EXPERIMENT 2: GAS ABSORPTION

CALCULATIONS

PART I: DRY COLUMN

1. Calculate gas mass flux (G_{air}, $kg/m^2.s$) and pressure drop per column length ($\Delta P/H_c$, Pa/m) for different gas flow rates.

$$*G_{air} = \frac{F_{air} \times \rho_{air}}{A_{column}}$$

*In order to find density of air, please assume air as an ideal gas. Moreover, take pressure as 693 mmHg and temperature as 20°C for our laboratory conditions.

2. Prepare Table 1.

F_{air} (L/min)	ΔP (mmH_2O)	F_{air} (m^3/s)	ΔP (Pa)	G_{air} ($kg/m^2.s$)	$\Delta P/Hc$ (Pa/m)

3. Plot the Figure 1: log (ΔP /Hc) versus log (G_{air})

PART II: WET COLUMN

1. Calculate mass flux of water (L_{water}, $kg/m^2.s$)

$$*L_{water} = \frac{F_{water} \times \rho_{water}}{A_{column}}$$

2. Calculate pressure drop per column length (DP/Hc, Pa/m) and prepare Table 2.

L_{water} ($kg/m^2.s$)	G_{air} ($kg/m^2.s$)	F_{air} (m^3/s)	ΔP (mmH_2O)	DP (Pa)	ΔP /Hc (Pa/m)

3. Plot the Figure 2: log (ΔP/Hc) versus log (G_{air}) at various mass flux of water.
4. Determine the experimental flooding points.
5. Calculate the flooding points using Figure 6 in your manual (Generalized flooding and pressure drop correlation) by trial and error method.
6. Calculate the optimum mass flux of air which is usually 50-75% of flooding flux and pressure drop per column length for these values. (Take 60% of flooding flux)

Exp. Cal

7. Prepare Table 3.

L_{water} $(kg/m^2.s)$	$G_{air,fl,exp}$ $(kg/m^2.s)$	$(\Delta P/Hc)_{fl,exp}$ (Pa/m)	$G_{air,fl,calc}$ $(kg/m^2.s)$	$(\Delta P/Hc)_{fl,calc}$ (Pa/m)	$G_{air,fl,opt}$ $(kg/m^2.s)$	$(\Delta P/Hc)_{fl,opt}$ (Pa/m)

PART III: GAS ABSORPTION

1. Calculate the mass flow rate of CO_2 absorbed into water.

* Volume fraction of CO_2 in inlet gas stream; $y_i = \left(\dfrac{F_{CO_2}}{F_{CO_2} + F_{air}} \right)_i$

and outlet; $y_o = \left(\dfrac{V_{CO_2}}{V_{sample}} \right)$ $y_o = \dfrac{V_{CO_2}}{V_{sample}}$ = 20 ml

* If F_a is liters/second of CO_2 absorbed between top and bottom, then;

$$[F_{CO_2} + F_{air}]y_i - [F_{CO_2} + (F_{air} + F_a)]y_o = F_a$$

* Calculate the mass flow rate of CO_2 absorbed into water in terms of kmol/s.

$$G_a = \frac{Pave \times Fa}{R \times Tave}$$ (by assuming ideal gas)

2. Prepare Table 4.

t(s)	y_i	y_o	$F_a(m^3/s)$	$G_a(kmol/s)$

3. Calculate the rate of absortion.

* $C_{sample} \times V_{sample} = C_{titrant} \times V_{titrant}$ where C_{NaOH}=0.0277 M and V_{sample}=20 ml

*Rate of absorption: $R_{abs} = F_{water} \times (C_{exit} - C_{tank})$

4. Prepare Table 5.

t(s)	$C_{tank}(kmol/m^3)$	$C_{exit}(kmol/m^3)$	$R_{abs}(kmol/s)$

5. Calculate the liquid mass transfer coefficient by using the equation of;

$$\frac{k_L \times a_p}{D_L} = \alpha\left(305\frac{L}{\mu_L}\right)^{1-n}\left(\frac{\mu_L}{\rho_L D_L}\right)^{0.5}$$

Where; k_L = liquid phase mass transfer coefficient for dilute system, a_p= specific surface area of packing, D_L=diffusion coefficient of liquid. (CO_2 in water)

6. Calculate the gas mass transfer coefficient by using the equation of;

$$\frac{k_g RT}{a_t D_g} = C_1\left(\frac{G}{a_t \mu_g}\right)^{0.7}\left(\frac{\mu_g}{\rho_g D_g}\right)^{1/3}\left(a_t D_p\right)^{-2.0}$$

Where; a_t=total surface area, D_g= diffusion coefficient of gas, D_p=diameter of packing. (CO_2 in air)

* **Note that** viscosity and density of <u>gas mixture</u> (CO_2 and air) must be used in this equation.

7. Calculate overall mass transfer coefficients for liquid and gas phases by using following equations;

$$\frac{1}{K_L a_p} = \frac{1}{k_L a_p} + \frac{1}{m k_G a_p}$$

$$\frac{1}{K_G a_p} = \frac{1}{k_G a_p} + \frac{m}{k_l a_p}$$

Where m =slope of the equilibrium curve.

8. Prepare Table 6.

$D_L(m^2/s)$	$D_G(m^2/s)$	K_La	K_Ga

9. Determine experimental overall mass transfer coefficients for liquid phase.

* $C^*_{exit} = \frac{P_{T,i} \times y_i}{H}$ * $C^*_{tank} = \frac{P_{T,o} \times y_o}{H}$

* $$\log \Delta C = \frac{[(C^*_{exit} - C_{exit}) - (C^*_{\tan k} - C_{\tan k})]}{\log\left[\frac{(C^*_{exit} - C_{exit})}{(C^*_{\tan k} - C_{\tan k})}\right]}$$

* $$K_L a = \frac{R_{abs}}{V_{column} \times \log \Delta C}$$

10. Prepare Table 7.

y_i	y_o	C_{exit}(kmol/m^3)	C^*_{exit}(kmol/m^3)	C_{tank}(kmol/m^3)	C^*_{tank}(kmol/m^3)	$\log \Delta C$	$K_L a$

11. Determine experimental overall mass transfer coefficients for gas phase.

* $P_i = P_{T,i} \times y_i$
* $P_o = P_{T,o} \times y_o$

* $P_i^* = H \times C_{exit}$
* $P_o^* = H \times C_{\tan k}$

* $$\log \Delta P = \frac{[(P_i - P_i^*) - (P_o - P_o^*)]}{\log\left[\frac{(P_i - P_i^*)}{(P_o - P_o^*)}\right]}$$

* $$K_G a = \frac{R_{abs}}{V_{column} \times \log \Delta P}$$

12. Prepare Table 8.

y_i	y_o	P_i	P_i*	P_o	P_o*	$\log \Delta P$	$K_G a$

13. Prepare Table 9.

$K_L a_{(calc)}$	$K_G a_{(calc)}$	$K_{la\ (exp,average)}$	$K_G a_{\ (exp,\ average)}$

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14. Determine the column performance.

$$* \%CP = 100 \times \frac{\left[(F_{CO_2} + F_{air}) \times y_i - \left(F_{CO_2} + F_{air} - F_a\right) \times y_o\right]}{(F_{CO_2} + F_{air}) \times y_i}$$

15. Prepare Table 10.

y_i	y_o	P_i	F_a (m^3/s)	%CP

APPENDIX-I

Characteristic of the packed column and packing

Column inside diameter : $D = 0.080m$

Packed height : $H_c = 1.2$ m

Raschig ring height : $L_p = 0.010m$

Raschig ring inside diameter : $D_i = 0.008m$

Raschig ring outside diameter : $D_o = 0.010$ m

Specific area of packing/ unit volume of tower: $a = 440\ m^2/m^3$

Void fraction : $\varepsilon = 0.811$

Packing factor: $Fp = 1280\ m^{-1}$ $\phi = 1$

Rasching ring parameters

$\alpha = 920$

$n = 0,35$

$C_1 = 5,23$

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HESAPLAMALAR

Part I : Dry Column

1) Calculate mass flux of air (G_{air}, $kg/m^2.s$)

TABLE 1

F_{air} (L/min)	ΔP (mmH_2O)	F_{air} (m^3/s)	ΔP (Pa)	G_{air} ($kg/m^2.s$)	ΔP/
10 20 30 ⋮	Deneysel veri	Hesap	Hesap	Hesap	Hesap

$F_{air} = 10 \, L/min \times 1 \, min/60 \, s \times 0.001 \, m^3/1L = 1.67 \times 10^{-4} \, m^3/s$

$$\rho_{air} = \frac{P.mw}{R.T} \Rightarrow$$

$P = 693$ mmHg for Beytepe [92000 Pa @ 20°C]

$mw = 29$ g/mol (air)

$R = 8314.34 \, m^3.Pa/kg\,mol$

$$\rho_{air} = \frac{92000 \times 29}{8314.34 \times 293} = 1.1 \, kg/m^3$$

$$A_{column} = \pi . D^2/4 = \frac{\pi \, (0.008)^2}{4} = 5 \times 10^{-3} \, m^2$$

48, 16 mm?

$$G_{air} = \frac{F_{air} \, (m^3/s) \times \rho_{air} \, (kg/m^3)}{A_{column} \, (m^2)} = \ldots kg/m^2.s$$

2. Calculate pressure drop per column length ($\Delta P/H_c$, (Pa/m))

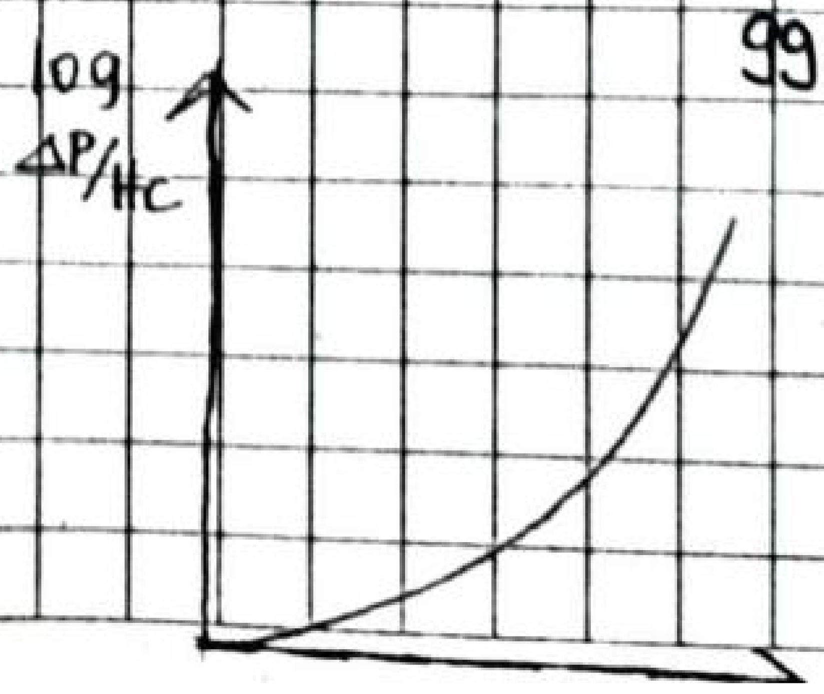
$\Delta P = h \, (mmH_2O) . \rho_{water} . g \rightarrow Pa$

$\rho_{water} \gg \rho_{air} \rightarrow$ neglected

998.2 kg/m^3 1.1 kg/m^3 @ 20°C

$\Delta P / H_c = Pa/m$

H_c ↓ column length (1.2 m)



→ Fig. 1

Part II : Wet Column

(1) Calculation of mass flux of water (L_w $kg/m^2.s$)

$$F_{water} = \frac{1L}{min} \times \frac{1min}{60s} \times \frac{1m^3}{1000L} = \ldots m^3/s$$

$$L_{water} = F_{water} \times \frac{\rho_{water}}{A_{column}} = \ldots (kg/m^2.s)$$

(2) Calculation of pressure drop per column length ($\frac{\Delta P}{H_c}$, Pa/m)

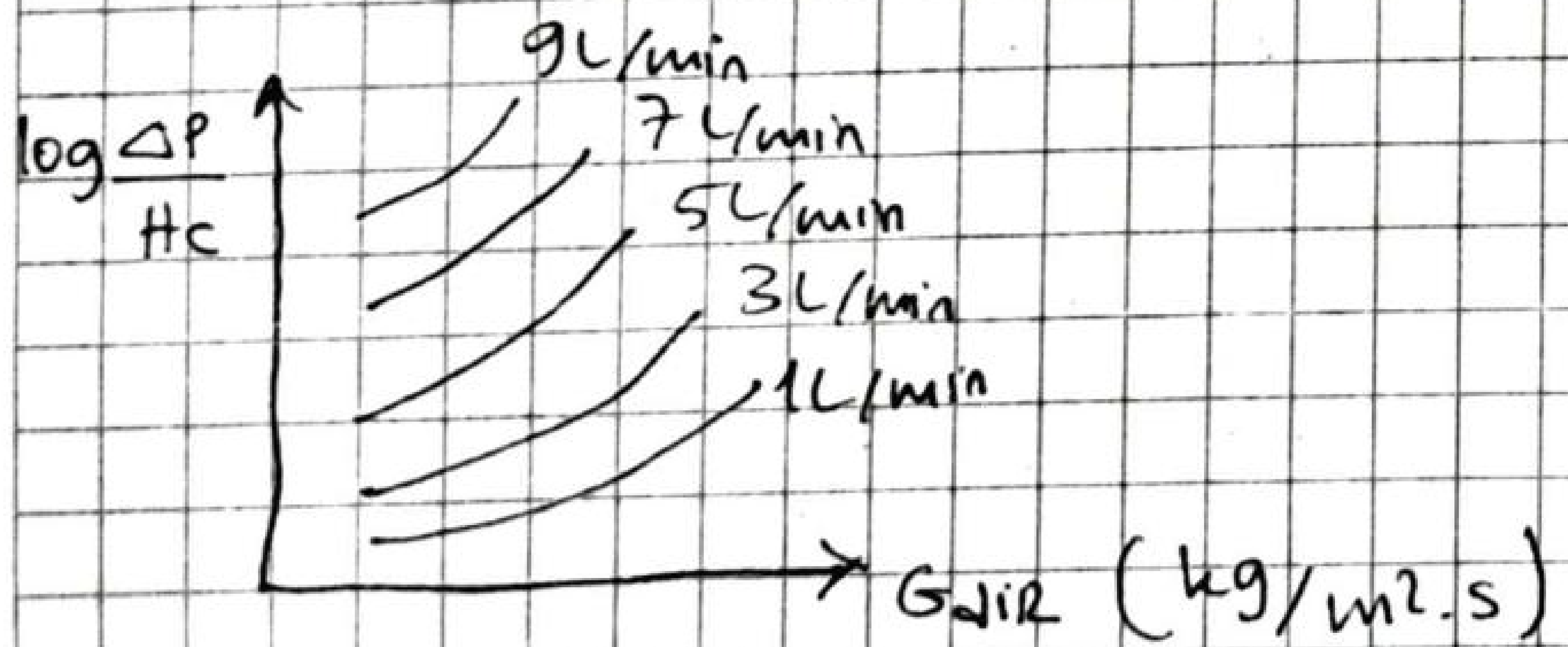
$$\Delta P = h \cdot \rho_{water} \cdot g \rightarrow Pa$$

$$\Delta P / H_c \rightarrow Pa/m$$

H_c = 1.2m (column length)

TABLE 2

F_{water}	L_{water} ($kg/m^2.s$)	F_{air} (L/min)	G ($kg/m^2.s$)	ΔP (mmH_2O)
1L/min				
3L/min				
5L/min				
7L/min				
9L/min				



(3) Determination of experimental flooding points.

Experimental flooding mass flow rate & ΔP for each high water flow rate (5, 7, 9) were determined and listed in Table 3.

4) Calculation of flooding point values

Bu kısımda föydeki Figure 6 kullanılıyor. (Generalized correlation for flooding and pressure drop in packed columns)

Trial-error yapılacak. [Taşma nok. gözlemlenen 5, 7, 9 için yapılacak] !

Örneğin; 5 L/dak su akış hızında, 80 L/dak hava akış hızında taşma gözlemleniyor ise;

16.62 kg/m².s (L_w)

0.29 kg/m².s ($G_{air,exp}$)

Fig 6'da x ekseni $\left(\frac{L}{G}\right)\left(\frac{\rho_g}{\rho_L}\right)^{0.5}$

$\rho_g = 1.1$
$\rho_L = 998.23$

Water	Air
5 L/min	60 L/min
7 L/min	50 L/min
9 L/min	30 L/min

$x = \left(\frac{L}{G}\right) . 0.0332$ → Buna göre trial-error yapılacak

1st trial → L = 5 L/dak
G = 80 L/dak için x = 1.905

Bu değerden flooding line'a çık.
y = 0.01

$$y = \frac{G^2 . F_P . \Psi . \mu_L^{0.2}}{\rho_G . \rho_L . g}$$

?

G calculated = 0.29 kg/m²s
G experimental = 0.29 kg/m²s

→ g = 9.81 m/s²

ρ_L, ρ_g → 998.23, 1.1 (kg/m³)

L, G (kg/m².s)

μ_L → mPa.s = cp

$\Psi = \frac{\text{density } H_2O}{\text{density liq.}}$ → $\Psi = 1$

Fp = packing factor (m^{-1})

1200 m^{-1} for Raschig Rings.

TABLE 3

Fw (L/min)	Lw (kg/m².s)	Gair (kg/m².s) (fl, ex)	ΔP/Hc (Pa/m) (fl/ex)
5			
7			
9			

x	y	Gair (fl, cal.)	ΔP/Hc (fl, cal.)	Gair, optimum

ΔP/Hc (opt)

Mass flux of air is usually selected 50-75% of flooding flux. This range is also called as loading zone of absorption packed column.

(5) Calculation of optimum mass flux of air.
This value is usually 50-75% of mass flow rate air.

Biz %60'dan hesaplatıyoruz.

$$G_{opt} = \underbrace{G_{exp}}_{0.29} \cdot (0.6) = 0.18\ kg/m^2.s$$

PART III. Gas Absorption

(1) Calculation of mass flow rate of CO_2 absorbed into water

volume fraction of CO_2 in gas stream inlet → $y_i = \frac{F_{CO_2}}{F_{CO_2} + F_{air}}$

$$y_i = \frac{6}{6+20} = 0.23$$ deney boyunca sabit

Volume fraction of CO_2 in gas stream outlet → $y_0 = \frac{V_{CO_2}}{V_{sample}}$

Her örnek alımında değişiyor. $y_0 = \frac{(\text{Hempl okunan})}{20 mL}$

$F_a = (F_{CO_2} + F_{air}) \cdot y_i - (F_{CO_2} + F_{air} - F_a) y_0$
(6, 20, 0.23; 6, 20)

L/dak × 60 = L/s

$F_a = (F_{air} + F_{CO_2}) (y_i - y_0) / (1 - y_0)$

MASS FLOW RATE OF CO_2 ABSORBED INTO WATER

$G_a = \frac{(P_{C,ave} \times F_a)}{R \times T_{C,ave}}$ → kmol/s (assuming ideal gas)

8.314

20°C = 293 K

$P_i > P_0$

$\Delta P_{ave} \rightarrow \frac{P_i + P_0}{2}$ deney sistemine göre değişiyor. II. kısma başlamadan önce ve bittiğinde aldığımız basınçların ortalaması

örneğin bu 8 mm H_2O ise

bunu önce mmHg'ye sonra da Pa'a çevirmemiz lazım.

$P_{ave} = \left(\frac{8}{13.6} + 690\right) \times 133.3 = 92055$ Pa

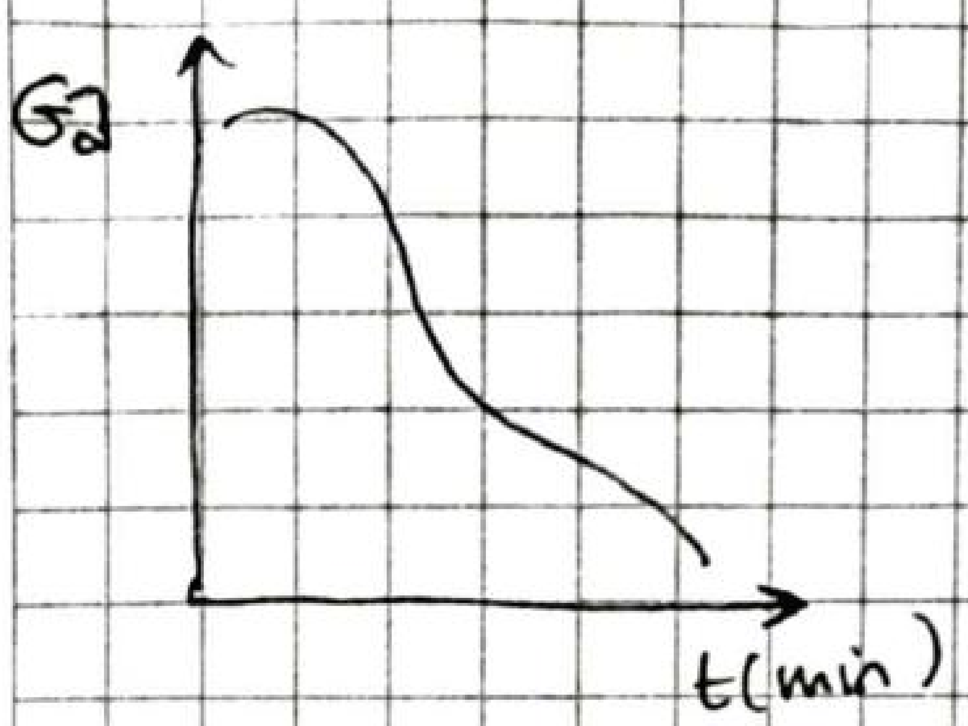
(1 mmHg = 133.3 Pa)

Sonra bunu F_a'yı, P_{ave}, ı yerine yazarak G_a'yı kmol/s cinsinden buluyoruz.

TABLE 4

t(min)	V_{CO_2} (mL)	t(s)	y_i	y_0 ↑	F_a (m^3/s) ↓	G_a (kmol/s) ↓
0	Hempl'den okunan	|	Sabit			
15		|	|			
30		|	|			
45		|	|			
60		|				

Figure 3



Sudaki CO_2 konsantrasyonu zamanla arttığı için, driving force (ΔC) azalacaktır.

2) Calculation of Rate of Absorption

Alınan örneklerin 0.0277 M NaOH ile titre edilmesi sonucu absorpsiyon akısı hesaplanacak.

$CO_2 + H_2O \rightarrow H_2CO_3$

$H_2CO_3 + NaOH \rightarrow NaHCO_3 + H_2O$

$NaHCO_3 + NaOH \rightarrow Na_2CO_3 + H_2O$

$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O$

$C_{sample} \times V_{sample} = C_{titrant} \times V_{titrant}$ → CO_2 conc. in water

V_{sample} → 20 mL

$C_{titrant}$ → $C_{NaOH} = 0.0277\,M$ * 0.05 M

$C_{sample}(M) = \frac{0.0277}{20} V_{titrant}$ *

@ t = ...

$V_{exit} \rightarrow C_{exit} = \ldots$

$V_{tank} \rightarrow C_{tank} = \ldots$

Rate of absorption: (Abs. hızı) (kmol/s)

$R_{abs} = F_{water} \times (C_{exit} - C_{tank})$ (kmol/s)

$= 5\frac{L}{min} \times \frac{1\,min}{60\,s} \times \frac{0.001\,m^3}{1\,L} (C_{exit} - C_{tank})$

Table 5

t (min)	V_{tit} (mL) tank	V_{tit} (mL) column	C_{tank} (M)	C_{column} (M)	R_{abs} (kmol/s)
⋮	⋮	⋮	⋮	⋮	⋮

Fig 4

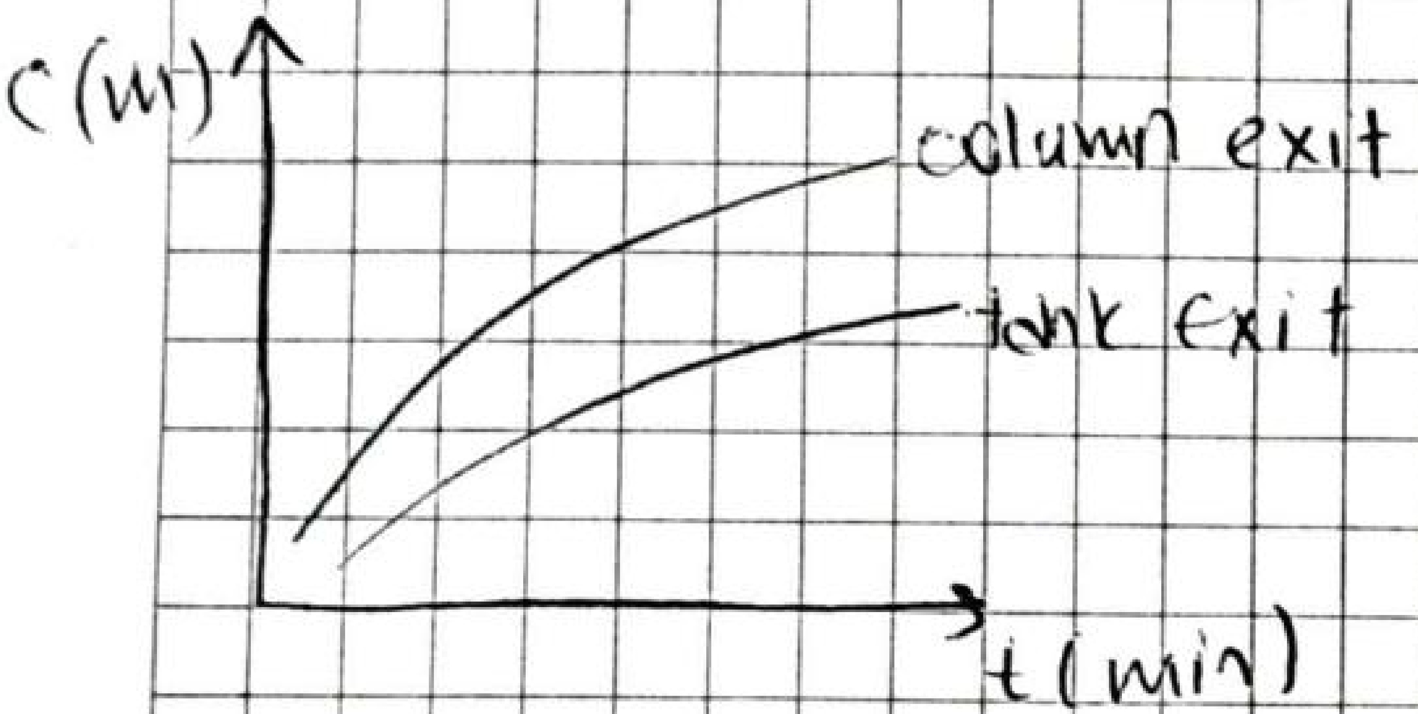


Fig 5

③ Calculation of mass tr. coeff.

→ Liquid mass tr. coeff.

$$\frac{k_L a_e}{D_e} = \alpha \left(305 \frac{L}{\mu_L}\right)^{1-n} \left(\frac{\mu_L}{\rho_L \cdot D_e}\right)^{0.5}$$

k_L = liquid phase mass trans. coeff. for dilute sys. (kmol/s.m²)

a_e = 440 m²/m³ (effective area) (specific surface area of packing) (9mmlik rashing ring icin birim tule hacmine duser birim dolgu maddesi alani)

D_L = 1.96 × 10^{-9} m²/s (@20°C) **[ref]**

μ_L = 1.005 × 10^{-3} Pa.s **[ref]**

ρ_L = 998.23 kg/m³ **[ref]**

α = 920 n = 0.35 (for 10mm rashing rings)

$$L = 5\frac{L}{min} \times \frac{1 min}{60 s} \times \frac{998.23 kg}{m^3} \times \frac{1}{5\times10^{-3} m^2}$$

$L = 16.637$ kg/m².s ⇒ $k_L = 3.75 \times 10^{-9}$ m²/s

Gas mass tr. coeff.

$$\frac{k_G \cdot R \cdot T}{a_t \cdot D_g} = C_1 \cdot \left(\frac{G}{a_t \cdot \mu_g}\right)^{0.7} \cdot \left(\frac{\mu_g}{\rho_g \cdot D_g}\right)^{1/3} \cdot (a_t \, D_p)^{-2}$$

↳ total surface area

$$\frac{\pi}{4} \cdot D^2 \cdot L \cdot a_p = a_t$$

✓ ✓ ✓ ?

k_g = gas phase mass tr. coeff. kmol/s m² Pa

$D_g = 1.38 \times 10^{-5}$ m²/s [ref]

$D_p = 10 - 8 = 2$ mm (equivalent diameter)

$C_1 = 5.23$ for ring about 12 mm from Perry's Handbook.

★ ⊳ μ ve ρ kısmına CO_2 + hava karışımının μ ve ρ değerleri yazılmalı.

$\mu_{mix} = \mu_{CO2} (1-y_i) + \mu_{air} \cdot y_i$

From Geankoplis Table A.3.3 → $\mu_{CO2} = 1.457 \times 10^{-5}$ kg/m.s [ref]

$\mu_{air} = 1.82 \times 10^{-5}$ kg/m.s [ref]

$\mu_{mix} = 1.548 \times 10^{-5}$ kg/m.s

$\rho_{mix} = \rho_{CO2} (1-y_i) + \rho_{air} \cdot y_i$

$\rho_{CO2} = 1.83$ kg/m³ [ref]

$\rho_{air} = 1.208$ kg/m³ [ref]

$\rho_{mix} = 1.6864$ kg/m³

$$G_{mix} = F_{air} + F_{CO2} = \frac{F_{mix} \cdot \rho_{mix}}{A_{column}}$$

$= 0.1116$ kg/m².s

$k_g = 1.257 \times 10^{-7}$ kmol/m².Pa.s

④ Calculation of Overall Mass Transfer Coefficients

Overall mass tr. coeff. for LIQUID PHASE

$$\frac{1}{K_L \cdot a_p} = \frac{1}{k_L \cdot a_p} + \frac{1}{H \cdot k_G \cdot a_p}$$

$a_p = 440$ m²/m³

$H = 3.2 \times 10^{9}$ Pa.m³/kmol

$k_L = 2.37 \times 10^{-3}$ s

$K_L \cdot a_p = 1.24$

↳ K_L'yi ucek (s^{-1})

Overall mass tr. coeff. for GAS PHASE

$$\frac{1}{K_G \cdot a_p} = \frac{1}{k_G \cdot a_p} + \frac{H}{k_L \cdot a_p}$$

$K_G \cdot a_p = 3.26 \times 10^{-10}$

↳ K_G'yi ucek (s^{-1})

$K_G = 7.4 \times 10^{-3} \, s^{-}$

Table 6

$D_{water-CO_2}$ (D_L) (m^2/s)	$D_{CO_2-water}$ (D_G) (m^2/s)	$K_L \cdot a_p$ (1/s)	$K_G \cdot a_t$ (1/s)
1.96×10^{-9}	1.38×10^{-5}	Hesap sonucu	

5) Determination of the experimental overall mass tr. coef.

FOR LIQUID PHASE

$$C^*_{exit} = \frac{P_{T,i} \cdot y_i}{H} \qquad C^*_{tank} = \frac{P_{T,0} \cdot y_0}{H}$$

(column)

↳ Buradaki $P_{T,i}$ ve $P_{T,0}$ (Başlangıç ve bitiş) deneysel olarak elde ediliyor ve birimleri mm H_2O. Bunları Pa'a çevirmek lazım.

$P_{T,i} = 10 \times 10^{-3}$ m $H_2O \times 998.23 \frac{kg}{m^3} \times 9.81 \frac{m}{s^2} = 97.926$ kg/m.s²

$P_{T,0} = 8 \times 10^{-3}$ m $H_2O \times 998.23$ kg/m³ $\times 9.81 \frac{m}{s^2} = 78.341$ kg/m.s²

→ $y_i = 0.23$ (hep sabit)

y_0 ⇒ değişiyor deney süresince

C_{tank} ve C_{exit} Table 5'te belirtilmiştir. C^*_{tank} ve C^*_{exit}'i de hesaplarsak log ΔC ve oradan da K_L bulunabilir.

$$\log \Delta C = -\left[\left(C^*_{exit} - C_{exit}\right) - \left(C^*_{tank} - C_{tank}\right)\right] \Big/ \log\left(\frac{C^*_{exit} - C_{exit}}{C^*_{tank} - C_{tank}}\right)$$

$$K_L \cdot a_p = \frac{R_{abs}}{V_C \cdot \log \Delta C}$$

→ Buradan K_L'yi çek

Buradaki V_C = kolonun hacmi ($A \times H$)

Kolonun yüksekliği = 1.2 m

" çapı = 0.08 m

FOR GAS PHASE

$P_i = P_{T,i} \cdot y_i$ $\quad$ $P_o = P_{T,o} \cdot y_o$

$P_i^* = H \cdot C_{exit}$ $\quad$ $P_o^* = H \cdot C_{tank}$

$$\log \Delta P = \frac{(P_i - P_i^*) - (P_o - P_o^*)}{\log\left[\frac{P_i - P_i^*}{P_o - P_o^*}\right]}$$

$$K_G \cdot a_t = \frac{R_{abs}}{V_C \cdot \log \Delta P}$$ → K_G'yi çek!

Table 7

y_i	y_o	C_{exit} (M)	C^*_{exit} (M)	C^*_{tank} (M)	log ΔC

$K_L \cdot a_p$ (m/s)

$(K_L a)_{ave}$

Table 8

y_i	y_o	P_i^* (Pa)	P_o (Pa)	P_o^* (Pa)	log ΔP	$K_G\,a t$

$(K_G \cdot a)_{ave}$

Table 9

K_L(cal)(1/s)	K_L(exp)(1/s)	$K_{G,cal}$ (kmol/k m^{2}Pa)	$K_{G,exp}$ (kmol/s.m^2.Pa)
↓ 4. kısım	↓ 5. kısım	↓ 4. kısım	↓ 5. kısım

⑥ Column performance

$$\%CP = 100 \times \frac{[(F_{CO_2} + F_{air})\, y_i - (F_{CO_2} + F_{air} - F_a)\, y_o]}{(F_{CO_2} + F_{air})\, y_i}$$

$$= 100 \times \frac{F_a}{(F_{CO_2} + F_{air})\, y_i}$$

Table 10

t(min)	y_i	y_o	F_a (L/min)	%CP
'	'	'	'	'
'	'	'	'	'

Figure 6