷⁾.

In the case of carbon dioxide, Loschmidt and von Obersmeyer¹⁸⁾ gave the following experimental values of the diffusion coefficient D_0 under the standard condition (0°C and 1 atm.).

Gas	D_0 (cm ² /sec.)
H ₂ -CO ₂	0.550
CO-CO ₂	0.137
Air-CO ₂	0.138
O ₂ -CO ₂	0.139
CH ₄ -CO ₂	0.156
N ₂ O-CO ₂	0.096

The relation between the diffusion coefficient in liquid D_L and the molecular properties effecting D_L , is much complicated, as the ionization, the association, the dissociation and the convection influence the operation.

Hence, any definite theory corresponding to the kinetic theory of gases, is yet unestablished. However, as in the case of the organic compounds or molecules, a similar treatment is applicable when the ionization, association etc., are negligible.

In accordance with the results arranged semi-theoretically by Arnold¹⁹⁾, D_L at the ordinary temperature is generally expressed by the following equation:—

$$D_L = \frac{B \sqrt{\frac{1}{M_1} + \frac{1}{M_2}}}{A_1 A_2 \mu^{1/2} (V_1^{1/3} + V_2^{1/3})^2} \quad \dots\dots\dots (12)$$

where B : constant.
 M_1, M_2 : molecular weight of solute and solvent respectively.
 V_1, V_2 : molecular volume of solute and solvent respectively.
 μ' : viscosity of solvent.
 A_1, A_2 : correction factor.

When Arnold derived equation (12), he made the calibration in the ordinary temperature or nearby so, using the following equation:—

$$D_t = D_0(1 + 0.030 t) \quad \dots\dots\dots (13)$$

where D_t, D_0 : diffusion coefficient at $t^\circ\text{C}$ and 0°C respectively.

Eqs. (12) and (13) are used for the calculation of D_L in engineering computation, when the experimental value is not obtained*.

As the viscosity of water hardly changes in the range up to several hundred atmospheres in ordinary temperature**, the influence of pressure upon D_L in the case employing water as solvent might be negligible within the range of the operating pressure (below 20 atm.) in the author's experiments.

2) Thickness of the gas and liquid films t_g, t_L .

The effective thickness of the gas and liquid films are presumably in direct proportion to viscosity of the fluid, and inversely proportional to the velocity and density.

Gilliland and Sherwood gave the results about the resistance in the gas film, when it controls the mass transfer in a wetted wall tower. The process of the mass transfer in packed towers is complicated and the results obtained in the wetted wall tower are not applicable as they stand. However, as an analogous equation may be taken into consideration in the case of packed towers, the author takes advantage of their results as a clue.

According to Gilliland and Sherwood²⁰⁾, the following dimensionless equation exists as to the thickness of the gas film t_g under conditions of turbulent gas flow in the wetted wall tower.

$$\frac{d}{t_g} = 0.023 \left(\frac{du\rho}{\mu} \right)^{0.83} \left(\frac{\mu}{\rho D} \right)^{0.44} \quad \dots\dots\dots (14)$$

* For Example, Fujita, Chem. Eng. (Japan) 11, 7 (1947); Sanka, Trans. Chem. Eng. (Japan) 6, 11 (1942).

** According to Landolt, "Tabellen" 5 Aufl., I Bd. 137 (1923); Hauser Ann. d. Physik, (4), 5, 597 (1901), the difference of viscosity of water in 0 atm. and 400 atm. is about $\Delta\mu'$ (%) = $0 - \pm 1.6\%$ at $18-40^\circ\text{C}$.

- where d : inside diameter of the tower.
 u : superficial linear velocity of the gas, based on the cross sectional area of the empty tower.
 μ : viscosity of gas.
 ρ : density of gas.
 D : diffusion coefficient of gas.

Gilliland and Sherwood confirmed, moreover, that t_g is independent of pressure within the range of the absolute pressure 110–2,330 mm Hg.

In the above equation, the mass velocity (G_m) of the gas in the empty tower equals $u\rho$, hence t_g varies inversely proportional to $G_m^{0.83}$.

The viscosity μ of the gas increases more or less, by increasing the temperature, its range is a little greater than the first approximation, $\mu \propto T^{1/2}$. However, in the case of the actual gases, the following relation is obtained experimentally at the ordinary temperature (approximately $288^\circ K$)²¹⁾ :—

$$\mu \propto T^{n'} \quad \dots\dots\dots (15)$$

sort of gas	He	H ₂	N ₂	CO ₂
value of n'	0.64	0.69	0.77	0.95

The explanations relating to Eq. (15) and the value of n' , are in the case of the single gas. As for the relation between the viscosity of a mixed gas and that of the component gas, it is not so simple²²⁾. But, as in the relation between the diffusion coefficient D and T , the gaseous system which deviated from the permanent gas, shows a similar deviation even in Eq. (15). In this case it may be regarded that $n' \approx 1$, and it is therefore concluded that $(\mu/\rho D)$ is approximately independent of T , under a fixed pressure*. Consequently, t_g may be regarded to increase proportionally to $T^{0.8}$ by increasing the temperature, under the condition that $t_g \propto \mu^{0.83}$ and d , G_m and the pressure are constant in Eq. (14).

Next, let us consider the influence of the variation of the pressure upon t_g . According to the kinetic theory of gas, as the first approximation, μ is independent of the density ρ , and μ is also independent of the pressure P , provided the temperature is constant. This reasoning well agrees with the fact, except for the cases of the liquidization of the gas or of a high vacuum. Hence, by means of $\rho \propto P$ and $D \propto 1/P$, the

* Kennard, "Kinetic Theory of Gases", p. 198 (1938). Raw gas in the author's experiments had the composition of N₂ (mainly), CO₂, CO, H₂ etc.

$(\mu/\rho D)$ is independent of P and by Eq. (14) t_g is independent of the pressure under the condition that Reynolds number is constant. The experiments by Gilliland and Sherwood confirmed the relation up to 3 atm. as above stated, and it can be said safely that μ is independent of P^* even within the range of experimental conditions of 3–20 atm. and ordinary temperature. Therefore the same (that t_g is to be independent of P) can also be said within that experimental condition, regarding the wetted wall tower.

In short, in the case of the wetted wall tower, the gas film thickness t_g is inversely proportional to $G_m^{0.8}$, and when G_m is constant, t_g is independent of P and varies directly proportionally to $T^{0.8}$ under the condition at ordinary temperature and 20 atm. In the case of gas absorption by packed tower, the gas-liquid contact area and the operating wet void vary in accordance with the liquid rate and the gas rate. As there are collisions, friction, and narrowing and enlarging of stream caused by the existence of the packings, or by the complicated current conditions of liquid, motion of the gas is regarded to become violent and complicated.

Let the same gas rate and same liquid rate be set counter current in a wetted wall tower and a packed tower of equal inside diameter: in this case, as the hold-up of liquid is greater in the packed tower, so the operating wet void is to be smaller. According to Uchida and Fujita²³⁾, the operating wet void of packed tower begins to decrease suddenly, as the superficial gas velocity increases above a certain rate under constant liquid rate, and when the gas velocity is still more increased, it reaches to the flooding point.

From these things, it may be conjectured that the influence of the superficial gas velocity upon the film is greater in the packed tower than in the wetted wall tower. Further, in the case of packed tower, even under ordinary absorption condition, a violent stirring action may well be expected. Accordingly, the film may become thinner compared with that in wetted wall tower (mass transfer is molecular diffusion mainly), and a considerable influence of turbulent diffusion participates in the mass transfer through the film.

The influence of D on k_g is far less in the case of packed tower,

* Increase of viscosity caused by increase of pressure from 1 atm. to 20 atm. at ordinary temperature, is 5% as to CO_2 , and 1% as to air, N_2 , and H_2 [Landolt, "Tabellen", 5 Aufl. III Erg. Bd., 189 (1935), *ibid.*, I Erg. Bd., 144 (1927); *ibid.*, I Bd., 185 (1923)]. The viscosities of air, N_2 and H_2 , increase remarkably in the case of 50 atm. [Landolt, *ibid.*; Hayami, Transportation of Fluid, 138 (1949)].

whereas $k_G = (\text{const}) D^{0.56}$ in the case of the wetted wall tower, combining Eqs. (14) and (7). Sherwood²⁴⁾ obtained the result of experiment as $k_G \alpha = (\text{const}) D^{0.17}$ in the humidification of air in packed tower. Fujita²⁵⁾ combined his experimental results on the humidification of air in packed tower and those of other investigators obtained in the cases the gas film resistance being controlling. Thus he obtained the following generalized equations indicating the relation between $k_G \alpha$ (1/hr.) and various factors:—

$$k_G \alpha d^2 / D = 0.0245 (u^2 / 2gd)^{-0.31} (du\rho / \mu)^{1.62} (\mu / \rho D)^{1.0} V_W^{-1.0} \quad \dots (16)$$

$$\text{or} \quad k_G \alpha d / u = 0.0304 (d^3 g \rho^2 / \mu^2)^{0.31} V_W^{-1.0} \quad \dots (17)$$

where d : size of the packings.

g : acceleration of gravity.

V_W : operating wet void (%).

Other symbols are the same as the case in Eq. (14). According to Eq. (16), $k_G \alpha$ is independent of D .

Next, it has been made plain that the thickness of the liquid film t_L is also regulated by Reynolds number* and Schmidt number. Thus t_L is inversely proportional to the superficial mass velocity of liquid L_m and directly proportional to the viscosity of liquid μ' . When the liquid velocity u' is constant, the increase of the temperature will considerably decrease t_L according to the decrease of the liquid density ρ' and of viscosity μ' . The increase of the pressure has no clear influence.

3) Solubility coefficient of CO_2 .

Henry's law constant H , Bunsen's solubility coefficient α , and the molecular volume v of CO_2 hold the relation of $H = \alpha/v$ respectively. However, H (the same as α) is remarkably lowered with temperature in the case of CO_2 .

3. Influence of Operating Factors Upon $K_L \alpha$.

Basing his observation on theoretical considerations, regarding both gas and liquid films, the author examines the influence of the variation of the operating factors upon $K_L \alpha^{**}$.

* But, what value should be taken as d in Reynolds number in this case is not so clear as it is in the wetted-wall tower.

** Yushkevich, Zhavoronkov and Zel'venskii also discussed briefly the influence of operating factors upon the over-all coefficient of mass transfer in the pressure absorption of CO_2 in their first report (J. Chem. Ind. (Moscow), 12, 472 (1935)).

The principal variable operating factors in the pressure absorption of carbon dioxide by water in a special packed tower (d_i, d, l, V_w , packing method and liquid feeding method being constant), are the following five items*:-

- (1) gas rate
- (2) water rate
- (3) operating pressure
- (4) operating temperature
- (5) composition of raw gas (the sort of inert gas and concentration of CO_2)

As some of these exert effect upon V_w (that is act upon k_a), as indicated by Eq. (16), the author considers at first briefly, V_w and then examines the operating factors.

According to the study of Uchida and Fujita²⁶⁾, main factors influencing (V_w/V_d) are shown as dimensionless groups ($u^2/2gd$) and $(u/u') \cdot (d^3g/\nu'^2)^n$, where $n=0.1$ in the case of water. The relation between these factors is diagrammatically given by them²⁶⁾. According to them V_w is affected greatly by u and u' , as compared with small effect by ν' , in the case of water; V_w decreases with increasing u' at any constant u , and increases somewhat with increasing u at any constant u' .

Next, the influence upon K_La provided one of the above mentioned five items is changed while the others remain constant, might be as follows.

1) Change in gas rate.

Fujita's equation (17) being $k_a a = \text{const } (u/V_w)$, $k_a a$ is directly proportional to u , and inversely proportional to V_w . Even taking into consideration that V_w somewhat increases by increasing u , one is informed of the increase of $k_a a$ by decreasing t_a , which has been shown in several experiments²⁷⁾ where the gas film is controlling. Many experiments on the absorption under ordinary pressure prove satisfactorily that $k_L a$ is independent of u , in so far as it deviates from the loading point (or flooding point).

From the above, it becomes evident that the increase of the gas rate (in case the gas film resistance substantially exists in the absorption

* d_i : inside diameter of tower, d : size of packings, l : height of packed bed, V_d, V_w : dry and operating wet void, respectively.

G_m, L_m : superficial mass velocity of gas and liquid, u, u' : superficial mean linear velocity of gas and liquid, ν' : kinematic viscosity of liquid, g : acceleration of gravity.

process) reduces the gas film resistance H/k_g and increases $K_L a$.

2) Change in water rate.

In case the water rate alone is increased, the contact area first increases and then the turbulence of the liquid stream is increased, and the k_L is enlarged as the film becomes thinner. While, as V_w decreases more or less, the increase of k_g may possibly be expected to take place*.

In the case when the resistance by the liquid film is controlling, $k_L a \propto L_s^{0.75}$ exists by Eq. (2). In the author's experiments, the liquid film making a major resistance, $k_L a$ increases if the water rate increases and hence the $K_L a$ increases remarkably.

3) Change in operating pressure.

The variation of the pressure does not affect k_L and acts only upon k_g .

In Eq. (7), as DP is not effected by the total pressure P and t_g is also approximately independent of P^{**} , hence k_g decreases showing inverse proportion to the mean partial pressure of the inert gas p_{BM} . However, as the pressure is increased under the condition of G_m remaining constant, the decrease of u is to take place (which is inversely proportional against the increase of P) and it naturally accompanies the increase of t_g and the lowering of k_g .

Overlapping these effects, the increase of the operating pressure might lower k_g after all, and as the result, it might lower $K_L a$ also, provided the resistance of the gas film is substantially in existence in the process of the absorption.

4) Change in operating temperature.

Although the changes of the operating temperature effect both film coefficients, the influence upon k_L is greater. As $D \propto T^2$ and t_g also increases with the temperature, the effect of T upon k_g may not be very remarkable, viewed from Eq. (7) (in the case of wetted wall tower: t_g is directly proportional to $T^{0.8}$ and $k_g \propto T^{0.3}$).

The gas film resistance H/k_g may become more or less weak by the decrease of H caused by the rise of the temperature.

Next, in the author's experiments, as the concentration of CO_2 in

* However, according to Fujita, in case only the gas-film resistance exists, gas-film coefficient is shown to be inversely proportional to $L_s^{0.3}$, and decreased with L_s . Chem. Eng. (Japan), 11, 42 (1947).

** In the case of wetted wall tower.

the washing water is really dilute*, C_A is negligible compared with C_B in Eq. (8); it follows:—

$$\frac{C_A + C_B}{C_{BM}} \doteq 1 \quad \dots\dots\dots (18)$$

and Eq. (8) may be written in the form

$$k_L = \frac{D_L}{t_L} \quad \dots\dots\dots (19)$$

When the temperature is raised, both viscosity and density of water decrease, and D_L increases (Eqs. (12) and (13)); then t_L will be remarkably decreased, and k_L will be noticeably increased according to Eq. (19).

In the author's experiment, as the liquid film is presumed to be the main resistance, $K_L a$ is considered to increase as a result of the rise of the temperature.

5) Composition of raw gas.

The variation of k_G and k_L in the case of dilute solution by the change of solute gas concentration is ordinarily negligible in engineering computations. However, when the $\text{CO}_2\%$ of the raw gas is increased remarkably, the k_G might be increased by the decrease of p_{BM} .

When the composition of the inert gas is changed, the diffusion coefficient D in the gas film varies in consequence. However, according to Sherwood²⁴⁾ and to Fujita,²⁵⁾ the variation of $k_G a$ by D is slight.

As above stated, the variation of $K_L a$ as influenced by the composition of raw gas would be very slight.

III. Apparatus and Procedure

1. Apparatus and Experimental Procedure.

The principal parts of the apparatus and procedure are similar to those explained in the preliminary experiments¹⁾. However, considering the foregoing experimental results^{1),2)}, some improvements were made to secure more accurate measurements of flow rates of gas and

* Saturated concentration of CO_2 under the standard experimental condition (CO_2 in raw gas: 18%, π : 20 atm and t : 20°C) is $3.16 \text{ (m}^3\text{-CO}_2\text{/m}^3\text{-H}_2\text{O)} = 0.141 \times 10^{-3} \text{ (g-mol-CO}_2\text{/cm}^3\text{-H}_2\text{O)}$; as to actual washing water, $C_A < 0.141 \times 10^{-3} \text{ (g-mol/cm}^3\text{)}$, $C_B = 55.6 \times 10^{-3} \text{ (g-mol/cm}^3\text{)}$, therefore, $C_A < 2.5 \times 10^{-3} \times C_B$. Through all the experiments, the highest concentration of outlet water was 4.36–5.16 ($\text{m}^3\text{-CO}_2\text{/m}^3\text{-H}_2\text{O}$) (Cf. Table 12). Even in this case $C_A = (3.5\text{--}4.1) \times 10^{-3} C_B$.

water, and to keep the feed water at a higher constant temperature, whenever necessary, than its original temperature. The main series of experiments was carried out with combustion gas made from coke burning as the raw gas, instead of the raw gas composed of CO_2 and H_2 used in the preliminary experiment¹⁾. The apparatus employed is indicated in Figure 4 and the photographs. The tower (6), constructed of a steel cylinder, had the total height of 4,000 mm and the diameter of 450 mm, and withstood normal working pressure of 20 kgs/cm², the same as used in the previous experiments¹⁾²⁾. The packed bed, 2,300 mm in height, was made up of 6,800 particles irregularly packed, of 35 mm

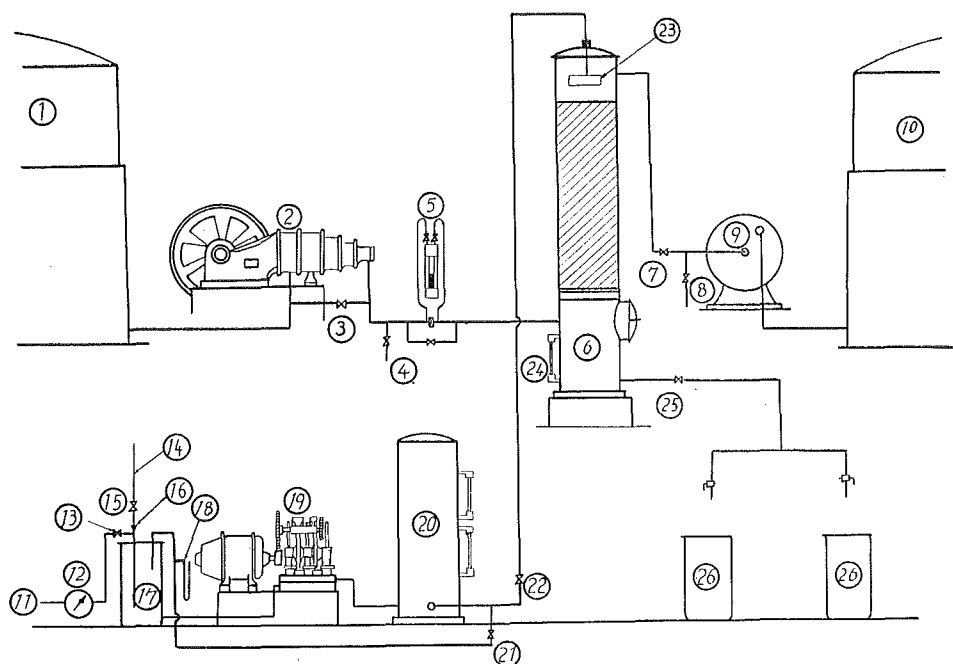
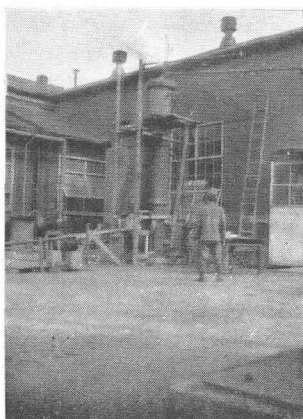
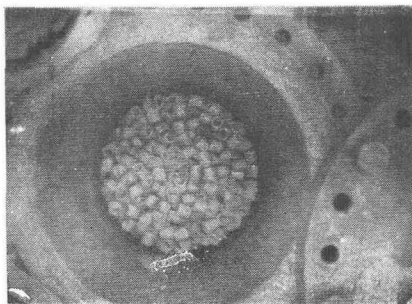


Fig. 4 Flow Diagram of Absorption Tower System.

- | | | |
|--|--|--------------------------------------|
| ① Gas Holder for Raw Gas. | ⑩ Gas Holder for Washed Gas. | ⑲ Plunger Pump. |
| ② Gas Compressor. | ⑪ Feed Water. | ⑳ Storage Vessel for Pressure Water. |
| ③ By-pass Valve. | ⑫ Water Meter. | ㉑ By-pass Valve. |
| ④ Cock for Gas Sampling. | ⑬ Valve for Water Feeding. | ㉒ Valve. |
| ⑤ Orifice Meter for High Pressure Raw Gas. | ⑭ Steam. | ㉓ Water Distributor. |
| ⑥ Absorption Tower. | ⑮ Steam Valve. | ㉔ Glass Level Gauge. |
| ⑦ Pressure Reducing Valve. | ⑯ Steam Blowing Nozzle. | ㉕ Pressure Reducing Valve. |
| ⑧ Cock for Gas Sampling. | ⑰ Vessel for Regulating Water Temperature. | ㉖ Vessel for Measuring Waste Water. |
| ⑨ Gas Meter for Washed Gas. | ⑱ Mercury Manometer. | |



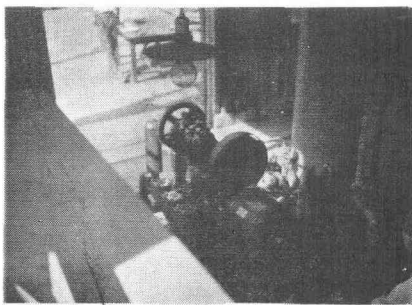
(1)



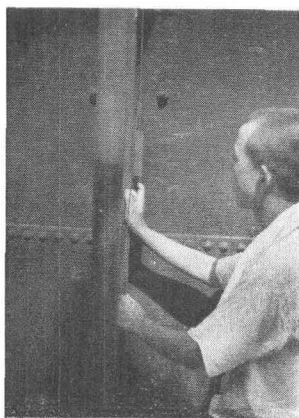
(4)



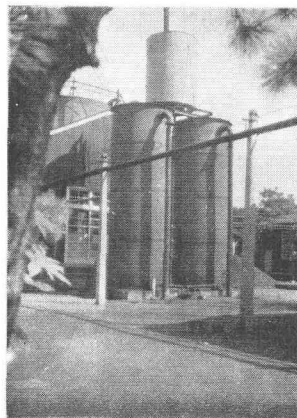
(2)



(5)



(3)



(6)

Photographs

- | | |
|---|-------------------------------------|
| (1) Absorption Tower. | (4) Packings (top of tower). |
| (2) Gas Compressor. | (5) High Pressure Water Pump. |
| (3) Gas Holder (measuring of gas volume). | (6) CO ₂ Recovery Tower. |

ceramic Raschig rings, which were supported on a mild steel packing support as shown in Figure 5. The free volume of the packed bed was 71.8%.

Water as solvent was underground water which, once pumped up into a storage tank, then passing through a water-meter (12) and a temperature regulating vessel (17), was sucked into a triple-acting plunger pump (high pressure water pump) (19), driven by a 10 H.P. induction motor. The compressed water was fed, through a high pressure storage vessel (20), to the

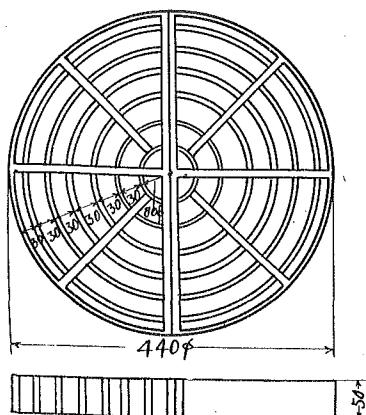


Fig. 5 Packing Support.

water distributor (23) at the top of the tower. The water distributor was of a perforated-plate type, having 67 through-holes of 8 mm diameter on its bottom plate as shown in Figure 6. Although the pump had a rated capacity of about 7.5 m³/hr.,* the rate of water fed to the tower could be changed easily by adjusting the opening of the by-pass valve (21) i. e., by changing the rate of return water through the by-pass. The temperature of the water from the storage tank was 16–23°C throughout the year. To keep the feed water at a higher temperature, whenever necessary, than its original temperature, a three hundred liter vessel for regulating the water temperature (17) was installed in front of the high pressure water pump. Steam of 3 kgs/cm² pressure in pipe (14) was sent, through a gun metal nozzle with a 7 mm bore (16), directly into the water pipe to warm the washing water. In steady state runs, as the water level in the vessel (17) was accurately fixed by controlling valve (13), the water temperature could be easily and accurately regulated by the steam valve (15). The raw gas was prepared by the combustion of coke in a gas producer** with steaming, and was composed of 16–18% CO₂, 55–75% N₂, 8–20% H₂, and 4–6% CO. A three-stage gas compressor (2) was used, with a normal suction

* The capacity of the pump is insufficient for a study over a wide range of greater water rate. However, from the point of view of economy of expenditure, the improvement was limited to the renewal of the electric motor only. A new induction motor of 10 H.P. was installed instead of the old direct current shunt motor of 7 H.P., the maximum capacity of the pump being thus increased to 7.5 m³/hr.

** The capacity of gasification: 100 kgs of raw material per hour divided by the sectional area of grate, consuming 2 tons of coke per day.

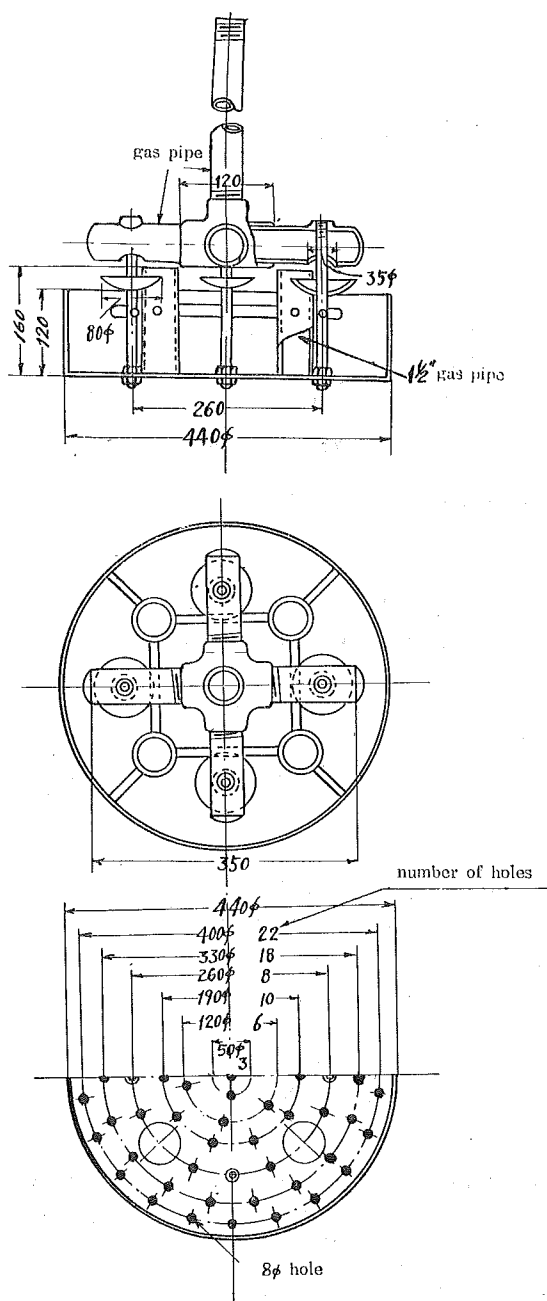


Fig. 6 Water Distributor.

capacity of 250 m³/hr. and normal working pressure of 20 kgs/cm².

The volume of raw gas consumed, was measured by an orifice meter (5) as well as by a 280 m³ gas holder (1) every twenty minutes in a run, and that of the washed gas, after its pressure was relieved, was measured by a 250 m³/hr. gas meter (9) and another 280 m³ gas holder (10) at the same time intervals.

Water rate was determined by a water-meter (12) as well as by measuring the volume of waste water by using two vessels (26), the capacity of each being about 150 liters, every ten minutes in a run. The orifice meter for the compressed raw gas (5) and the water-meter (12) were newly installed to measure the flow rates at the inlets of the tower.

When beginning a run, the gas compressor was started and air in the tower was replaced by the raw gas; then the pressure of the gas in the tower was gradually raised to a working pressure; the plunger pump was also driven, and the water was allowed to flow down through the packed bed

making a counter-current to the gas stream under pressure. The level of the water absorbing CO_2 at the bottom part of the tower was held exactly at a fixed point in a glass level gauge throughout a run, by adjusting the rate of water fed as well as by the opening of a valve (25) for reducing the pressure of the waste water. To make the measurement of the water temperature in the tower more accurate, a drain-sampling tube was newly installed at the bottom part of the tower (at a height equal to the center line of the drain pipe of the pressure waste water and also in nearest possible position to that drain pipe). The water temperature in the tower outlet was measured with a mercury thermometer through this sampling tube. The working temperature of the gas absorption was set at the average of the temperatures of the water in the storage vessel (20), a portion of which was drained and measured at intervals, and of the above stated temperature at the tower outlet.

The working pressure of the gas absorption was set at the average value of the pressures measured by two Bourdon type pressure gauges at positions at top and bottom of the tower. Gas analysis was carried out by Hempel's method, and residual CO_2 content in the washed gas leaving the tower was measured by alkaline solution at intervals of five minutes in a run. After the concentration of CO_2 in the washed gas became constant under a prescribed operation condition, the apparatus was allowed to run usually for forty minutes in a steady state. During such time of steady state operation, measurements of flow rates of gas and water, temperatures, pressures and analyses* of the gas stream at points both of inlet and of outlet of the tower, were taken for the calculation of the coefficient of material transfer.

The accuracy of the measuring instruments was examined as follows whenever deemed necessary:—

The gas meter for washed gas, by two gas holders;

The water-meter for feed water, by two 150-liter vessels;

The mercury thermometer for the measurement of water temperature (50°C , minimum calibration 0.2°C), by a standard thermometer;

The Bourdon type pressure gauges (40 kgs/cm^2 , minimum calibration 2 kgs/cm^2) indicating the pressure of the tower, by the "Katsuma" standard pressure gauge (minimum calibration 0.1 kg/cm^2).

Regarding the error of the measurements, the following were

* As for the raw gas, the combustion gas of coke was used in every experiment, and the analysis of components of the inert gas was often omitted.

considered as the possible percentages of error:—

Of the water temperature and of the water rate 1–2%;

Of the operating pressure 2–2.5% (20 atm. case);

Of 5 atm. case 8–10%; and

Of the gas rate 3–8%.

Of the error of the CO_2 concentration in gas, determined by Hempel's method, more than 10% was considered as the possible percentage of error in case the concentration of CO_2 in gas was under 1%. But taking the average,

Of the raw gas, 2–3%; and

Of the washed gas, 8–10% (maximum)

errors were estimated respectively.

Moreover, as part of the equipments (absorption tower and gas holders) were outdoor, the author found that the cloudy or rainy days of spring (Mar.–May) and autumn (Oct.–Nov.) are the proper time for getting most accurate measurements.

2. Calculation of Over-all Capacity Coefficient K_{La} .

For the purpose of engineering computation of the capacity coefficient K_{La} , the author assumed that Henry's law was applicable over the range of the experimental conditions, and employed a simplified way of numerical calculation¹⁾ with the following equations (20), (21) and (22), instead of the usual graphical integration method.

$$G(y-y_0) = L(x-x_0) \quad \dots\dots\dots (20)$$

$$x_G = \alpha\pi \frac{y}{1+y} \quad \dots\dots\dots (21)$$

$$\int_{x_0}^{x_1} \frac{dx}{x_G - x} = \frac{K_{La} \cdot S \cdot H}{L} \quad \dots\dots\dots (22)$$

The height per over-all transfer unit, $[\text{H.T.U.}]_{oL}$ was calculated by the following equation (23):—

$$[\text{H.T.U.}]_{oL} = \frac{H}{\int_{x_0}^{x_1} \frac{dx}{x_G - x}} \quad \dots\dots\dots (23)$$

where L : water rate, ($\text{m}^3/\text{hr.}$).

G : inert gas flow, ($\text{m}^3/\text{hr.}$).

β : ratio of water rate to inert gas flow, (L/G).

- x : CO_2 concentration in liquid, $(\text{m}^3\text{-CO}_2)/(\text{m}^3\text{-water})$.
 y : CO_2 concentration in gas, $(\text{m}^3\text{-CO}_2)/(\text{m}^3\text{-inert-gas})$.
 x_1 : CO_2 concentration of the liquid leaving the bottom (gas inlet), $(\text{m}^3\text{-CO}_2)/(\text{m}^3\text{-water})$.
 y_1 : CO_2 concentration of the gas entering the column, $(\text{m}^3\text{-CO}_2)/(\text{m}^3\text{-inert-gas})$.
 x_0 : CO_2 concentration of the liquid fed at the top (gas outlet), $(\text{m}^3\text{-CO}_2)/(\text{m}^3\text{-water})$.
 y_0 : CO_2 concentration of gas leaving the top of the column, $(\text{m}^3\text{-CO}_2)/(\text{m}^3\text{-inert-gas})$.
 x_a : CO_2 concentration corresponding to equilibrium with the CO_2 concentration in the main body of the gas, $(\text{m}^3\text{-CO}_2)/(\text{m}^3\text{-water})$.
 π : operating pressure, (absolute atm.).
 α : Bunsen's solubility coefficient of CO_2 in water, $(\text{m}^3\text{-CO}_2)/(\text{m}^3\text{-water})$ (atm.).
 H : height of packed bed, (m).
 S : sectional area of column, (m^2).

The data of Bohr⁽²³⁾ taken from the Landolt "Tabellen" were employed for the solubility coefficient α .

All components of gases except CO_2 were regarded as the inert gas. The flow of inert gas contained in the raw gas was taken for the value of G in the calculation. The loss of inert gas was obtained from the gas balance, calculated on the rates of both raw gas and washed gas, and on their compositions. The loss was usually evaluated under 5–6% of the inert gas contained in the raw gas. The data obtained from those experiments indicating a loss of inert gas above 10%, were not adopted for the calculation of the capacity coefficient.

IV. Experimental Results

1. Influence of Water Rate.

- 1) Case where operating pressure is 20 atm. in different temperatures.

$K_L a$ was found under the following conditions:—

CO_2 in the raw gas	14–17%,
Operating pressure	20 atm.,
Operating temperature	19–22°C,
Raw gas rate	67–75 $\text{m}^3/\text{hr.}$,

Inert gas rate, G_s :	350–422 m ³ /m ² ·hr.,
Water rate	2.61–7.00 m ³ /hr.
L_s :	16.4–44.0 m ³ /m ² ·hr.

The data obtained are shown in Table 2.*

Next, with a view to examine the influence of the operating temperature, the water temperature was raised to 27–28°C by steaming (other conditions being unchanged); the data are shown in Table 3. The relations between $K_L a$ and the water rate L_s in Tables 2 and 3, plotted on logarithmic paper, are shown in Figures 7 and 8 respectively. In Figure 7, some values of $K_L a$ are scattered above the upper broken line, although most of the values are included between the two broken lines. Those scattered values of $K_L a$ were obtained in the experiments where larger losses of solute-free gas were recorded, and in those experiments, therefore, the raw gas rates were surmised to be over-estimated because of inaccurate measuring. In the case of Figure 8, the values of $K_L a$ are well concentrated.

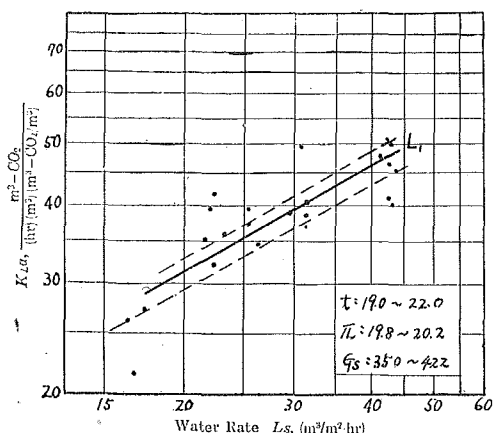


Fig. 7 Influence of Water Rate I
(20 atm.)

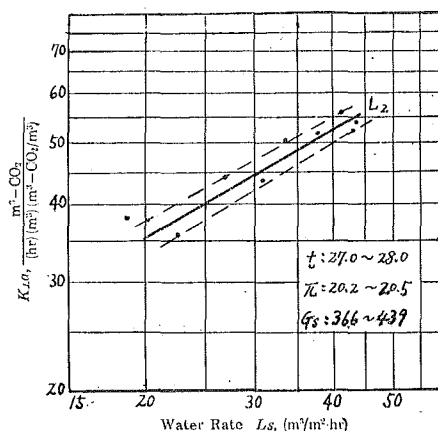


Fig. 8 Influence of Water Rate II
(20 atm.)

The full lines, L_1 , L_2 in both figures show the mean values of $K_L a$. The differences between the full line and the broken lines are $\pm 10\%$ at maximum. The empirical equations of these full lines are as follows.

$$L_1 \text{ line: } K_L a = 5.7 L_s^{0.56} \dots\dots\dots (24)$$

where L_s : 17–43 m³/m²·hr.

* Tables 2-7 & Tables 9-13: see p. 657-685.

t : 19.0–22.0°C
 π : 19.8–20.2 atm.

$$L_2 \text{ line: } K_L a = 6.7 L_s^{0.56} \dots\dots\dots (25)$$

where L_s : 20–44 m³/m² · hr.
 t : 27.0–28.0°C
 π : 20.2–20.5 atm.

Thus the gradients of both lines are quite equal and $K_L a$ increases directly proportional to 0.56 power of the water rate L_s .

Sherwood, Draemel and Ruckman⁷⁾ explained ordinary pressure desorption of CO₂ by the Eq. (1). The equation presented by Sanka⁸⁾ relating to the absorption of C₂H₂ by water was shown as Eq. (3).

In the author's experiment on the CO₂ absorption under 20 atm., the influence of the liquid rate upon $K_L a$ is a little smaller compared with the above Eqs. (1) and (3).

In Figure 9 the difference of the value of $K_L a$ showed by the lines L_1 , L_2 is not very great, but by the rise of the liquid temperature, the liquid film coefficient is increased, and $K_L a$ is also increased more or less. However, the changes of $K_L a$ by liquid temperature are not so acute as in the case of the ordinary absorption of CO₂.^{6),8)}

The influence of the water temperature and that of the liquid rate, is slow compared with the ordinary pressure absorption where the liquid film resistance is controlling. These results show an appreciable role of the gas film resistance in the high pressure CO₂ absorption.

2) Case where operating pressure differs.

As operating pressures of 10–20 atm. range are usually applied in industrial absorption of CO₂, the author carried out experiments on the influence of the operating pressure upon $K_L a$, by changing the pressure to 15 atm. and to 10 atm. (the other operating factors being similar

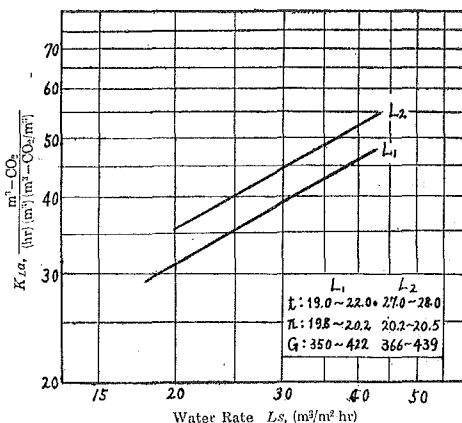


Fig. 9 Influence of Water Rate (20 atm.).

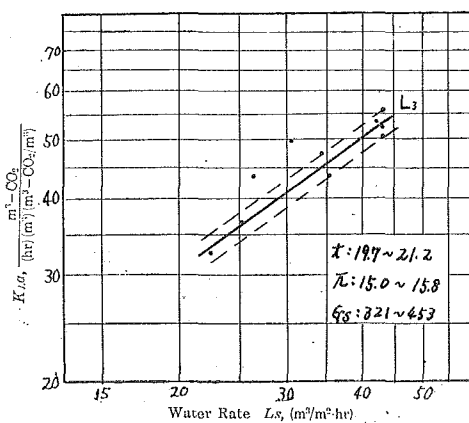


Fig. 10 Influence of Water Rate
III (15 atm.).

Next, the points plotted from the data in Table 5 are scattered (the reason is not clear) as shown in Figure 11, however, the general tendency of K_La vs. L_s would be indicated by the broken line L_4 , and K_La therefore increases with L_s .

In Figure 12, the results of the above three series of tests (full lines in Figures 7, 10 and 11) in which other conditions were similar and only the operating pressure varied, are compared with each other.

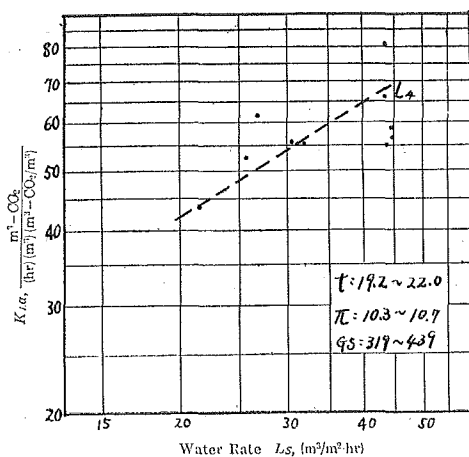


Fig. 11 Influence of Water Rate
IV (10 atm.).

to those indicated in Table 2). The results are shown in Tables 4 and 5.

The relation of K_La and the water rate in Table 4 is as shown in Figure 10; K_La increases with the water rate. The full line L_3 is expressed as the following equation:—

$$L_3 \text{ line: } K_La = 3.8 L_s^{0.70} \quad \dots\dots\dots (26)$$

where L_s : 22.0–43.0 m³/m²·hr.
 t : 19.7–21.0°C
 π : 15.0–15.8 atm.

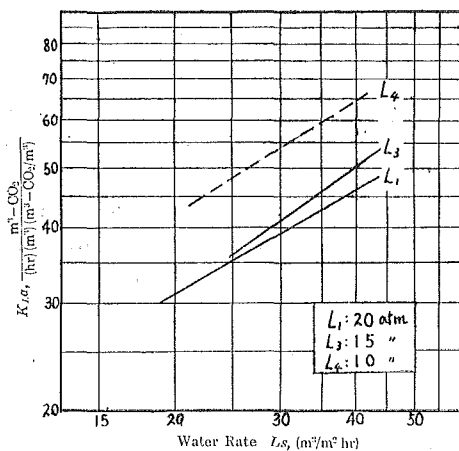


Fig. 12 Influence of Water Rate
under Various Pressures.

As has been mentioned, so far as the experiments relating to the influence of the operating pressure upon $K_L a$ are concerned, only two reports may be found – one by Yushkevich and the other by Sanka. The former treats of the pressure absorption of CO_2 . Figure 12 prepared by the present author, roughly coincides with the decreasing tendency of $K_L a$ with the increasing operating pressure (Figure 13) shown by Yushkevich and others. Figure 12 shows the fall of $K_L a$ accompanied by the rise of the operating pressure from 10 atm. to 20 atm.

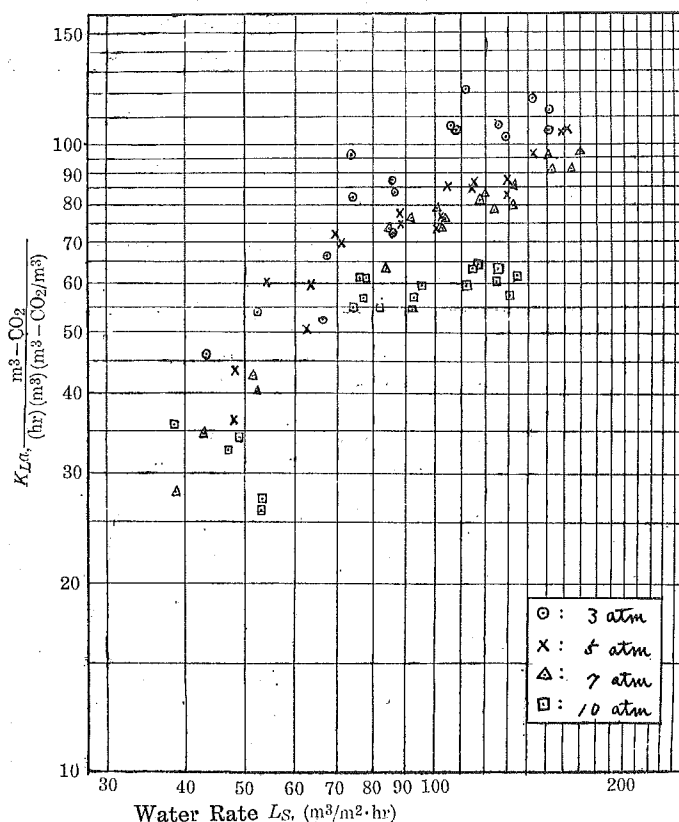


Fig. 13 Influence of Water Rate under Various Pressures
(by Yushkevich, Zhavoronkov & Zel'venskii).

According to the author's experiments, $K_L a$ is directly proportionate to $L_s^{0.56}$ at the operating pressure of 20 atm. and to $L_s^{0.70}$ at 15 atm.; thus it shows a greater gradient in the latter.

The L_1 and L_2 lines of Figure 12 seem to coincide almost with each

other on $L_s < 25 \text{ m}^3/\text{m}^2 \cdot \text{hr.}$ range, while on the range of $L_s > 25 \text{ m}^3/\text{m}^2 \cdot \text{hr.}$ their difference is gradually noticeable.

These results qualitatively agree with the theoretical considerations stated above in Section II; that is, when the operating pressure is lowered (under 20 atm.), the gas film resistance falls, causing the relative increase of the ratio of the liquid film resistance. The influence of L_s becomes greater at low pressure. When the liquid rate is increased under certain operating pressure, the liquid film resistance decreases, a stronger role of the gas film resistance being revealed. Thus the influence of the difference between the operating pressures (15 atm. and 20 atm.) upon K_L becomes gradually noticeable as L_s increases.

2. Influence of Gas Rate.

1) Case where liquid rate differs.

Combustion gas of coke (CO_2 15–18%) as raw gas;

Operating pressure (absolute) 20 atm.;

Operating temperature 18–21°C;

Liquid rate 6.7–7.0 m^3/hr ;

L_s : 41.9–44.0 $\text{m}^3/\text{m}^2 \cdot \text{hr.}$

Under these conditions, the raw gas rate was changed within the range of 55.1–163.5 $\text{m}^3/\text{hr.}$ (inert gas rate G_s : 291–847 $\text{m}^3/\text{m}^2 \cdot \text{hr.}$); the data obtained are shown in Table 6.

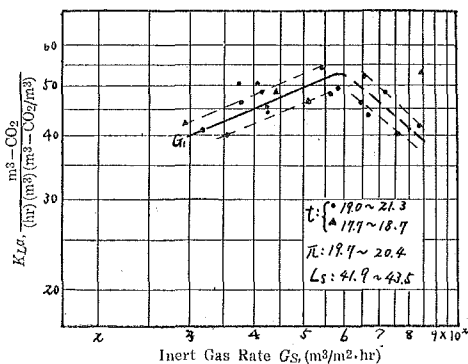


Fig. 14 Influence of Gas Rate
I (20 atm.).

showing average value, is expressed by the following equation: —

$$G_s \text{ line: } K_L a = 3.8 G_s^{0.41} \dots \dots \dots (27)$$

If the relation between the inert gas velocity G_s in the empty tower and $K_L a$ (Table 6) is dotted on logarithmic paper, Figure 14 is obtained. The Figure includes the data at somewhat low operating temperature (about 18°C), however, the influence of temperature would be negligible within the range of G_s : 300–600, that coincides as estimated from the theoretical considerations in Section II. The full line G_s

provided G_s : 300–600 $\text{m}^3/\text{m}^2\cdot\text{hr.}$

(L_s : 43 $\text{m}^3/\text{m}^2\cdot\text{hr.}$, π : 20 atm., t : 20°C).

However, it seems that K_La shows the lowering tendency with increasing gas rate within the range of G_s : 600–800 $\text{m}^3/\text{m}^2\cdot\text{hr.}$ Within the range of $G_s > 600$, some changes of the counter-current contact of gas and liquid are supposed to take place.

Next, let the liquid rate be decreased to 5.0 $\text{m}^3/\text{hr.}$ (L_s : 30.9–32.0 $\text{m}^3/\text{m}^2\cdot\text{hr.}$) and to 3.5 $\text{m}^3/\text{hr.}$ (L_s : 22.2 $\text{m}^3/\text{m}^2\cdot\text{hr.}$), the other conditions being unchanged. The results of those two series of experiments are shown in Table

7. Its graphical illustration is as Figure 15, the same tendency as in Figure 14 is noted again, though the obtained experimental values

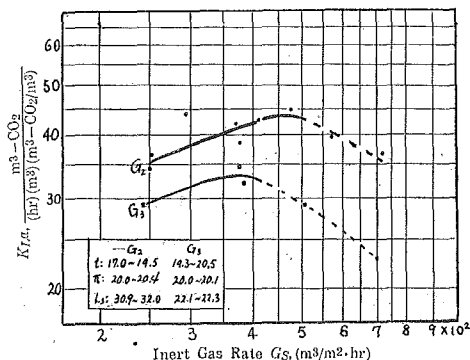


Fig. 15 Influence of Gas Rate II (20 atm.).

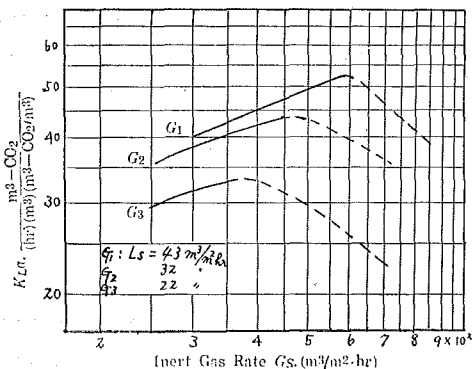


Fig. 16. Influence of Gas Rate (20 atm.).

are not numerous. That is to say, K_La shows a tendency to increase with G_s in the range of lower gas rate, and has the inverse tendency in the range of higher gas rate. Figure 16 is a superposition of Figures 14 and 15 and by this, support is gained for the assertion of the following facts:—

(1) The influence of liquid rate on K_La was confirmed, that is, the lines G_1 , G_2 , and G_3 lie in

order of greater value of K_La .

(2) If G_c ($\text{m}^3/\text{m}^2\cdot\text{hr.}$) represents the critical inert gas rate over which K_La begins to decrease with the increase of inert gas rate in Figure 16, the following table is obtained (Table 8).

In Table 8, as L_s is decreased, G_c becomes smaller. The ratio of the critical gas rate to the liquid rate and its value under the operat-

TABLE 8

Name of curve	G_1	G_2	G_3
G_c [$\text{m}^3/\text{m}^2\cdot\text{hr.}$]	600	480	370
L_s [$\text{m}^3/\text{m}^2\cdot\text{hr.}$]	43	32	22
G_c / L_s	14	15	17
$G_c / L_s \cdot \pi$	0.70	0.75	0.84

π : 20 atm.

ing pressure are:—

$$G_c / L_s = 14-17$$

$$G_c / L_s \cdot \pi = 0.70-0.84$$

Then $G_c / L_s \cdot \pi$ corresponds* to an important factor u/u' roughly which affects the operating wet void. When the gas-liquid ratio becomes a certain value (0.7–0.8), some changes in the conditions of absorption (perhaps of gas and liquid contact) seem to take place. Further, $K_L a$ will be lowered if the gas velocity increases over this value.**

But no experiments indicate the existence of the influence of the gas velocity as has been suggested by the present author. Elgin and Weiss²⁰⁾ stated that the liquid hold-up inside the packed bed is not affected by gas rate until the loading velocity is reached. Sherwood and Holloway⁸⁾, approving their opinion, mentioned that the gas stream does not appreciably affect the mechanism of flow of the liquid below loading nor does any appreciable spray action occur within the packing in packed towers. These are statements connected with absorption under the ordinary pressure.

2) Case where operating pressure differs.

The influence of gas rate was examined at the operating pressure of 15, 10 and 5 atm. respectively, keeping the water rate L_s at about $44 \text{ m}^3/\text{m}^2\cdot\text{hr.}$ and the operating temperature at about 20°C . The results of the experiments are shown in Tables 9, 10 and 11. G_4 line in Figure 17 and G_5 line in Figure 18 are obtained by plotting $K_L a$ at 15

* Though u is superficial mean velocity of total raw gas; because the raw gas of the author's experiments had constant concentration of CO_2 (15–18%), $G_s/L_s \cdot \pi$ corresponds to u/u' generally.

** According to the author's survey (1942), the operation of pressure absorption of CO_2 in factories of synthetic ammonia or synthetic fuel in Japan, had been practised under the conditions of $G_s/L_s \cdot \pi = 0.3-0.5$, therefore, it was considered to be a safety operation with no decrease of operating capacity caused by such phenomena.

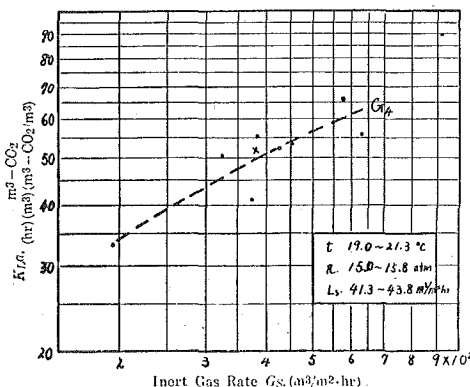


Fig. 17 Influence of Gas Rate III
(15 atm.).

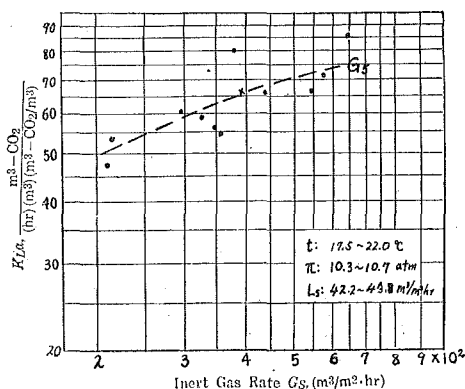


Fig. 18 Influence of Gas Rate IV
(10 atm.).

atm. and 10 atm., against the inert gas rate G_s respectively. In Figure 19 these lines are compared with G_1 line.

Some experimental values in Figures 17 and 18 are not so accurate as those of experiments described in Section IV-1, as they were obtained during summer when the atmospheric temperature was high. The lines G_4 and G_5 are expressed by the broken lines, and the points marked $\times$ are obtained by examining the straight lines L_3 and L_4 which indicate the influence of the liquid rate (Figures 10 and 11).

Based upon these data, the following statement may be made:—

- (1) $K_L a$ increases with the gas rate in the case of 15 atm. and 10 atm., and no decreasing of $K_L a$, as was seen in the case of 20 atm., is noticed within the experimental range of G_s .
- (2) The ratio of the maximum inert gas rate (within the experimental range of G_s) to the liquid rate is as follows:—

$$\text{Case 15 atm.: } \frac{600}{15} \cdot \frac{1}{43} = 0.93$$

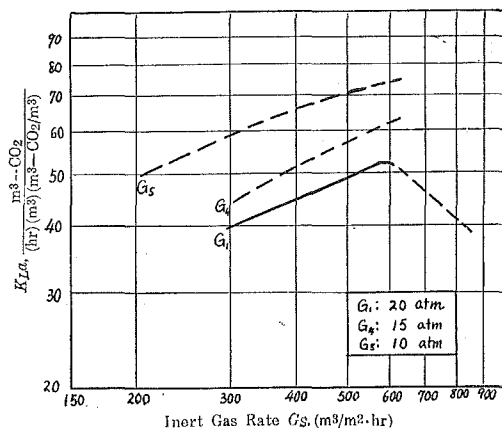


Fig. 19 Influence of Gas Rate under
Various Pressures.



$$\text{Case 10 atm.: } \frac{600}{10} \cdot \frac{1}{43} = 1.4$$

In spite of these ratios over the critical value 0.7 in the case of 20 atm. (Table 8, G_1), the decreasing of $K_L a$ is not yet clearly noticed. It may be concluded that the conception of the critical gas velocity is to be taken into consideration only in the high pressure absorption under 20 atm. or so.

- (3) According to Figure 19, $K_L a$ decreases evidently with the increasing of operating pressure, thus affording support for a statement made above.

Yushkevich, Zhavoronkov and Zel'venskii¹⁰⁾ reported on the influence of the gas velocity upon $K_L a$ in CO_2 absorption under pressure of 5 atm. as shown in Figure 20*.

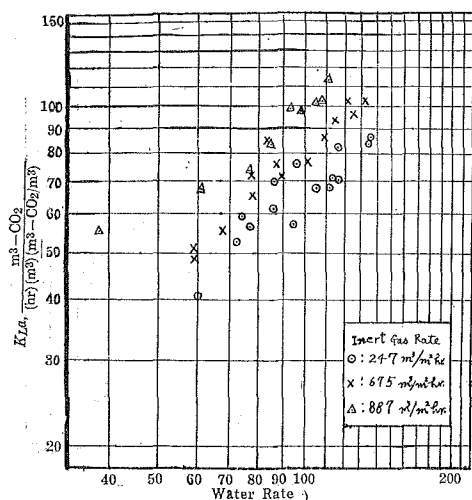


Fig. 20 Influence of Water Rate under 5 atm. and Various Gas Rates

(by Yushkevich, Zhavoronkov & Zel'venskii).

According to that Figure, the tendency of $K_L a$ to increase with G_s is greater than that of the author's experiment. This would be attributable to that, because the packed tower used by Yushkevich had a small ratio of diameter to packing dimension and a great packed depth, and therefore, the influence of the gas velocity was presumably greater than that in author's tower. Excepting this, the results obtained by the author qualitatively coincide with those by Yushkevich. To repeat, the result attained by the author mentioned in Section IV-1 and -2 coincide with those of Yushkevich (about the influence of the operating pressure and that of the gas velocity),

and are in opposition to the results expressed by Sanka, who did not admit the influence of the operating pressure on $K_L a$ in the pressure absorption of acetylene.

* $K_L a$ in Figure 20 differs from the values in the original paper, and is recalculated by the author.

Next, the data of Table 11, those of the absorption under 5 atm. pressure, are graphed in Figure 21, plotted on logarithmic paper. In this series of experiments, a little inaccuracy in the measurements was unavoidable, as it was pretty difficult to keep the steady state of operating pressure (5 atm.) as well as gas rate during a run, because of using a gas compressor having normal working pressure of 20 atm.

As a matter of fact, however, the industrial absorption is not practised in so low pressure as at 5 atm. The results under such pressure will serve only as reference.

3. Influence of the Composition of Raw Gas.

1) Influence of the CO₂ concentration in raw gas.

The CO₂ concentration of raw gas, used in industrial high pressure absorptions, differs according to the method of manufacturing the raw gas and the purpose for which the gas is to be used. For instance, the raw gas made by the catalytic reaction between steam and water gas (by water gas shift reaction), has about 30% of CO₂.

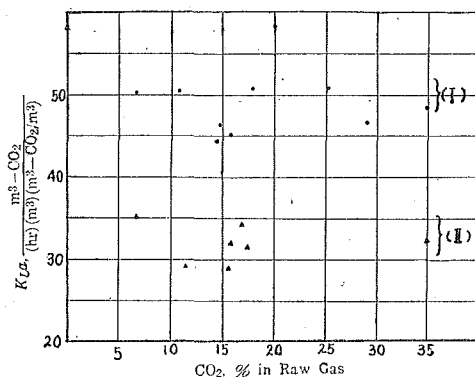


Fig. 22 Influence of CO₂ Concentration in Raw Gas.

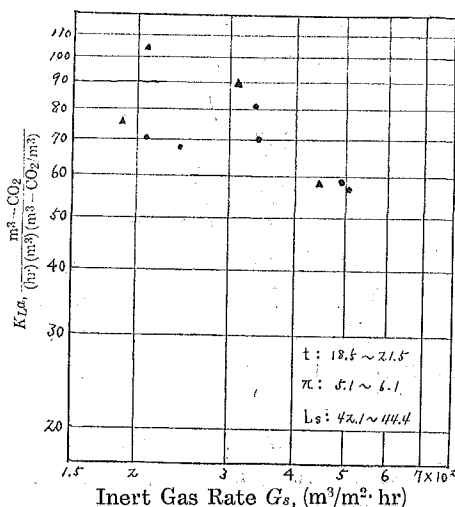


Fig. 21 Influence of Gas Rate V (5 atm.).

The influence of CO₂ concentration (7–35%) on K_La at the operating pressure of 20 atm. was examined in two series: one was under the liquid rate of 43 m³/m²·hr., and the other was of 22 m³/m²·hr.

In this case the raw gas having CO₂ concentration up to 35% was prepared by adding CO₂ to the combustion gas of coke. The carbon dioxide added, was recovered from the waste water

absorbing CO_2 through the pressure absorption of the combustion gas of coke.

The results of the experiments are shown in Table 12 and Figure 22.

In Figure 22, notes are as follows:—

Operating conditions	I (marks ●)	II (marks ▲)
L_s ($\text{m}^3/\text{m}^2\cdot\text{hr.}$)	41.9–43.5	20.8–24.4
t ($^{\circ}\text{C}$)	19.2–20.5	17.0–20.7
π (atm.)	19.9–20.4	19.8–20.1
G_s ($\text{m}^3/\text{m}^2\cdot\text{hr.}$)	374–426	350–507

From these the following considerations may be formulated:—

(1) The influence of the change of CO_2 concentration in raw gas upon K_La , is almost negligible. The variation of the CO_2 concentration in raw gas may be considered as having no effect upon the diffusion coefficient, provided the inert gas is of the same kind.

The following data are obtained by calculating the partial pressure of the inert gas using Table 12, in the cases of the maximum and minimum of CO_2 concentration.

Series	Exp. (No.)	Operating pressure (atm.)	CO_2 %		Partial pressure of inert gas in the main body of gas (atm.)			Difference of mean (atm.)
			Inlet	Outlet	Inlet	Outlet	Mean	
(I)	179	20.2	6.6	0.3	18.9	20.1	19.5	3.7
	157	19.9	35.0	6.0	12.9	18.7	15.8	
(II)	180	20.2	6.6	1.6	18.9	19.6	19.3	4.4
	158	19.9	35.0	15.0	12.9	16.9	14.9	

Changing CO_2 concentration in raw gas from 6.6% to 35%, the partial pressure of the inert gas (in the main body of gas) decreased by 3.7–4.4 atm.* This corresponds to 19–23% (ca. 20%) of the partial pressure of the inert gas in raw gas containing 6.6% CO_2 . If the gas film resistance were controlling, K_La is to be influenced by the 20% fall of the partial pressure of inert gas. In point of fact there is no considerable change in K_La (Figure 22).

In sections IV–1 and –2 above, the existence of the gas film resistance has been shown, investigating the influence of the variation of the operating pressure upon K_La . Judging from the results, how-

* The difference of mean value of partial pressure of inert gases (in the main body of gas) at the inlet and outlet of the tower is taken instead of the difference of p_{BM} in discussion.

ever, a conclusion is drawn to the effect that the gas film resistance is not so strong as to be called controlling.

(2) Among those experiments with the raw gas containing more than 25% CO_2 , a big loss of the inert gas has been observed in Exps. 157, 158 and 160. Dealing with the raw gas of high CO_2 concentration, the tendency for a considerable loss to occur in the inert gas may be noticed.

2) Case of raw gas consisting of H_2 and CO_2 .

In all above described experiments, the author used combustion gas of coke as the raw gas. In case the kind of inert gas was changed, a change therefrom is noticed in the diffusion coefficient.

The value of diffusion coefficient D in CO_2 - H_2 system is about four times as great as the values of D in CO_2 -air, CO_2 - O_2 , and CO_2 - CO systems, according to Eq. 7, gas-film coefficient k_G is probably influenced by the kind of inert gas.

According to Sherwood and Fujita, the influence of D upon the gas-film coefficient is very slight (Sherwood) or rather relationless (Fujita) in the case of gas absorption in packed tower under ordinary pressure. The author carried out a few absorption experiments under 20 atm., using hydrogen as the main component of the inert gas. The results are shown in Table 13. The relation between $K_L a$ and the inert gas velocity is illustrated as Figure 23.

According to that Figure, the following points are to be noticed:—

(1) Comparing the average value G_1 line in Figure 14 (N_2 and CO as the main component of the inert gas) with the case where H_2 is the main component, one finds that $K_L a$ is greater by 15–20%. This percentage exceeds the experimental error.* Therefore, the influence of the diffusion coefficient

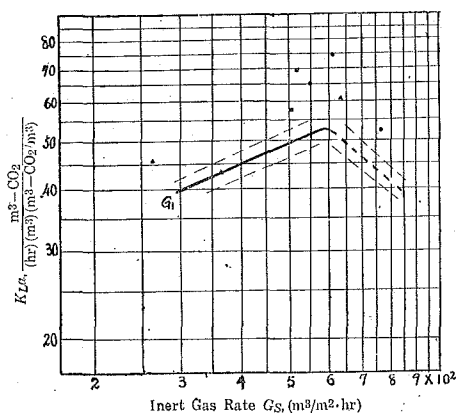


Fig. 23 Case of Hydrogen as Inert Gas (20 atm.).

* $\text{CO}_2\%$ in raw gas in experiments of Table 13 is somewhat less than the standard composition of raw gas (CO_2 : 18%), but the influence of this fact on $K_L a$ need not be considered. Assuming the influence was not negligible, k_G or $K_L a$ is rather apt to decrease as a result of increasing partial pressure of inert gas, in the case of total pressure being constant and of low CO_2 concentration in raw gas.

of the gas seems to have appeared qualitatively in the present experimental results.

(2) The existence of the maximum value of $K_L a$ near $G_s = 600$ $\text{m}^3/\text{m}^2 \cdot \text{hr.}$, has been observed, though not so plain as in the case of G_1 line, owing to the small number of experiments.

(3) The values of $K_L a$ in Tables 1-12 may be applicable to the absorption towers for the manufacture of H_2 from CO_2 - H_2 mixture with a rather large safety factor.

V. Summary

The author considered about the factors of over-all capacity coefficient $K_L a$ and of coefficients of gas and liquid films according to the literatures. Based on this, the author presumed the influence of operating factors—water rate, gas rate, pressure, temperature and composition of raw gas—upon $K_L a$ in the pressure absorption of CO_2 . Then the apparatus and experimental procedure employed were explained.

The tower, constructed of a steel cylinder, had a total height of 4,000 mm with a diameter of 450 mm. It withstood normal working pressure of 20 kgs/cm². The tower was irregularly packed to a height of 2,300 mm with ceramic Raschig rings of 35 mm nominal diameter.

The raw gas was prepared by the combustion of coke in a gas producer, and underground water was used as the washing water.

During the time of a steady state operation, measurements of flow rates of gas and water, temperatures, pressures and analyses of the gas stream at both the inlet and the outlet of the tower, were taken for the calculation of the coefficient of material transfer.

The experimental results including the values of $K_L a$ and $[\text{H.T.U.}]_{OL}$ obtained under various operating conditions, were reported together with a discussion of the results, especially on the influences of the above mentioned operating factors upon $K_L a$.

(1) Influence of water rate.

Changing water rate L_s within the range of 16.4–44.0 $\text{m}^3/\text{m}^2 \cdot \text{hr.}$ and raw gas rate of 65–80 $\text{m}^3/\text{hr.}$, 55 measured values of $K_L a$ and $[\text{H.T.U.}]_{OL}$ were obtained from the following two series of experiments:—

a) Experiments under operating pressure, π : 20 atm., and at different temperatures (t : 20°C and 28°C); and

b) Experiments at temperature t : 20°C, and under different pressures (π : 15 atm. and 10 atm.).

It was found that $K_L a$ increased with the increase of water rate and temperature respectively, and was lowered by raising the operating pressure from 10 atm. to 20 atm. As shown in Eqs. (24) and (25), $K_L a$ increased directly proportional to 0.56 power of L_s in the case of 20 atm. Compared with the case of CO_2 absorption under ordinary pressure where the liquid film resistance is controlling, the influence of L_s upon $K_L a$ was less. The influence of operating temperature was not so sharp as those reported by other investigators of CO_2 absorption under ordinary pressure as well.

The influences of water rate, temperature and of pressure, or the difference between the slopes of two lines, $K_L a$ vs. L_s , obtained under 20 atm. and 15 atm. respectively, agree qualitatively with those presumed in theoretical considerations, and showed a similar tendency as the result (lowering of $K_L a$ with increasing pressure) reported by Yushkevich, Zhavoronkov and Zel'venskii.

(2) Influence of gas rate (or inert gas velocity).

a) Experiments with π : 20 atm. and various water rates.

Changing raw gas rate within the range of 55–164 m³/hr. (inert gas rate G_s : 291–847 m³/m²·hr.) under the conditions of π : 20 atm., t : 20°C and L_s : 43 m³/m²·hr., 14 measured values of $K_L a$ and $[\text{H.T.U.}]_{\text{OL}}$ were obtained.

By adding the data obtained in the above experiments ((1), a)) to these measured values, the influence of G_s was examined in the case 21 measured values of $K_L a$ in total. As shown in Eq. (27), $K_L a$ increased directly proportional to 0.4 power of G_s within the range of $G_s < 600$ m³/m²·hr., and that agrees qualitatively with the presumption from theoretical considerations. But $K_L a$ decreased with increasing G_s within the range of $G_s > 600$ m³/m²·hr.

The similar tendency was also observed in experiments of the other two series (π : 20 atm., L_s : 32 and 22 m³/m²·hr.). In the case of absorption under 20 atm., when the gas-liquid ratio reaches a certain critical value (G_s/L_s : π : 0.7–0.8), some change in the absorption process (perhaps of gas and liquid contact) seems to take place. And $K_L a$ will be lowered if the gas velocity increases over this critical value G_c .

b) Experiments with L_s : 43 m³/m²·hr. and various pressures.

Changing raw gas rate within the range of 40–120 m³/hr. (G_s : 200–600 m³/m²·hr.) under the condition of t : 20°C and L_s : 43 m³/m²·hr., three series of experiments under different pressures (π : 15, 10 and 5 atm.)

were performed. Comparison was made with the case of 20 atm. $K_L a$ increased with the gas rate in the case of 15 atm. and 10 atm. as well, but no decreasing of $K_L a$ within the range of high gas rate as was seen in the case of 20 atm., was noticed within the experimental range of G_s . The lowering of $K_L a$ with increasing pressure was confirmed.

The result attained by the author coincides qualitatively with those of Yushkevich (about the influence of the operating pressure and that of the gas velocity), but are in opposition to the results expressed by Sanka, who did not admit the influence of the operating pressure on $K_L a$ in the pressure absorption of acetylene.

Judging from the influence of operating pressure and of gas rate upon $K_L a$, the existence of gas film resistance in the over-all resistance is noticed in the case of the pressure absorption of CO_2 , although the gas film resistance is not so large as to be called controlling.

(3) Influence of the composition of raw gas.

a) Influence of the CO_2 concentration in raw gas.

Changing the CO_2 concentration in raw gas within the range of CO_2 6–35% under the condition of π : 20 atm., t : 20°C and raw gas rate: 65–90 $\text{m}^3/\text{hr.}$, two series of experiments with L_s : 43 and 22 $\text{m}^3/\text{m}^2\cdot\text{hr.}$ respectively, were performed. The influence of change of CO_2 concentration in raw gas upon $K_L a$, was almost negligible within the experimental range.

b) Case of raw gas consisting of H_2 and CO_2 .

In all above described experiments, N_2 and CO were used as the main components of the inert gas. In this case, by changing gas rate under the condition of π : 20 atm., t : 18–20°C and L_s : 44 $\text{m}^3/\text{m}^2\cdot\text{hr.}$, 8 experiments were performed using hydrogen as the inert gas, and compared with the results in (2), a). According to the comparison, the value of $K_L a$ was greater by 15–20% in the case of CO_2 – H_2 system. Therefore, in this case (π : 20 atm.) the influence of the diffusion coefficient of the gas seems to have appeared qualitatively, though it is not very great.

The values of $K_L a$ obtained by the author are applicable to the absorption towers for the manufacture of H_2 from CO_2 – H_2 mixture with a rather large safety factor.

Nomenclature for the Following Tables

- L_s : Water rate, ($\text{m}^3/\text{m}^2 \cdot \text{hr.}$)
 G_s : inert gas rate, ($\text{m}^3/\text{m}^2 \cdot \text{hr.}$)*
 β : ratio of water rate to inert gas rate
 π : operating pressure, (absolute atm.)
 x_0 : CO_2 concentration of the liquid fed at the top of the column (gas outlet), ($\text{m}^3\text{-CO}_2/(\text{m}^3\text{-water})^*$)
 y_0 : CO_2 concentration of gas leaving the top of the column, ($\text{m}^3\text{-CO}_2/(\text{m}^3\text{-inert-gas})^*$)
 x_1 : CO_2 concentration of the liquid leaving the bottom of the column (gas inlet), ($\text{m}^3\text{-CO}_2/(\text{m}^3\text{-water})^*$)
 y_1 : CO_2 concentration of the gas entering the column, ($\text{m}^3\text{-CO}_2/(\text{m}^3\text{-inert-gas})^*$)
 K_{La} : over-all capacity coefficient, ($\text{m}^3\text{-CO}_2/(\text{hr.})(\text{m}^3)(\text{m}^3\text{-CO}_2/\text{m}^3)^*$)
[H. T. U.] $_{OL}$: height of over-all liquid-phase transfer unit, (m)

* The gas volume is calculated at 0°C and 760 mm Hg.

TABLE 2(i) Influence of Water

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
40	40	14.3	85.7	75.2	6.56	21.5
41	40	14.0	86.0	72.8	4.00	22.0
42	40	14.0	86.0	75.0	3.55	22.2
61	40	16.4	83.6	69.3	3.69	21.5
62	40	16.4	83.6	68.4	3.02	21.5
63	40	16.4	83.6	73.4	4.03	21.6
64	30	16.4	83.6	71.2	2.61	22.0
71	40	15.8	84.2	72.3	3.52	20.5
73	40	15.7	84.3	79.6	6.91	20.5
74	40	15.6	84.4	73.0	2.73	21.2
76	40	15.6	84.4	73.6	4.70	21.0
77	40	15.6	84.4	73.6	2.65	21.3
110	40	14.8	85.2	70.5	5.00	19.0
111	40	14.2	85.8	64.8	4.98	19.5
112	40	15.0	85.0	59.3	6.82	19.8
113	40	14.6	85.4	70.5	6.80	20.0
143	40	17.8	82.2	78.1	6.75	19.4
175	40	16.2	83.8	66.8	6.84	21.3
177	40	15.6	84.4	70.5	4.92	21.3
183	40	17.4	82.6	71.8	3.50	20.7
185	40	17.0	83.0	70.0	4.15	19.8
187	40	10.8	89.2	66.7	6.80	19.5
49	40	15.8	84.2	77.9	7.00	21.0

Rate upon K_1a . I

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
19.7	33-35	1.5	98.5	64.7	0.6	0.9
19.7	35-36	3.8	96.2	63.3	1.6	2.4
19.8	33	4.6	95.4	64.1	3.3	5.1
19.6	29-30	4.7	95.3	59.0	1.7	2.9
19.4	30-31	6.3	93.7	57.4	3.4	5.9
19.4	33	4.8	95.2	62.0	2.4	3.9
19.3	33	8.1	91.9	62.2	2.3	3.9
19.8	22-23	5.2	94.8	63.1	1.0	1.6
19.7	26-27	1.9	98.1	66.0	2.3	3.4
19.8	28-29	7.3	92.7	64.2	2.1	3.4
19.9	29-27	3.2	96.8	62.9	1.2	1.9
19.8	28	8.0	92.0	62.9	4.2	6.8
19.7	16-17	2.2	97.8	—	—	—
19.9	19-21	1.5	98.5	52.6	3.8	6.8
19.7	11-12	0.7	99.3	50.5	0.3	0.6
19.8	12-13	1.0	99.0	60.5	0.3	0.5
19.7	18	1.4	98.6	64.8	0.3	0.4
19.9	28	1.4	98.6	54.6	2.2	3.9
19.9	27	2.0	98.0	56.3	4.3	7.2
19.8	22-23	5.2	94.8	57.3	5.0	8.4
19.6	19-20	4.4	95.6	60.2	0.3	0.5
19.7	19	0.5	99.5	56.9	2.9	4.9
19.4	30	1.6	98.4	64.1	2.5	3.8

TABLE 2 (ii)

Exp. (No.)	L_s	G_s	β	π	α_0
40	41.3	405	0.102	20.0	0.001
41	25.2	394	0.064	20.0	0.001
42	22.3	406	0.055	20.1	0.001
61	23.2	364	0.064	19.9	0.0004
62	19.0	360	0.053	19.8	0.0004
63	25.3	386	0.066	19.8	0.0004
64	16.4	374	0.044	20.1	0.0004
71	22.1	383	0.058	20.1	0.0004
73	43.5	422	0.103	20.0	0.001
74	17.2	387	0.044	20.1	0.001
76	29.6	391	0.757	20.2	0.001
77	16.7	391	0.043	20.1	0.001
110	31.5	378	0.083	20.0	0.001
111	31.3	350	0.090	20.2	0.001
112	42.9	317	0.135	20.0	0.005
113	42.8	379	0.113	20.1	0.005
143	42.5	404	0.105	20.0	0.005
175	43.0	352	0.122	20.2	0.005
177	30.9	374	0.083	20.2	0.005
183	22.0	373	0.059	20.1	0.005
185	26.1	365	0.071	19.9	0.005
187	42.8	374	0.114	20.0	0.005
49	44.0	413	0.107	19.7	0.001

y_0	x_1	y_1	K_{La}	[H.T.U.] _{OL}
0.015	1.50	0.167	47.4	0.868
0.040	1.93	0.163	39.5	0.637
0.048	2.08	0.163	41.6	0.525
0.049	2.30	0.196	36.0	0.644
0.067	2.45	0.196	32.0	0.593
0.050	2.21	0.196	37.1	0.682
0.088	2.49	0.196	26.1	0.628
0.055	2.30	0.188	32.0	0.691
0.019	1.62	0.186	45.1	0.962
0.079	2.40	0.185	27.1	0.632
0.033	2.01	0.185	38.6	0.764
0.087	2.30	0.185	21.6	0.772
0.023	1.82	0.174	38.3	0.821
0.015	1.68	0.166	40.3	0.777
0.007	1.25	0.176	41.0	1.05
0.010	1.43	0.171	46.2	0.931
0.014	1.93	0.217	50.8	0.836
0.014	1.47	0.193	40.0	1.09
0.020	2.00	0.185	49.3	0.628
0.055	2.63	0.211	39.2	0.561
0.042	2.30	0.205	34.6	0.754
0.005	1.02	0.121	50.5	0.846
0.016	1.61	0.188	49.0	0.906

TABLE 3 (i) Influence of Water

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
78	40	16.1	83.9	83.2	6.97	27.5
79	40	16.8	83.2	79.1	4.91	27.5
80	40	17.0	83.0	71.7	5.31	27.8
81	40	16.9	83.1	70.4	4.25	28.0
82	30	17.1	82.9	75.4	6.83	27.6
83	40	16.9	83.1	75.7	5.99	27.3
84	40	17.2	82.8	75.6	3.57	27.6
89	40	17.2	82.8	76.8	6.53	27.0
90	40	17.2	82.8	70.3	3.17	28.0
91	40	17.2	82.8	70.3	2.92	28.0

TABLE 3 (ii)

Exp. (No.)	L_s	G_s	β	π	x_0
78	43.8	439	0.0999	20.3	0.001
79	30.9	414	0.0746	20.2	0.001
80	33.4	374	0.0892	20.3	0.001
81	26.7	368	0.0727	20.5	0.001
82	43.0	393	0.109	20.4	0.001
83	37.7	396	0.0952	20.3	0.001
84	22.5	394	0.0570	20.4	0.001
89	41.1	400	0.103	20.2	0.001
90	19.9	366	0.0545	20.2	0.001
91	18.4	366	0.0502	20.3	0.001

Rate upon K_La . II

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
20.0	29	2.8	97.2	65.2	6.4	9.2
19.9	29-30	5.2	94.8	66.4	2.8	4.3
20.0	33	3.2	96.8	60.5	0.9	1.5
20.2	33-32	5.0	95.0	60.2	1.3	2.2
20.1	26	2.3	97.7	63.6	0.4	0.6
20.0	27-28	3.0	97.0	64.6	0.3	0.5
20.1	28	7.5	92.5	66.6	1.0	1.6
19.9	30	2.4	97.6	64.5	0.6	0.9
19.9	32	7.8	92.2	62.6	0.5	0.9
20.0	33	8.4	91.6	63.0	0.5	0.9

y_0	x_1	y_1	K_La	[H.T.U.] _{OL}
0.0288	1.64	0.192	53.8	0.816
0.0549	1.98	0.202	43.3	0.712
0.0331	1.92	0.205	50.1	0.667
0.0526	2.08	0.203	44.0	0.607
0.0236	1.67	0.206	52.2	0.821
0.0309	1.82	0.203	51.5	0.730
0.0811	2.21	0.208	35.7	0.628
0.0246	1.78	0.208	55.8	0.735
0.0846	2.26	0.208	37.8	0.528
0.0917	2.33	0.208	38.0	0.483

TABLE 4 (i) Influence of Water

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
52	40	15.2	84.8	70.3	6.96	21.0
95	40	11.0	89.0	80.9	6.68	21.2
146	40	16.4	83.6	61.0	6.81	19.7
147	40	17.2	82.8	82.0	6.79	19.7
176	40	16.0	84.0	72.5	6.82	21.0
178	40	15.8	84.2	68.3	4.82	21.0
182	40	16.2	83.8	69.1	5.56	19.7
184	40	16.6	83.4	68.6	3.54	20.5
186	40	17.6	82.4	70.4	4.17	20.0
191	40	15.6	84.4	70.5	5.41	20.0
192	40	15.4	84.6	68.8	3.99	20.0

TABLE 4 (ii)

Exp. (No.)	L_s	G_s	β	π	α_0
52	43.8	375	0.117	15.0	0.001
95	42.0	453	0.093	15.4	0.001
146	42.8	321	0.134	15.5	0.005
147	42.7	427	0.100	15.8	0.005
176	42.9	383	0.112	15.5	0.005
178	30.3	362	0.084	15.5	0.005
182	35.0	364	0.096	15.2	0.005
184	22.3	360	0.062	15.3	0.005
186	26.2	365	0.072	15.2	0.005
191	34.0	374	0.091	15.3	0.005
192	25.1	366	0.069	15.3	0.005

Rate upon K_La . III

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
14.5	36	3.2	96.8	58.4	3.0	5.5
14.9	30-31	2.4	97.6	72.1	1.6	2.2
15.0	25	1.4	98.6	49.2	2.5	4.9
15.3	28	3.4	96.6	67.0	3.2	4.7
15.0	28	2.4	97.6	57.4	4.9	8.0
15.0	27	4.0	96.0	55.9	3.8	6.6
14.7	22	3.7	96.3	59.2	0.9	1.6
14.8	22	7.4	92.6	57.9	3.6	6.3
14.7	21	6.2	93.8	61.0	0.8	1.4
14.8	22	3.6	96.4	58.9	2.7	4.5
14.8	22	5.8	94.2	59.6	2.1	3.6

y_0	x_1	y_1	K_La	[H.T.U.] _{OL}
0.331	1.25	0.179	41.0	1.07
0.025	1.64	0.124	53.5	0.785
0.014	1.37	0.196	50.2	0.788
0.035	1.73	0.208	52.1	0.821
0.025	1.49	0.191	55.5	0.772
0.042	1.75	0.188	49.6	0.610
0.038	1.62	0.193	43.5	0.804
0.030	1.93	0.199	32.6	0.682
0.066	2.07	0.214	43.3	0.607
0.037	1.63	0.185	47.4	0.917
0.062	1.76	0.182	36.4	0.691

TABLE 5 (i) Influence of Water

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
51	40	15.4	84.6	67.0	6.97	22.0
54	40	16.0	84.0	65.7	7.05	21.0
134	40	17.4	82.6	62.7	6.91	17.5
151	40	17.0	83.0	84.2	6.87	19.5
162	40	15.4	84.6	71.4	6.92	21.5
163	40	15.8	84.2	64.5	4.25	21.3
164	40	16.2	83.8	63.6	4.83	21.7
165	40	16.6	83.4	60.8	3.39	21.5
189	40	14.2	85.8	67.2	5.08	19.2
190	40	14.4	85.6	68.0	4.08	19.5

TABLE 5 (ii)

Exp. (No.)	L_s	G_s	β	π	x_0
51	43.8	357	0.123	10.3	0.001
54	44.3	347	0.128	10.4	0.001
134	44.4	327	0.133	10.6	0.001
151	43.2	439	0.098	10.5	0.005
162	43.5	380	0.115	10.7	0.005
163	26.7	342	0.078	10.6	0.005
164	30.4	335	0.091	10.7	0.005
165	21.3	319	0.067	10.6	0.005
189	32.0	363	0.088	10.6	0.005
190	25.7	366	0.070	10.6	0.005

Rate upon K_La . IV

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
9.6	36	5.0	95.0	58.9	0.2	1.2
9.7	31	4.7	95.3	59.1	-1.1	-2.0
9.9	10-11	3.6	96.4	51.1	2.7	5.2
9.9	22	6.5	93.5	69.6	4.7	6.7
10.1	27-28	4.2	95.8	59.8	3.1	5.1
10.0	27	7.5	92.5	56.4	2.1	3.9
10.1	30	6.8	93.2	54.6	2.4	4.5
10.0	29	9.4	90.6	55.1	0.8	1.6
10.0	20	5.6	94.4	60.4	0.6	1.0
10.0	21	7.2	92.8	60.9	1.7	2.9

y_0	x_1	y_1	K_La	[H.T.U.] _{OL}
0.053	1.05	0.182	54.8	0.799
0.049	1.11	0.190	56.1	0.790
0.037	1.31	0.211	58.6	0.742
0.070	1.37	0.205	65.8	0.655
0.044	1.22	0.182	80.3	0.541
0.081	1.37	0.188	61.8	0.432
0.073	1.33	0.193	55.3	0.549
0.104	1.42	0.199	43.6	0.488
0.059	1.21	0.166	55.2	0.578
0.078	1.29	0.168	52.5	0.488

TABLE 6 (i) Influence of Gas

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
96	40	14.5	85.5	79.3	6.66	19.2
97	30	14.8	85.2	104.1	6.69	19.5
100	40	15.6	84.4	157.0	6.73	19.7
105	40	16.0	84.0	122.5	6.82	19.0
112	40	15.0	85.0	59.3	6.82	19.8
113	40	14.6	85.4	70.5	6.80	20.0
114	40	15.2	84.8	141.5	6.79	20.3
115	40	15.2	84.8	101.3	6.80	20.0
141	40	17.6	82.4	97.7	6.81	18.1
142	40	17.6	82.4	126.2	6.81	19.0
143	40	17.8	82.2	78.1	6.75	19.4
170	40	15.8	84.2	125.0	6.80	21.0
171	40	16.0	84.0	135.8	6.77	21.0
49	40	15.8	84.2	77.9	7.00	21.0
73	40	15.7	84.3	79.6	6.91	20.5
175	40	16.2	83.8	66.8	6.84	21.3
187	40	10.8	89.2	66.7	6.80	19.5
130	40	16.2	83.8	110.4	6.79	17.7
131	40	16.2	83.8	55.1	6.83	18.2
132	40	17.6	82.4	163.5	6.71	18.7
133	40	17.8	82.2	85.0	6.71	18.4

Rate upon $K_L a$. I

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
19.7	19-20	1.6	98.4	66.5	2.4	3.5
19.8	20-21	3.2	96.8	91.1	1.5	1.7
20.0	21-22	7.0	93.0	142.2	0.3	0.2
19.7	18	4.7	95.3	109.4	—	—
19.7	11-12	0.7	99.3	50.5	0.2	0.4
19.8	12-13	1.0	99.0	60.5	0.3	0.5
19.6	14-15	5.7	94.3	126.3	0.9	0.8
19.7	15-16	2.7	97.3	86.8	1.4	1.6
20.1	15	2.8	97.2	77.6	5.1	6.3
19.8	20	5.0	95.0	100.2	8.8	8.5
19.7	18	1.4	98.6	64.8	0.3	0.5
19.9	26	5.4	94.6	109.3	1.9	1.8
19.6	26-27	6.0	94.0	121.0	0.4	0.4
19.4	30	1.6	98.4	64.1	2.5	3.8
19.7	26-27	1.9	98.1	66.0	2.3	3.4
19.9	28	1.4	98.6	54.6	2.2	3.9
19.7	19	0.5	99.5	56.9	2.9	4.9
19.7	12-13	3.4	96.6	85.3	10.1	10.9
19.6	14-15	0.4	99.6	—	—	—
19.8	15-16	7.4	92.6	—	—	—
19.9	14-13	1.8	98.2	—	—	—

TABLE 6 (ii)

Exp. (No.)	L_s	G_s	β	π	α_0
96	41.9	426	0.0982	20.0	0.001
97	42.1	564	0.0746	20.1	0.001
100	42.3	833	0.0508	20.3	0.001
105	42.9	647	0.0663	20.0	0.001
112	42.9	317	0.135	20.0	0.005
113	42.8	379	0.113	20.1	0.005
114	42.7	755	0.0566	19.9	0.004
115	42.8	540	0.0792	20.0	0.004
141	42.8	506	0.0846	20.4	0.005
142	42.8	654	0.0655	20.1	0.005
143	42.5	404	0.105	20.0	0.005
170	42.8	662	0.0648	20.2	0.005
171	42.6	718	0.0593	19.9	0.005
49	44.0	413	0.107	19.7	0.001
73	43.5	422	0.103	20.0	0.001
175	43.0	352	0.122	20.2	0.005
187	42.8	374	0.114	20.0	0.005
130	42.7	582	0.073	20.0	0.005
131	43.0	291	0.148	19.9	0.005
132	42.2	847	0.050	20.1	0.005
133	42.2	440	0.096	20.2	0.005

y_0	x_1	y_1	K_{La}	[H.T.U.] $_{OL}$
0.0163	1.56	0.170	44.4	0.943
0.0331	1.86	0.175	48.2	0.871
0.0753	2.16	0.185	41.9	1.01
0.0493	2.13	0.191	46.8	0.916
0.00705	1.25	0.176	41.0	1.05
0.0101	1.43	0.171	46.2	0.931
0.0605	2.10	0.179	40.5	1.06
0.0278	1.92	0.179	54.4	0.785
0.0288	2.19	0.214	46.9	0.913
0.0526	2.46	0.214	52.8	0.810
0.0142	1.93	0.214	50.8	0.836
0.0571	2.02	0.187	44.0	0.970
0.0638	2.13	0.191	48.4	0.879
0.016	1.61	0.188	49.0	0.906
0.019	1.62	0.186	45.1	0.962
0.014	1.47	0.193	40.0	1.09
0.005	1.02	0.121	50.5	0.846
0.035	2.16	0.193	49.5	0.861
0.004	1.29	0.193	42.3	1.01
0.080	2.69	0.214	53.5	0.783
0.018	2.07	0.217	48.8	0.865

TABLE 7 (i) Influence of Gas

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
101	40	15.4	84.6	46.7	4.91	19.0
102	40	15.4	84.6	77.3	5.04	19.3
103	40	15.6	84.4	107.7	5.07	19.3
104	40	16.0	84.0	135.7	4.94	19.5
110	40	14.8	85.2	70.5	5.00	19.0
111	40	14.2	85.8	64.8	4.98	19.5
144	40	17.6	82.4	56.8	5.09	18.3
145	40	17.6	82.4	91.5	5.09	18.6
138	40	18.0	82.0	48.78	4.94	17.0
139	40	18.0	82.0	71.9	4.99	17.5
106	40	15.4	84.6	45.5	3.55	19.5
107	40	16.0	84.0	71.3	3.53	19.8
108	40	15.6	84.4	95.5	3.54	19.3
109	30	15.6	84.4	132.0	3.52	19.5
71	40	15.8	84.2	72.3	3.52	20.5

TABLE 7 (ii)

Exp. (No.)	L_s	G_s	β	π	z_0
101	30.9	249	0.124	20.0	0.001
102	31.7	411	0.0771	20.1	0.001
103	31.9	572	0.0558	20.1	0.001
104	31.1	717	0.0443	20.0	0.001
110	31.5	378	0.0832	20.0	0.001
111	31.3	350	0.0895	20.2	0.001
144	32.0	294	0.109	20.1	0.005
145	32.0	474	0.0675	20.0	0.005
138	31.1	251	0.124	20.4	0.005
139	31.4	371	0.0846	20.3	0.005
106	22.3	242	0.0902	20.0	0.001
107	22.2	377	0.0589	20.0	0.001
108	22.3	507	0.0439	20.1	0.001
109	22.1	701	0.0316	20.0	0.001
71	22.1	333	0.0578	20.1	0.0004

Rate upon $K_L a$. II

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
19.7	17-19	0.6	99.4	40.5	—	—
19.8	18-20	2.6	97.4	66.1	1.0	1.5
19.8	20	5.6	94.4	95.7	0.6	0.7
19.7	19	8.0	92.0	122.0	1.8	1.6
19.7	16-17	2.2	97.8	—	—	—
19.9	19-21	1.5	98.5	52.6	3.8	6.8
19.8	14	0.7	99.3	45.1	2.0	4.3
19.7	18	4.2	95.8	75.0	3.5	4.6
20.1	9	0.5	99.5	41.0	-0.8	-2.0
20.1	10	2.1	97.9	—	—	—
19.7	17-19	1.5	98.5	39.8	—	—
19.7	20-21	4.8	95.2	64.0	—	—
19.8	16-18	7.4	92.6	86.9	0.1	0.1
19.7	18	10.0	90.0	114.8	8.1	7.3
19.8	22-23	5.2	94.8	63.1	1.0	1.6

y_0	x_1	y_1	$K_L a$	[H.T.U] _{OL}
0.00604	1.42	0.182	34.0	0.906
0.0267	2.02	0.182	42.5	0.744
0.0593	2.25	0.185	39.2	0.810
0.0870	2.39	0.191	36.5	0.849
0.0225	1.82	0.174	38.3	0.821
0.0152	1.68	0.166	40.3	0.777
0.00705	1.91	0.214	43.9	0.728
0.0438	2.52	0.214	44.7	0.717
0.00502	1.74	0.220	36.1	0.861
0.0215	2.34	0.220	41.6	0.754
0.0152	1.80	0.182	29.0	0.780
0.0504	2.38	0.1905	34.3	0.648
0.0799	2.39	0.185	29.0	0.754
0.111	2.33	0.185	22.7	0.975
0.0549	2.30	0.188	32.0	0.691

TABLE 9 (i) Influence of Gas

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
52	40	15.2	84.8	70.3	6.96	21.0
67	40	16.0	84.0	36.7	6.56	21.3
95	40	11.0	89.0	80.9	6.68	21.2
146	40	16.4	83.6	61.0	6.81	19.7
147	40	17.2	82.8	82.0	6.79	19.7
148	40	16.6	83.4	110.2	6.85	19.0
154	30	17.2	82.8	120.8	6.68	19.0
176	40	16.0	84.0	72.5	6.82	21.0

TABLE 9 (ii)

Exp. (No.)	L_s	G_s	β	π	x_0
52	43.8	375	0.117	15.0	0.001
67	41.3	194	0.213	15.5	0.004
95	42.0	453	0.0928	15.4	0.001
146	42.8	321	0.134	15.5	0.005
147	42.7	427	0.100	15.8	0.005
148	43.1	578	0.0745	15.1	0.005
154	42.0	629	0.0668	15.1	0.005
176	42.9	383	0.112	15.5	0.005

Rate upon K_La . III

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
14.5	36	3.2	96.8	58.4	3.0	5.5
15.0	33-34	0.6	99.4	32.5	-1.5	-4.9
14.9	30-31	2.4	97.6	72.1	1.6	2.2
15.0	25	1.4	98.6	49.2	2.5	4.9
15.3	28	3.4	96.6	67.0	3.2	4.7
14.6	20	5.4	94.6	92.1	4.8	5.2
14.6	20	7.1	92.9	110.5	-2.7	-2.7
15.0	28	2.4	97.6	57.4	4.9	8.0

y_0	x_1	y_1	K_La	[H.T.U.] _{OL}
0.331	1.25	0.179	41.0	1.07
0.00604	0.87	0.190	33.0	1.25
0.0246	1.06	0.124	53.5	0.785
0.0142	1.37	0.196	50.2	0.788
0.0352	1.73	0.208	52.1	0.821
0.0571	1.92	0.199	65.9	0.653
0.0764	1.97	0.208	55.8	0.752
0.0246	1.49	0.191	55.5	0.772

TABLE 10 (i) Influence of Gas

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
51	40	15.4	84.6	67.0	6.97	22.0
54	40	16.0	84.0	65.7	7.05	21.0
60	40	15.8	84.2	103.0	6.98	21.5
66	40	15.8	84.2	39.7	6.71	20.5
134	40	17.4	82.6	62.7	6.91	17.5
135	40	17.6	82.4	41.4	6.89	18.0
150	40	16.6	83.4	56.2	6.91	18.4
151	40	17.0	83.0	84.2	6.87	19.5
152	40	17.0	83.0	110.3	6.86	19.5
153	40	17.2	82.8	123.8	6.83	19.0
162	40	15.4	84.6	71.4	6.92	21.5

TABLE 10 (ii)

Exp. (No.)	L_s	G_s	β	π	α_0
51	43.8	357	0.123	10.3	0.001
54	44.3	347	0.128	10.4	0.001
60	43.9	545	0.081	10.5	0.001
66	42.2	210	0.201	10.6	0.001
134	44.4	327	0.133	10.6	0.001
135	43.3	214	0.202	10.6	0.001
150	43.5	295	0.147	10.7	0.005
151	43.2	439	0.098	10.5	0.005
152	43.1	575	0.075	10.5	0.005
153	42.9	644	0.067	10.5	0.005
162	43.5	380	0.115	10.7	0.005

Rate upon K_La . IV

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
9.6	36	5.0	95.0	58.9	0.7	1.2
9.7	31	4.7	95.3	59.1	-1.1	-2.0
9.8	36-37	8.0	92.0	89.5	4.4	5.1
9.9	31	1.4	98.6	34.5	-0.6	-1.8
9.9	10-11	3.6	96.4	51.1	2.7	5.2
9.9	12	1.0	99.0	32.2	2.2	6.5
10.0	19	2.5	97.5	48.3	-0.2	-0.4
9.9	22	6.5	93.5	69.6	4.7	6.7
9.8	23	8.8	91.2	94.8	5.1	5.5
9.8	20	9.5	90.5	114.9	-1.5	-1.5
10.1	27-28	4.2	95.8	59.8	3.1	5.1

y_0	x_1	y_1	K_La	[H.T.U.] _{or}
0.053	1.05	0.182	54.8	0.799
0.049	1.11	0.190	56.1	0.790
0.087	1.25	0.188	66.7	0.657
0.014	0.87	0.188	47.6	0.888
0.037	1.31	0.211	58.6	0.742
0.010	1.01	0.214	53.5	0.810
0.026	1.18	0.199	60.6	0.717
0.070	1.37	0.205	65.8	0.655
0.097	1.46	0.205	71.1	0.607
0.105	1.55	0.203	85.6	0.502
0.044	1.22	0.182	80.3	0.541

TABLE 11 (i) Influence of Gas

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
53	60	16.0	84.0	62.8	7.05	21.0
59	40	15.5	84.5	92.2	7.06	21.0
65	60	15.8	84.2	35.3	6.69	20.8
69	40	15.8	84.2	64.2	7.06	20.3
70	40	15.8	84.2	95.5	7.06	20.0
94	40	11.0	89.0	86.4	6.90	21.5
166	40	16.2	83.8	39.5	6.88	21.0
167	40	16.2	83.8	45.7	6.88	21.0
86	50	16.7	83.3	84.4	6.98	20.5
92	40	16.0	84.0	58.7	6.97	20.0
136	40	17.8	82.2	40.3	6.96	18.5

TABLE 11 (ii)

Exp. (No.)	L_s	G_s	β	π	x_0
53	44.3	332	0.134	5.6	0.001
59	44.4	490	0.091	6.1	0.001
65	42.1	187	0.225	5.9	0.0004
69	44.4	340	0.131	5.7	0.0004
70	44.4	506	0.088	5.8	0.0004
94	43.4	484	0.090	5.7	0.001
166	43.3	208	0.208	6.0	0.005
167	43.3	241	0.180	5.9	0.005
86	43.9	442	0.099	5.3	0.001
92	43.8	310	0.141	5.1	0.001
136	43.8	208	0.210	5.3	0.005

Rate upon K_La . V

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
4.8	32	8.6	91.4	57.0	0.6	1.1
5.3	36-37	10.5	89.5	83.8	2.9	3.7
5.1	30	3.4	96.6	30.1	0.6	2.0
4.9	23-24	8.6	91.4	60.6	-1.4	-2.6
5.0	23	11.0	89.0	90.5	-0.1	-0.1
4.9	30-31	7.6	92.4	80.4	2.6	3.4
5.2	30	4.6	95.4	36.4	-1.6	-4.8
5.1	30-32	6.2	93.8	42.3	-1.4	-3.6
4.5	29	11.6	88.4	81.2	-1.5	-2.1
4.3	22-23	8.6	91.4	53.3	0.6	1.2
4.5	16-18	4.6	95.4	31.5	3.0	9.1

y_0	x_1	y_1	K_La	[H.T.U.] _{oz}
0.094	0.722	0.190	82.4	0.537
0.117	0.730	0.183	59.0	0.752
0.035	0.680	0.188	76.0	0.553
0.094	0.717	0.188	70.0	0.634
0.124	0.730	0.188	56.9	0.780
0.032	0.465	0.124	49.8	0.871
0.048	0.703	0.193	70.5	0.613
0.066	0.717	0.193	68.0	0.635
0.131	0.703	0.201	58.5	0.752
0.094	0.690	0.191	87.9	0.493
0.048	0.805	0.217	106	0.413

TABLE 12 (i) Influence of CO₂

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
73	40	15.7	84.3	79.6	6.91	20.5
96	40	14.5	85.5	79.3	6.66	19.2
112	40	15.0	85.0	59.3	6.82	19.8
113	40	14.6	85.4	70.5	6.80	20.0
143	40	17.8	82.2	78.1	6.75	19.4
155	40	19.4	80.6	70.5	6.85	19.5
157	40	35.0	65.0	94.0	6.66	20.5
159	40	29.0	71.0	85.4	6.78	20.3
160	40	25.3	74.7	83.4	6.75	20.5
179	40	6.6	93.4	63.6	6.72	20.0
187	40	10.8	89.2	66.7	6.80	19.5
71	40	15.8	84.2	72.3	3.52	20.5
107	40	16.0	84.0	71.3	3.53	19.8
108	40	15.6	84.4	95.5	3.54	19.3
158	40	35.0	65.0	85.2	3.88	20.7
180	40	6.6	93.4	63.6	3.43	20.4
119	20	11.4	88.6	62.3	3.52	17.0
124	40	17.4	82.6	67.3	3.30	17.8

Concentration upon $K_L a$.

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
19.7	26-27	1.9	98.1	66.0	2.3	3.4
19.7	19-20	1.6	98.4	66.5	2.4	3.5
19.7	11-12	0.7	99.3	50.5	0.2	0.4
19.8	12-13	1.0	99.0	60.5	0.3	0.5
19.7	18	1.4	98.6	64.8	0.3	0.5
19.8	22	1.4	98.6	52.7	4.8	8.4
19.6	25	6.0	94.0	58.1	6.5	10.6
20.1	24	3.4	96.6	59.8	2.8	4.6
19.8	24	2.6	97.4	58.9	4.9	7.9
19.9	22	0.3	99.7	57.6	2.0	3.4
19.7	19	0.5	99.5	56.9	2.9	4.9
19.8	22-23	5.2	94.8	63.1	1.0	1.6
19.7	20-21	4.8	95.2	64.0	—	—
19.8	16-18	7.4	92.6	86.9	0.1	0.1
19.6	26-27	15.0	85.0	59.8	4.6	8.2
19.9	23	1.6	98.4	58.9	1.4	2.4
19.5	3	2.5	97.5	58.5	—	—
19.4	9	5.0	95.0	56.1	2.3	4.1

TABLE 12 (ii)

Exp. (No.)	L_s	G_s	β	π	α_0
73	43.5	422	0.103	20.0	0.001
96	41.9	426	0.0982	20.0	0.001
112	42.9	317	0.135	20.0	0.005
113	42.8	379	0.113	20.1	0.005
143	42.5	404	0.105	20.0	0.005
155	43.1	357	0.121	20.1	0.005
157	41.9	384	0.109	19.9	0.005
159	42.6	381	0.112	20.4	0.005
160	42.4	392	0.108	20.1	0.005
179	42.4	374	0.113	20.2	0.005
187	42.8	374	0.114	20.0	0.005
71	22.1	383	0.0578	20.1	0.0004
107	22.2	377	0.0589	20.0	0.001
108	22.3	507	0.0439	20.1	0.001
158	24.4	348	0.0700	19.9	0.005
180	21.6	374	0.0577	20.2	0.005
119	22.1	347	0.0638	19.9	0.005
124	20.8	350	0.0594	19.8	0.005

y_0	x_1	y_1	KLa	[H.T.U.] _{OL}
0.0194	1.62	0.186	45.1	0.962
0.0163	1.56	0.170	44.4	0.943
0.00705	1.25	0.176	41.0	1.05
0.0101	1.43	0.171	46.2	0.931
0.0142	1.93	0.217	50.8	0.836
0.0142	1.89	0.241	42.5	1.01
0.0638	4.36	0.539	48.5	0.865
0.0352	3.35	0.408	46.6	0.913
0.0267	2.88	0.339	50.7	0.836
0.0030	0.600	0.0707	50.1	0.842
0.0050	1.02	0.121	50.5	0.846
0.0549	2.30	0.188	32.0	0.691
0.0504	2.38	0.191	34.3	0.648
0.0799	2.39	0.185	29.0	0.754
0.177	5.16	0.539	32.3	0.754
0.0163	0.938	0.0707	35.1	0.613
0.0256	1.62	0.129	29.1	0.759
0.0526	2.67	0.211	31.5	0.657

TABLE 13 (i) Case where Hydrogen

Exp. (No.)	Time of Steady State (min)	Composition of Raw Gas (Inlet)		Raw Gas Rate (m ³ /hr)	Water Rate (m ³ /hr)	Tempera- ture (°C)
		CO ₂ (%)	Inert Gas (%)			
17-a	40	4.2	95.8	127.3	7.06	20.0
17-b	30	4.2	95.8	84.1	7.06	20.0
21	60	8.0	92.0	105.8	6.93	19.0
26-a	60	11.0	89.0	98.2	7.05	20.3
27	40	14.6	85.4	96.4	7.00	20.5
16	40	13.4	86.6	47.9	6.97	18.0
18-a	40	12.8	87.2	115.4	7.02	18.0
18-b	40	12.8	87.2	66.4	6.91	18.0

TABLE 13 (ii)

Exp. (No.)	L_s	G_s	β	π	α_0
17-a	44.4	767	0.0579	20.1	0.005
17-b	44.4	507	0.0876	20.1	0.005
21	43.6	612	0.0712	19.9	0.005
26-a	44.3	550	0.0807	20.3	0.001
27	44.0	518	0.0851	19.8	0.001
16	43.8	261	0.168	20.3	0.005
18-a	44.2	633	0.0698	20.8	0.005
18-b	43.5	364	0.119	22.3	0.005

TABLE 13 (iii)

Exp. (No.)	Composition of Raw Gas						
	CO ₂	C _m H _n	O ₂	CO	CH ₄	H ₂	N ₂
17-a	4.2	0.0	0.1	0.4	0.0	93.8	1.5
17-b	4.2	0.0	0.1	0.4	0.0	93.8	1.5
21	8.0	0.0	0.0	1.4	0.0	80.0	10.6
26-a	11.0	0.0	0.2	1.2	0.0	77.7	9.9
27	14.6	0.0	0.1	1.4	0.0	78.3	5.6
16	13.4	0.0	0.4	1.2	0.0	72.5	12.5
18-a	12.8	0.0	0.3	0.6	2.2	78.1	6.0
18-b	12.8	0.0	0.3	0.6	2.2	78.1	6.0

is Inert Gas

Gauge Pressure (kg/cm ²)	Outdoor Temperature (°C)	Composition of Washed Gas (Outlet)		Washed Gas Rate (m ³ /hr)	Loss of Inert Gas Calculated	
		CO ₂ (%)	Inert Gas (%)		(m ³ /hr)	(%)
19.8	23-24	1.2	98.8	113.0	10.3	8.4
19.8	24	0.4	99.6	69.6	—	—
19.6	17	1.3	98.7	89.1	9.4	9.7
20.0	23-24	1.3	98.7	81.1	7.4	8.5
19.5	23-24	1.6	98.4	79.1	4.5	5.5
20.0	6-7	0.1	99.9	—	—	—
20.5	12	2.1	97.9	97.3	5.3	5.3
22	12-14	0.4	99.6	56.4	1.7	2.9

y_0	x_1	y_1	K_La	[H.T.U.] _{OL}
0.0121	0.552	0.0438	52.1	0.852
0.0040	0.461	0.0439	57.7	0.769
0.0132	1.04	0.087	74.4	0.585
0.0132	1.36	0.124	64.6	0.686
0.0163	1.83	0.171	69.1	0.637
0.001	0.920	0.155	45.7	0.958
0.0215	1.80	0.147	60.8	0.726
0.0040	1.20	0.147	43.3	1.00

Composition of Washed Gas						
CO ₂	C _m H _n	O ₂	CO	CH ₄	H ₂	N ₂
1.2	—	—	—	—	—	—
0.4	—	—	—	—	—	—
1.3	—	—	—	—	—	—
1.3	0.0	0.2	0.7	0.0	91.1	6.7
1.6	—	—	—	—	—	—
0.1	0.0	0.6	0.6	0.0	93.6	5.1
2.1	—	—	—	—	—	—
0.4	0.0	0.4	1.7	1.9	95.1	0.5

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