APPENDICES

APPENDIX - I EXPERIMENTAL DATA

A1.1 - Setup - 1 Single nozzle horizontal jet ejector

A1.1.1 - Temperature 30^0C, Cl_2 - Aquas NaOH system

L = 396 10^{-3} m^3/hr, G_{air} = 1458 10^{-3} m^3/hr, Pressure = 1.00 atm.

Run No.	Nozzle No.	Number of Orifice	$10^3 G_{Cl2}$ m^3/hr	C_{B0} kmol/m_3	BR_1 ml	BR_2 ml	BR_3 ml	10^3 $C_{Ag,in}$ kmol/m^3	$10^3 C_{Ag1}$ kmol/m^3	$10^3 C_{Ag2}$ kmol/m^3	$10^3 C_{Ag3}$ kmol/m^3	$10^3 R_Aa$ kmol/sec.m^3
101	N1	1	22.05	0.95	0.15	0.25	0.25	0.602	0.000	0.000	0.000	4.331
102	N1	1	44.10	0.95	0.4	0.3	0.4	1.204	0.000	0.000	0.000	11.059
103	N1	1	88.20	0.95	0.75	0.65	0.7	2.409	0.001	0.001	0.001	19.350
104	N1	1	176.40	0.95	0.8	0.7	1	4.818	0.003	0.003	0.002	27.641
105	N1	1	22.05	0.75	0.175	0.125	0.15	0.602	0.000	0.000	0.000	4.151
106	N1	1	44.10	0.75	0.325	0.35	0.4	1.204	0.000	0.000	0.000	11.059
107	N1	1	88.20	0.75	0.9	0.65	0.775	2.409	0.000	0.001	0.001	21.431
108	N1	1	176.40	0.75	1.6	1.3	1.55	4.818	0.001	0.002	0.001	42.851
109	N1	1	22.05	0.525	0.2	0.175	0.225	0.602	0.000	0.000	0.000	6.221
110	N1	1	44.10	0.525	0.4	0.35	0.4	1.204	0.000	0.000	0.000	11.059
111	N1	1	88.20	0.525	0.25	0.24	0.2	2.409	0.002	0.002	0.002	5.569
112	N1	1	176.40	0.525	1.55	1.6	1.7	4.818	0.001	0.001	0.001	47.003
113	N1	1	22.05	0.03	0.2	0.15	0.2	0.602	0.000	0.000	0.000	5.535
114	N1	1	44.10	0.03	0.2	0.4	0.3	1.204	0.001	0.000	0.000	8.291
115	N1	1	88.20	0.03	0.7	0.6	0.7	2.409	0.002	0.002	0.002	19.924
116	N1	1	176.40	0.03	4.25	6.35	5	4.818	0.002	0.001	0.002	33.604
117	N1	1	22.05	0.00	0.1	0.2	0.1	0.602	0.000	0.000	0.000	--
118	N1	1	44.10	0.00	0.125	0.25	0.2	1.204	0.001	0.001	0.001	--
119	N1	1	88.20	0.00	0.15	0.3	0.25	2.409	0.002	0.002	0.002	--
120	N1	1	176.40	0.00	0.2	0.4	0.3	4.818	0.004	0.004	0.004	--

BR = ml of 0.0905 N $Na_2 S_2O_3$ required to neutralized 5 ml of sample.

A1.1.2 - Temperature 30^0C, CO_2 - Aquas NaOH system

L = 396 10^{-3} m^3/hr, G_{air} = 1458 10^{-3} m^3/hr, Pressure = 1.00 atm.

Run No.	Nozzle No.	Number of Orifice	10^3 G_{CO2} m^3/hr	C_{B0} kmol/m_3	10^3 $C_{Ag,in}$ kmol/m^3	BR_1 ml	BR_2 ml	ΔBR ml	$10^3 R_Aa$ kmol/sec.m^3
121	N1	1	88.200	0.95	2.555	47.50	47.00	0.50	16.364
122	N1	1	88.200	0.75	2.555	37.50	37.15	0.35	11.864
123	N1	1	88.200	0.525	2.555	26.30	26.00	0.30	10.739
124	N1	1	88.200	0.31	2.555	15.50	15.25	0.25	9.641

BR = ml of 0.1 N HCl required to neutralized 5 ml of sample.

A1.2 - Setup - 2 Vertical multi nozzle jet ejector

A1.2 - Temperature 30^0C, Cl_2 - Aquas NaOH system

$L = 310\ 10^{-3}\ m^3/hr$, $G_{air} = 1500\ 10^{-3}\ m^3/hr$, Pressure = 1.00 atm.

Run No.	Nozzle No.	Number of Orifice	10^3 G_{Cl2} m^3/hr	C_{B0} $kmol/m_3$	BR_1 ml	BR_2 ml	BR_3 ml	10^3 $C_{Ag.in}$ $kmol/m^3$	$10^3\ C_{Ag1}$ $kmol/m^3$	$10^3\ C_{Ag2}$ $kmol/m^3$	$10^3\ C_{Ag3}$ $kmol/m^3$	$10^3\ R_Aa$ $kmol/sec.m^3$
201	N2	1	110.00	0.52	2.45	1.75	1.25	2.950	1.937	2.588	2.691	2.917
202	N2		75.00	0.52	1.55	1.05	1.20	2.011	1.370	1.794	1.763	2.793
203	N2		50.00	0.52	1.20	0.95	0.80	1.341	0.845	1.144	1.175	1.869
204	N2		35.00	0.52	0.85	0.75	0.60	0.938	0.587	0.783	0.814	1.396
205	N3	3	110.00	0.52	2.50	1.45	1.25	2.950	1.916	2.650	2.691	2.917
206	N3		75.00	0.52	1.60	1.20	1.00	2.011	1.350	1.763	1.804	2.331
207	N3		50.00	0.52	1.20	0.95	0.85	1.341	0.845	1.144	1.165	1.982
208	N3		35.00	0.52	0.75	0.65	0.55	0.938	0.628	0.804	0.825	1.273
209	N4	5	110.00	0.52	2.55	0.65	1.00	2.950	1.896	2.815	2.743	30.016
210	N4		75.00	0.52	1.65	0.50	0.60	2.011	1.329	1.908	1.887	20.475
211	N4		50.00	0.52	1.25	0.35	0.25	1.341	0.824	1.268	1.289	0.586
212	N4		35.00	0.52	0.80	0.30	0.20	0.938	0.608	0.876	0.897	0.462

BR = ml of 0.0905 N $Na_2\ S_2O_3$ required to neutralized 5 ml of sample.

A1.2 - Temperature 30^0C, CO_2 - Aquas NaOH system (Pressure = 1.00 atm.)

Run No.	Nozzle No.	Number of Orifice	10_3 L m^3/hr	10_3 G_{air} m^3/hr	10^3 G_{CO2} m^3/hr	C_{B0} $kmol/m_3$	10^3 $C_{Ag.in}$ $kmol/m^3$	BR_1 ml	BR_2 ml	ΔBR ml	$10^3\ R_Aa$ $kmol/sec.m^3$
221	N2	1	310	2940	150.000	0.14	2.54	2.70	2.45	0.25	14.504
222	N2	1	310	2940	150.000	0.13	2.54	2.55	2.30	0.25	14.504
223	N2	1	310	2940	150.000	0.11	2.54	2.15	1.95	0.20	13.519
224	N2	1	310	2940	150.000	0.09	2.54	1.70	1.55	0.15	12.533
225	N2		310	2940	150.000	0.08	2.54	1.50	1.35	0.15	12.533
226	N3	3	483	2880	150.000	0.22	2.20	4.30	4.00	0.30	13.591
227	N3	3	483	2880	150.000	0.13	2.20	2.55	2.30	0.25	11.778
228	N3	3	483	2880	150.000	0.09	2.20	1.70	1.50	0.20	9.965
229	N3	3	483	2880	150.000	0.08	2.20	1.50	1.35	0.15	8.152
230	N3	3	483	2880	150.000	0.06	2.20	1.20	1.05	0.15	8.152
231	N4	5	428	1500	150.000	0.18	4.22	4.95	4.55	0.40	15.566
232	N4	5	428	1500	150.000	0.14	4.22	3.55	3.20	0.35	13.959
233	N4	5	428	1500	150.000	0.10	4.22	2.85	2.55	0.30	12.353
234	N4	5	428	1500	150.000	0.08	4.22	1.90	1.65	0.25	10.746
235	N4	5	428	1500	150.000	0.06	4.22	1.50	1.30	0.20	9.139

BR = ml of 0.1 N HCl required neutralized 5 ml of sample.

A.1.3 - Setup - 3 Multi nozzle jet ejector (Industrial scale)

A1.1 - Temperature 30^0C, Cl_2 - Aquas NaOH system

L = 3520 x 10^{-3} m^3/hr, G_{air} = 7771 x 10^{-3} m^3/hr, Pressure = 1.00 atm.

Run No.	Nozzle No.	Number of Orifice	$10^3 G_{Cl2}$ m^3/hr	C_{B0} $kmol/m_3$	BR_1 ml	BR_2 ml	BR_3 ml	10^3 $C_{Ag,in}$ $kmol/m^3$	10^3 C_{Ag1} $kmol/m^3$	10^3 C_{Ag2} $kmol/m^3$	10^3 C_{Ag3} $kmol/m^3$	10^3 R_Aa $kmol/sec.m^3$
301	N5	1	571	0.79	1.8	0.8	0.55	2.955	0.917	2.049	2.333	1.069
302	N5	1	380	0.79	1.6	0.95	0.75	1.967	0.155	0.891	1.117	1.461
303	N5	1	285	0.79	1.25	0.7	0.9	1.475	0.06	0.682	0.456	1.751
304	N5	1	190	0.79	0.75	0.65	0.85	0.983	0.134	0.247	0.021	1.653
305	N6	3	571	0.79	2.5	1.75	0.45	2.955	0.124	0.974	2.446	0.875
306	N6	3	380	0.79	1.6	1.4	0.5	1.967	0.155	0.381	1.401	0.973
307	N6	3	285	0.79	1.25	1.3	0.25	1.475	0.06	0.003	1.192	0.486
308	N6	3	190	0.79	0.75	0.6	0.25	0.983	0.134	0.304	0.7	0.486
309	N7	5	571	0.79	2.55	0.75	0.6	2.955	0.068	2.106	2.276	1.167
310	N7	5	380	0.79	1.65	0.6	0.5	1.967	0.098	1.287	1.401	0.973
311	N7	5	285	0.79	1.25	0.4	0.35	1.475	0.06	1.022	1.079	0.681
312	N7	5	190	0.79	0.35	0.4	0.2	0.983	0.587	0.53	0.757	0.388
313	N7	5	571	0.578	2.6	0.6	0.5	2.955	0.011	2.276	2.389	0.973
314	N7	5	380	0.578	1.7	0.45	0.35	1.967	0.042	1.457	1.57	0.682
315	N7	5	285	0.578	1.3	0.3	0.25	1.475	0.003	1.135	1.192	0.486
316	N7	5	190	0.578	0.85	0.25	0.2	0.983	0.021	0.7	0.757	0.388
317	N6	3	571	0.578	2.55	1.4	1.2	2.955	0.068	1.37	1.596	2.336
318	N6	3	380	0.578	1.65	1.15	1	1.967	0.098	0.665	0.834	1.947
319	N6	3	285	0.578	1.25	1	0.9	1.475	0.06	0.343	0.456	1.751
320	N6	3	190	0.578	0.8	0.75	0.55	0.983	0.077	0.134	0.361	1.069
321	N5	1	571	0.578	2.5	1.5	1.25	2.985	0.154	1.286	1.569	2.382
322	N5	1	380	0.578	1.6	1.05	1	1.986	0.175	0.797	0.854	1.913
323	N5	1	285	0.578	1.2	1	0.75	1.49	0.131	0.357	0.641	1.433
324	N5	1	190	0.578	0.75	0.75	0.55	0.993	0.144	0.144	0.37	1.054
325	N5	1	571	0.11	2.55	1	0.95	2.985	0.097	1.853	1.909	1.798
326	N5	1	380	0.11	1.7	0.75	0.6	1.986	0.061	1.137	1.307	1.134
327	N5	1	285	0.11	1.25	0.5	0.45	1.49	0.074	0.924	0.98	0.851
328	N5	1	190	0.11	0.8	0.4	0.3	0.993	0.087	0.54	0.654	0.565
329	N6	3	571	0.11	2.5	1.5	1.3	2.985	0.154	1.286	1.513	2.478
330	N6	3	380	0.11	1.65	1	0.75	1.986	0.118	0.854	1.137	1.426
331	N6	3	285	0.11	1.2	0.65	0.5	1.49	0.131	0.754	0.924	0.947
332	N6	3	190	0.11	0.75	0.55	0.45	0.993	0.144	0.37	0.484	0.858
333	N7	5	571	0.11	1.8	1.6	1.2	2.985	0.947	1.173	1.626	2.284
334	N7	5	380	0.11	1.5	1.15	1.1	1.986	0.288	0.684	0.741	2.107
335	N7	5	285	0.11	1	0.8	0.75	1.49	0.357	0.584	0.641	1.433
336	N7	5	190	0.11	0.65	0.55	0.4	0.993	0.257	0.37	0.54	0.761

BR = ml of 0.02 N $Na_2S_2O_3$ required to neutralized 5 ml of sample.

Appendix 2

Analytical procedure

A 2.1 Testing of available chlorine

The available chlorine was analyzed by the iodometric method. Known amount of (5 ml) of sample was pipetted in a 250 ml of conical flask. Then 5 ml of 10 % Aqueous KI solution was added. Then 2 ml of glacial acetic acid was added. The liberated I_2 was titrated against standard Sodium thiosulphate ($Na_2S_2O_3$) by using freshly prepared starch solution as indicator. The end point of titration was -blue color just disappeared.

A 2.2 Determination of free sodium hydroxide

In a 250 ml conical flask 50 ml of 10% $BaCl_2$ solution was taken. Then 30 ml of 3% H_2O_2 was added. This mixture was neutralized by 0.1 N NaOH using phenolphthalein as indicator. After neutralizing solution, 5 ml of sample was added by pipette. It was properly shaken. Carbonate ion precipitated out $BaCO_3$ and H_2O_2 will convert sodium hypochloride to sodium chloride. This mixture was filtered, washed and filtrate was titrated against standard 0.1 N HCl. The amount of 0.1 N HCl used gives the amount of CO_2 absorbed by NaOH solution.

A 2.3 Calculation of chlorine reacted

In this work the different concentration of Cl_2 - air mixture was brought in contact with deferent concentrations of caustic soda (NaOH). The reaction is as follow.

$$2NaOH + Cl_2 \rightarrow NaOCl + NaCl + H_2O \qquad (A2.1)$$

40x2 71 74.5 58.5 18

The amount of chlorine reacted was estimated by using iodometry. The KI solution is added. The iodine liberate is proportion to available chlorine. The liberated iodine is titrated with standard sodium thiosulfate solution. The reactions are

$$NaOCl + 2KI + H_2O \rightleftarrows NaCl + 2KOH + I_2 \qquad (A2.2)$$

74.5 166x2 18 58.5 56x2 254

$$I_2 \quad + \ 2Na_2S_2O_3 \rightleftarrows 2\,NaI \quad + \quad Na_2S_4O_6 \qquad (A.2.3)$$

254 2x158 2x150 270

Thus

71 gm of Cl_2	=	158 x 2 gms of $Na_2S_2O_3$
71 gm of Cl_2	=	2000 ml of 1 N $Na_2S_2O_3$
35.5 gm Cl_2	=	1000 ml of 1 N NaS_2O_3
0.0355 gm Cl_2	=	1 ml of 1 N $Na_2S_2O_3$
gm of Cl_2	=	0.0355 x BR x N

Where

N - Normality of $Na_2S_2O_3$ Sol

BR - Burette Reading in ml

A 2.4 Calculation of C_{Ag}

Different diameter of soap film meter were used to measure flow rate of chlorine and air,

Volumetric flow rate = Cross section area x velocity

Now, inside diameter of soap film meter used for Air = 70 mm

$$\therefore Volumetric\ flow\ area\ of\ Air = G_{Ag} = \frac{\pi/4\,(7)^2 \times 40 \times 3600}{1000 \times t_f} \qquad (A.24)$$

$$= 5.5389 \times 10^3 / t_f\ litter/hr \qquad (A2.4)$$

Where t_f = time required in second to travel soap film 40 cm.

Similarly, inside diameter of film meter for chlorine = 25 mm

$$\therefore Volumetric\ flow\ rate\ of = Cl_2 = G_{Cl} = \frac{\pi/4\ 2.5^2 \times 400 \times 3600}{1000 \times t_f} \qquad (A2.5)$$

$$= 706.4/\,t_f\ litter/hr \qquad (A2.5)$$

$$\frac{Moles\ of\ Cl_2/Air}{hr} = \frac{vol.flowrate\ \times\ 273\ \times\ P}{22.4\ \times\ T} \qquad (A2.6)$$

Where P is pressure in atmosphere

T is temperature of Cl_2

$$\therefore Moles\ of\ Cl_2/hr \quad = \frac{706.4\ \times\ 12.187\ \times\ P}{t_f\ \times\ T} \qquad (A2.7)$$

$$= 8608.89\ \times P/\ t_f \text{x T}$$

Similarly,

$$m_{AIR} = mole\ of \frac{Air}{hr} = \frac{67.5053\ \times\ 10^3\ \times\ P}{t_f\ \times\ T} \qquad (A2.8)$$

$C_{Ag,in}$ = Initial Cl_2 concentration gmole/lit = (m_{Cl_2}) / $(V_A + V_{Cl_2})$ (A2.9)

y_{in} = Initial mole fraction of A = (m_{Cl_2}) / $(m_{AIR} + m_{Cl})$ (A2.10)

Now as $m_{AIR} >> m_{cl}$

$$\therefore y_{Cl_2} = \frac{m_{cl_2}}{m_{AIR}}\ and\ C_{Ag,in} = (m_{Cl_2})/\ (V_A)\ kmole/m^3 \qquad (A2.11)$$

A 2.5 Calculation Concentration of chlorine at different sample point in ejector (C_{Ag})

$C_A \quad = C_{Ag,in} -$ moles of Cl_2 reacted litter of mixture

$$= C_{Ag,in} - \frac{gm\ of\ Cl_2\ \times\ 1000\ ^{ml}/_{lit}\ \times\ L}{ml.of\ sample\ \times\ 71\ ^{gm}/_{mole}\ \times\ G}$$

$$= C_{Ag,in} - \frac{0.0355\ \times\ BR\ \times\ N\ \times\ 1000\ \times\ L}{ml.of\ sample\ \times\ 71\ \times\ G}$$

$$= C_{Ag,in} - \frac{0.5\ \times\ BR\ \times\ N\ \times\ L}{ml.of\ sample\ \times\ G} \qquad (A2.12)$$

$$G_{AIR} \gg G_{cl}\ \therefore G \cong G_{AIR} \qquad (A2.13)$$

A 2.6 Calculation of ($\bar{R}$.a) volumetric rate of reaction for Cl_2

$$\bar{R}.\mathrm{a} = \frac{kgmoles\ of\ Cl_2 absobed}{m^2\ sec} \times \frac{m^2}{m^3} = \frac{kgmol}{sec\ m^3}$$

$$= \frac{gmoles\ of\ Cl_2 absobed}{hr\ x\ 3600} \times \frac{1}{volume\ of\ reactor\ in\ m^3}$$

$$= \frac{\left(C_{Ag,in} - C_{Ag}\right)}{3600} \times \frac{G}{1000} \times \frac{10^6}{volume\ of\ reactor\ in\ cm^3 (V_R)}$$

A 2.7 Calculation of ($\bar{R}$.a) volumetric rate of reaction for CO_2

For measuring ($\bar{R}$.a) the carbon dioxide (pure) and sodium hydroxide solution is used. The CO_2 react with NaOH to produce $Na_2\,CO_3$. The amount of CO_2 reacted in particular part of system is measured by estimating amount of NaOH un-reacted. It involves the following reactions.

$$NaOH + HCl \rightarrow NaCl + H_2O \qquad \text{(A2.14)}$$

40 36.5 58.5 18

$$2NaOH + CO_2 \rightarrow Na_2\,CO_3 + H_2O \qquad \text{(A2.15)}$$

80 44 106 18

$$Na_2\,CO_3 + BaCl_2 \rightarrow BaCO_3 + 2NaCl \qquad \text{(A2.16)}$$

Thus,

44 gm CO_2 = 2000 ml 1 N NaOH

∴ 44 gm CO_2 = 2000 ml 1 N HCl

∴ 0.022 gm CO_2 = 1ml 1 N HCl.

If $(BR_2 - BR_1)$ = Differential Amount of HCl required to neutralize w ml of sample before and after addition to $BaCl_2$ solution.

Then,

$$CO_2 absorbed = \frac{(BR_2 - BR_1) \times 0.022 \times N_{HCl}}{w} \ \frac{gm}{cc} \qquad (A2.17)$$

If flow rate of liquid is L lit / hr

Then Now

$$Amount\ of\ gm\ of\ CO_2\ absorbed/sec\ = \frac{(BR_2 - BR_1) \times 0.022 \times N_{HCl} \times L}{W \times 3600} \qquad (A2.18)$$

$$Amount\ of\ moles\ of\ CO_2\ absorbed/sec\ = \frac{(BR_2 - BR_1) \times 0.022 \times N_{HCl} \times L}{W \times 44 \times 3600} \qquad (A2.19)$$

$$C_{CO_2,out} = C_{CO_2,in} - \frac{(BR_2 - BR_1) \times 0.022 \times N_{HCl} \times L}{W \times 44 \times 3600 \times G}\ kmol/m^3 \qquad (A2.20)$$

$$\bar{R}.\mathrm{a} = \frac{kgmoles\ of\ CO_2 absobed}{time\ in\ sec \times volume\ of\ reactor\ in\ m^3}$$

$$= \frac{gms\ of\ CO_2 absobed}{time\ in\ sec \times volume\ of\ reactor\ in\ m^3 \times mol\ wt\ of\ CO_2 \times 1000} \qquad (A2.21)$$

Now, $\bar{R}\mathrm{a} = (kg\ mols\ CO_2 absorbed)\ /\ time\ in\ \mathrm{sec}\, x\ (m^3 of\ reactor\ volume)$

$$\bar{R}.\mathrm{a} = \frac{(BR_2 - BR_1) \times 0.022 \times N \times L \times 1000}{w \times 3600 \times V_R \times 44} = \frac{1.3889 \times 10^{-4} (BR_2 - BR_1) \times N \times L}{w \times V_R} \quad \frac{k\ mol}{m^3 sec} \qquad (A2.22)$$

$$\bar{R}.\mathrm{a} = \frac{1.3889 \times 10^{-1} (BR_2 - BR_1) \times N \times L}{w \times V_R}\ kgmol/m^3\,\mathrm{sec} \qquad (A2.23)$$

where BR_2 - is a burette reading before adding barium carbonate

BR_1- is a burette reading after adding barium carbonate

w – ml of sample titrated

N – Normality of hydrochloric acid

V_R-Volume of reactor m^3

L -Liquid flow in lit/hr m^3/hr

Appendix 3

Prediction of physical properties

For different calculations we need different physico-chemical properties. In some cases we have properties at particular temperature developed by researchers. We can predict the value at required temperature followings are some of the co-relation used to predict value at required temperature.

A 3.1 Henry's law constants

The well known expression of Henry's law is given by the correlation:

$$p_A^* = H_e x_A \text{ or } p_A^* = H_e' C_A$$

Where x_A = mole fraction of the solute in the liquid phase;

C_A = concentration of A in kmole/m^3

p_A^* = partial pressure of the solute in the gas phase, expressed in atmospheres or kilopascals

H_e = the Henry's law coefficient expressed in kilopascals/ mole-fraction solute in liquid

H_e' = the Henry's law coefficient expressed in kilopascals/ kmole m^3

In case of electrolyte solution Henry's law constants can be estimated by using the method of evan Krevelen and Hoftijzr described by Danckwerts (1970). According to this method Henry's law constant for electrolyte solutions ($H_{solution}$) is related with Henry's law constant of pure water (H_{water}) by the correlation :

$$log_{10}\left(\frac{H_{solution}}{H_{water}}\right) = -k_s i$$

or

$$log_{10}\left(\frac{H_{solution}'}{H_{water}}\right) = -k_s i$$

or

$$log_{10}\left(\frac{C_A{}^*{}_{water}}{C_A{}^*{}_{solution}}\right) = -k_s i$$

where k_s is the salting-out factor, and I is the ionic strength of the aqueous electrolyte solution. The salting out factor k_s, is defined in terms of the contributions of the positive and negative ions in the aqueous solution, respectively, and the contribution of the gas,

$$k_s = k_s + k_{s-} + k_{sG} \qquad (8.37)$$

when the value of k_s for ion or gas is not known then the value of a similar ion/gas can be used.

The ionic strength of the aqueous electrolyte solution I, is defined in terms of the concentration of the ionic species that are present in the solution 'c_i' and their valences, Z_i, according to the following equation:

$$I = \left(\frac{1}{2}\right)\sum c_i Z_i^2 \tag{8.38}$$

The compiled values of, k_s, evaluated by Barret (1966) and van Krevelen and Hoftijzr (1948) are reported in Danckewert (1970).

Calculated values for Cl_2 - aqueous $NaCl$ solution system.

$Temperature^0 C$	k_s	i_g
20	0.1005	- 0.0145
30	0.0903	- 0.0247
40	0.0854	- 0.0296
50	0.0793	- 0.0357

A 3.2 Temperature correction of diffusivity

The diffusivities are either predicted theoretically by using different correlations available in the literature or determined experimentally. But the diffusivities are corrected for temperature by using Stokes-Einstein equation

$$\frac{D_i \mu}{T} = constant \tag{8.39}$$

Where T is temperature in K, μ is the viscosity at temp T in $kg/(m.s)$, and D_i is the diffusivity of solute i in m^2/s.

In the present work , we have assumed that the diffusion coefficients of the ionic chemical spices $(Cl^-, OCl^-$ and $H^+)$ are equal to the that of OH^-. The value of the diffusion coefficient for OH^- in water at $298\,K$ is considered to be $3.42 \times 10^{-9}\ m^2/s$, (Hikita et al., 1973) and was correct for temperature and viscosity of the aqueous $NaOH$ solutions by using above Stokes-Einstein equation.

A 3.3 Dissociation equilibrium constant

Values of equilibrium constant of a chemical reaction can be estimated at $298.15K$ in standard Gibbs energy change of reaction $\Delta G^0_{298.15}$ by using the following equations:

$$K_1(298.15) = exp\left(\frac{-\Delta G^0_{298.15}}{298.15R}\right)$$

The correction of equilibrium constant of a chemical reaction for temperature may be carried by can be done by van't Hoff's equation.

A3.4 - Average properties used

Species	Property	Value	Condition	Reference
Chlorine	Diffusivity	$1.48 \times 10^{-9} m^2/sec$	$Water, 298K$	Splalding (1962)
		$1.68 \times 10^{-9} m^2/sec$	$Water, 303K$	Calculated
		$1.67 \times 10^{-9} m^2/sec$	$0.03\ M\ NaOH\ 303K$	Calculated
		$1.636 \times 10^{-9} m^2/sec$	$0.11\ M\ NaOH\ 303K$	Calculated
		$1.51 \times 10^{-9} m^2/sec$	$0.523\ M\ NaOH\ 303K$	Calculated
		$1.44 \times 10^{-9} m^2/sec$	$0.578\ M\ NaOH\ 303K$	Calculated
		$1.435 \times 10^{-9} m^2/sec$	$0.75\ M\ NaOH\ 303K$	Calculated
		$1.42 \times 10^{-9} m^2/sec$	$0.79\ M\ NaOH\ 303K$	Calculated
		$1.38 \times 10^{-9} m^2/sec$	$0.95\ M\ NaOH\ 303K$	Calculated
	Physical Solubility	$0.0525\ kmol/m^3$	$Water, 303\ K$	Brian et al. (1996)
		$0.0520\ kmol/m^3$	$0.03\ M, NaOH, 303K$	Calculated
		$0.0473\ kmol/m^3$	$0.523\ M, NaOH, 303K$	Calculated
		$0.0444\ kmol/m^3$	$0.75\ M, NaOH, 303K$	Calculated
		$0.0438\ kmol/m^3$	$0.95\ M, NaOH, 303K$	Calculated
		$0.0513\ kmol/m^3$	$0.11\ M, NaOH, 303K$	Calculated
		$0.0464\ kmol/m^3$	$0.57\ M, NaOH, 303K$	Calculated
		$0.044\ kmol/m^3$	$0.79\ M, NaOH, 303K$	Calculated
	Henry's law const.	$19.55\ atm.m^3/kmol$	$NaOH, 303K$	Ashour (1996)
		$16.4\ atm.m^3/kmol$	Water, 298.15K	Rulz-Ibanez (1991)
$HOCl$	Diffusivity	$1.75 \times 10^{-9} m^2/sec$	$0.1\ M\ NaOH, 303\ K$	Ashour (1996)
OH^-	Diffusivity	$3.89 \times 10^{-9} m^2/sec$	$0.1\ M\ NaOH, 303\ K$	Ashour (1996)
$NaOH$ Solution	Density	$0.9960 \times 10^3 kg/m^3$	$0.0996\ M, 303\ K$	Ashour (1996)
	Viscosity	$0.802 \times 10^{-3} kg/ms$	$0.0996\ M, 303\ K$	Ashour (1996)
	D_{NaOH}/D_{Cl_2}	2.32	At infinity dilution of $NaOH$ solution	Hikita (1993)
	D_{HOCl}/D_{Cl_2}	1.04	"	"
	D_{Cl^-}/D_{Cl_2}	1.4	"	"
	D_{OCl^-}/D_{Cl_2}	0.786	"	"
CO_2	Diffusivity	$2.05 \times 10^{-9} m^2/sec$	$0.5\ M\ NaOH, 303\ K$	Hikita (1976)
		$2.15 \times 10^{-9} m^2/sec$	$0.25\ M\ NaOH, 303\ K$	Hikita (1976)
		$2.19 \times 10^{-9} m^2/sec$	$0.125\ M\ NaOH, 303\ K$	Hikita (1976)
	Physical Solubility	$2.66\ kmol/m^3$	$0.125\ M\ NaOH, 303\ K$	Hikita (1976)
		$2.49\ kmol/m^3$	$0.25\ M\ NaOH, 303\ K$	Hikita (1976)
		$2.17\ kmol/m^3$	$0.5\ M\ NaOH, 303\ K$	Hikita (1976)
	H_e	$32\ atm.m^3/kmol$	$0.5\ M\ NaOH, 303\ K$	Patel (2004)

Values of rate constant

Equilibrium constant K	at	reaction	Reference
4.5×10^{-4} $(kmol/m^3)$	298	$Cl_2 + H_2O \xleftrightarrow{K_1,k_1} HOCl + H^+ + Cl^-$ (8.2)	Connick et al. (1959)
2.2×10^6 $l/gmole$	303	$Cl_2 + OH^- \xleftrightarrow{K_1,k_1} HOCl + Cl^-$ (8.3)	Morris (1966)
3.1×10^{10} $m^3/kmol$	303	$HOCl + OH^- \xleftrightarrow{K_1,k_1} OCl^- + H_2O$ (8.4)	Connick et al. (1959)
1.447×10^{-14} $(gmol/l)^2$	303	$H_2O \xleftrightarrow{K_1,k_1} OH^- + H^+$	Olofsson and Hepler (1975)
9.61×10^{-3} $l/gmole$	303	$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$	Hikita (1976)
1.57	293	For equation (8.2) $k_1 = 1.4527 \times 10^{10}\, exp.\left(\frac{-6138.6}{T}\right)$ $m^3/kmol.s$	Brian et al. (1966)
16.4	298		
23.0	303		
32.0	308		
44.0	313		

A. 4.1 Calculation of interfacial area for setup 1 and setup 2 using CO_2-NaOH system

Run No.	10^3 RaA	y_i	y_o	Gm' kmol/sec	He atm.m^3/kmol	10^3 k_{LR} m/sec	P atm.	10^6 Vj m^3	term 1	term 2	a m^2/m^3
221	14.504	0.0602	0.0440	2.7821E-05	32	1.703	1	37	14132.439	1.455	5298.936
222	14.504	0.0602	0.0440	2.7821E-05	32	1.641	1	37	14665.925	1.455	5498.966
223	13.519	0.0602	0.0453	2.7821E-05	32	1.509	1	37	15943.542	1.408	5455.004
224	12.533	0.0602	0.0466	2.7821E-05	32	1.365	1	37	17626.248	1.363	5463.344
225	12.533	0.0602	0.0466	2.7821E-05	32	1.287	1	37	18695.460	1.363	5794.751
226	13.591	0.0521	0.0390	3.2178E-05	32	2.134	1	37	13039.560	1.399	4380.409
227	11.778	0.0521	0.0411	3.2178E-05	32	1.641	1	37	16962.998	1.321	4716.797
228	9.965	0.0521	0.0432	3.2178E-05	32	1.365	1	37	20386.986	1.249	4528.198
229	8.152	0.0521	0.0453	3.2178E-05	32	1.287	1	37	21623.664	1.183	3628.754
230	8.152	0.0521	0.0453	3.2178E-05	32	1.115	1	37	24968.857	1.183	4190.124
231	15.566	0.1000	0.0706	1.6759E-05	32	2.275	1	37	6370.933	1.588	2947.910
232	13.959	0.1000	0.0742	1.6759E-05	32	1.930	1	37	7508.217	1.499	3038.102
233	12.353	0.1000	0.0777	1.6759E-05	32	1.703	1	37	8513.518	1.416	2960.027
234	10.746	0.1000	0.0813	1.6759E-05	32	1.439	1	37	10073.330	1.339	2937.316
235	9.139	0.1000	0.0848	1.6759E-05	32	1.287	1	37	11262.325	1.266	2659.204
121	16.364	0.0605	0.0273	1.6290E-05	32	4.435	1	36	3264.952	2.409	2871.054
122	11.864	0.0605	0.0373	1.6290E-05	32	3.941	1	36	3674.582	1.747	2050.951
123	10.739	0.0605	0.0398	1.6290E-05	32	3.297	1	36	4391.965	1.631	2147.933
124	9.614	0.0605	0.0423	1.6290E-05	32	2.533	1	36	5715.546	1.527	2418.449

A. 4.2.1 Calculation of gas hold up and k_G for setup 1 and setup 2 using Cl_2-NaOH system

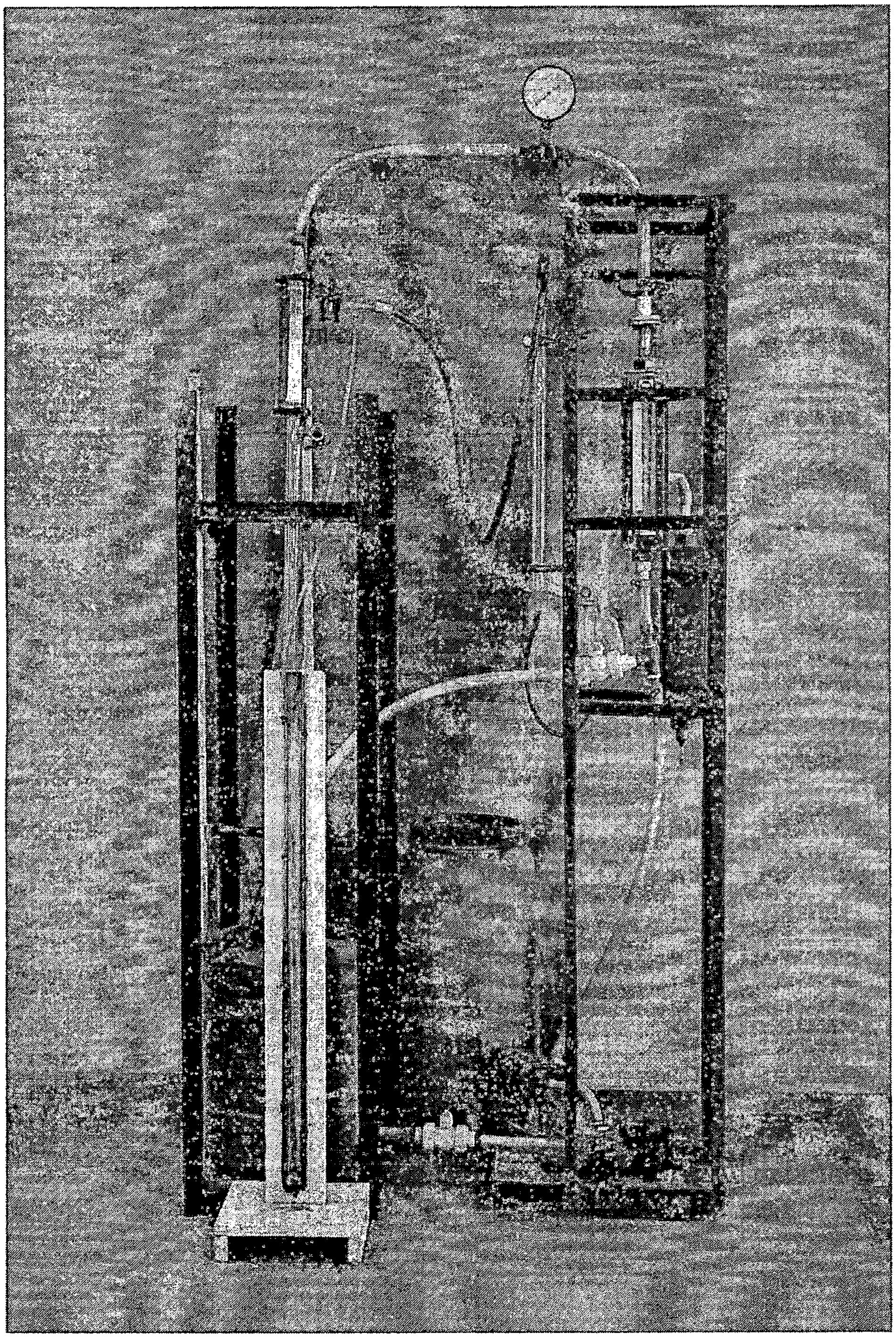
Run No.	10^3 RaA	10^6 V m^3	liuqid holdup Radha-krishnan (1984) eq.no. (4.4.1)	liuqid holdup present model eq. no. (4.4.2)	actual liquid holdup	y_i	y_o	Gm' kmol/sec	P atm.	H_e atm.m^3/kmol	a m^2/m^3	10^3 $K_g a$ eq. no. (4.4.10)	10^5 K_G eq. no. (4.4.17)	10^5 k_G eq. no. (4.4.11)	$k_G.a = R_A.a / p_a^*$ eq. no. (4.4.16a)	$k_G = k_G a / a$ eq .no. (4.4.17)
101	4.331	36	0.32	0.17	0.21	0.015	0.005	1.62901E-05	1	22.83	2871.05	623.667	16.112	16.152	0.2879	0.00010
102	11.059	36	0.32	0.17	0.21	0.029	0.005	1.62901E-05	1	22.83	2871.05	2081.679	27.817	27.936	0.3729	0.00013
103	19.350	36	0.32	0.17	0.21	0.057	0.015	1.62901E-05	1	22.83	2871.05	1115.739	22.529	22.606	0.3362	0.00012
104	27.641	36	0.32	0.17	0.21	0.108	0.048	1.62901E-05	1	22.83	2871.05	338.203	15.332	15.368	0.2535	0.00009
105	4.151	36	0.32	0.17	0.21	0.015	0.006	1.62901E-05	1	22.52	2050.95	885.382	21.004	21.078	0.2759	0.00013
106	11.059	36	0.32	0.17	0.21	0.029	0.005	1.62901E-05	1	22.52	2050.95	2782.877	38.940	39.194	0.3728	0.00018
107	21.431	36	0.32	0.17	0.21	0.057	0.010	1.62901E-05	1	22.52	2050.95	2715.145	39.664	39.928	0.3724	0.00018
108	42.851	36	0.32	0.17	0.21	0.108	0.014	1.62901E-05	1	22.52	2050.95	3032.683	47.623	48.004	0.3930	0.00019
109	6.221	36	0.32	0.17	0.21	0.015	0.001	1.62901E-05	1	21.14	2147.93	7853.881	51.863	52.357	0.4139	0.00019
110	11.059	36	0.32	0.17	0.21	0.029	0.005	1.62901E-05	1	21.14	2147.93	3341.322	37.182	37.435	0.3728	0.00017
111	5.569	36	0.32	0.17	0.21	0.057	0.045	1.62901E-05	1	21.14	2147.93	59.996	5.852	5.858	0.0968	0.00005
112	47.003	36	0.32	0.17	0.21	0.108	0.005	1.62901E-05	1	21.14	2418.45	5454.406	59.161	59.805	0.4310	0.00018
113	5.535	36	0.32	0.17	0.21	0.015	0.003	1.62901E-05	1	19.05	2418.45	10316.604	31.574	32.239	0.3678	0.00015
114	8.291	36	0.32	0.17	0.21	0.029	0.011	1.62901E-05	1	19.05	2418.45	3292.343	18.561	18.789	0.2796	0.00012
115	19.924	36	0.32	0.17	0.21	0.057	0.014	1.62901E-05	1	19.05	2418.45	1157.915	28.405	28.941	0.3461	0.00014
116	33.604	36	0.32	0.17	0.21	0.108	0.035	1.62901E-05	1	19.05	2418.45	4899.900	24.203	24.591	0.3082	0.00013
201	2.917	37	0.32	0.18	0.17	0.068	0.067	1.67594E-05	1	21.14	5298.94	0.390	0.240	0.240	0.8408	0.00016
202	2.793	37	0.32	0.18	0.17	0.048	0.044	1.67594E-05	1	21.14	5498.97	4.268	0.819	0.819	1.1875	0.00022
203	1.869	37	0.32	0.18	0.17	0.032	0.029	1.67594E-05	1	21.14	5455.00	4.464	0.927	0.928	1.1863	0.00022
204	1.396	37	0.32	0.18	0.17	0.023	0.020	1.67594E-05	1	21.14	5463.34	6.404	1.073	1.073	1.2768	0.00023
205	2.917	37	0.30	0.19	0.17	0.068	0.067	1.67594E-05	1	21.14	4380.41	0.558	0.291	0.291	0.8408	0.00019
206	2.331	37	0.30	0.19	0.17	0.048	0.045	1.67594E-05	1	21.14	4716.80	2.954	0.694	0.694	0.9911	0.00021
207	1.982	37	0.30	0.19	0.17	0.032	0.029	1.67594E-05	1	21.14	4528.20	6.951	1.212	1.212	1.2578	0.00028
208	1.273	37	0.30	0.19	0.17	0.023	0.021	1.67594E-05	1	21.14	3628.75	10.941	1.435	1.436	1.1636	0.00032
209	30.016	37	0.30	0.19	0.17	0.068	0.007	1.67594E-05	1	21.14	2947.91	0.000	36.139	36.380	8.6524	0.00294
210	20.475	37	0.30	0.19	0.17	0.048	0.005	1.67594E-05	1	21.14	3038.10	0.000	35.092	35.319	8.7058	0.00287
211	0.586	37	0.30	0.19	0.17	0.032	0.032	1.67594E-05	1	21.14	2960.03	0.000	0.116	0.116	0.3716	0.00013
212	0.462	37	0.30	0.19	0.17	0.023	0.022	1.67594E-05	1	21.14	2937.32	0.000	0.376	0.376	0.4222	0.00014

A. 4.2.2 Calculation of gas hold up and k_G for setup 3 using Cl_2-NaOH system

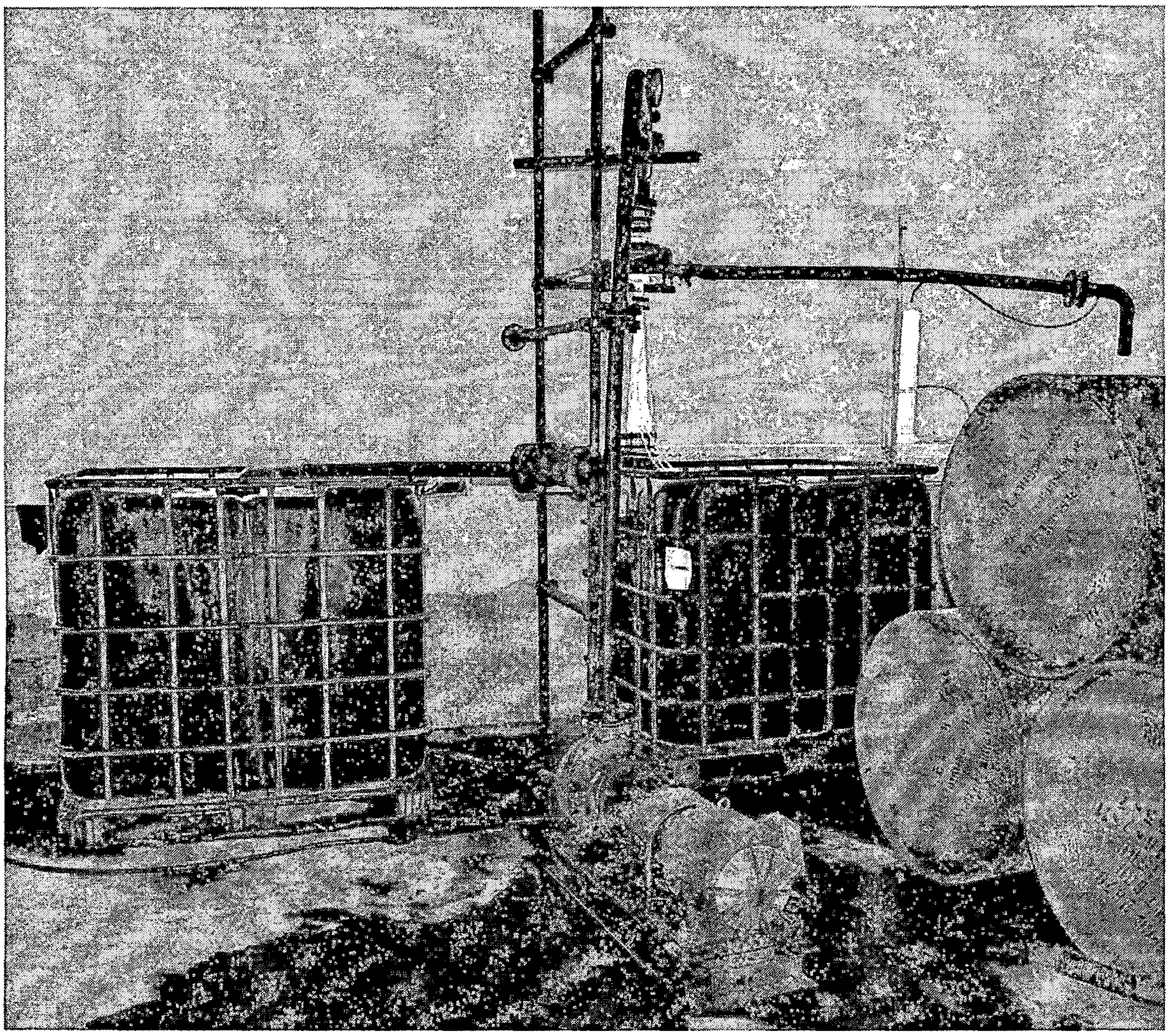
Run No.	10^3 RaA	10^6 V m^3	liuqid holdup Radha-krishnan (1984) eq.no. (4.4.1)	liuqid holdup present model eq. no. (4.4.2)	actual liquid holdup	y_i	y_o	Gm' kmol/sec	P atm.	H_e atm.m^3/kmol	a m^2/m^3	10^3 K_{ga} eq. no. (4.4.10)	10^5 K_G eq. no. (4.4.17)	10^5 k_G eq. no. (4.4.11)	$k_G.a = R_A.a / p_a^*$ eq. no. (4.4.16a)	$k_G = k_{Ga}.a / a$ eq .no. (4.4.17)
301	1.069	1256	0.23	0.28	0.31	0.068	0.058	8.68246E-05	1	22.52	5298.94	0.090	0.051	0.051	0.0146	0.000003
302	1.461	1256	0.23	0.28	0.31	0.047	0.028	8.68246E-05	1	22.52	5498.97	0.474	0.138	0.138	0.0299	0.000005
303	1.751	1256	0.23	0.28	0.31	0.035	0.011	8.68246E-05	1	22.52	5455.00	2.344	0.285	0.285	0.0478	0.000009
304	1.653	1256	0.23	0.28	0.31	0.024	0.001	8.68246E-05	1	22.52	5463.34	31.891	0.924	0.924	0.0677	0.000012
305	0.875	1256	0.22	0.29	0.31	0.068	0.061	8.68246E-05	1	22.52	4380.41	0.031	0.037	0.037	0.0119	0.000003
306	0.973	1256	0.22	0.29	0.31	0.047	0.035	8.68246E-05	1	22.52	4716.80	0.198	0.080	0.080	0.0199	0.000004
307	0.486	1256	0.22	0.29	0.31	0.035	0.030	8.68246E-05	1	22.52	4528.20	0.070	0.048	0.048	0.0133	0.000003
308	0.486	1256	0.22	0.29	0.31	0.024	0.017	8.68246E-05	1	22.52	3628.75	0.147	0.081	0.081	0.0199	0.000005
309	1.167	1256	0.21	0.30	0.31	0.068	0.057	8.68246E-05	1	22.52	2947.91	0.105	0.058	0.058	0.0159	0.000005
310	0.973	1256	0.21	0.30	0.31	0.047	0.035	8.68246E-05	1	22.52	3038.10	0.152	0.080	0.080	0.0199	0.000007
311	0.681	1256	0.21	0.30	0.31	0.035	0.027	8.68246E-05	1	22.52	2960.03	0.184	0.074	0.074	0.0186	0.000006
312	0.388	1256	0.21	0.30	0.31	0.024	0.019	8.68246E-05	1	22.52	2937.32	0.106	0.061	0.061	0.0159	0.000005
313	0.973	1256	0.21	0.30	0.31	0.068	0.059	8.68246E-05	1	21.14	2947.91	0.043	0.044	0.044	0.0132	0.000004
314	0.682	1256	0.21	0.30	0.31	0.047	0.039	8.68246E-05	1	21.14	3038.10	0.062	0.050	0.050	0.0140	0.000005
315	0.486	1256	0.21	0.30	0.31	0.035	0.030	8.68246E-05	1	21.14	2960.03	0.091	0.048	0.048	0.0133	0.000004
316	0.388	1256	0.21	0.30	0.31	0.024	0.019	8.68246E-05	1	21.14	2937.32	0.136	0.061	0.061	0.0159	0.000005
317	2.336	1256	0.22	0.29	0.31	0.068	0.040	8.68246E-05	1	21.14	4380.41	0.703	0.152	0.152	0.0318	0.000007
318	1.947	1256	0.22	0.29	0.31	0.047	0.021	8.68246E-05	1	21.14	4716.80	1.515	0.210	0.210	0.0398	0.000008
319	1.751	1256	0.22	0.29	0.31	0.035	0.011	8.68246E-05	1	21.14	4528.20	2.797	0.285	0.285	0.0478	0.000011
320	1.069	1256	0.22	0.29	0.31	0.024	0.009	8.68246E-05	1	21.14	3628.75	2.062	0.243	0.243	0.0437	0.000012
321	2.382	1256	0.23	0.28	0.31	0.068	0.039	8.68246E-05	1	21.14	5298.94	0.696	0.157	0.157	0.0324	0.000006
322	1.913	1256	0.23	0.28	0.31	0.047	0.021	8.68246E-05	1	21.14	5498.97	1.284	0.204	0.204	0.0391	0.000007
323	1.433	1256	0.23	0.28	0.31	0.035	0.016	8.68246E-05	1	21.14	5455.00	1.270	0.203	0.203	0.0391	0.000007
324	1.054	1256	0.23	0.28	0.31	0.024	0.009	8.68246E-05	1	21.14	5463.34	1.852	0.237	0.237	0.0431	0.000008
325	1.798	1256	0.23	0.28	0.31	0.068	0.047	8.68246E-05	1	19.55	5298.94	0.688	0.106	0.106	0.0245	0.000005
326	1.134	1256	0.23	0.28	0.31	0.047	0.032	8.68246E-05	1	19.55	5498.97	0.627	0.098	0.098	0.0232	0.000004
327	0.851	1256	0.23	0.28	0.31	0.035	0.024	8.68246E-05	1	19.55	5455.00	0.689	0.098	0.098	0.0232	0.000004
328	0.565	1256	0.23	0.28	0.31	0.024	0.016	8.68246E-05	1	19.55	5463.34	0.707	0.098	0.098	0.0231	0.000004
329	2.478	1256	0.22	0.29	0.31	0.068	0.038	8.68246E-05	1	19.55	4380.41	1.860	0.166	0.166	0.0337	0.000008
330	1.426	1256	0.22	0.29	0.31	0.047	0.028	8.68246E-05	1	19.55	4716.80	1.174	0.134	0.134	0.0292	0.000006
331	0.947	1256	0.22	0.29	0.31	0.035	0.023	8.68246E-05	1	19.55	4528.20	0.843	0.113	0.113	0.0258	0.000006
332	0.858	1256	0.22	0.29	0.31	0.024	0.012	8.68246E-05	1	19.55	3628.75	2.049	0.172	0.172	0.0351	0.000010
333	2.284	1256	0.21	0.30	0.31	0.068	0.040	8.68246E-05	1	19.55	2947.91	1.396	0.148	0.148	0.0311	0.000011
334	2.107	1256	0.21	0.30	0.31	0.047	0.018	8.68246E-05	1	19.55	3038.10	3.875	0.239	0.239	0.0431	0.000014
335	1.433	1256	0.21	0.30	0.31	0.035	0.016	8.68246E-05	1	19.55	2960.03	2.340	0.203	0.203	0.0391	0.000013
336	0.761	1256	0.21	0.30	0.31	0.024	0.013	8.68246E-05	1	19.55	2937.32	1.437	0.145	0.145	0.0312	0.000011

APPENDIX – 5

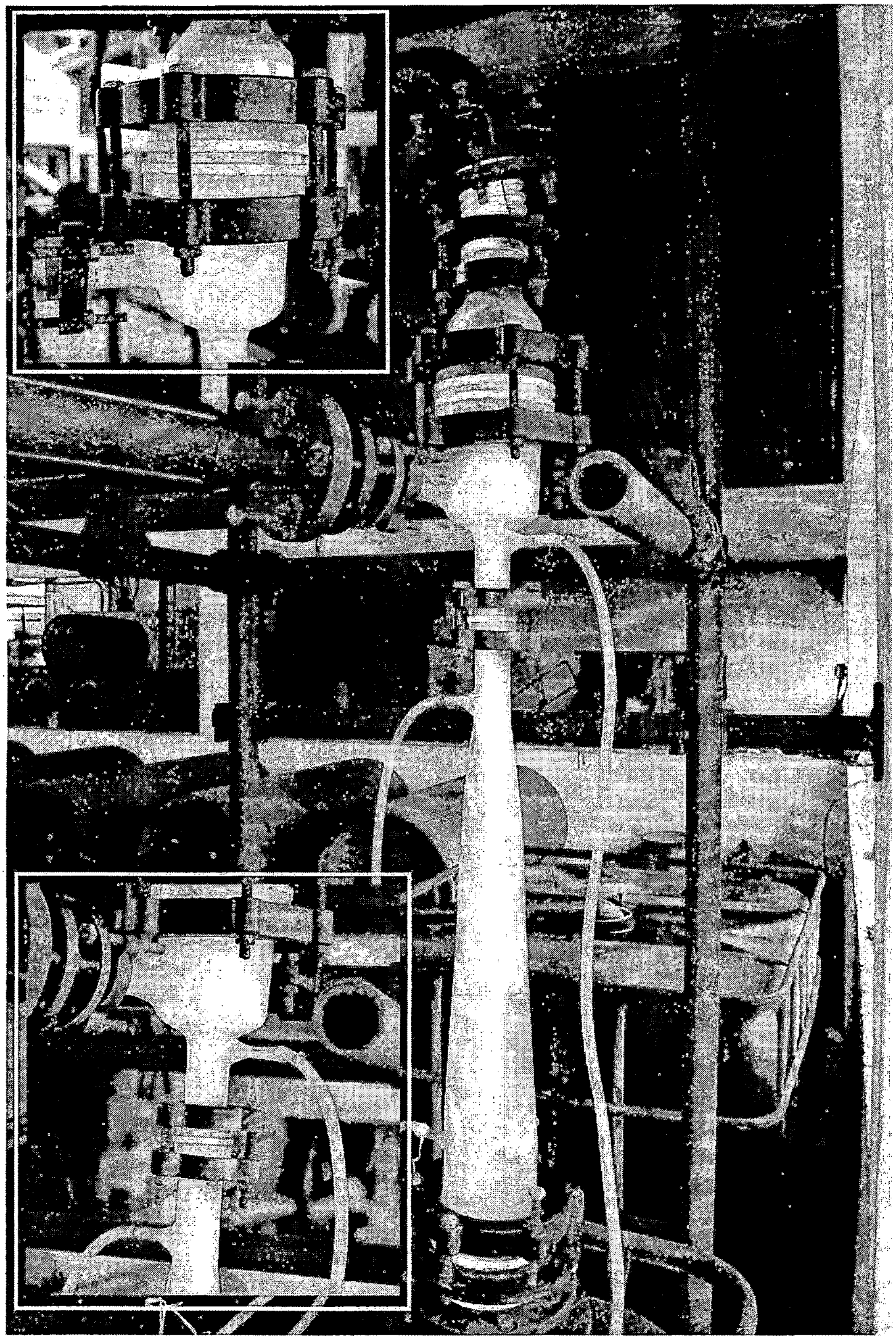
PHOTOGRPAHS OF EXPERIMENTS



A.5.1 : Photograph of experimental set up 2



A.5.2 : Photograph of experimental set up 3



A.5.3 : Photograph of industrial scale ejector used in set up 3