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APPENDICES

Appendix A

PHYSICAL PROPERTIES OF SYSTEM

1. Diffusivity of Benzoic Acid in Water

Diffusivity of benzoic acid in water as a function of temperature was taken from VANADURONGWAN[7] and is shown in Fig.A.1.

2. Saturated Concentration of Benzoic Acid in Water

Solubility of benzoic acid in water as a function of temperature is shown in Fig.A.2. The values were taken from reference[11].

3. Viscosity of NaOH Solutions

Viscosity of NaOH solutions at different concentrations were evaluated from reference[12] and are shown in Fig.A.3.

4. Density of NaOH Solutions

Density of NaOH solutions at different concentrations were evaluated from reference[13] and are shown in Fig.A.4.

5. Density of Benzoic Acid Particles

Density of benzoic acid particles was determined by using the density bottle method. Data and results are shown in Table A.1. The calculation method is given in Appendix D.

Table A.1 Density of Benzoic Acid Particles

$N = 250$, $V = 0.5 \times 10^{3}\ m^{3}$, $T = 35.0^{o}C$

Run No.	$W_B \times 10^3$, kg	$W_{BW} \times 10^3$, kg	ρ_s, kg/m^3
1	31.8	503.9	1,277
2	31.7	503.8	1,273
3	31.8	503.8	1,272
4	31.6	503.8	1,274
5	31.7	503.9	1,278

Average density of benzoic acid particles, ρ_s = 1,275 kg/m^3

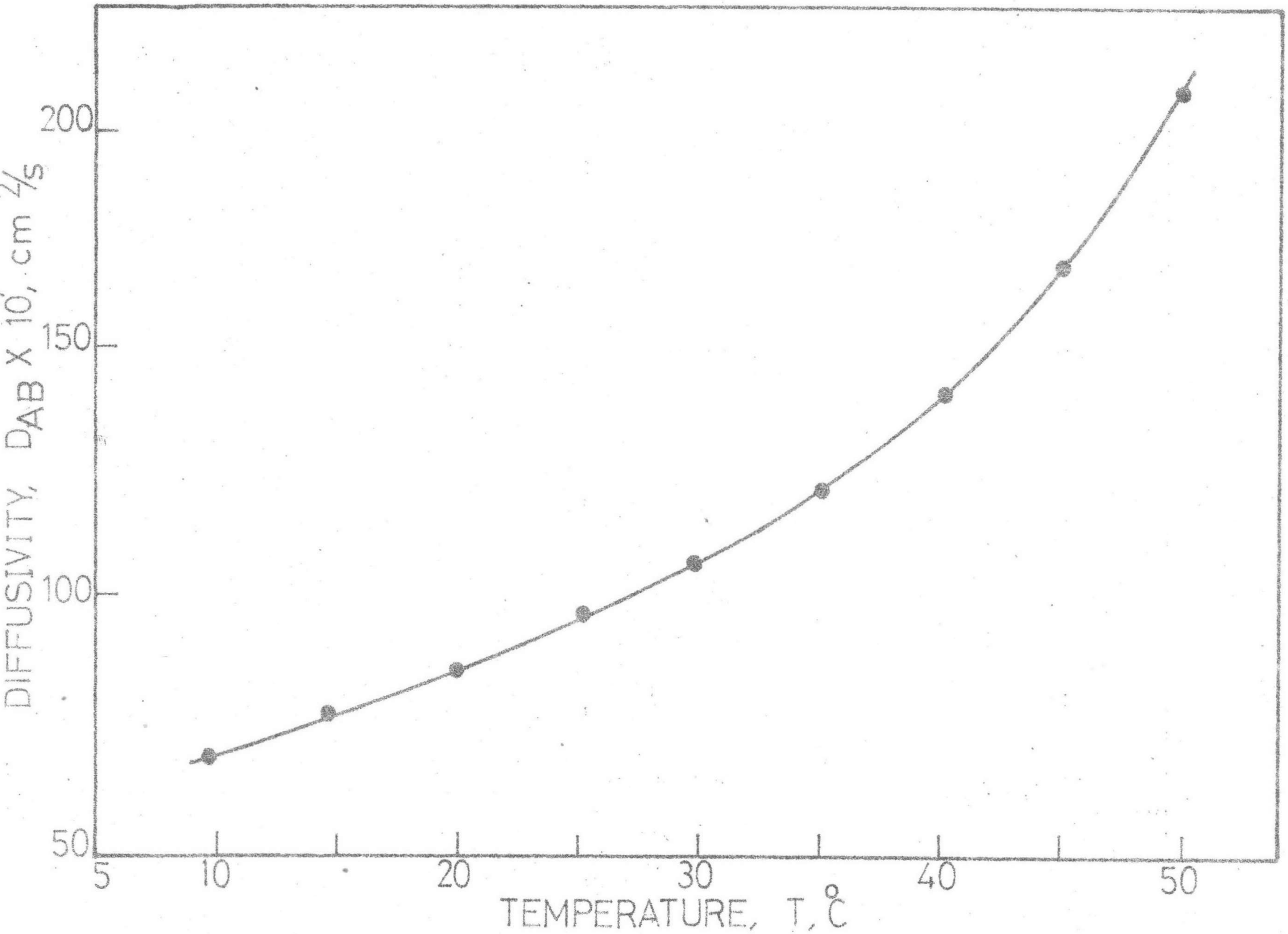

Fig.A.1 Diffusivity of Benzoic Acid in Water

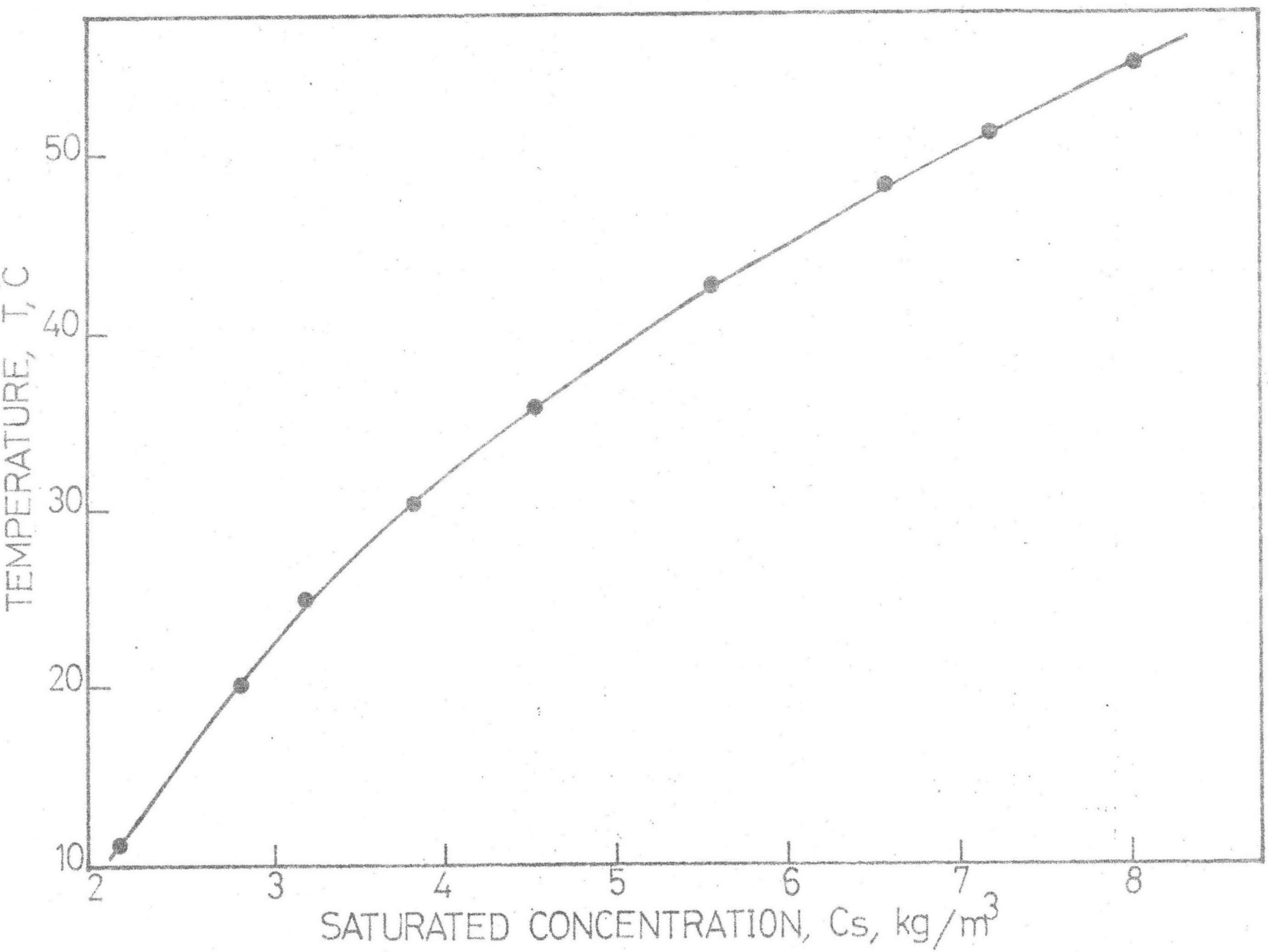

Fig.A.2 Saturated Concentration of Benzoic Acid in Water

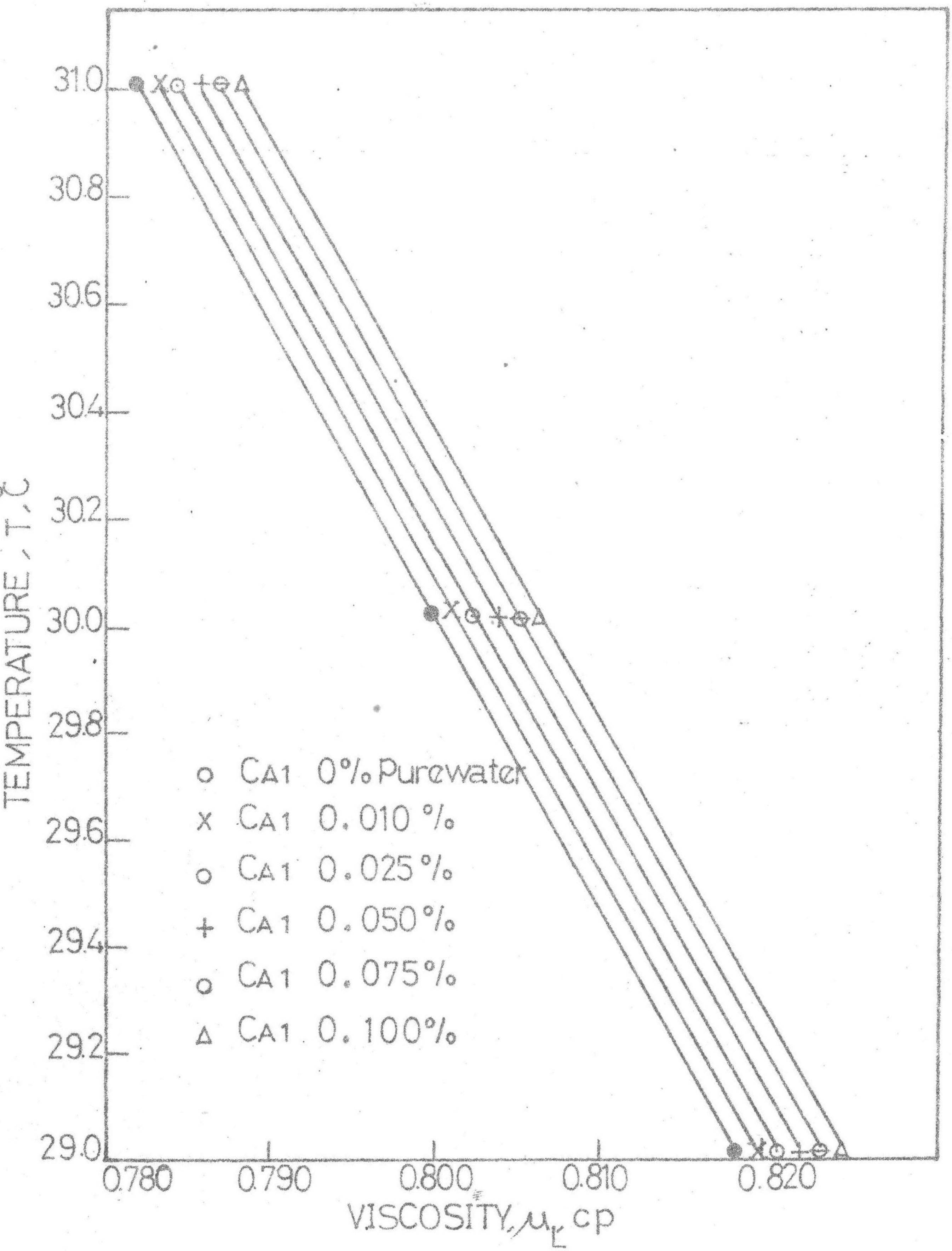

Fig.A.3 Viscosity of NaOH Solutions

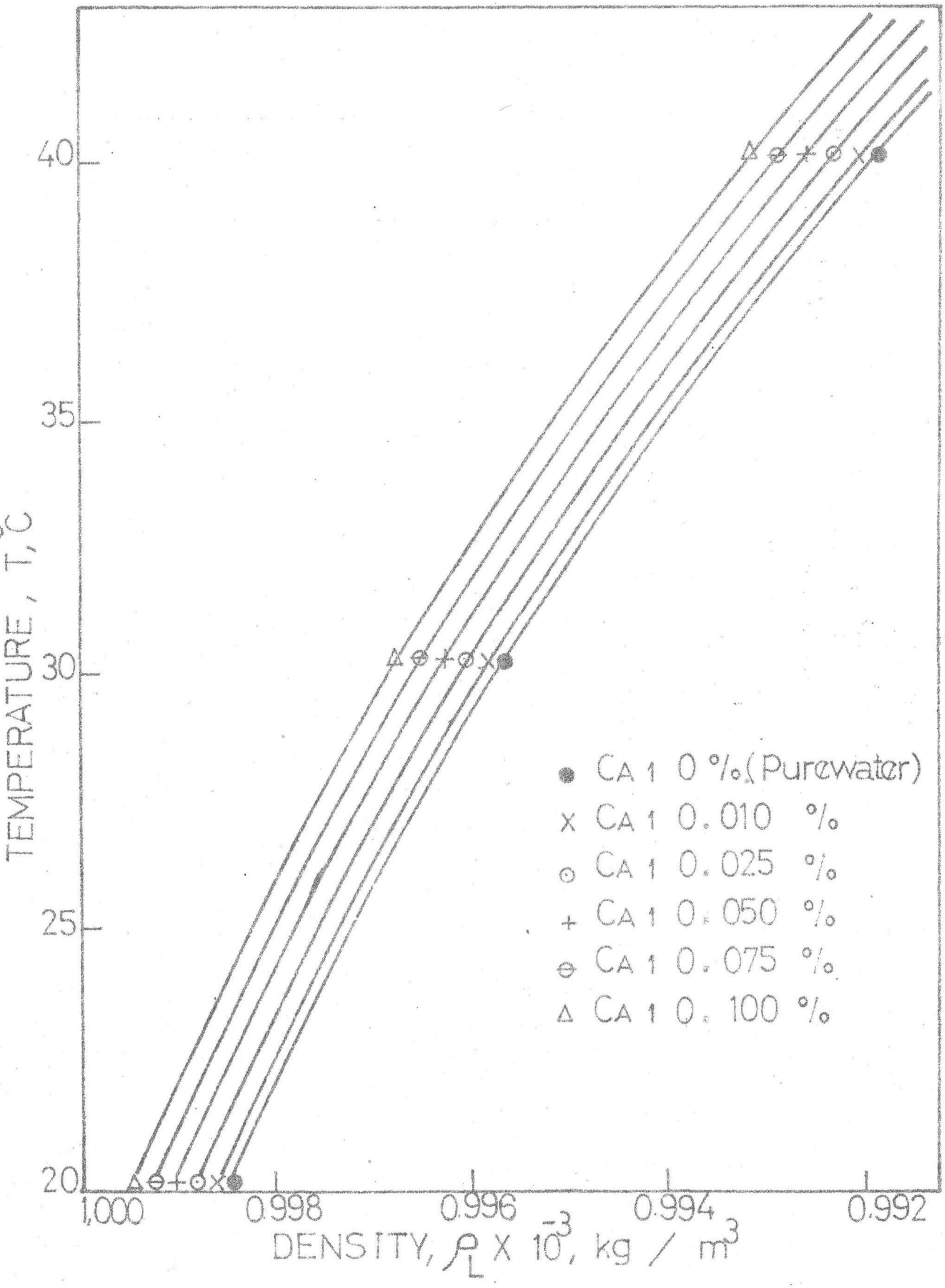

Fig.A.4 Density of NaOH Solutions

Appendix B

CALIBRATION OF ORIFICE METER

An orifice meter was used to indicate the flow rates of liquid. When liquid flows through the orifice meter, a pressure drop is developed for a particular flow-rate. This pressure drop is generally indicated by height of liquid manometer.

Calibration of the orifice meter was carried out by varying the rate of liquid flowing through the meter. Each flow rate was calculated by recording the weight of liquid per constant time. The corresponding pressure drop for each flow rate was also measured from the attached manometer, and it was recorded. The calibration of the meter was calculated as volumetric flow-rate of liquid in m^3/hr with reading in cm liquid, as is shown in Table B.1 and was plotted in Fig.B.1.

Table B.1 Calibration of Orifice Meter

T = 30.0°C ρ_L = 995.7 kg/m^3

Run No.	$W \times 10^2$, kr/hr	ΔP, cm.	Q, m^3/hr.
1	274.3	7.8	0.275
2	422.3	11.3	0.425
3	499.7	15.7	0.502
4	799.9	23.0	0.804
5	1,090.8	31.1	1.096
6	1,666.8	47.0	1.675
7	2,068.9	62.5	2.079
8	2,307.6	69.5	2.319
9	2,500.2	77.0	2.512
10	2,727.0	87.0	2.741

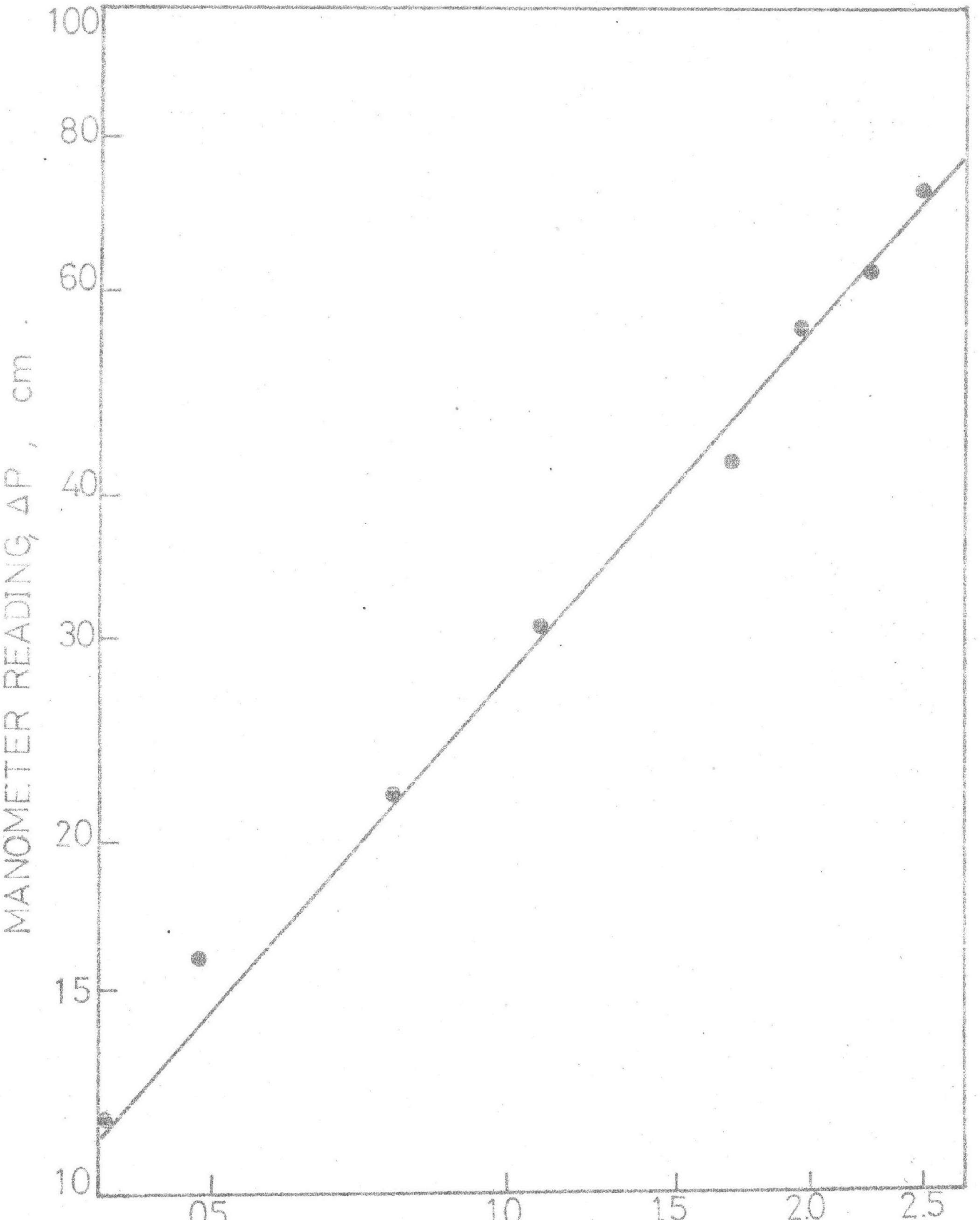

Fig.B.1 Calibration Curve of Orifice Meter

Appendix C

EXPERIMENTAL DATA AND RESULTS

1. Mass Transfer between Benzoic Acid and NaOH Solutions

The experimental data and results of the experiments are included in Tables C.1, C.2, C.3, C.4, C.5 and C.6 respectively.

2. Evaluation of Mass Transfer due to Chemical Reaction

The experimental results are tabulated in Table C.7.

Table C.1 Mass Transfer between Benzoic Acid and Pure Water

$d_c = 9.4 \times 10^{-2}$ m, N = 3,500, t = 15 min, $d_p = 0.5850 \times 10^{-2}$ m, $C_{A1} = 0$ (Pure water)

$T = 30.0^{\circ}C$, $\rho_L = 995.7$ kg/m^3, $\mu_L = 0.8007$ cp, $D_{AB} = 102 \times 10^{-11}$ m^2/s, $C_s = 4.125$ kg/m^3

$T = 30.1^{\circ}C$, $\rho_L = 995.7$ kg/m^3, $\mu_L = 0.7990$ cp, $D_{AB} = 100 \times 10^{-11}$ m^2/s, $C_s = 4.125$ kg/m^3

Run No.	ΔP	$L_f \times 10^2$	M_1	M_2	T	$d_p \times 10^2$	Q	Re	ϵ	Sc	Sh	$\frac{Sh\epsilon^{1.25}}{Sc^{1/3}}$	C_{A2}
1	16.0	11.00	0.5021	0.4460	30.0	0.5874	0.583	172	0.513	788	240	11.28	0
2	17.8	11.70	0.4973	0.4380	30.0	0.5847	0.678	199	0.549	788	254	12.99	0
3	23.3	13.45	0.4998	0.4380	30.0	0.5852	0.830	244	0.607	788	263	15.25	0
4	26.0	14.25	0.5027	0.4398	30.1	0.5862	0.906	265	0.627	787	266	16.07	0
5	29.3	15.40	0.4953	0.4308	30.1	0.5827	1.032	300	0.661	787	274	17.69	0
6	31.5	16.95	0.4981	0.4317	30.1	0.5835	1.095	319	0.691	787	282	19.24	0

Table C.2 Mass Transfer between Benzoic Acid and 0.011% NaOH Solution

$d_c = 9.4\times10^{-2}$ m, N = 3,500, t = 15 min, $d_P = 0.5594\times10^{-2}$ m, $C_{A1} = 0.011$ %

T = 30.0°C, $\rho_L = 995.8$ kg/m³, $\mu_L = 0.8025$ cp, $D_{AB} = 102\times10^{-11}$ m²/s, $C_s = 4.125$ kg/m³

T = 30.1°C, $\rho_L = 995.8$ kg/m³, $\mu_L = 0.8005$ cp, $D_{AB} = 102\times10^{-11}$ m²/s, $C_s = 4.125$ kg/m³

Run No.	ΔP	$L_f\times10^2$	M_1	M_2	T	$d_p\times10^2$	Q	Re	ϵ	Sc	Sh	$\frac{Sh\,\epsilon^{1.25}}{Sc^{1/3}}$	C_{A2}
1	15.8	9.50	0.4380	0.3614	30.0	0.5546	0.573	158	0.526	790	258	12.50	-0.0019
2	17.8	10.45	0.4380	0.3790	30.0	0.5454	0.648	180	0.559	790	265	13.86	-0.0009
3	20.2	11.60	0.4308	0.3706	30.0	0.5552	0.738	208	0.602	790	270	15.49	-0.0003
4	25.6	13.15	0.4398	0.3788	30.1	0.5592	0.911	259	0.656	788	271	17.33	+0.0022
5	28.1	14.25	0.4318	0.3707	30.1	0.5555	0.991	280	0.682	788	272	18.26	+0.0029
6	29.8	14.80	0.4460	0.3829	30.1	0.5615	1.029	288	0.684	788	275	18.59	+0.0030

Table C.3 Mass Transfer between Benzoic Acid and 0.026% NaOH Solution

$d_c = 9.4\times10^{-2}$ m, N = 3,500, t = 15 min, $d_P = 0.4012\times10^{-2}$ m, $C_{A1} = 0.026$ %

$T = 29.6^\circ C$,, $\rho_L = 966.0\ kg/m^3$, $\mu_L = 0.811$ cp, $D_{AB} = 101\times10^{-11}\ m^2/s$, $C_s = 4.100\ kg/m^3$

$T = 29.7^\circ C$, $\rho_L = 966.0\ kg/m^3$, $\mu_L = 0.809$ cp, $D_{AB} = 101\times10^{-11}\ m^2/s$, $C_s = 4.100\ kg/m^3$

Run No.	ΔP	$L_f\times10^2$	M_1	M_2	T	$d_p\times10^2$	Q	Re	ϵ	Sc	Sh	$\frac{Sh\epsilon^{1.25}}{Sc^{1/3}}$	C_{A2}
1	15.6	3.50	0.1571	0.1263	29.6	0.3942	0.574	102	0.556	806	197	10.16	0.0190
2	18.7	4.45	0.1628	0.1293	29.6	0.3963	0.667	130	0.630	806	211	12.72	0.0194
3	20.5	5.00	0.1658	0.1303	29.6	0.3981	0.733	145	0.666	806	223	14.42	0.0196
4	22.7	5.80	0.1762	0.1385	29.7	0.4062	0.809	162	0.694	804	232	15.80	0.0199
5	23.5	6.00	0.1760	0.1383	29.7	0.4060	0.829	166	0.705	804	233	16.19	0.0200
6	25.6	6.85	0.1793	0.1400	29.7	0.4082	0.905	182	0.738	804	240	17.65	0.0203

Table C.4 Mass Transfer between Benzoic Acid and 0.049% NaOH Solution

$d_c = 9.4\times10^{-2}$ m, $N = 3,500$, $t = 15$ min, $d_p = 0.5196\times10^{-2}$ m, $C_{A1} = 0.049$ %

$T = 29.7^{\circ}C$, $\rho_L = 966.3$ kg/m^3, $\mu_L = 0.8105$ cp, $D_{AB} = 101\times10^{-11}$ m^2/s, $C_s = 4.100$ kg/m^3

$T = 29.8^{\circ}C$, $\rho_L = 966.3$ kg/m^3, $\mu_L = 0.808$ cp, $D_{AB} = 101\times10^{-11}$ m^2/s, $C_s = 4.100$ kg/m^3

Run No.	ΔP	$L_f\times10^2$	M_1	M_2	T	$d_p\times10^2$	Q	Re	ϵ	Sc	Sh	$\frac{Sh\epsilon^{1.25}}{Sc^{1/3}}$	C_{A2}
1	11.5	6.75	0.3614	0.2833	29.7	0.5368	0.429	109	0.4628	805	406	16.66	0.0252
2	14.4	7.45	0.3706	0.2851	29.7	0.5413	0.524	135	0.5026	805	438	20.10	0.0276
3	24.0	9.45	0.3707	0.2822	29.7	0.5414	0.854	220	0.6118	805	439	25.53	0.0354
4	25.0	10.50	0.3790	0.2893	29.8	0.5454	0.882	230	0.6425	802	441	27.27	0.0357
5	27.8	11.35	0.3788	0.2875	29.8	0.5453	0.976	253	0.6704	802	447	29.15	0.0368
6	33.3	13.25	0.3829	0.2867	29.8	0.5472	1.132	294	0.7164	802	469	33.23	0.0379

Table C.5 Mass Transfer between Benzoic Acid and 0.075 NaOH Solution

d_c = 9.4x10^{-2} m, N = 3,500, t = 15 min, d_P = 0.3596x10^{-2} m, C_{A1} = 0.075 %

T = 30.1°C, ρ_L = 996.4 kg/m^3, μ_L = 0.8045 cp, D_{AB} = 102x10^{-11} m^2/s, C_s = 4.125 kg/m^3

T = 30.0°C, ρ_L = 996.4 kg/m^3, μ_L = 0.8075 cp, D_{AB} = 102x10^{-11} m^2/s, C_s = 4.125 kg/m^3

Run No.	ΔP	$L_f \times 10^2$	M_1	M_2	T	$d_p \times 10^2$	Q	Re	ϵ	Sc	Sh	$\frac{Sh\,\epsilon^{1.25}}{Sc^{1/3}}$	C_{A2}
1	16.0	3.25	0.1263	0.0831	30.1	0.3535	0.582	102	0.641	792	304	18.85	0.0653
2	16.7	3.45	0.1293	0.0845	30.1	0.3559	0.606	107	0.655	792	314	19.99	0.0653
3	18.1	3.75	0.1303	0.0850	30.1	0.3567	0.656	116	0.680	792	316	21.09	0.0660
4	19.5	4.25	0.1383	0.0901	30.1	0.3638	0.682	123	0.701	792	329	22.81	0.0662
5	21.8	5.00	0.1385	0.0895	30.0	0.3635	0.780	140	0.746	795	334	24.99	0.0668
6	24.4	6.00	0.1400	0.0898	30.0	0.3644	0.867	156	0.787	795	340	27.24	0.0674

Table C.6 Mass Transfer between Bwnzoic Acid and 0.099% NaOH Solution

$d_c = 9.4\times10^{-2}$ m, N = 3,500, t = 15 min, $d_P = 0.4567\times10^{-2}$ m, $C_{A1} = 0.099$ %

T = 30.8°C, $\rho_L = 996.4$ kg/m³, $\mu_L = 0.786$ cp, $D_{AB} = 103\times10^{-11}$ m²/s, $C_s = 4.250$ kg/m³

T = 30.7°C, $\rho_L = 996.4$ kg/m³, $\mu_L = 0.789$ cp, $D_{AB} = 103\times10^{-11}$ m²/s, $C_s = 4.250$ kg/m³

Run No.	ΔP	$L_f\times10^2$	M_1	M_2	T	$d_P\times10^2$	Q	Re	ϵ	Sc	Sh	$\frac{Sh\epsilon^{1.25}}{Sc^{1/3}}$	C_{A2}
1	15.4	5.70	0.2875	0.1793	30.8	0.4617	0.564	132	0.544	766	596	30.43	0.0739
2	19.3	6.25	0.2867	0.1760	30.8	0.4596	0.695	162	0.590	766	602	34.02	0.0782
3	21.3	6.80	0.2893	0.1762	30.7	0.4605	0.756	176	0.621	769	611	36.81	0.0794
4	23.7	7.05	0.2851	0.1658	30.7	0.4550	0.844	194	0.648	769	637	40.48	0.0808
5	26.0	7.45	0.2833	0.1628	30.7	0.4530	0.918	210	0.670	769	655	43.40	0.0818
6	35.6	9.10	0.2822	0.1571	30.7	0.4505	1.232	280	0.742	769	676	50.87	0.0856

Table C.7 Evaluation of Mass Transfer Due to Chemical Reaction

Re = 150

Expt. No.	C_{A1} %	$\frac{Sh\,\epsilon^{1.25}}{Sc^{1/3}}$	K_2Cr^n	C_s	Cr
1	0	10.5	0	4.125	0
2	0.011	11.8	1.3	4.125	0.0267
3	0.026	14.8	4.3	4.100	0.0634
4	0.049	22.4	11.9	4.100	0.1195
5	0.075	26.0	15.5	4.125	0.1818
6	0.099	32.6	22.1	4.250	0.2329

Appendix D

SAMPLE OF CALCULATIONS

1. Density of Benzoic Acid Particles, ρ_S

$$\rho_S = \frac{W_B \rho_W}{W_B - (W_{BW} - V\rho_L)}$$

From Table A.1 Run No.1

$N = 250$, $T = 35.0^{\circ}C$, $V = 0.5\times10^{-3}\ m^3$, $W_B = 31.8\times10^{-3}$ kg

$W_{BW} = 503.9\times10^{-3}$ kg, $\rho_L = 994.0\ kg/m^3$, $\rho_W = 10^3\ kg/m^3$

$$\rho_S = \frac{31.8\times10^{-3}\times10^{3}}{31.8\times10^{-3}-(503.9\times10^{3}- 0.5\times10^{-3}\times994)}$$

$$= 1{,}277 \quad kg/m^3$$

2. Volumetric Flow-rate of Liquid, Q

$$Q = \frac{W}{\rho_L}$$

From Table B.2 Run No.1

$T = 30.0^{\circ}C$, $W = 274.3$ kg/hr, $\Delta P = 7.8$ cm,

$\rho_L = 995.7\ kg/m^3$

$$Q = \frac{274.3}{995.7}$$

$$= 0.275 \quad m^3/hr$$

3. Diameter of Benzoic Acid Particles, d_P

$$d_P = \frac{1}{2}(d_{P1} + d_{P2})$$

$$= \frac{1}{2}\left[\frac{6}{\pi N \rho_S}\right]^{1/3}\left[M_1^{1/3} + M_2^{1/3}\right]$$

From Table C.4 Run No.1

$N = 3,500$, $\rho_S = 1,273\ kg/m^3$, $M_1 = 0.3614\ kg$,

$M_2 = 0.2833\ kg$

$$d_P = \frac{1}{2}\left[\frac{6}{\pi \times 3,500 \times 1,273}\right]^{1/3}\left[(0.3614)^{1/3} + (0.2833)^{1/3}\right]$$

$$= 0.5161 \times 10^{-2}\ m$$

4. Reynolds Number, Re

$$Re = \frac{d_P U \rho_L}{\mu_L} = \frac{d_P Q \rho_L}{s\,\mu_L} = \frac{4 d_P Q \rho_L}{\pi \mu d_c^2}$$

From Table C.4 Run No.1

$d_P = 0.5159 \times 10^{-2}\ m$, $\Delta P = 11.5\ cm$, $Q = 0.429\ m^3/hr$

$T = 29.7^{\circ}C$, $\rho_L = 996.3\ kg/m^3$, $\rho_L = 0.8105\ cp = 0.8105 \times 3.6\ kg/mhr$

$d_c = 9.4 \times 10^{-2}\ m$

$$Re = \frac{4 \times 0.5159 \times 10^{-2} \times 0.429 \times 996.3}{\pi (0.094)^2 (0.8105 \times 3.6)}$$

$$= 109$$

5. Voidage, ϵ

$$\epsilon = \frac{\left[\dfrac{L_f \pi d_c^2}{4} - \dfrac{\pi d_p^3 N}{6}\right]}{\left[\dfrac{L_f \pi d_c^2}{4}\right]}$$

From Table C.4 Run No.1

$L_f = 6.75\times10^{-2}$ m, $d_c = 0.94$ m^2, N = 3,500,

$d_P = 0.5159\times10^{-2}$ m

$$\epsilon = \frac{\left[\dfrac{6.75\times10^{-2}\times \pi (0.094)^2}{4} - \dfrac{\pi \times 3,500(0.5161\times10^{-2})^3}{6}\right]}{\left[\dfrac{6.75\times10^{-2}\times \pi (0.094)^2}{4}\right]}$$

$$= 0.4628$$

6. Schmidt Number, Sc

$$= \frac{\mu_L}{\rho_L D_{AB}}$$

From Table C.4 Run No.1

T = 29.7°C, μ_L = 0.8105x3.6 kg/mhr, ρ_L = 996.3 kg/m^3

$D_{AB} = 101\times10^{-11}$ m^2/s = $3.6\times101\times10^{-8}$ m^2/hr

$$Sc = \frac{0.8105\times3.6}{996.3\times3.6\times101\times10^{-8}}$$

$$= 805$$

7. Sherwood Number, Sh

$$Sh = \frac{k\ d_P}{D_{AB}}$$

$$k = \frac{M_1 - M_2}{s\ t\ \Delta C_{LM}} = \frac{M_1 - M_2}{\pi d_P^{\ 2} N\ t\ \Delta C_{LM}}$$

$$\Delta C_{LM} = \frac{C_2 - C_1}{\left[\ln \frac{C_s - C_1}{C_s - C_2}\right]}$$

$$C_2 = \frac{M_1 - M_2}{Q\ t}$$

From Table .C.4 Run No.1

$M_1 = 0.3614$ kg, $M_2 = 0.2833$ kg, $Q = 0.429\ m^3/hr$,

$t = 15$ min $= 15\times60$ s, $T = 29.7^{o}C$, $C_s = 4.10\ kg/m^3$, $N = 3{,}500$,

$d_P = 0.5161\times10^{-2}$ m, $D_{AB} = 101\times10^{-11}\ m^2/s$, $C_1 = 0$

$$C_2 = \frac{4(0.3641-0.2833)}{0.429}$$

$$= 0.728 \quad kg/m^3$$

$$\Delta C_{LM} = \frac{0.728}{\left[\ln \frac{4.10}{4.10-0.728}\right]}$$

$$= 3.724 \quad kg/m^3$$

$$k = \frac{(0.3614-0.2833)}{\pi(0.5161\times10^{-2})^2\times3{,}500\times15\times60\times3.724}$$

$$= 7.952\times10^{-5}\ m/s$$

$$Sh = \frac{7.952\times10^{-5}\times0.5161\times10^{-2}}{101\times10^{-11}}$$

$$= 406$$

8. Total Mass Transfer, $\frac{Sh\epsilon^{1.25}}{Sc^{1/3}}$

From Table C.4 Run No.1

$Sh = 406$, $\epsilon = 0.4628$, $Sc = 805$

$$\frac{Sh\epsilon^{1.25}}{Sc^{1/3}} = \frac{406(0.4628)^{1.25}}{(805)^{1/3}}$$

$$= 16.66$$

9. Outlet Concentration of NaOH Solution, C_{A2}

$$C_{A2} = C_{A1} - C_2 \left[\frac{MW_A}{MW}\right]$$

From Table C.4 Run No.1

$C_{A1} = 0.049\%$, $MW_A = 40.01$, $MW = 122.12$, $C_2 = 0.782\ kg/m^3 =$ 0.0728%

$$C_{A2} = 0.049 - 0.0728 \left[\frac{40.01}{122.12}\right]$$

$$= 0.0252\ \%$$

10. Mass Transfer Due to Chemical Reaction, K_2Cr^n

From Table C.7 Run No.2

$Re = 150$, $C_{A1} = 0.011\% = 0.11\ kg/m^3$, $C_s = 4.125\ kg/m^3$,

$\frac{Sh\epsilon^{1.25}}{Sc^{1/3}}$ of total mass transfer = 11.8, $\frac{Sh\epsilon^{1.25}}{Sc^{1/3}}$ of mass transfer without chemical reaction = 10.5

$$K_2Cr^n = 11.8 - 10.5 = 1.3$$

$$Cr = \frac{C_{A1}}{C_s}$$

$$= \frac{0.11}{4.125}$$

$$= 0.0267$$

Appendix E

NOMENCLATURE

A,B	reactants
a,b,c	exponents
C_1	inlet concentration of liquid, Kg/m^3
C_2	outlet concentration of liquid, Kg/m^3
C_{A1}	initial concentration of A or NaOH solution, Kg/m^3
C_{A2}	final concentration of A or NaOH solution, Kg/m^3
C_{B1}	initial concentration of B, Kg/m^3
Cr	concentration ratio (C_{A1}/C_s)
C_s	saturated concentration of benzoic acid in water, Kg/m^3
D_{AB}	mass diffusivity, m^2/s
d,e,f,g	exponents
d_c	diameter of fluidized column, m
d_p	average diameter of benzoic acid particle, m
d_{p1}, d_{p2}	diameter of benzoic acid particle before and after run, m
Ga	Galieo number $(d_p^3 \rho_L^2 g/\mu_L^2)$
g	acceleration gravity, m/s^2
K, K_1, K_2	constants
k	mass transfer coefficient, m/s
k'	reaction rate constant, s^{-1}
k"	reaction rate constant, $m^3/kg\ s$
L_f	height of the fluidized bed, m
M	dissolved mass per unit time, kg/s
M_1, M_2	weight of benzoic acid particle before and after run, kg

M_V	density number $(\rho_s - \rho_L)/\rho_L$
MW	molecular weight of benzoic acid
MW_A	molecular weight of NaOH
N	number of benzoic acid particles
ΔP	pressure drop of water manometer, cm
Q	volumetric flow-rate of liquid, m^3/hr
Re	Reynolds number $(d_p U \rho_L / \mu_L)$
r_A	rate of disappearance of A, $kg/m^3 s$
Sc	Schmidt number $(\mu_L / \rho_L D_{AB})$
Sh	Sherwood number $(k\, d_p / D_{AB})$
s	mass transfer area, m^2
T	operating temperature, °C
t	operating time, min
U	superficial velocity of liquid, m/s
V	volume of density bottle, m^3
W_B	weight of benzoic acid particles in air, kg
W_{BW}	weight of benzoic acid particles and water in the density bottle, kg
W	mass flow-rate of liquid, kg/hr
X, Y	products
ϵ	void fraction or bed voidage
μ_L	viscosity of liquid, cp
ρ_L	density of liquid, kg/m^3
ρ_s	density of benzoic acid particle, kg/m^3
ρ_W	density of pure water at 4°C, kg/m^3

VITA

Mr. Chub Tescharoen recieved his Bachelor Degree of Science in Chemical Engineering from Faculty of Science, Chulalongkorn University in 1965.

He has been teaching for the past 12 years at Department of Chemical Technology, Faculty of Science, Chulalongkorn University. His previous research topics were about: Distillation of Essential Oil, Production of Activated Carbon from Local Raw Materials and Industrial Burner Design.

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