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## ABSTRACT

The main objective of this project is to measure heat of dissolution of CO<sub>2</sub> in carefully selected mixed alkanolamine solvent systems, and provide such directly measured data that might be used for efficient design of CO<sub>2</sub> capture processes, or for better understanding of thermodynamics of CO<sub>2</sub>- 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 CO<sub>2</sub>, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. For more economical CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub>. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO<sub>2</sub> capture with potential for commercialization.

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## 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 CO<sub>2</sub>, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. The idea of capturing CO<sub>2</sub> 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 CO<sub>2</sub>, especially for use in enhanced oil recovery operations where CO<sub>2</sub> is injected into oil reservoirs to increase the mobility of the oil and, therefore, the productivity of the reservoir. Several commercial CO<sub>2</sub> 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 CO<sub>2</sub>, started operation in 1978 and is still operating today. However, when the price of oil dropped in mid-1980s, the recovered CO<sub>2</sub> was too expensive for enhanced oil recovery operations and all of the other CO<sub>2</sub> capture plants were closed.

Historically, CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> and H<sub>2</sub>S, from natural gas streams. The process was modified to incorporate inhibitors to resist solvent degradation and equipment corrosion when applied to CO<sub>2</sub> 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 CO<sub>2</sub> and was then sent to a stripper. In the stripper, the CO<sub>2</sub>-rich MEA solution was heated to release almost pure CO<sub>2</sub>. The lean MEA solution was then recycled to the absorber.

Other processes have been considered to capture CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> dissolved per unit amount of solvent), and the rate of CO<sub>2</sub> 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 CO<sub>2</sub> by aqueous alkanolamines, the energy penalty or the cost of the process depends mostly on three factors: (1) the loading of CO<sub>2</sub> (moles of CO<sub>2</sub> absorbed per mole of amine), (2) the rate of CO<sub>2</sub> absorption, and (3) the energy requirement for the release of CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> (approaching 1) which is attributed to the stoichiometry of the reaction forming carbamate. However, the rate of CO<sub>2</sub> 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 CO<sub>2</sub> loading. Recently researchers have also started looking at other additives to aqueous MEA and MDEA mixtures to enhance solubility and rate of absorption of CO<sub>2</sub>. These include sulfolane, N-methylpyrrolidone (NMP), and piperazine (PZ). Of these, piperazine seems to be the most effective in increasing the solubility of CO<sub>2</sub>. 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 CO<sub>2</sub> in the aqueous alkanolamine solvents. Data are available only for a few systems and at limited conditions.

For more economical CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub>. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO<sub>2</sub> capture with potential for commercialization.

## EXECUTIVE SUMMARY

The main objective of this project is to measure heat of dissolution of CO<sub>2</sub> in carefully selected mixed alkanolamine solvent systems, and provide such directly measured data that might be used for efficient design of CO<sub>2</sub> capture processes, or for better understanding of thermodynamics of CO<sub>2</sub>- 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 CO<sub>2</sub>, these technologies are far too expensive for economical commercialization. Reduction of cost would require research for refinement of the technology. For more economical CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub>. At the end of the project, observations, conclusions, and recommendations will be derived for the choice of mixed solvents for efficient CO<sub>2</sub> capture with potential for commercialization.

During the current period of performance, September 2003 to March 2004, the apparatus for the heat of dissolution measurements has been designed and built. The apparatus consists of a CO<sub>2</sub> gas cylinder, a mass flowmeter, a liquid solvent metering pump, the isothermal micro-calorimeter with the flow cells made by Calorimetry Sciences Corporation (CSC), a back pressure regulator, switch valve for online chromatographic analysis, the GC, and many thermocouples and pressure sensors. The apparatus has been pressure tested for leaks. MEA-CO<sub>2</sub> system has been chosen as the test system. Data for this system will be measured over a range of CO<sub>2</sub> compositions, at a single temperature of 25°C, and a fixed composition of aqueous solution. The measured data will be compared with the limited data available in the literature for this system. The data measurements have just begun.

Simultaneously, a more thorough literature search was carried out for enthalpy data on CO<sub>2</sub>-alkanolamine systems. The available literature data for aqueous CO<sub>2</sub>-MEA, CO<sub>2</sub>-MDEA, CO<sub>2</sub>-DEA, CO<sub>2</sub>-MDEA-Sulfolane, and CO<sub>2</sub>-MDEA-PZ systems have been extracted and compiled. The variables for data measurements are temperature, CO<sub>2</sub> composition or partial pressure, and the composition of the aqueous mixture. Design of our data measurements should be such that the result will be a complete data set for the CO<sub>2</sub>-MEA-MDEA-PZ system. This design will be completed in the next phase of the project.

## EXPERIMENTAL APPARATUS

During the current period of performance, September 2003 to March 2004, the apparatus for the heat of dissolution measurements has been designed and built. The apparatus consists of a CO<sub>2</sub> gas cylinder, a mass flowmeter, a liquid solvent metering pump, the isothermal micro-calorimeter with the flow cells made by Calorimetry Sciences Corporation (CSC), a back pressure regulator, switch valve for online chromatographic analysis, the GC, and many thermocouples and pressure sensors. Specifications of some major equipment are given below.

Isothermal micro-calorimeter (IMC): The calorimeter is made by Calorimetry Sciences Corporation (CSC), and has the following specifications,

- **High Sensitivity:** Detectable Heat Effect 10  $\mu$ cal (40  $\mu$ Joules)
- **Response Time:** Raw Signal  $t=150$  sec, Deconvoluted Signal,  $t=15$  sec
- **Baseline Stability:** 0.25  $\mu$ cal/sec/hr (1  $\mu$ Watt)
- **Low Noise Level:**  $\pm 0.025$   $\mu$ cal/sec ( $\pm 0.1$   $\mu$ Watt)
- **Sample Well Size and Configuration:** Standard cylindrical dimensions: 3.81 cm dia. x 7.32 cm deep, four test wells of which one serves as the reference well.
- **Measurement Well Volume:** 15 ml to 150ml (custom sizes also available)
- **Temperature Stability:**  $\pm 0.0005^{\circ}\text{C}$  at  $25^{\circ}\text{C}$

The IMC is a heat flow design for the absolute maximum in sensitivity. The ultra-stable liquid bath yields superior operation over the entire temperature range. It is designed specifically to measure very slow or very small heat changes. Since virtually all chemical and physical processes are accompanied by changes in heat, the IMC is a universal detector that can be used to follow the progress of slow reactions at modest temperatures. The IMC can detect changes in heat flow as small as 25 nanocalories/sec (0.1  $\mu$ Watt) and heat effects as small as 10  $\mu$ cal (40  $\mu$ Joules) in the temperature range from  $-40$  to  $+80^{\circ}\text{C}$ . The IMC can provide both kinetic and thermodynamic information for almost any process occurring in any sample. The measurements are non-destructive and can be made on solid or liquid samples.

The measurements are done in four sample wells, of which one serves as a reference well. The instrument outputs represent the heat duties for the sample cells relative to the reference well for an isothermal operation. For our application two flow mixing cells (purchased from CSC) are used, one serves as the sample cell and the other one as the reference cell. A cross-section of the flow mixing cell is shown in Figure 1. The flow cell has two inlet tubes and one outlet tube each 1/16" OD. It is provided with a top access cover which acts as an insulator. The two inlet tubes run into the inlet flow thermal equilibration chamber where they coil around thereby increasing the residence time of the inlet fluids, and allowing for thermal equilibration at the desired temperature. At the exit of the thermal equilibration chamber, the tubes run into a thermal shunt. The shunt consists of a tee, the exit end of the tee goes into the flow heat exchanger which is the heat signal measurement zone. This line consists of concentric 1/32" and 1/16" OD

tubing, with the gas (CO<sub>2</sub>) flowing through the inner tubing and the liquid solvent flows through the annulus. At the bottom of the flow heat exchanger, the two fluids are mixed, the mixture flows through coiled tubing and exits the calorimetric well.

**Gas mass flowmeter:** The mass flowmeter ( model FMA-8503 made by Omega, Inc.) is used to accurately monitor and measure the flow rate of carbon dioxide gas. It has a flow range of 0 to 100 SCCM (standard cubic centimeters per minute), operating pressures upto 4500 psi, and operating temperatures from 4°C to 66°C. It has an accuracy of  $\pm 1\%$  full scale, and the flow sensor produces an output signal linear to the mass flow rate for use in recording and for control purposes.

**Solvent metering pump:** Lab Alliance Series II digital isochratic pump is used to pump the liquid solvent. It has a flow range of 0.01 to 9.99 ml/min, and a pressure rating 6000 psi.

**Gas chromatograph:** The liquid mixture at the exit of the calorimeter is periodically analyzed by an on-line gas chromatograph (GC) made by Agilent Technologies Inc. (model HP6890). The analysis is done using a packed column and thermal conductivity detector.

**Procedure:** A schematic of the experimental apparatus is shown in Figure 2. The liquid solvent is pumped at the desired rate by setting the metering pump, and carbon dioxide is introduced through the other inlet tubing with the desired flow rate set by the mass flowmeter. The calorimeter is set at the desired measurement temperature, and the pressure is set by the back pressure regulator and displayed by the digital pressure gage. The measurements are done in the sample cell with the reference cell kept empty. The calorimeter gives a signal in  $\mu\text{W}$  which is recorded. Once a stable signal is obtained, heat of mixing is easily calculated by dividing the signal by the molar flow rate of the mixture. Composition of the mixture is calculated from the inlet flow rates of the pure solvent and the CO<sub>2</sub> gas. For further check on the mixture composition, periodically mixture samples are analyzed by an on-line GC. At a fixed temperature and pressure, the liquid solvent flow rate is kept constant at about 1 ml/min and measurements are done at increasing flow rates of the gas starting at 5 SCCM, and in increments of 5 SCCM. As CO<sub>2</sub> composition in the mixture is increased, initially the heat signal is expected to increase. However beyond the solubility limit of CO<sub>2</sub> the heat signal should not change with further increase in the gas flow rate. At this point the measurements are stopped. Indirectly this also allows for an estimate of the solubility of CO<sub>2</sub> in the liquid solvent.

The apparatus has been pressure tested for leaks. MEA-CO<sub>2</sub> system has been chosen as the test system. Data for this system will be measured over a range of CO<sub>2</sub> compositions, at a single temperature of 25°C, and a fixed composition of aqueous solution. The measured data will be compared with the limited data available in the literature for this system. The data measurements have just begun, and will be completed in the next quarter of the project.

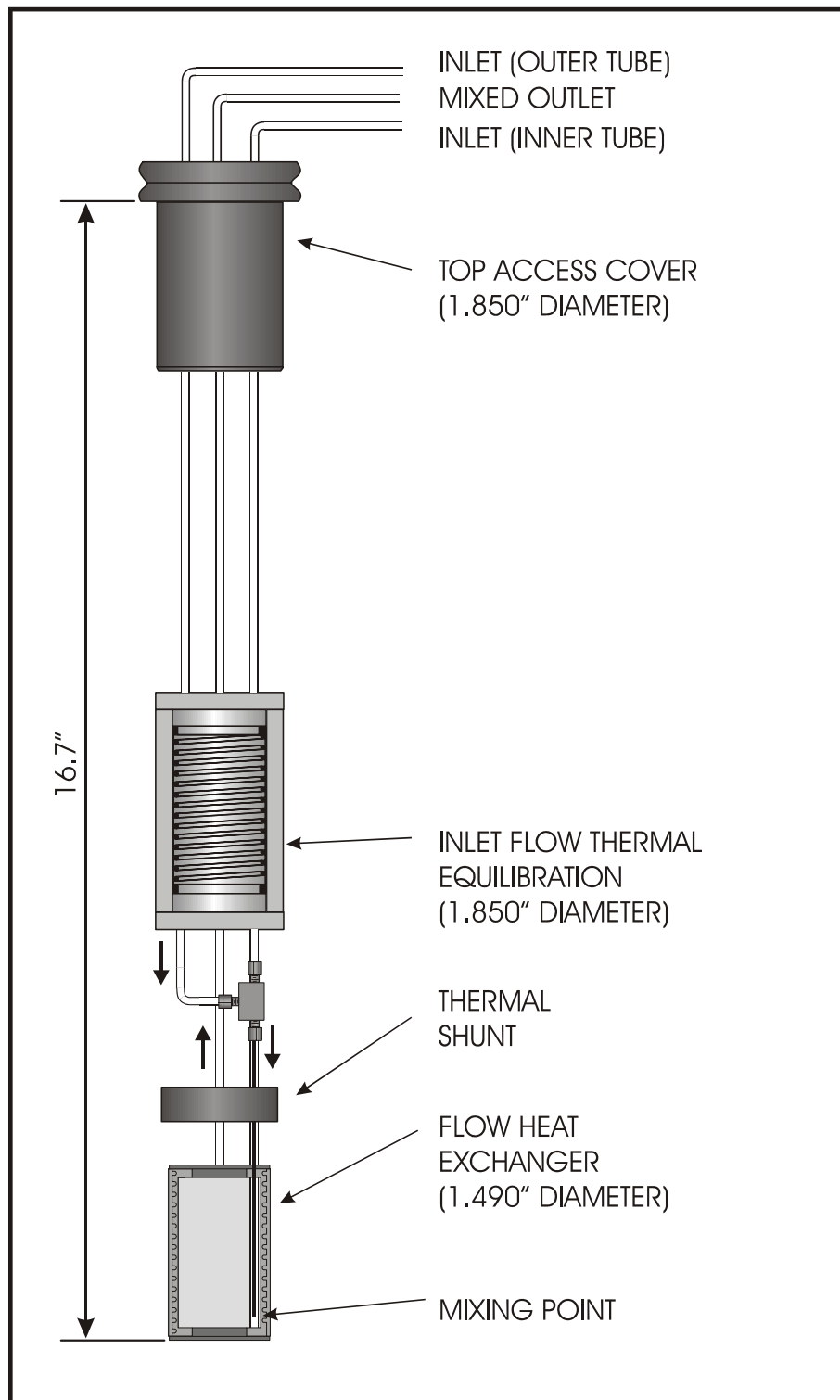


Figure 1. Diagram of a flow mixing cell.

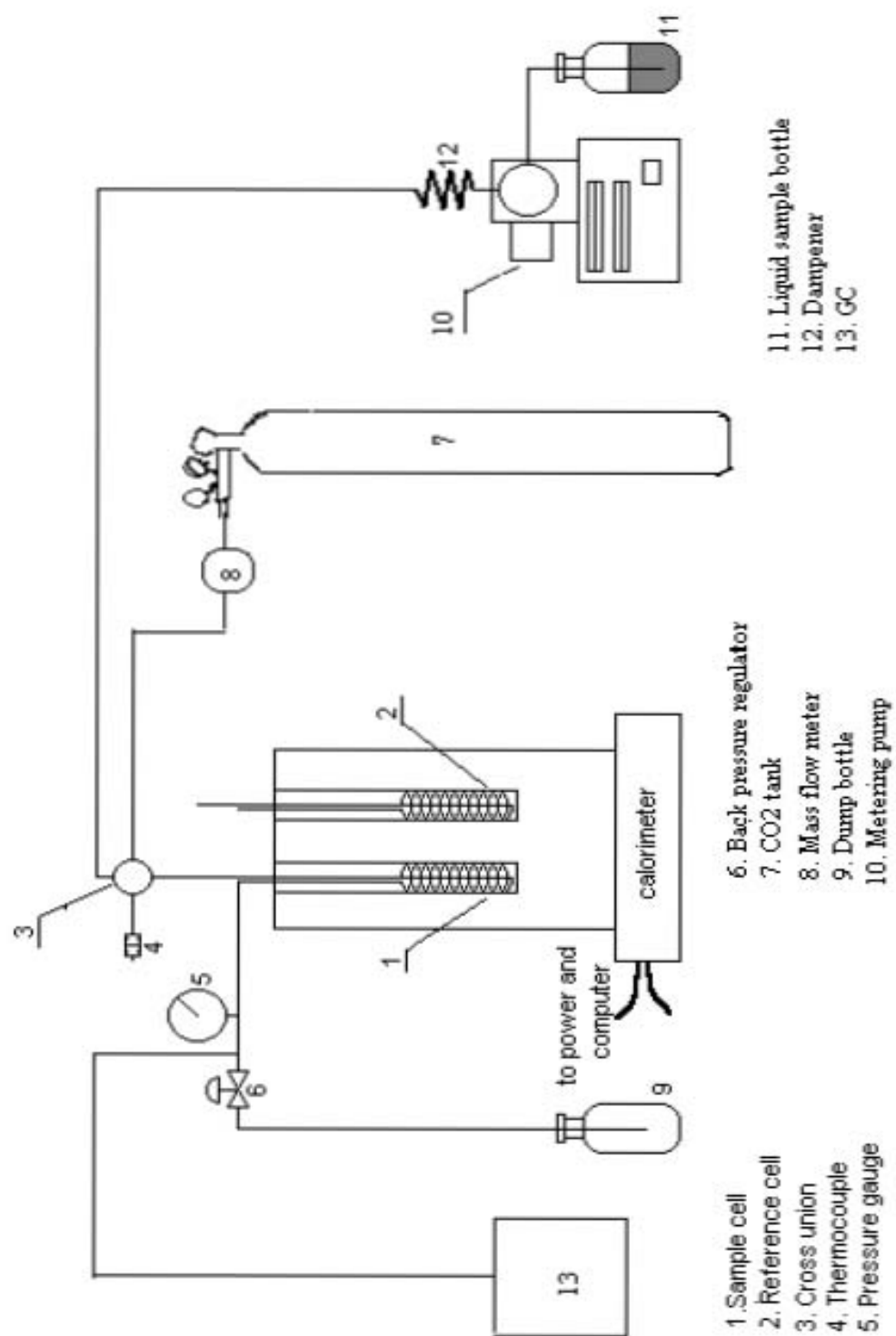


Figure 2: Experimental apparatus for heat of dissolution measurements.

## **LITERATURE DATA AND DESIGN OF EXPERIMENTS**

A thorough literature search was carried out for solubility and enthalpy data for mixtures of carbon dioxide and alkanolamines. The available data are listed in Tables 1 and 2. It is clear that extensive data are available for solubility of CO<sub>2</sub> in aqueous solutions of MEA, DEA, MDEA and their mixtures over a range of temperatures and compositions. Literature data also indicate that enhancement in solubility is obtained by use of additives especially piperazine and sulfolane. It is however clear from Table 2 that enthalpy data are relatively scarce. Data are available for heat of mixing of CO<sub>2</sub> at 25°C in aqueous solutions of MEA of three different compositions and a fixed partial pressure of the gas. Corresponding data in aqueous solutions of MDEA and DEA are available over a wider range of temperatures. Data at two temperatures 25°C and 40°C and fixed partial pressure of CO<sub>2</sub> are available for heat of mixing of the gas in aqueous mixtures of MDEA and piperazine. For a comprehensive analysis of the relative economics of solvents for application in CO<sub>2</sub> capture, more extensive data over a wider range of temperatures, solvent compositions, and gas partial pressures would be required. A detailed design of experiments involving solvents MEA, MDEA, piperazine and water is currently under way and will be completed in the next quarter of the project.

## **CONCLUSIONS AND PLANS FOR THE NEXT QUARTER**

During the first six months of the project, the experimental apparatus for the heat of dissolution of CO<sub>2</sub> in aqueous alkanolamine solvents has been designed and built. Experimental measurements for the CO<sub>2</sub>-MEA systems have been initiated. A thorough literature search for all solubility and enthalpy data for CO<sub>2</sub> in aqueous alkanolamine solvents has been completed and the data have been compiled.

During the next phase of the project, heat of mixing data for CO<sub>2</sub> in three compositions of aqueous MEA solutions at 25°C and over a range of gas compositions will be completed. A comprehensive design of experiments for future data measurements for heat of mixing of CO<sub>2</sub> in aqueous mixtures of MEA, MDEA, and piperazine will be completed and a timetable for all data measurements will be prepared.

***Table 1. Literature data for solubility of CO<sub>2</sub> in aqueous alkanolamine solvents***

<i>Aqueous Solvent</i>	<i>SCCM of CO<sub>2</sub></i>	<i>Temperatures (°C)</i>	<i>CO<sub>2</sub> Partial Pressure (kPa)</i>	<i>Reference</i>
<i>MEA (2.5 kmol/m<sup>3</sup>)</i>	14.952 – 37.856	40, 80	0.0934 – 228.7	1
<i>MEA (4.2 M)</i>	50.897 – 68.0198	100	455 – 3863	9
<i>MEA (15.3 wt %)</i>	31.4777 – 58.8594	40	15.7 – 2550	39
<i>MEA (15.3 wt %)</i>	0.9539 – 40.8481	40, 60, 80, 100, 120, 140	0.03 – 930.99	15
<i>MEA (30 wt %)</i>	12.7369 – 45.2247	40, 60, 80, 100	1.1 – 1975	39
<i>MEA (10, 20, 30 wt %)</i>	1.2934 – 4.7264	25	265	6
<i>MEA (15.2, 30 wt %)</i>	10.0851 – 91.4997	104, 140, 176, 200 212, 248, 274, 284	1.3332 – 2786.438	27
<i>MEA ( 30 wt %)</i>	0.2222 – 146.4361	0, 25, 40, 60, 80, 100, 120, 150	0.0012 – 19954	18
<i>DEA (50 %)*</i>	=====	25, 35, 45, 55	0 – 101.325	5
<i>DEA (4.2 M)</i>	28.1299 – 68.208	100	93 – 3742	9
<i>DEA (10, 20, 30 wt %)</i>	1.2875 – 4.6088	25	265	6
<i>DEA (10, 20, 30 wt %)</i>	12.3709 – 91.3309	100 – 200, 205	165.5 - 4137	25
<i>DEA (25, 50 wt %)</i>	9.9068 – 62.1571	100, 150, 175, 200, 225, 250	2.0 - 4373	27
<i>DEA (0.5, 2, 3.5, 5, 6.5, 8 N)</i>	0.5488 – 76.608	0, 25, 50, 75, 100, 120, 140	0.6895 – 6894.75	28
<i>DEA (30 wt %)</i>	25.8215 – 46.4661	40, 60, 80	4.85 – 357.3	38
<i>MDEA (2.0, 4.28 kmol/m<sup>3</sup>)</i>	0.2701 – 64.3301	40	0.0056 – 93.6	1

<i>MDEA (4.28 M)</i>	1.2463 – 3.0679	40	0.108 – 0.730	3
<i>MDEA (1.69, 4.28 M)</i>	1.2463 – 125.017	100, 140, 160, 180, 200	138 - 4930	7
<i>MDEA (4.28 M)</i>	8.7243 – 78.9026	100, 120	162 – 3832	9
<i>MDEA (3.954 mol/kg)</i>	74.771 – 110.0736	40	176.5 – 6469	22
<i>MDEA (7.994 mol/kg)</i>	22.559 – 206.6848	40, 80, 120	228 – 7565	22
<i>MDEA (2.0 mol/dm<sup>3</sup>)</i>	5.552 – 53.8944	40	1 - 370	31
<i>MDEA (30 wt %)*</i>	~ 0 – 78.9262	40, 60, 80, 100	100 - 20000	20*
<i>MDEA (30 wt %)</i>	4.4565 – 31.8569	40, 60, 80, 100	1.1 – 1979	39
<i>MDEA (50 mass %)</i>	0.8175 – 46.2564	25, 50, 75, 100	0.78 – 140.4	36
<i>MDEA (2, 4.28 kmol/m<sup>3</sup>)</i>	0.0166 – 82.1184	25, 40, 70, 100, 120	0.001 - 6630	17
<i>MDEA (3 M)</i>	63.2352 – 82.5216	25	2270 - 7080	19
<i>MDEA (4.28 kmol/m<sup>3</sup>)</i>	0.8724 – 84.4248	40, 55, 70, 80, 100	0.876 - 1013	40
<i>MDEA (3.46 kmol/m<sup>3</sup>)</i>	13.4857 – 65.7854	55, 70, 80, 90	115 – 992	40
<i>MDEA (3.04 kmol/m<sup>3</sup>)</i>	6.6666 – 62.0355	55, 70	6.152 – 806.8	40
<i>MDEA (30 wt %)</i>	28.7517 – 76.1074	40, 80, 120	2000, 5000, 10000	32
<i>MDEA (10, 20, 30 wt %)</i>	1.5034 – 4.7495	25	265	6
<i>MDEA (1.949 mol/kg)</i>	46.256 – 61.7568	40	837.4 – 4883	23
<i>MDEA (1.99, 1.95, 3.97 mol/kg)</i>	0 – 100.688	40, 60, 100, 120, 140	73.5 – 5036.7	26
<i>MDEA (35, 50 wt %)</i>	1.71 – 16.5745	25, 40, 80, 95, 100	354.6375 – 830.865	35
<i>MDEA (4.28M)</i>	5.3603 – 41.3056	30, 40, 55, 70	0.507 – 42.06	41
<i>MDEA (35 wt %)</i>	0.1315 – 52.2886	40, 100	0.004 – 262	16
<i>PZ (0.6 M)</i>	2.154 – 12.9024	40, 70	0.032 - 40	2
<i>PZ (1.995 mol/kg)</i>	28.8736 – 75.3984	40, 60, 80	13.3 – 8421	24
<i>PZ (2.035 mol/kg)</i>	24.8416 – 74.8608	60, 100, 120	155.6 – 9131	24
<i>PZ (3.964 mol/kg)</i>	75.242 – 120.2656	60, 80	42.8 – 9560	24
<i>PZ (3.950 mol/kg)</i>	44.3744 – 104.899	100, 120	175.6 - 8999	24

<b>MDEA + MEA</b>					
(2.0 + 2.0 kmol/m <sup>3</sup> )	6.7738 – 69.9776	40, 80	0.0506 – 312.9		1
(2.06 + 1.0 M)	22.6195 – 49.3517	100	134.8 – 1905		9
(3.4 + 0.8 M)	4.7936 – 84.7508	70, 100, 120, 140, 160, 180	190 – 3876		9
(2.1 + 2.1 M)	6.2317 – 87.9146	70, 100, 120, 140, 160, 180	137 – 3859		9
(24 + 6 wt %)	12.4143 – 68.1112	40, 60, 80, 100	1.12 – 2080		29
(12 + 18 wt %)	14.7898 – 78.0232	40, 60, 80, 100	1.37 – 1973		29
(18 + 12 wt %)	15.3332 – 73.7082	40, 60, 80, 100	0.9 – 2016		39
(6 + 24 wt %)	23.3334 – 84.2979	40, 60, 80, 100	1.5 - 1987		39
(27 + 7 wt %)	1.5169 – 4.7852	25	265		6
<b>MDEA + DEA</b>					
(2.0 + 2.0 kmol/m <sup>3</sup> )	2.1504 – 71.8592	40, 80	0.136 – 309.3		1
(3.4 + 0.8 M)	4.0266 – 87.3393	70, 100, 120, 140, 160, 180	65 - 3807		9
(2.1 + 2.1 M)	4.3142 – 88.9692	70, 100, 120, 140, 160, 180	224 - 3845		9
(15 + 10 wt %)	11.5248 – 66.0128	40	3.5 – 2612		13
(20 + 10 wt %)	15.5232 – 68.992	40, 120	2.8 – 2833.6		13
(10 + 20 wt %)	22.9130 – 90.2272	40	4.5 – 2377.1		13
(35 + 10 wt %)	29.3238 – 88.5651	40	3.8 – 2638.3		13
<b>MDEA + PZ</b>					
(4 + 0.6 M)	0.6182 – 29.3664	40, 70	0.033 – 7.48		3
(1.53 + 0.17 kmol/m <sup>3</sup> )	14.737 – 37.3184	50, 70	21.18 – 688.8		30
(1.35 + 0.35 kmol/m <sup>3</sup> )	13.2899 – 36.3664	50, 70	17.6 – 586.9		30
(3.15 + 0.35 kmol/m <sup>3</sup> )	11.5248 – 66.0128	30, 50, 70	16.73 – 573		30

<i>(2.8 + 0.7 kmol/m<sup>3</sup>)</i>	15.5232 – 68.992	30, 50, 70	15.6 – 935.3	30
<i>(4.77 + 0.53 kmol/m<sup>3</sup>)</i>	22.9130 – 90.2272	50, 70	35.83 – 753.7	30
<i>(3.75 + 1.55 kmol/m<sup>3</sup>)</i>	29.3238 – 88.5651	50, 70	13.16 – 678.3	30
<i>(4.28 + 0.103, 0.308, 0.696 kmol/m<sup>3</sup>)</i>	0.3737 – 2.5778	104	8.722 – 9.297	40
<i>(3.46 + 0.103, 0.154, 0.206 kmol/m<sup>3</sup>)</i>	0.3147 – 0.4704	103	8.196 – 8.591	40
<i>(1.72 + 0.103, 0.154, 0.206 kmol/m<sup>3</sup>)</i>	0.2861 – 0.4289	101	7.148 – 7.537	40
<i>(1.975 + 1.966 mol/kg)</i>	56.5824 – 100.307	80	180.7 – 6400	24
<i>(4 + 0.6 M)</i>	0.1546 – 32.0454	22, 40, 70	0.015 – 27.3	4
<i>(4.21 + 0.1, 0.041, 0.21 M)</i>	8.4672 – 47.8912	30, 40, 55, 70,	3.307 – 69.43	41
<i>(3.04, 1.75 + 0.1 M)</i>	11.0835 – 36.8256	40	4.51 – 32.14	41
<b>MDEA + SULFOLANE</b>				
<i>(20.9 + 30.5 wt %)</i>	1.8852 – 61.5442	40, 100	0.43 – 5770	31
<b>MDEA + H<sub>2</sub>SO<sub>4</sub></b>				
<i>(1.989 + 0.9936 mol/kg)</i>	4.032 – 22.848	40, 60, 100, 120, 140	190.5 – 10607	23
<i>(3.992 + 0.9862 mol/kg)</i>	3.853 – 56.672	40, 80, 120	172 - 2530	23
<b>MDEA + Na<sub>2</sub>SO<sub>4</sub></b>				
<i>(1.968 + 1.009 mol/kg)</i>	36.96 – 53.6704	40, 60	128.7 – 4294	23
<i>(1.952 + 0.9933 mol/kg)</i>	3.127 – 46.0544	100, 140	331.5 - 4536	23
<b>MEA + N-methylpyrrolidone</b>				
<i>(15 wt %) non - aqueous</i>	14.3837 – 81.0668	25, 50, 100	33.8 – 2178.9	11
<b>MEA + Sulfolane</b>				

<i>(15, 30 wt %)</i>	13.066 – 94.3216	30, 50, 100	1.5 – 2210.5	12
<i>DEA + N-methylpyrrolidone</i>				
<i>(15, 30 wt %) non - aqueous</i>	1.8071 – 91.5283	25, 50, 100	24.2 - 2211	11
<i>DEA + 2-amino-2-methyl-1-propanol</i>				
<i>(25 + 5 wt %)</i>	20.9321 – 63.9148	40, 100	162 – 2908	13
<i>(20 + 10 wt %)</i>	17.6298 – 53.2623	40, 100	22 - 2597	13
<i>(6 + 24 wt %)</i>	3.3491 – 10.35419	40, 60, 80	1.61 – 269.9	38
<i>(12 + 24 wt %)</i>	8.7691 – 19.1233	40, 60, 80	11.0 – 364.9	38
<i>(18 + 12 wt %)</i>	13.1536 – 28.6849	40, 60, 80	3.8 – 357.3	38

Table 2. Literature data for Heats of mixing of CO<sub>2</sub> in aqueous alkanolamine solvents

<i>Aqueous Solvent</i>	<i>Type of Data</i>	<i>Temperatures (°C)</i>	<i>CO<sub>2</sub> Partial Pressure ( kPa )</i>	<i>Reference</i>
<i>MEA (10, 20, 30 wt %)</i>	Enthalpy	25	265	6
<i>MDEA (10, 20, 30 wt %)</i>	Enthalpy	25	265	6
<i>MDEA (20, 40, 60 wt %)</i>	Enthalpy	15, 60, 115, 149	156 -1121	33
<i>MDEA (30 wt %)</i>	Enthalpy	40, 80, 120	2000, 5000, 10000	32
<i>DEA (10, 20, 30 wt %)</i>	Enthalpy	25	265	6

<i>DEA (2.0, 3.5, 5.0 M)</i>	Enthalpy	25, 70	1121	34
<i>DEA (2.0, 3.5, 5.0 M)</i>	Enthalpy	25, 50, 75	=====	21
<i>DGA (10, 20, 40, 60 wt %)</i>	Enthalpy	15, 60, 115, 149	156, 225, 570, 1121	8
<i>MDEA + MEA</i>				
<i>(27 + 7 wt %)</i>	Enthalpy	25	=====	6
<i>MDEA + Sulfolane</i>				
<i>(20 + 10 wt %)</i>	Enthalpy	25, 40	295	37
<i>(20 + 20 wt %)</i>	Enthalpy	25, 40	295	37
<i>(20 + 30 wt %)</i>	Enthalpy	25, 40	295	37
<i>(10 + 10 wt %)</i>	Enthalpy	25, 40	295	37
<i>(30 + 30 wt %)</i>	Enthalpy	25, 40	295	37
<i>MDEA + PZ</i>				
<i>(18.7 + 10 wt %)</i>	Enthalpy	25, 40	295	37
<i>(30 + 10 wt %)</i>	Enthalpy	25, 40	295	37

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