TITLE: Heat of Dissolution Measurements for CO₂ in Mixed Alkanolamine Solvents

REPORT TYPE: Semi-Annual Technical Report

REPORTING PERIOD: 10/1/2004 to 3/31/2005

PRINCIPAL AUTHOR: Vinayak N. Kabadi

DATE: May 23, 2005

DOE AWARD NUMBER: DE-FG26-03NT41912

SUBMITTING INSTITUTION: North Carolina A&T State University
1601 East Market Street
Greensboro, NC 27411

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ABSTRACT

The main objective of this project is to measure heat of dissolution of CO₂ in carefully selected mixed alkanolamine solvent systems, and provide such directly measured data that might be used for efficient design of CO₂ capture processes, or for better understanding of thermodynamics of CO₂- alkanolamine systems. Carbon dioxide is one of the major greenhouse gases, and the need for stabilization of its composition in earth's atmosphere is vital for the future of mankind. Although technologies are available for capture and storage of CO₂, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. For more economical CO₂ capture and regeneration, there is a need for development of more efficient solvent systems. In this project we will extend the thermodynamic database by measuring heat of solution data of CO₂ in mixed solvents made of MEA (monoethanolamine), MDEA (methyldiethanolamine), piperazine, and water. Mixed solvents of different compositions will be selected and in each case data will be measured at temperatures 40 and 80C and various partial pressures of CO₂. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO₂ capture with potential for commercialization.

EXECUTIVE SUMMARY

The main objective of this project is to measure heat of dissolution of CO₂ in carefully selected mixed alkanolamine solvent systems, and provide such directly measured data that might be used for efficient design of CO₂ capture processes, or for better understanding of thermodynamics of CO₂- alkanolamine systems. Carbon dioxide is one of the major greenhouse gases, and the need for stabilization of its composition in earth's atmosphere is vital for the future of mankind. Although technologies are available for capture and storage of CO₂, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. For more economical CO₂ capture and regeneration, there is a need for development of more efficient solvent systems. In this project we will extend the thermodynamic database by measuring heat of solution data of CO₂ in mixed solvents made of MEA (monoethanolamine), MDEA (methyldiethanolamine), piperazine, and water. Mixed solvents of different compositions will be selected and in each case data will be measured at temperatures 40 and 80°C and various partial pressures of CO₂. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO₂ capture with potential for commercialization.

During the current period of performance, October 2004 to March 2005, heat of dissolution data were measured for CO₂ in aqueous MEA and MDEA solvents. Data were measured for three solvent concentrations and at two temperatures, 15°C and 75°C. Data at an additional temperature, 40°C are currently being measured. Experimental design for data measurements in mixed solvents containing MEA, MDEA, and piperazine has been initiated.

Some work has been done in formulating a model for heats of solution of carbon dioxide in the aqueous alkanolamine solvents. It involves a simple extension of the model available in the literature for solubility of CO₂ in aqueous alkanolamine solvents that is based on the electrolyte-NRTL activity coefficient correlation, and equilibrium chemical reactions between various component electrolytic species.

In the next quarter, measurements with aqueous MEA and MDEA solvents will be completed, and some measurements with solvents involving mixtures of MEA and MDEA will be carried out. Work will be continued on the model for solubilities and heats of solution of CO₂ in aqueous alkanolamine solvents

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1. Introduction

Carbon dioxide is one of the major greenhouse gases, and the need for stabilization of its composition in earth's atmosphere is vital for the future of mankind. Although technologies are available for capture and storage of CO₂, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. The idea of capturing CO₂ from the flue gas of power plants did not start with concern about the greenhouse effect. Rather, it gained attention as a possible economic source of CO₂, especially for use in enhanced oil recovery operations where CO₂ is injected into oil reservoirs to increase the mobility of the oil and, therefore, the productivity of the reservoir. Several commercial CO₂ capture plants were constructed in the late 1970s and early 1980s in the US. The North American Chemical Plant in Trona, CA, which uses the carbonation of brine to produce CO₂, started operation in 1978 and is still operating today. However, when the price of oil dropped in mid-1980s, the recovered CO₂ was too expensive for enhanced oil recovery operations and all of the other CO₂ capture plants were closed.

Historically, CO₂ capture processes have required significant amounts of energy, which reduces the power plant's net power output. For example, the output of a 500 MW (net) coal-fired power plant may be reduced to 400 MW (net) after CO₂ capture. This imposes an "energy penalty" of 20%. The energy penalties of current capture technologies range from about 30% for conventional coal to about 15% for advanced coal. It is desired that in the next decade these numbers be brought to 50% of their current values.

To date, all commercial CO₂ capture plants use processes based on chemical absorption with the monoethanolamine (MEA) solvent. MEA was developed over 60 years ago as a general, non-selective solvent to remove acid gases, such as CO₂ and H₂S, from natural gas streams. The process was modified to incorporate inhibitors to resist solvent degradation and equipment corrosion when applied to CO₂ capture from flue gas. Also, the solvent strength was kept relatively low, resulting in large equipment sizes and high regeneration energy requirements. The process allowed flue gas to contact an MEA solution in the absorber. The MEA selectively absorbed the CO₂ and was then sent to a stripper. In the stripper, the CO₂-rich MEA solution was heated to release almost pure CO₂. The lean MEA solution was then recycled to the absorber.

Other processes have been considered to capture CO₂ from the flue gas of a power plant, e.g., membrane separation, cryogenic fractionation, and adsorption using molecular sieves. These processes are even less efficient and more expensive than the chemical absorption. The reason can be attributed to the very low CO₂ partial pressure in the flue gas. Therefore, a high priority research need is to formulate new solvents that can significantly reduce the energy penalty associated with chemical absorption. The new solvents must increase the loading (amount of CO₂ dissolved per unit amount of solvent), and the rate of CO₂ dissolution while maintaining a low heat of solution, so as to minimize the energy requirements during the solvent regeneration.

For the processes based on the absorption of CO₂ by aqueous alkanolamines, the energy penalty or the cost of the process depends mostly on three factors: (1) the loading of CO₂ (moles of CO₂ absorbed per mole of amine), (2) the rate of CO₂ absorption, and (3) the energy

requirement for the release of CO₂ in the stripper. For a number of solvents, detailed studies are available in the literature for the first two factors. Aqueous MEA solvents suffer from the limitation that CO₂ loading cannot exceed much higher than 0.5. An amine that is considered as a potential replacement for MEA is methyldiethanolamine (MDEA) because of the high loading of CO₂ (approaching 1) which is attributed to the stoichiometry of the reaction forming carbamate. However, the rate of CO₂ absorption by MDEA is too low for commercial applications. Mixed solvents containing MEA and MDEA, and diethanolamine (DEA) and MDEA in water seem to provide good solutions to give high absorption rates as well as CO₂ loading. Recently researchers have also started looking at other additives to aqueous MEA and MDEA mixtures to enhance solubility and rate of absorption of CO₂. These include sulfolane, N-methylpyrrolidone (NMP), and piperazine (PZ). Of these, piperazine seems to be the most effective in increasing the solubility of CO₂. The data available in the literature indicate that aqueous mixtures of MEA, MDEA and piperazine have potential to provide a solvent system superior to aqueous MEA solvent of the current commercial capture plants. However, a true determination of this is difficult without a detailed study of the relative energy requirements for each of the solvents. Such a study is not available in the literature, mostly because of lack of experimental data on the heats of dissolution of CO₂ in the aqueous alkanolamine solvents. Data are available only for a few systems and at limited conditions.

For more economical CO₂ capture and regeneration, there is a need for development of more efficient solvent systems. In this project we will extend the thermodynamic database by measuring heat of solution data of CO₂ in mixed solvents made of MEA (monoethanolamine), MDEA (methyldiethanolamine), piperazine, and water. Mixed solvents of different compositions will be selected and in each case data will be measured at a few temperatures and at different concentrations of the aqueous solutions. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO₂ capture with potential for commercialization.

2. Progress of Experimental Measurements

The experimental apparatus and the procedure for measurements were described in the previous report. A couple of preliminary measurements were also reported. The apparatus was modified by replacing the gas mass flow meter with a mass flow meter with a scale of 0 – 20 sccm made by Omega Company. This was done to increase the accuracy of the measurements of gas flow rates significantly. Another modification that was found necessary involves installation of a check valve to prevent back flow of the liquid into the gas line.

CO₂ with a purity of > 99.99% was obtained from National Welders Company. MEA and MDEA with purities of 99.5% were purchased from Sigma-Aldrich Company. The apparatus was leak tested at 750 psi pressure.

Experimental enthalpy data are available for CO₂ in MDEA solution (30 wt% at 40 °C, 20, 40, 60 wt% at 15, 60 °C, and 10, 20, 30 wt % at 25 °C) in the literature. The pressure at which these experiments were conducted was 14.7 - 10000 kPa. The pressure effect on enthalpy

is generally found to be negligible. The solubility limit (α) of CO₂ however is a function of pressure. For aqueous MEA solutions heat of solution data for CO₂ are available for 10, 20, 30 wt% at 25⁰C. Solubility data for CO₂ in MEA and MDEA solutions are available at wide ranges of temperatures, pressures and concentrations. The objective of our measurements is to expand the enthalpy data base to cover a range of temperatures from 15⁰C to 75⁰C and range of concentrations of MEA and MDEA in the aqueous solution ranging from 15 wt% to 50 wt%.

Data for MEA and MDEA solutions at 15⁰C and 75⁰C and over the desired range of concentrations have been measured. All the data at 15⁰C and some data at 75⁰C are given in Figures 1 thru 12 and Tables 1 thru 10. The data at 75⁰C are currently being tested for consistency and the entire data set will be reported in the next report. Data measurements at 40⁰ are currently under way.

3. Data Analysis and Other Current Work

An observation of the heat of solution curves indicates that the heat of solution per mole of CO₂ is fairly constant with CO₂ loading at low CO₂ concentrations, but it decreases closer to the saturation concentration. Attempts are being made to model this behavior, and obtain expressions for heats of mixing as function of CO₂ concentration. The results will be presented in the next report. Figures 1 thru 11 give saturation loading of CO₂ in addition to the heats of solution. Although, in most cases literature values are not available at the exact conditions of our experiments, our data are consistent with the interpolated saturation loadings obtained from the literature data.

Some work has been done in formulating a model for heats of solution of carbon dioxide in the aqueous alkanolamine solvents. It involves a simple extension of the model available in the literature for solubility of CO₂ in aqueous alkanolamine solvents that is based on the electrolyte-NRTL activity coefficient correlation, and equilibrium chemical reactions between various component electrolytic species. The model will be evaluated with the literature data for saturation loading of CO₂ in aqueous alkanolamine solvents, and the heat of solution data being measured in this project. The results of this study will be presented in a future report.

4. Conclusions and Plans for the Next Quarter

In the next quarter, measurements with aqueous MEA and MDEA solvents will be completed, and some measurements with solvents involving mixtures of MEA and MDEA will be carried out. A thorough analysis of the measured data for aqueous MEA and MDEA solvents will be carried out. Work will be continued on the model for solubilities and heats of solution of CO₂ in aqueous alkanolamine solvents.

Figure 1: Enthalpy v/s Loading of CO_2 in 20 wt% MDEA solution at 15⁰C and system pressure of 114.7 psi

Table 1: Data for 20 wt % MDEA solution at 15 °C and system pressure of 114.7 psi

<i>20 wt % MDEA solution, 114.7 psi , 15 °C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MDEA	Enthalpy ΔH (Average) kJ / mol MDEA	Enthalpy ΔH (High) kJ / mol MDEA
1.00	7.4E-07	0.8	2.3E-05	0.033	-32.2	-32.9	-33.4	-43.22	-44.18	-44.89	-1.42	-1.45	-1.47
1.00	7.4E-07	0.6	1.7E-05	0.044	-31.7	-32.5	-33.0	-42.63	-43.61	-44.33	-1.87	-1.91	-1.94
2.00	1.5E-06	0.6	1.7E-05	0.088	-61.0	-61.0	-61.1	-40.97	-41.02	-41.08	-3.59	-3.59	-3.60
2.00	1.5E-06	0.5	1.4E-05	0.105	-63.6	-63.3	-63.2	-42.71	-42.56	-42.44	-4.49	-4.47	-4.46
4.00	3.0E-06	0.4	1.1E-05	0.263	-125.8	-125.8	-125.9	-42.25	-42.28	-42.31	-11.10	-11.10	-11.11
6.00	4.5E-06	0.5	1.4E-05	0.315	-191.9	-193.0	-193.8	-42.99	-43.24	-43.40	-13.55	-13.63	-13.68
8.00	6.0E-06	0.6	1.7E-05	0.350	-261.1	-262.0	-263.4	-43.87	-44.01	-44.26	-15.36	-15.41	-15.50
9.50	7.1E-06	0.5	1.4E-05	0.499	-303.8	-304.2	-304.8	-42.98	-43.04	-43.12	-21.44	-21.47	-21.52
7.00	5.2E-06	0.3	8.5E-06	0.613	-226.3	-226.3	-226.4	-43.44	-43.45	-43.46	-26.62	-26.62	-26.63
6.00	4.5E-06	0.2	5.7E-06	0.788	-199.4	-200.5	-201.4	-44.66	-44.91	-45.11	-35.18	-35.38	-35.54
8.00	6.0E-06	0.2	5.7E-06	1.050	-255.9	-255.9	-256.0	-42.99	-43.00	-43.01	-45.15	-45.17	-45.18
8.00	6.0E-06	0.2	5.7E-06	1.050	-259.2	-259.4	-259.6	-43.55	-43.57	-43.61	-45.75	-45.77	-45.81
8.26	6.1E-06	0.2	5.7E-06	1.085	-263.4	-263.7	-263.8	-42.87	-42.90	-42.93	-46.49	-46.53	-46.56
8.50	6.3E-06	0.2	5.7E-06	1.116	-267.7	-267.8	-267.9	-42.32	-42.34	-42.36	-47.23	-47.26	-47.28
8.76	6.5E-06	0.2	5.7E-06	1.150	-271.3	-271.5	-271.7	-41.62	-41.66	-41.69	-47.87	-47.92	-47.95
9.00	6.7E-06	0.2	5.7E-06	1.182	-274.0	-274.3	-274.6	-40.92	-40.96	-41.00	-48.36	-48.40	-48.45
10.00	7.4E-06	0.2	5.7E-06	1.313	-276.3	-277.1	-277.3	-37.14	-37.24	-37.27	-48.76	-48.90	-48.94
12.00	8.9E-06	0.2	5.7E-06	1.576	-275.3	-275.4	-275.4	-30.83	-30.84	-30.85	-48.57	-48.60	-48.60
12.00	8.9E-06	0.2	5.7E-06	1.576	-274.3	-274.8	-275.0	-30.72	-30.78	-30.80	-48.40	-48.50	-48.54

Figure 2: Enthalpy Vs Loading of CO_2 in 30 wt % MDEA solution at 15 °C and system pressure of 114.7 psi

Table 2: Data for 30 wt % MDEA solution at 15° C and system pressure of 114.7 psi

<i>30 wt % MDEA solution, 114.7 psi, 15 ° C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MDEA	Enthalpy ΔH (Average) kJ / mol MDEA	Enthalpy ΔH (High) kJ / mol MDEA
1.50	1.1E-06	0.7	3.0E-05	0.037	-53.2	-53.6	-54.4	-47.69	-48.03	-48.76	-1.76	-1.77	-1.80
3.50	2.6E-06	0.6	2.6E-05	0.101	-129.6	-129.8	-129.9	-49.78	-49.84	-49.89	-5.01	-5.01	-5.02
7.00	5.2E-06	0.5	2.2E-05	0.241	-250.9	-251.0	-251.1	-48.18	-48.20	-48.22	-11.63	-11.63	-11.64
4.50	3.3E-06	0.3	1.3E-05	0.259	-162.7	-162.7	-162.8	-48.59	-48.61	-48.62	-12.57	-12.57	-12.58
9.00	6.7E-06	0.5	2.2E-05	0.310	326.0	-327.9	-329.0	48.68	-48.96	-49.12	15.11	-15.20	-15.25
6.00	4.5E-06	0.2	8.6E-06	0.518	-212.1	-212.4	-212.6	-47.50	-47.58	-47.62	-24.59	-24.63	-24.65
7.00	5.2E-06	0.2	8.6E-06	0.604	-245.7	-243.8	-243.8	-47.17	-46.81	-46.82	-28.49	-28.27	-28.28
8.00	6.0E-06	0.2	8.6E-06	0.690	-281.0	-281.7	-282.4	-47.21	-47.32	-47.44	-32.58	-32.67	-32.74
9.50	7.1E-06	0.2	8.6E-06	0.820	-331.0	-331.4	-331.6	-46.83	-46.89	-46.91	-38.39	-38.43	-38.45
11.00	8.2E-06	0.2	8.6E-06	0.948	-375.3	-375.5	-375.6	-45.85	-45.88	-45.90	-43.49	-43.51	-43.53
6.00	4.5E-06	0.1	4.3E-06	1.035	-205.0	-205.0	-205.2	-45.91	-45.93	-45.96	-47.50	-47.52	-47.55
6.26	4.7E-06	0.1	4.3E-06	1.079	-209.5	-209.8	-209.9	-44.98	-45.04	-45.06	-48.56	-48.62	-48.64
6.50	4.8E-06	0.1	4.3E-06	1.121	-210.1	-211.1	-211.4	-43.45	-43.65	-43.72	-48.70	-48.92	-49.00
7.00	5.2E-06	0.1	4.3E-06	1.207	-210.5	-210.9	-211.2	-40.42	-40.48	-40.55	-48.78	-48.86	-48.94
7.00	5.2E-06	0.1	4.3E-06	1.207	-210.3	-210.7	-211.0	-40.38	-40.46	-40.51	-48.75	-48.83	-48.90
8.00	6.0E-06	0.1	4.3E-06	1.379	-210.9	-211.3	-211.5	-35.43	-35.50	-35.53	-48.88	-48.97	-49.01
9.00	6.7E-06	0.1	4.3E-06	1.552	-210.6	-210.7	-210.8	-31.45	-31.47	-31.48	-48.81	-48.83	-48.86
10.00	7.4E-06	0.1	4.3E-06	1.724	-208.9	-209.1	-209.3	-28.07	-28.11	-28.13	-48.40	-48.47	-48.51

Figure 3: Enthalpy Vs Loading of CO_2 in 40 wt % MDEA solution at 15 ° C and system pressure of 114.7 psi

Table 3: Data for 40 wt % MDEA solution at 15° C and system pressure of 114.7 psi

<i>40 wt % MDEA solution, 114.7 psi, 15 ° C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MDEA	Enthalpy ΔH (Average) kJ / mol MDEA	Enthalpy ΔH (High) kJ / mol MDEA
1.00	7.4E-07	0.8	4.7E-05	0.016	-39.3	-39.9	-40.3	-52.88	-53.59	-54.12	-0.84	-0.85	-0.86
1.00	7.4E-07	0.6	3.5E-05	0.021	-40.2	-40.0	-41.1	-53.99	-53.80	-55.19	-1.15	-1.14	-1.17
3.00	2.2E-06	0.8	4.7E-05	0.048	-120.4	-120.9	-121.7	-53.95	-54.14	-54.50	-2.58	-2.59	-2.61
5.00	3.7E-06	0.6	3.5E-05	0.106	-200.1	-200.7	-201.6	-53.79	-53.94	-54.19	-5.72	-5.73	-5.76
8.00	6.0E-06	0.6	3.5E-05	0.170	-314.0	-315.6	-317.6	-52.75	-53.02	-53.35	-8.97	-9.02	-9.07
4.00	3.0E-06	0.2	1.2E-05	0.255	-158.5	-160.0	-161.4	-53.24	-53.75	-54.23	-13.58	-13.71	-13.83
8.00	6.0E-06	0.2	1.2E-05	0.510	-306.9	-308.2	-309.5	-51.55	-51.78	-51.99	-26.30	-26.42	-26.52
6.00	4.5E-06	0.1	5.8E-06	0.765	-234.1	-234.4	-234.8	-52.43	-52.50	-52.59	-40.12	-40.18	-40.25
7.00	5.2E-06	0.1	5.8E-06	0.893	-266.6	-266.9	-267.1	-51.19	-51.24	-51.28	-45.71	-45.75	-45.78
7.25	5.4E-06	0.1	5.8E-06	0.925	-273.2	-273.6	-274.1	-50.64	-50.72	-50.80	-46.83	-46.90	-46.98
7.50	5.6E-06	0.1	5.8E-06	0.957	-278.0	-278.4	-278.7	-49.82	-49.90	-49.94	-47.66	-47.73	-47.78
7.76	5.8E-06	0.1	5.8E-06	0.990	-280.2	-280.9	-281.4	-48.53	-48.65	-48.74	-48.03	-48.15	-48.24
10.00	7.4E-06	0.1	5.8E-06	1.276	-280.1	-281.7	-282.4	-37.64	-37.86	-37.95	-48.01	-48.30	-48.41
12.00	8.9E-06	0.1	5.8E-06	1.531	-279.2	-279.4	-279.6	-31.27	-31.29	-31.31	-47.86	-47.90	-47.93

Figure 4: Enthalpy Vs Loading of CO₂ in 50 wt % MDEA solution at 15 ° C and system pressure of 114.7 psi

Table 4: Data for 50 wt % MDEA solution at 15° C and system pressure of 114.7 psi

<i>50 wt % MDEA solution, 114.7 psi, 15 ° C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MDEA	Enthalpy ΔH (Average) kJ / mol MDEA	Enthalpy ΔH (High) kJ / mol MDEA
2.00	1.5E-06	0.80	5.9E-05	0.025	-79.2	-80.1	-81.5	-53.21	-53.84	-54.76	-1.35	-1.37	-1.39
2.00	1.5E-06	0.60	4.4E-05	0.034	-79.7	-80.8	-81.9	-53.58	-54.32	-55.05	-1.81	-1.84	-1.86
5.00	3.7E-06	0.10	7.3E-06	0.508	-199.1	-199.7	-200.4	-53.52	-53.67	-53.86	-27.19	-27.26	-27.36
6.50	4.8E-06	0.10	7.3E-06	0.661	-254.1	-255.8	-256.6	-52.54	-52.89	-53.05	-34.75	-34.99	-35.09
8.50	6.3E-06	0.10	7.3E-06	0.865	-337.8	-338.9	-339.8	-53.42	-53.59	-53.73	-46.21	-46.35	-46.48
9.00	6.7E-06	0.10	7.3E-06	0.916	-355.6	-356.9	-358.1	-53.11	-53.29	-53.48	-48.64	-48.81	-48.98
9.26	6.9E-06	0.10	7.3E-06	0.942	-359.0	-360.3	-361.6	-52.10	-52.29	-52.48	-49.10	-49.28	-49.45
10.00	7.4E-06	0.10	7.3E-06	1.018	-364.3	-364.5	-364.6	-48.97	-48.98	-49.00	-49.83	-49.85	-49.86
12.00	8.9E-06	0.10	7.3E-06	1.221	-361.7	-362.2	-362.5	-40.51	-40.57	-40.60	-49.46	-49.53	-49.57
10.00	7.4E-06	0.07	5.1E-06	1.453	-255.0	-255.6	-256.1	-34.28	-34.36	-34.42	-49.80	-49.92	-50.01
11.00	8.2E-06	0.07	5.1E-06	1.598	-254.9	-255.8	-256.3	-31.15	-31.25	-31.31	-49.79	-49.96	-50.05

Figure 5: Enthalpy Vs Loading of CO₂ in MDEA solutions at 15 ⁰ C and system pressure of 114.7 psi

Figure 6: Enthalpy Vs Loading of CO_2 in 30 wt% MDEA solution at 40 ° C and system pressure of 114.7 psi

Table 5: Data for 30 wt % MDEA solution at 40° C and system pressure of 114.7 psi

<i>30 wt % MDEA solution, 114.7 psi, 40 ° C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MDEA	Enthalpy ΔH (Average) kJ / mol MDEA	Enthalpy ΔH (High) kJ / mol MDEA
4.12	3.1E-06	1.0	4.3E-05	0.071	-143.2	-144.4	-146.5	-46.71	-47.09	-47.79	-3.32	-3.35	-3.40
4.12	3.1E-06	0.5	2.2E-05	0.142	-157.6	-159.2	-161.1	-51.40	-51.92	-52.55	-7.31	-7.39	-7.48
7.58	5.6E-06	0.5	2.2E-05	0.262	-280.9	-282.7	-283.4	-49.81	-50.13	-50.24	-13.04	-13.12	-13.15
11.41	8.5E-06	0.5	2.2E-05	0.394	-406.3	-408.8	-410.3	-47.86	-48.15	-48.33	-18.86	-18.98	-19.05
3.24	2.4E-06	0.1	4.3E-06	0.559	-128.6	-130.5	-133.0	-53.34	-54.13	-55.16	-29.82	-30.26	-30.84
4.81	3.6E-06	0.1	4.3E-06	0.830	-178.3	-180.5	-181.1	-49.81	-50.45	-50.61	-41.33	-41.86	-42.00
5.60	4.2E-06	0.1	4.3E-06	0.967	-208.7	-210.6	-212.5	-50.06	-50.52	-50.99	-48.42	-48.87	-49.32
6.28	4.7E-06	0.1	4.3E-06	1.084	-212.4	-214.8	-216.6	-45.45	-45.96	-46.36	-49.24	-49.80	-50.23
8.04	6.0E-06	0.1	4.3E-06	1.387	-213.9	-215.1	-217.6	-35.76	-35.95	-36.38	-49.61	-49.87	-50.46
9.42	7.0E-06	0.1	4.3E-06	1.625	-213.7	-215.2	-218.5	-30.49	-30.71	-31.18	-49.55	-49.90	-50.67
12.83	9.5E-06	0.1	4.3E-06	2.214	-213.1	-215.4	-217.6	-22.33	-22.56	-22.79	-49.42	-49.95	-50.46

Figure 7: Enthalpy Vs Loading of CO_2 in 20 wt% MDEA solution at 75 ° C and system pressure of 114.7 psi

Table 6: Data for 20 wt % MDEA solution at 75 °C and system pressure of 114.7 psi

<i>20 wt % MDEA solution, 114.7 psi, 75 °C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MDEA	Enthalpy ΔH (Average) kJ / mol MDEA	Enthalpy ΔH (High) kJ / mol MDEA
1.89	1.4E-06	0.30	8.5E-06	0.165	-71.8	-72.2	-72.8	-51.04	-51.33	-51.75	-8.40	-8.45	-8.52
4.49	3.3E-06	0.30	8.5E-06	0.391	-172.4	-172.7	-173.0	-51.60	-51.68	-51.77	-20.18	-20.22	-20.25
4.93	3.7E-06	0.30	8.5E-06	0.429	-182.0	-182.7	-183.4	-49.61	-49.81	-49.99	-21.30	-21.39	-21.47
4.49	3.3E-06	0.20	5.7E-06	0.587	-176.0	-176.8	-177.8	-52.67	-52.93	-53.21	-30.91	-31.06	-31.23
4.91	3.7E-06	0.20	5.7E-06	0.642	-182.5	-183.7	-184.5	-49.95	-50.29	-50.51	-32.05	-32.26	-32.41
5.06	3.8E-06	0.17	4.8E-06	0.778	196.9	-198.3	198.9	52.29	-52.68	52.84	40.68	-40.99	41.11
5.08	3.8E-06	0.16	4.6E-06	0.830	-196.0	-197.0	-197.6	-51.85	-52.11	-52.28	-43.03	-43.24	-43.38
5.05	3.8E-06	0.15	4.3E-06	0.880	-194.2	-194.8	-195.4	-51.70	-51.86	-52.02	-45.48	-45.63	-45.77
4.52	3.4E-06	0.13	3.7E-06	0.909	-171.1	-172.1	-172.5	-50.87	-51.17	-51.29	-46.22	-46.50	-46.60
5.01	3.7E-06	0.14	4.0E-06	0.935	-185.4	-185.6	-186.0	-49.73	-49.78	-49.88	-46.51	-46.56	-46.65
4.85	3.6E-06	0.13	3.7E-06	0.975	-171.9	-172.5	-173.2	-47.63	-47.80	-47.99	-46.45	-46.61	-46.80
4.96	3.7E-06	0.10	2.8E-06	1.296	-128.2	-128.4	-128.6	-34.75	-34.80	-34.85	-45.04	-45.11	-45.17

Figure 8: Enthalpy Vs Loading of CO_2 in 30 wt% MDEA solution at 75 ° C and system pressure of 114.7 psi

Table 7: Data for 30 wt % MDEA solution at 75° C and system pressure of 114.7 psi

<i>30 wt % MDEA, 114.7 psi, 75° C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy DH (Low) kJ / mol CO ₂	Enthalpy DH (Average) kJ / mol CO ₂	Enthalpy DH (High) kJ / mol CO ₂	Enthalpy DH (Low) kJ / mol MDEA	Enthalpy DH (Average) kJ / mol MDEA	Enthalpy DH (High) kJ / mol MDEA
1	7.4E-07	0.7	3.0E-05	0.025	-36.8	-37.0	-37.1	-49.49	-49.70	-49.86	-1.22	-1.22	-1.23
2.00	1.5E-06	0.7	3.0E-05	0.049	-75.2	-75.4	-75.5	-50.57	-50.68	-50.76	-2.49	-2.50	-2.50
3.00	2.2E-06	0.6	2.6E-05	0.086	-115.3	-115.5	-115.7	-51.66	-51.75	-51.85	-4.45	-4.46	-4.47
5.00	3.7E-06	0.5	2.2E-05	0.172	-192.6	-192.7	-192.9	-51.77	-51.81	-51.85	-8.93	-8.93	-8.94
7.00	5.2E-06	0.4	1.7E-05	0.302	-272.6	-272.6	-272.7	-52.33	-52.34	-52.35	-15.79	-15.80	-15.80
11.00	8.2E-06	0.5	2.2E-05	0.379	-426.7	-427.2	-427.6	-52.13	-52.19	-52.24	-19.78	-19.81	-19.83
11.00	8.2E-06	0.4	1.7E-05	0.474	-429.9	-430.0	-430.1	-52.53	-52.54	-52.55	-24.91	-24.91	-24.92
11.00	8.2E-06	0.3	1.3E-05	0.632	-434.8	-434.9	-435.0	-53.13	-53.14	-53.15	-33.59	-33.60	-33.60
9.00	6.7E-06	0.2	8.6E-06	0.776	-357.1	-357.2	-357.2	-53.33	-53.34	-53.35	-41.38	-41.39	-41.39
9.50	7.1E-06	0.2	8.6E-06	0.819	-374.9	-374.9	-375.0	-53.03	-53.04	-53.05	-43.44	-43.45	-43.45
9.76	7.3E-06	0.2	8.6E-06	0.841	-382.6	-382.7	-382.7	-52.69	-52.69	-52.70	-44.34	-44.34	-44.34
10.00	7.4E-06	0.2	8.6E-06	0.862	-386.7	-386.8	-386.9	-51.97	-51.99	-52.00	-44.81	-44.82	-44.83
7.00	5.2E-06	0.1	4.3E-06	1.207	-189.0	-189.5	-190.0	-36.28	-36.39	-36.48	-43.80	-43.92	-44.03
8.00	6.0E-06	0.1	4.3E-06	1.379	-186.7	-186.8	-186.9	-31.37	-31.38	-31.40	-43.27	-43.29	-43.32
11.00	8.2E-06	0.1	4.3E-06	1.897	-183.7	-184.1	-184.5	-22.45	-22.50	-22.55	-42.58	-42.67	-42.77

Heat of Solution Vs Loading (15 wt %, 15 ° C, 114.7 psi)

Figure 9: Enthalpy Vs Loading of CO₂ in 15 wt% MEA solution at 15 ° C and system pressure of 114.7 psi

Table 8: Data for 15 wt % MEA solution at 15^o C and system pressure of 114.7 psi

<i>15 wt % MEA solution, 114.7 psi, 15 °C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MEA	Enthalpy ΔH (Average) kJ / mol MEA	Enthalpy ΔH (High) kJ / mol MEA
1.00	7.4E-07	0.80	3.3E-05	0.023	-53.0	-53.9	-54.7	-71.25	-72.42	-73.51	-1.61	-1.64	-1.66
3.00	2.2E-06	0.70	2.9E-05	0.077	-155.6	-156.0	-157.5	-69.70	-69.87	-70.55	-5.40	-5.41	-5.46
4.00	3.0E-06	0.60	2.5E-05	0.120	-209.8	-210.3	-210.5	-70.50	-70.66	-70.73	-8.50	-8.51	-8.52
6.50	4.8E-06	0.40	1.6E-05	0.294	-350.8	-351.0	-351.2	-72.54	-72.57	-72.62	-21.30	-21.31	-21.33
10.00	7.4E-06	0.30	1.2E-05	0.602	-535.0	-535.6	-536.1	-71.91	-71.99	-72.06	-43.32	-43.37	-43.41
12.00	8.9E-06	0.30	1.2E-05	0.723	-598.9	-599.3	-599.4	-67.07	-67.12	-67.13	-48.49	-48.52	-48.53
9.00	6.7E-06	0.20	8.2E-06	0.813	-425.3	-425.4	-425.5	-63.51	-63.53	-63.54	-51.66	-51.67	-51.68
10.00	7.4E-06	0.20	8.2E-06	0.904	-443.5	-443.7	-443.8	-59.61	-59.63	-59.65	-53.87	-53.89	-53.91
6.00	4.5E-06	0.10	4.1E-06	1.084	-225.0	-225.1	-225.3	-50.41	-50.43	-50.47	-54.66	-54.69	-54.73
8.00	6.0E-06	0.10	4.1E-06	1.446	-220.8	-221.1	-221.5	-37.09	-37.15	-37.21	-53.63	-53.71	-53.80
10.00	7.4E-06	0.10	4.1E-06	1.807	-213.8	-213.9	-214.1	-28.74	-28.75	-28.77	-51.94	-51.97	-52.00

Figure 10: Enthalpy Vs Loading of CO₂ in 30 wt% MEA solution at 15 ° C and system pressure of 114.7 psi

Table 9: Data for 30 wt % MEA solution at 15° C and system pressure of 114.7 psi

<i>30 wt % MEA solution, 114.7 psi, 15 ° C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MEA	Enthalpy ΔH (Average) kJ / mol MEA	Enthalpy ΔH (High) kJ / mol MEA
1.00	7.4E-07	0.70	5.8E-05	0.013	-53.5	-53.9	-54.5	-71.95	-72.50	-73.24	-0.92	-0.93	-0.94
4.00	3.0E-06	0.60	5.0E-05	0.060	-211.7	-212.0	-212.3	-71.14	-71.23	-71.34	-4.26	-4.26	-4.27
6.00	4.5E-06	0.50	4.1E-05	0.108	-328.8	-329.3	-329.8	-73.66	-73.77	-73.87	-7.93	-7.94	-7.95
8.00	6.0E-06	0.40	3.3E-05	0.179	-453.5	-453.6	-453.7	-76.19	-76.20	-76.22	-13.67	-13.67	-13.68
10.00	7.4E-06	0.30	2.5E-05	0.299	-571.6	-571.6	-571.7	-76.82	-76.83	-76.84	-22.98	-22.98	-22.98
10.00	7.4E-06	0.20	1.7E-05	0.449	-572.5	-572.7	-572.9	-76.95	-76.97	-77.00	-34.53	-34.53	-34.55
12.00	8.9E-06	0.20	1.7E-05	0.538	-693.8	-694.0	-694.5	-77.70	-77.73	-77.79	-41.83	-41.85	-41.88
7.00	5.2E-06	0.10	8.3E-06	0.628	-379.2	-379.6	-380.0	-72.81	-72.88	-72.96	-45.70	-45.74	-45.79
8.00	6.0E-06	0.10	8.3E-06	0.717	-405.8	-406.2	-406.5	-68.17	-68.23	-68.30	-48.90	-48.94	-48.99
8.50	6.3E-06	0.10	8.3E-06	0.763	-419.0	-419.5	-419.9	-66.26	-66.33	-66.39	-50.54	-50.59	-50.64
8.76	6.5E-06	0.10	8.3E-06	0.785	-425.9	-426.0	-426.4	-65.34	-65.36	-65.41	-51.32	-51.34	-51.38
9.00	6.7E-06	0.10	8.3E-06	0.807	-431.2	-431.6	-432.0	-64.40	-64.46	-64.51	-51.97	-52.02	-52.05
12.00	8.9E-06	0.10	8.3E-06	1.076	-427.9	-428.1	-428.4	-47.93	-47.95	-47.98	-51.57	-51.59	-51.62
10.00	7.4E-06	0.07	5.8E-06	1.281	-300.6	-301.0	-301.3	-40.41	-40.46	-40.50	-51.75	-51.82	-51.87
12.00	8.9E-06	0.07	5.8E-06	1.537	-295.2	-295.6	-295.9	-33.07	-33.10	-33.14	-50.83	-50.88	-50.94

Figure 11: Enthalpy Vs Loading of CO_2 in 50 wt% MEA solution at 15 ⁰ C and system pressure of 114.7 psi

Table 10: Data for 50 wt % MEA solution at 15^o C and system pressure of 114.7 psi

<i>50 wt % MEA solution, 114.7 psi , 15 ° C</i>													
CO ₂ Flow Rate SCCM	CO ₂ Mol/sec	MDEA Flow Rate ml/min	MDEA Mol/sec	Loading of CO ₂	Low Enthalpy mJ/sec	Average Enthalpy mJ/sec	High Enthalpy mJ/sec	Enthalpy ΔH (Low) kJ / mol CO ₂	Enthalpy ΔH (Average) kJ / mol CO ₂	Enthalpy ΔH (High) kJ / mol CO ₂	Enthalpy ΔH (Low) kJ / mol MDEA	Enthalpy ΔH (Average) kJ / mol MDEA	Enthalpy ΔH (High) kJ / mol MDEA
1.00	7.4E-07	0.70	9.8E-05	0.008	-56.4	-56.7	-57.0	-75.75	-76.15	-76.66	-0.58	-0.58	-0.58
2.00	1.5E-06	0.60	8.4E-05	0.018	-113.4	-113.6	-113.8	-76.17	-76.34	-76.47	-1.35	-1.36	-1.36
3.00	2.2E-06	0.50	7.0E-05	0.032	-171.6	-172.3	-173.0	-76.86	-77.20	-77.52	-2.46	-2.47	-2.48
4.00	3.0E-06	0.40	5.6E-05	0.053	-230.5	-230.6	-230.7	-77.44	-77.48	-77.51	-4.13	-4.13	-4.14
6.00	4.5E-06	0.30	4.2E-05	0.107	-351.6	-351.7	-351.8	-78.75	-78.77	-78.81	-8.40	-8.41	-8.41
8.00	6.0E-06	0.20	2.8E-05	0.213	-479.7	-480.2	-480.7	-80.59	-80.67	-80.75	-17.20	-17.21	-17.23
7.00	5.2E-06	0.10	1.4E-05	0.373	-427.4	-427.6	-427.8	-82.07	-82.10	-82.14	-30.64	-30.65	-30.67
10.00	7.4E-06	0.10	1.4E-05	0.533	-597.7	-598.2	-598.8	-80.33	-80.40	-80.48	-42.84	-42.88	-42.92
9.00	6.7E-06	0.07	9.8E-06	0.686	-478.8	-479.2	-479.5	-71.49	-71.56	-71.61	-49.02	-49.06	-49.09
9.50	7.1E-06	0.07	9.8E-06	0.724	-493.0	-493.3	-493.6	-69.74	-69.79	-69.84	-50.46	-50.49	-50.53
9.76	7.3E-06	0.07	9.8E-06	0.743	-500.4	-500.7	-500.9	-68.91	-68.95	-68.98	-51.21	-51.25	-51.27
10.00	7.4E-06	0.07	9.8E-06	0.762	-505.6	-506.1	-506.9	-67.95	-68.02	-68.13	-51.76	-51.81	-51.89
10.26	7.6E-06	0.07	9.8E-06	0.781	-510.6	-511.0	-511.4	-66.88	-66.94	-67.00	-52.27	-52.31	-52.36
10.50	7.8E-06	0.07	9.8E-06	0.800	-512.6	-512.9	-513.2	-65.62	-65.66	-65.69	-52.48	-52.51	-52.55
12.00	8.9E-06	0.07	9.8E-06	0.914	-510.8	-511.2	-511.7	-57.20	-57.25	-57.31	-52.30	-52.34	-52.39
10.00	7.4E-06	0.05	7.0E-06	1.066	-364.5	-364.8	-365.4	-48.98	-49.04	-49.11	-52.24	-52.30	-52.37
12.00	8.9E-06	0.05	7.0E-06	1.280	-395.4	-365.9	-366.3	-44.28	-40.98	-41.02	-56.69	-52.46	-52.52

Figure 12: Enthalpy Vs Loading of CO₂ in MDEA solutions at 15⁰ C and system pressure of 114.7 psi