Study On The Solubility And Foaming Of CO$_2$ In Aqueous Amine Solutions

by

Norlizayani Mohamad Akhir

Dissertation submitted in partial fulfillment of

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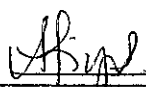
CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

July 2005

i

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NORLIZAYANI MOHAMAD AKHIR

ABSTRACT

The desire to alleviate the problem of global warming has resulted in environmental concern over a reduction of greenhouse emission especially CO_2 from industrial sources. The removal of CO_2 from natural gas purification and petrochemicals manufacturing is a very important operation in industry. Absorption with amine-based absorbents is the most common technology for CO_2 removal today. In view of this, many research works have been done to determine the CO_2 solubility in different types of amines at different temperatures and pressures and to identify the way to reduce its operational problems such as foaming. The objectives of this experimental based project, 'Study on the solubility and foaming of CO_2 in aqueous amine solutions' are to determine the CO_2 loading capacity in selected single and mixed amine solutions at different temperatures and foaming tendency of CO_2 absorption in amine solutions. This study focused on the CO_2 solubility in primary, secondary and tertiary amines and also mixture of these amines with variation of temperature and concentration. The method used for the solubility test is by directing the CO_2 and N_2 gas into the conical flask that contains amine solution and the outlet gas is analyzed by IR Gas Analyzer to determine the CO_2 slippage. In the foaming test, a small amount of petrol as the source of contaminant is added into the amine solution. The height of the foam and its foaming phenomena are considered. The amine solution with highest loading CO_2 capacity and the effects of temperature, concentration, concentration ratio and foaming can be determined from the results. Mixed amine gives the highest loading capacity compared to the single amines. For the temperature ranging from 25-40°C the absorption capacity increases as the temperature increases. Within solvent concentration of 10-30 weight percent (wt%), the absorption capacity is increased at higher solvent concentration. Primary amine has the highest foaming tendency compared to the secondary and tertiary amines.

AKNOWLEDGEMENT

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

CO_2	Carbon Dioxide
MEA	Methylethanolamine
DEA	Diethanolamine
MDEA	N-methyldiethanolamine
DGA	Diglycolamine
DIPA	Diisopropanolamine
H_2S	Hydrogen Sulfide
HCO_3^-	Bicarbonate Ion
COS	Carbon Oxysulfide
CS_2	Carbon Disulfide
O_2	Oxygen
IR	Infra Red
wt%	Weight Percent
vol%	Volume Percent
N_2	Nitrogen

CHAPTER1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Removal of acidic gases such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S) is an important industrial operation. CO_2 is produced in large quantities by many important industries such as fossil-fuel-fired power plants, steel production, chemical and petrochemical manufacturing, cement production and natural gas purification. The reasons for the CO_2 removal are traditionally technical and economical concerns. CO_2 present in natural gas will reduce the heating value of the gas and as an acid component it has the potential to cause corrosion in pipes and process equipment and also to cause catalyst poisoning in ammonia synthesis.

In the past decades, CO_2 removal from flue gas streams started as potentially economics source of CO_2, mainly for enhanced oil recovery operations. Capturing CO_2 from a power plant is already commercial process. More than a dozen capture plants exist worldwide, with the CO_2 being sold in the commercial markets. CO_2 is significant for other industrial applications such as carbonation of brine, welding as an inert gas, food and beverage carbonation, dry ice, urea production, and soda ash industry[1].

However, environmental concerns, such as the global climate change, are now focused as one of the most important and challenging environmental issues facing the world community, and have motivated intensive research on CO_2 capture and sequestration. The Kyoto protocol and other political and diplomatic initiatives will ultimately require

1

significant reduction of CO_2 emissions to minimize their impact on global climate[2]. CO_2, one of the greenhouse gases is currently responsible of over 60% of the enhanced greenhouse effect, methane (CH_4) contributes 20% and the remaining 20% is caused by nitrous oxide (N_2O), a number of industrial gases and ozone. Scientific evidence strongly suggests that the increase in level greenhouse gases may lead to higher temperature, and cause climate change on a global scale. Various climate models estimate that the global average temperature may rise about 1.4-5.8°C by the year 2100[1]. Hence, the reduction of CO_2 emissions from the industrial operation is considered to be the most urgent to slow down the global warming trend. Several alternative strategies have been proposed to reduce the emission of CO_2 into the atmosphere. These strategies include fuel alternative, energy conservation and improving power generation efficiency. However their implementation may have a limited impact on the reduction of CO_2. Therefore, various technologies have also been tested to remove and recover CO_2 from flue gas streams[3]. With current technologies, CO_2 separation can be performed by several approaches including absorption into liquid solvents, adsorption on solids, permeation through membranes, and chemical conversion. For removing CO_2 from high volume gas stream, absorption into liquid solvents is the suitable process approach.

The chemical absorption process is based on reactions between CO_2 and the liquid absorbent. Commonly in the chemical absorption process for CO_2 recovery, CO_2 is removed from a gas stream into an absorbent. CO_2-rich absorbent is regenerated in a desorption column (or stripper) by raising the temperature and returned to the absorber (closed-loop process)[4]. Absorption with amine-based absorbents is the most common technology for CO_2 removal today and has been existing for more than 70 years[5]. The conventional alkanolamines absorbents used in industries include monoethanolamine (MEA), diethanolamine (DEA), diisopropanolamine (DIPA) and methyldiethanolamine (MDEA). Although conventional chemical absorption techniques are widely used for removal of CO_2 from gas stream, they must be improved in term of energy saving and minimal cost. The disadvantages of this technique are problems of corrosion,

degradation of absorbents and limited loadings. Currently, there are many research works done to improve the performance of conventional amines and determine the ability of other amines to remove CO_2. Recently, the new class of amines, sterically hindered amines 2-amino-2-methyl-1-propanol (AMP), has been introduced as commercially attractive absorbent over conventional amines for its advantages in absorption and stripping[6].

1.2 PROBLEM STATEMENT

Currently, the desire to alleviate the problem of global warming has resulted in the environmental concern over a reduction of greenhouse gas emissions from industrial sources. Among these greenhouse gasses, CO_2 is the primary contributor to the problem due to its abundance, and is thus a major target of reduction. The solubility and absorption of acid gases in aqueous solutions becomes a high industrial importance and many research works have been done regarding this issue. Aqueous alkanolamines solutions are frequently used for removal of acid gases such as CO_2 and H_2S from gas stream in natural gas, synthesis, and refinery industries. However the chemical reaction between the acid gases and component of aqueous solution contribute many operational problems such as corrosion, fouling and foaming that can reduce the effectiveness of the process equipments. Foaming will reduce the efficiency of CO_2 absorption in amine solutions. In view of this, this project investigates on the solubility and foaming of CO_2 in aqueous single and mixed amine solutions.

1.3 OBJECTIVE AND SCOPE OF STUDY

i. To determine the CO_2 loading capacity in single amine solutions (primary, secondary and tertiary amines)
ii. To determine CO_2 loading capacity in mixed amine solutions.

3

iii. To investigate the effect of different temperatures on absorption of CO_2 in amines solutions

iv. To determine the effect of foaming in CO_2 absorption

This study is an experimental based project that requires experiment works on some samples of single and mixed amines. From the experiment, the amounts of the CO_2 being absorbed into the amine solution at different temperatures can be determined using the gas analyzer. Meanwhile, the effect of foaming only can be determined by introducing some impurities into the solutions. The experiments for the effect of temperatures and foaming are conducted separately.

This study is relevant since the absorption and solubility of CO_2 in aqueous amine solutions has becomes one of the important issues in various industries. Therefore, there are many research works done at the moment to determine the ability of amines solutions to remove CO_2 and to find out the way to minimize the operational problems as stated in the problem statement. From this experiment the characteristics of solubility and foaming of CO_2 in aqueous amine solutions in smaller scale can be determined.

The main challenge in this study is the limited time frame since there are many samples need to be tested and each run requires quite some times to stabilize. Some modifications to the experiments have been done to obtain better results.

CHAPTER 2

LITERATURE REVIEW

In recent years, the importance of chemical absorption process rises as a competitive process to reduce the discharge CO_2 into atmosphere. At the meantime, aqueous alkanolamines solutions are the most widely used solvents for the gas absorption process. CO_2 absorption with a chemically reacting solvent involves mass-transfer with chemical reaction. The role of the chemical reaction is to speed up the mass-transfer rate as well as to provide greater solvent loading capacity at lower CO_2 partial pressure conditions. The reaction between dissolved CO_2 and amine is reversible and proceeds through a series of reactions. In general, the chemical reaction proceeds forward in the absorption direction under low temperature and high partial pressure conditions. Ideally, higher reaction rate constants for both the forward and the reverse reactions are favorable. This will allow the absorption and regeneration to be accomplished within as short time frame as possible. With current technologies, CO_2 separation also can be performed by several approaches including absorption on solids, permeation through membranes, chemical conversion cryogenic separation and biological fixation. However, for removing CO_2 in high volume, absorption into liquid solvents is a suitable process approach[4].

2.1   Absorption Process

Although there are many different types of amines and different configurations for an amine sweetening facility, the fundamental process is the same in nearly all cases. Some complex facilities may include series and parallel configurations for economic advantages.

Figure 2.1 represents a simple amine treating facility that contains the main equipments, absorber and stripper. Sour gas (H_2S or CO_2) is introduced in the absorber where it contacts lean amine solution traveling down the column. The acid gas components, H_2S and CO_2, are absorbed by the amine solution and the sweet gas leaves the absorber for further processing. The rich amine is sent to a flash tank and absorbed hydrocarbons exit as the flash-tank vapor. The rich amine flows through the lean/rich exchanger increasing the temperature to about 377.7K (104°C). The hot rich amine is stripped at low pressure removing the absorbed acid gases, dissolved hydrocarbons, and some water[7].

The energy required to strip the amine is the sum of the sensible heat required to raise the solution temperature, the energy of absorption, and latent heats. Stripping columns should be operated at a high pressure as possible to increase the reboiler temperature for optimum stripping. However, the amine degradation temperature should not be exceeded. The stripped or lean amine is sent back through the lean/rich exchanger decreasing its temperature. A pump boosts the pressure such that it is greater than the absorber column. Finally, a heat exchanger cools the lean solution before completing the loop back to the absorber. The lean amine entering the absorber is usually 322.2K (49°C)[7].

The same configuration is applied to the three CO_2 removal plants in PETRONAS Fertilizer Kedah, PFK (an integrated Ammonia and Urea Plant) where the absorber with the absorbent solution is used to remove the CO_2 from the natural gas (NG) feed. The stripper then regenerates back to CO_2 rich solution by strip out the CO_2 from solution by introducing heat. The CO_2 will remove from the top of stripper while the lean solution will recycle back into the absorber. In PFK the three CO_2 removal plants play the different roles although they used the same absorption principal, CO_2–alkanolamines absorption.

The first unit is the Feed Gas CO_2 Removal Unit that used to remove the CO_2 to a low level from the NG feed before entering the furnace (the natural gas is mixed with the process steam and heated up to 535°C). High CO_2 present in natural gas will reduce the heating value of the gas thus require high fuel consumption to crack the hydrocarbon gas and as an acid component it has the potential to cause corrosion in pipes and process equipment. This unit uses the Ucarsol AP 814-MDEA based solvent as the absorbent. The second unit is the Flue Gas CO_2 Removal Unit which removes the CO_2 in flue gas from the radiant section of the furnace. Although this unit only removes low CO_2, it is important for environmental purpose to recover the CO_2 rather than vent to the atmosphere. This unit uses sterically hindered amine KS-1 solution as the absorbent. The third unit is the CO_2 removal plant that uses the Benfield solution (hot potassium carbonate with DEA as the activator) as the absorbent. This unit removes the CO_2 from the process gas to protect the ammonia synthesis catalyst in the downstream that sensitive to the oxide component. The CO_2 removed from this unit is combined with the CO_2 removed from Flue Gas CO_2 Removal Unit and sent as the feed for the Urea plant. These three CO_2 removal units in the same plant show its role of importance in industries[8].
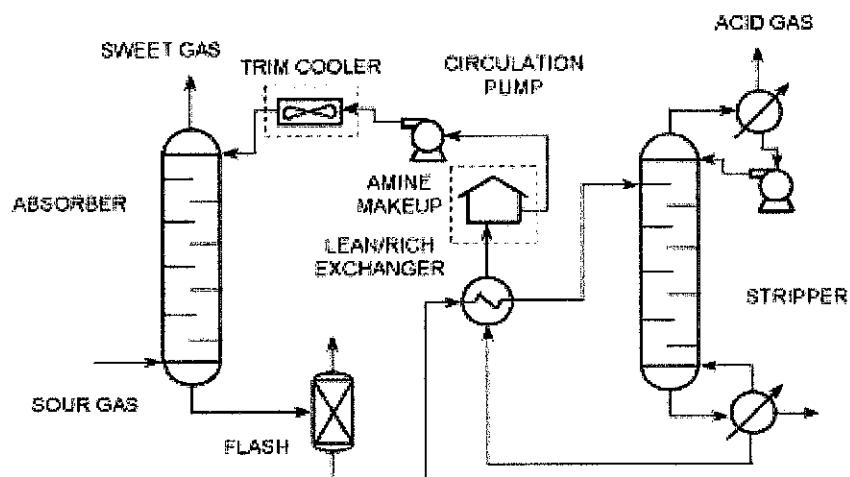
Figure 2.1: Schematic diagram of simple amine sweetening plant

2.2 Types of alkanolamines absorbents

Solutions of alkanolamines are the industrially important classes of compound used in the natural gas, petroleum chemicals plants, and ammonia industries for removal of CO_2 and H_2S from gas streams. The alkanolamines most commonly used in industrial applications are monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA), and diglycolamine (DGA). The alkanolamines are classified by the degree of substitution of hydrogen atom on the central nitrogen; a single substitution denoting primary amine, a double substitution, secondary amine, and triple substitution, a tertiary amine as in Figure 2.2. Each of the alkanolamines has at least one hydroxyl group and one amino group[9].

In general, the hydroxyl group serves to reduce the vapor pressure and increase the water solubility, while the amino group provides the necessary alkalinity in water solutions to promote the reaction with acid gases. It is readily apparent looking at the molecular structure that the non-fully substituted alkanolamines have hydrogen atoms at the non-substituted valent sites on the central nitrogen. This structural characteristic plays the important role in the acid gas removal capabilities of the various treating solvents. The other types of amine that used in research for CO_2 removal are 2-amino-2-methyl-1-propanol (AMP) and 2-amino-2-ethyl-propanediol (EPD) as the primary amine, Piperazine (PZ) the secondary amine and triisopropanolamine (TIPA) as the tertiary amine[9].

MEA and DGA are primary amines. MEA with one ethanol group attached to the basic nitrogen atom is the strongest amine. It reacts quickly with both H_2S and CO_2, forming strong but regenerative chemicals bond[7]. MEA is effective at removing virtually all H_2S and CO_2, but requires a large quantity of heat to regenerate, break the chemical bonds. MEA is used when the specification requires maximum H_2S and CO_2 removal,

8

particularly at low pressure. MEA reacts with carbonyl sulfide and carbon disulfide, forming non-regenerative degradation products[3].
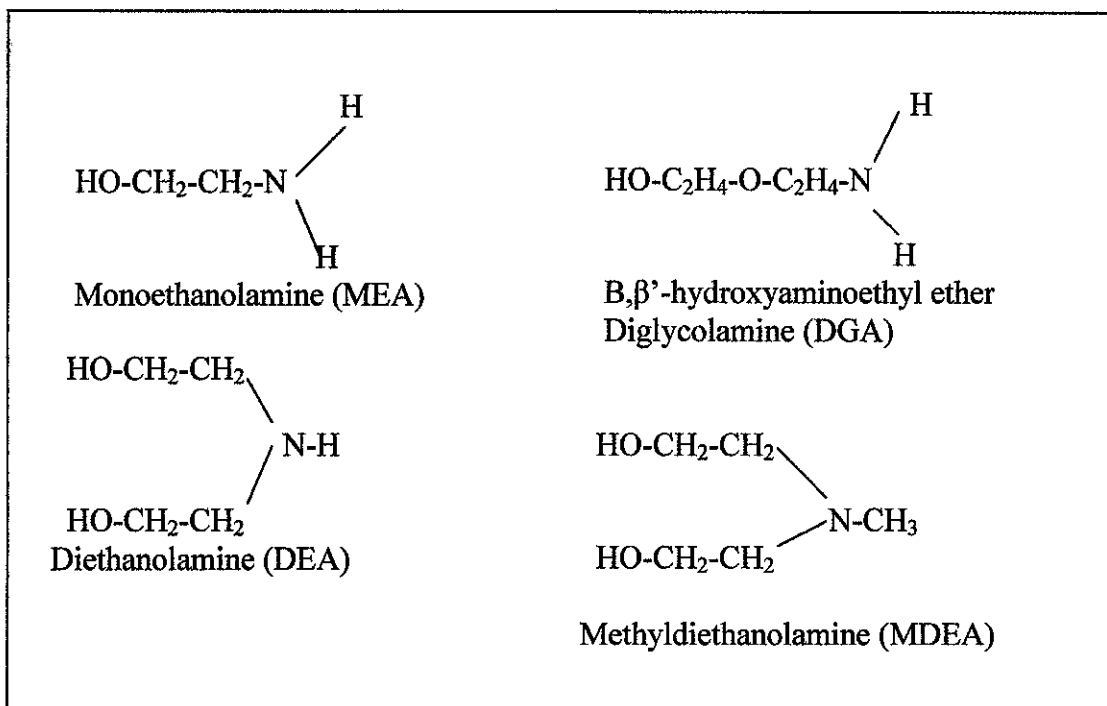
Figure 2.2: Structure of alkanolamines most commonly used in industrial applications

Although MEA have the properties of high reactivity, low solvent cost, ease of reclamation and low absorption of hydrocarbons, the cost of MEA process is prohibitively high mainly due to a significant amount of energy required for solvent regeneration and severe operation problem including corrosion and solvent loss. The high cost of MEA process leads to considerable efforts to find an alternative solvent that offers significant cost-saving and makes the CO_2 capture economically available. Table 2.1 shows that MEA has the higher heat of reaction that indicates it higher heat requirement.

Table 2.1: Heat of reaction of acid gases[10]

	Heat of Reaction (kJ/kg)	
Amines	H_2S	CO_2
MDEA	450	577
DEA	493	650
MEA	650	820

DEA and diisopropylamine (DIPA) are secondary amines with two ethanol groups or two isopropanol groups, respectively attached to the nitrogen atom. The additional alcohol groups draw more of free electrons character away from the nitrogen atom, which makes the secondary amines somewhat weaker bases. Secondary amines are suited with for gas steam with less stringent product specifications. DEA is used when the specification allows for some CO_2 to be left in the treated gas. DEA does not form non-regenerative degradation products with carbonyl sulfide which makes it a suitable choice for treating refinery gases. DIPA is used almost exclusively in refinery operation to remove carbonyl sulfide and H_2S [9].

MDEA and TEA are tertiary amines. MDEA has two ethanol groups attached to the nitrogen atom, along with a methyl group. MDEA is a weak base that react much faster with H_2S than with CO_2 making it particularly selective under proper design conditions. MDEA can also be used non-selectively for bulk removal of CO_2 from gas stream, but bulk removal required the aid of absorption enhancing additives[9]. Tertiary alkanolamines show high absorption capacity towards the acid gases, are selectively towards the H_2S and do not present the reaction which produces the carbamate. Thus reducing the foaming, corrosion and fouling in equipment used in industrial process for the purification of hydrocarbon rich gas steams[11]. Those properties give a positive global effect that the amount of aqueous solution of tertiary amine utilized in the process is substantially lower than the amount employed in the process using aqueous

solution of primary and secondary alkanolamines. Therefore the quantity of energy employed in the process, mainly in the solvent regeneration after the absorption with acid gases, is substantially reduced. As a result, the operating costs are lower.

Recently, the use of mixtures of alkanolamines, a solution of two or more amines in varying concentration, has shown to produce absorbent with excellent absorption characteristics as well as superior stripping qualities[12]. Mixtures of alkanolamines combine the absorption characteristics of the constituent amines such as a higher loading capacity, faster reaction rates and lesser energy requirements for regeneration. However reported experimental data on the solubility of acid gases in mixtures alkanolamines are not plentiful. There exist some data on mixture of two and three alkanolamines.

The CO_2 loading capacity in various amine solutions has been analyzed to determine and model the gas solubility in different types of amines solutions and their mixtures. Gas absorption using alkanolamines appears to be the best available technology for capturing CO_2 from low pressure industrial gas streams. MDEA is a promising choice of absorption solvents since it reacts with CO_2 at a fast rate and the cost of raw material is relatively low compared to other alkanolamines.

At present, use of blended-alkanolamines is of great interest in several acid gas treating applications such as Natural Gas purification. Blending of primary or secondary alkanolamines with a tertiary alkanolamines in a certain proportion offers number of advantages over single-alkanolamines and allows custom formulation to meet specific acid removal targets. The most common blend is the mixture of MEA-MDEA and DEA- MDEA. The blends combine the favorable feature of MDEA (higher equilibrium absorption capacity and lower energy requirement for solvent regeneration) with the favorable feature MEA or DEA (higher reaction with CO_2)[13].

2.3 Reaction mechanism in amines

It should be noted that CO_2 absorption in aqueous solution of alkanolamines have two steps. First CO_2 molecules physically dissolve in water and then, these CO_2 molecules chemically react with alkanolamines species in the solution. The reactions between CO_2 and alkanolamines solution have been described by the Zwitterion mechanism. In aqueous solution of primary and secondary alkanolamines the following reactions with CO_2 occur. Reaction (1) indicates the overall reaction and carbamate formation, (RR'NCOO⁻).

$$CO_2 + 2RR'NH \rightleftharpoons RR'NCOO^- + RR'NH_2^+ \qquad (1)$$

Where R is alkyl and R' is H for primary amines and alkyl group for secondary amines.

$$CO_2 + RR'NH \rightleftharpoons RR'NH^+COO^- \qquad (2)$$
$$RR'NH^+COO^- + B' \rightarrow RR'NCOO^- + B'H^+ \qquad (3)$$
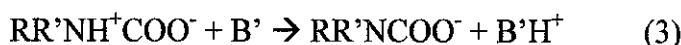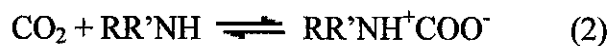
The zwitterion mechanisms comprises two steps, namely, formation of the CO_2-amine zwitterion (reaction (2)), followed by base catalyzed deprotonataion of this zwitterion (reaction (3)). Here B' is base which could be amine, OH^- or H_2O. Thus the equilibrium loading capacity for primary and secondary alkanolamines are limited by stoichiometric of reaction (1) to 0.5 mol CO_2/mol of amine.

For normal primary and secondary, such as MEA and DEA, the carbamate formed (reaction (1)) are quite stable[6]. For tertiary amine which does not have any hydrogen atom attached to the nitrogen atom, the CO_2 reaction can only occur after the CO_2 dissolves in water to form bicarbonate ion. The bicarbonate ion then undergoes an acid-base reaction with amine to yield the overall CO_2 reaction:

$$CO_2 + RR'R''N + H_2O \rightleftharpoons RR'R''NH^+ + HCO_3^- \qquad (4)$$

12
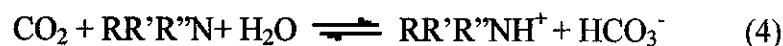
2.4 Foaming

The cause of foaming has invariably been particulates, which can be either produced internally or introduced into the system and contaminate the solution. Foaming also reduces the mass transfer efficiency in the contactors and increases the acid gas content of the treated gas leaving the contactors. Normally the amine processes are cycles of absorption and desorption in order to optimize the use of the absorbent. Due to the closed loop nature of these processes, non-regenerable contaminants tend to accumulate and can cause major reduction in the efficiencies of the absorption column and further give rise to operational problems. High contaminants levels usually increase the viscosity of amine solutions which reduces the mass transfer rates in the absorber and stripper. Higher viscosity also increases the foaming tendency in the solutions[14].

Contaminants in amine solutions can arise from various sources and usually exist in several different forms. Although a single contaminant may necessitate a certain plan of action, gas treating solutions rarely contain only one or two impurities. Amine solutions frequently become contaminated with amine degradation products, heat stable salts, heavy hydrocarbons and particulates. Instead, many different impurities exist in varying concentrations, many of which have some adverse effect on the process.

2.4.1 Sources of impurities

1. Amine Degradation Products

Although the acid gas-amine reactions are reversible, irreversible reactions may also occur, resulting in products from which the amines are not easily recovered. This phenomenon is called degradation.

Amines may be degraded through the following routes:

1. Thermal degradation

2. CO_2 induced degradation

3. Degradation caused by COS and CS_2

4. Degradation by carbon monoxide

5. Amine loss through the formation of heat stable salts and the reaction of amines with strong acids

6. Oxidation

7. Sulfur and polysulfide degradation

2. Suspended solid

Non-volatile contaminants arise from diverse sources such as gas wells or make up water. Other common types of non-volatile contaminants are particulates, which may be carried into the amine solution by the raw feed gas. Iron sulfide is very common and undesirable, usually because of its potential to stabilize foams or enhance foaming tendencies. Solid contaminants of any type can decrease the efficiency of the absorber and stripper by plugging contactor trays, contactor packing and process piping. One solution is to use filter cartridges with very small pore sizes inside the inlet separators to catch the very fine particles whose average diameters are sometimes smaller than 5 microns. However, some particles can pass through the most efficient filter cartridges[14].

3. Hydrocarbons

At the high pressure and low temperature prevailing in the absorption tower, heavy hydrocarbons and even some lower boiling constituents of the feed gas are dissolved in the amine solutions. Most of the low boiling hydrocarbons are flashed off in the flash drum or are removed in the stripping tower. However, the heavy hydrocarbons tend to stay in solution and pose another form of contamination in amine solutions.

14

4. Other Contaminants

In addition to the aforementioned impurities, other contaminants may exist in the amine solutions such as anti-foaming agents, sealants, lubricants and corrosion inhibitors. Despite their low concentration in amine solutions, they may accumulate over time and affect the overall solution efficiency and plant performance.

2.4.2   Foaming causes fouling

The presence of particulate matter, which exacerbates foaming, may lead to severe fouling in heat exchanger and accumulation on the contactor and stripping tower internals. Furthermore, hydrocarbon contaminants cause changes in interfacial tension which may stabilize amine foams. In extreme cases, this can cause significant pressure drops across the contactor and amine entrainment. Foaming also reduces the mass transfer efficiency in the contactors and increases the acid gas content of the treated gas leaving the contactors. Activated carbon filtration is often used to contain hydrocarbon contamination, but heavy hydrocarbons are difficult to remove (especially when the pore size of the carbon is too small to capture the molecules). Mechanical filtration can be used to deal with coarse fines. However some fines are so small that conventional filtration media cannot capture them. Leaving such fine particulates in solution can lead to fouling of heat transfer surfaces, which in turn lowers, their efficiencies[10].

2.5   Corrosion

Several types of corrosion can result from contaminated amine solutions. In the case of increased circulation rates, erosion corrosion may occur which is physical wearing away of metals by the abrasive action of either suspended solids or extremely high fluid velocities in restricted areas. Fouling which causes solid deposition or scaling may result crevice corrosion. Concentration cells can be set up beneath the deposit or scale

15

leading to high localized corrosion rates. Some degradation products such as ethylenediamine are suspected to be very corrosive due to the formation of iron complexes. Chlorides entering the plant via poor inlet filtration or cooling water exchanger leaks can accelerate pitting corrosion in stagnant areas. High levels of heat stable salts contribute significantly to the corrosion rates found in amine units. Corrosion rate depends on of type and quantity of amine salt present[14]. The corrosion rates for certain alkanolamines concentration are as given in Table 2.2. The solvents are more corrosive at higher concentration. The MDEA has the slowest corrosion rate while the MEA is the fastest.

Table 2.2: Corrosion Rate for different wt % of solvent[10]

Solvent	Corrosion Rate *(mm/a)
30% wt MEA	0.81
50% wt DEA	0.64
15% wt MEA	0.33
20% wt DEA	0.20
50% wt MDEA	0.08

*(mm/a) = millimeter per annual

16

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 Experiment on the solubility of CO_2 in aqueous amine solutions at different temperatures

Firstly, the IR Gas Analyzer is calibrated with N_2 to ensure that there is no gas left in the analyzer. Then the analyzer is warmed up for a few minutes to stabilize it. N_2 is added with the CO_2 to reduce the overall CO_2 volume percent since the IR Gas Analyzer can detect CO_2 outlet up to 20 volume percent only. The CO_2 and N_2 inlet to the system is regulated to get the desired initial volume percent. The initial CO_2 is kept constant around 8-9 volume percent (vol%). The initial reading is taken by directing the gas mixture into an empty conical flask where the volume percent of gas inlet will be the same as outlet. After obtaining a stabilized CO_2 volume percent inlet, the empty conical flask is changed immediately with the one that contain the amine solution. The reading of the CO_2 volume percent outlet from the system is taken at every minute until it gives a stable reading. The CO_2 absorbed (vol%) is the different in the CO_2 inlet and outlet vol% given by the analyzer. The experiment for the same concentration of amine solutions is run at two different temperatures, about 25 and 40^oC.

3.2 Experiment on the foaming of CO_2 in aqueous amine solutions

10 ml petrol (liquid hydrocarbon) as the source of contaminant that can cause foaming is added into the amine solution. Since the petrol does not dissolve in the amine solution, it will form a visible thin layer on the surface of the solution. The time when

the foaming starts, the height of the foam per minute are measured. This experiment is conducted at ambient temperature.

3.3 Materials

Both MEA and DEA were obtained from R&M Marketing, U.K. MDEA was obtained from E. Merck, Germany. All amines were of 98% purity. To make desired amine solutions, fresh distilled water was used. For CO_2 and N_2, commercial gas cylinders were used which the purities of both gases were better than 99%. The set up of the apparatus and equipments used in the solubility and foaming experiments are shown in Figures 3.1 and 3.2, respectively. The gas analyzer that was used is the Yokogawa IR Gas Analyzer IR 200.The setup is the modified version of experimental setup from Yeh (1999)[3] for studying the reaction between CO_2 and ammonia solvent.
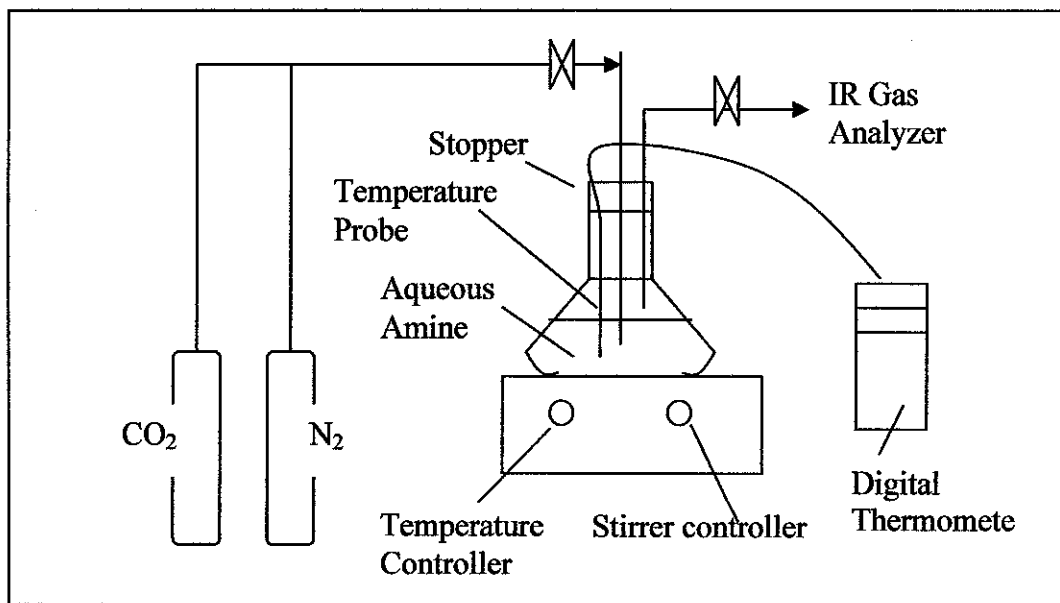
Figure 3.1: Schematic diagram on the experiment setup for solubility of CO_2 in aqueous amine solutions at different temperatures
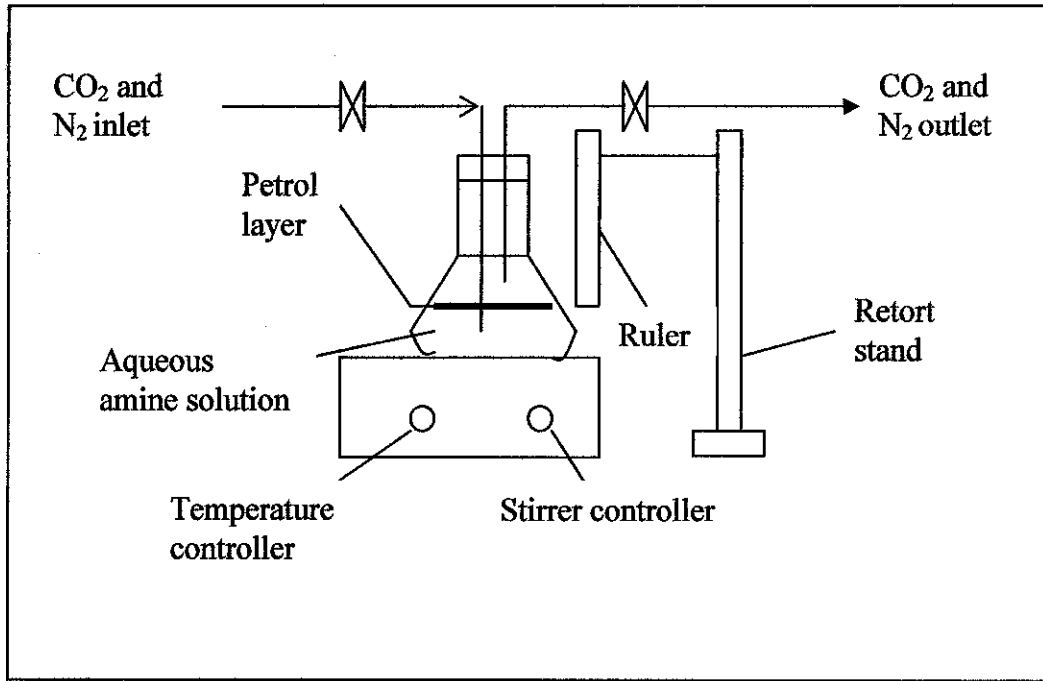
Figure 3.2: Schematic diagram on the experiment setup for foaming tendency test

3.4 List of samples of the experiment

Table 3.1 shows the samples used in this study.

Table 3.1: List of the samples of the solubility CO_2 in aqueous amine solutions

Amine solutions (wt%)	Temperature			
	25°C		40°C	
Single amine				
MEA	10	30*	10	30
DEA	10	30*	10	30
MDEA	10	30*	10	30
Mixed amine				
MEA+MDEA	15+5*	5+15*	15+5	5+15
DEA+MDEA	15+5	5+15	15+5	5+15

* Also tested for foaming tendency

CHAPTER 4
RESULTS AND DISCUSSION

The experimental data are shown in Appendix 3 including the CO_2 vol% inlet and the temperature range. The operating temperature and stirrer speed are kept constant for all experiment. However, the temperature variations are unavoidable due to exothermal reaction between CO_2 and alkanolamines[3]. There are some modifications done to the equipment setup as the experiments were carried out to get better results. The main obstacle to make good comparison between the results is to maintain certain parameters at constant values such as CO_2 vol% and pressure. It is difficult to maintain the CO_2 vol% inlet around 8 vol% since it uses the spring type regulator that operated manually. The experiment started by testing the gas flow into the connection tube by submerges it into the water container. If there are bubbles formed that means there is gas flow.

Although the solubility of gases into aqueous solution is highly influenced by the gas partial pressure, the effect of pressure on the CO_2 solubility test cannot be determined from this experiment set up since it only can withstand at very low pressure. Moreover the IR Gas Analyzer only can analyze gas at very low pressure. Gases as might be expected increase in solubility with an increase in pressure. Henry's Law states that: The solubility of a gas in a liquid is directly proportional to the pressure of that gas above the surface of the solution. If the pressure is increased, the gas molecules are "forced" into the solution since this will best relieve the pressure that has been applied. The number of gas molecules is decreased. The number of gas molecules dissolved in solution has increased.

20

4.1 CO₂ loading capacity in single and mixed amine solutions at 25 and 40°C
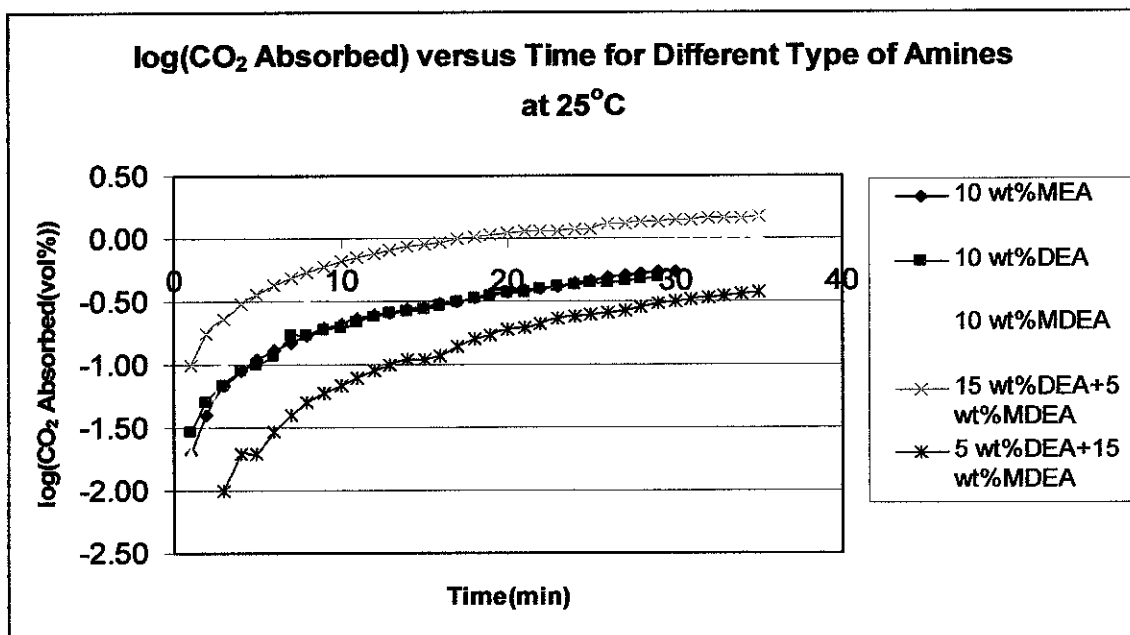
Figure 4.1.1: Graph of CO₂ Absorbed versus Time for Different Type and Concentration of Amines at 25°C
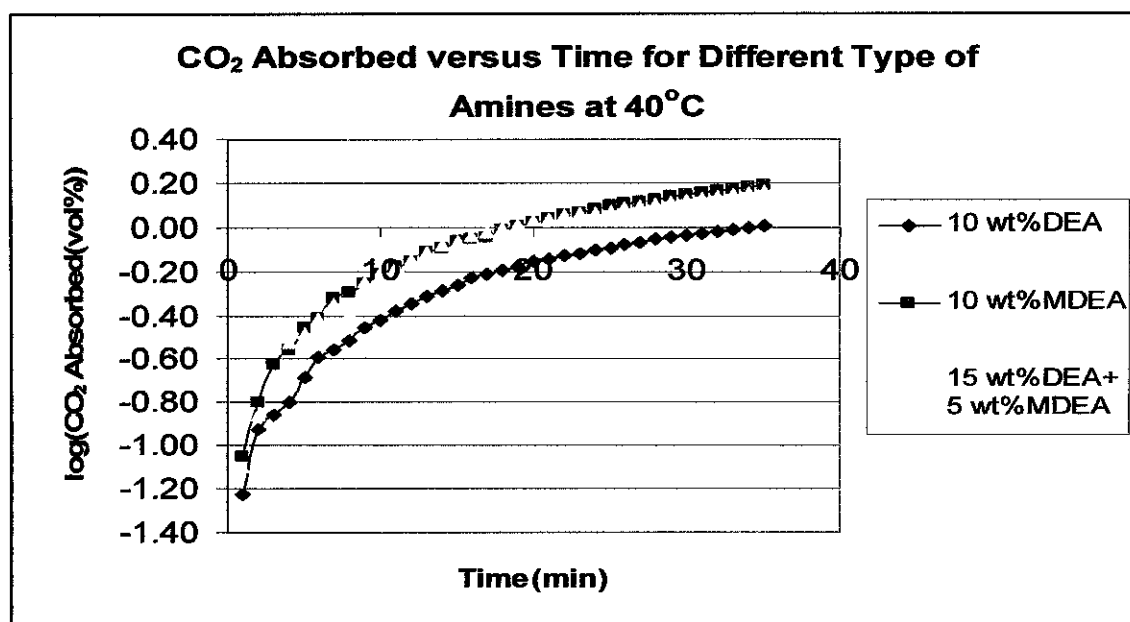
Figure 4.1.2: Graph CO₂ Absorbed versus Time for Different Type and Concentration of Amines at 40°C

From Figure 4.2.1 and 4.2.2, the CO_2 loading capacity in selected single and mixed amine solutions at 25 and 40°C can be determined. In both figures, 15 wt% DEA+ 5 wt% MDEA show the highest CO_2 loading capacity at both temperatures. Meanwhile, for the single amines, 10 wt% MDEA has higher loading capacity compared to DEA and MEA. This supports the theory as explained in reaction(4) section 2.3 that shows the equilibrium loading capacity for tertiary alkanolamine is 1 mol CO_2 /mol of amine. However, loading capacity for primary and secondary alkanolamines are limited by stoichiometric of reaction(1) to 0.5 mol CO_2/mol of amine. Therefore MDEA has higher loading capacity since it can absorb more CO_2 per mol compared to DEA and MEA.

This shows that by varying in concentration mixed amines have many advantageous over the single amines since it gives greater loading capacity. In the experiment, by adding 5wt% MDEA into single DEA improve the solution overall absorption capability. Mixtures of alkanolamines combined the absorption characteristics of the constituent amines such as higher loading capacity (MDEA), faster reaction rate (MEA and DEA) and lesser energy requirements for regeneration (MDEA)[15]. Recently it has been shown that a solution of two or more amines improves the absorption rate and reduces the solvent regeneration energy.

In all cases, increasing the concentration of the MDEA in the solution decreases the concentration of CO_2 in the sweet gas (CO_2 slippage from system). More interesting is the effect of wt% MDEA on the minimum CO_2 concentration in the sweet gas as a function of lean amine temperature (plant condition). With DEA alone, the minimum CO_2 concentration is at temperature of 322K. With the addition of 5 wt% MDEA the minimum occurs at 319K. From there, the temperature for minimum CO_2 concentration in the sweet gas decreases with increasing MDEA concentration[7].

There are two other methods to quantify the amount CO_2 being absorbed which are by calculating the absorption capacity and CO_2 removal efficiency:

1. Absorption capacity = $\dfrac{\text{Kg } CO_2 \text{ removed}}{\text{Kg solvent used}}$

2. CO_2 removal efficiency (%) = $\dfrac{CO_2 \text{ vol\% inlet- } CO_2 \text{ vol\% outlet}}{CO_2 \text{ vol\% inlet}}$ x 100%

However these two calculations can not be performed in this experiment due to lack of data. The mass, Kg of CO_2 removed cannot be determined because the flowrate of the gas cannot be measured as there is no portable rotameter or flowmeter available in the laboratory to attach to the experiment setup. CO_2 removal efficiency can only be calculated if the experiment gives constant CO_2 outlet where the different in CO_2 inlet and outlet will represent the whole CO_2 that being removed from the gas stream. Since the rate of absorption in this experiment is slow, it will take very long time to wait until the CO_2 outlet becomes constant.

4.2 Effect of temperatures on the absorption of CO_2

4.2.1 Single Amines
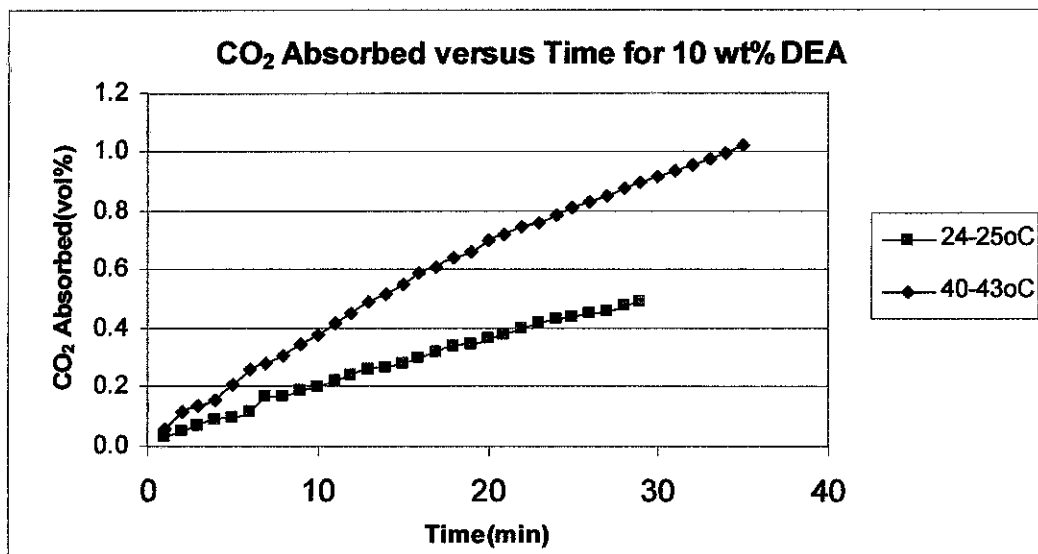
Figure 4.2.1: Graph of CO_2 Absorbed versus Time at two different temperatures for 10 wt% DEA
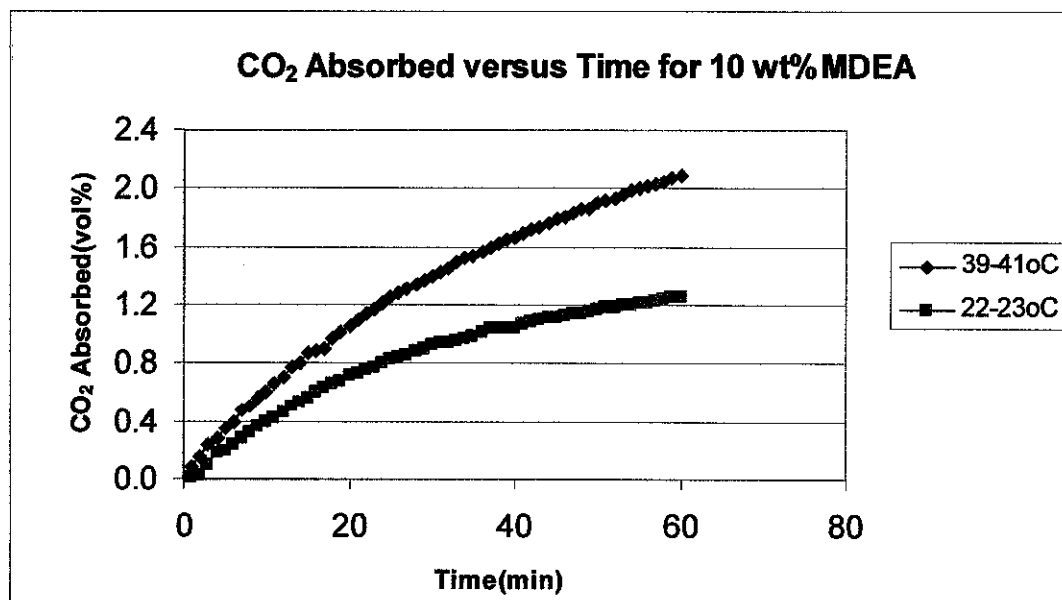
Figure 4.2.2: Graph of CO_2 Absorbed versus Time at two different temperatures for 10 wt% MDEA

4.2.2 Mixed Amines
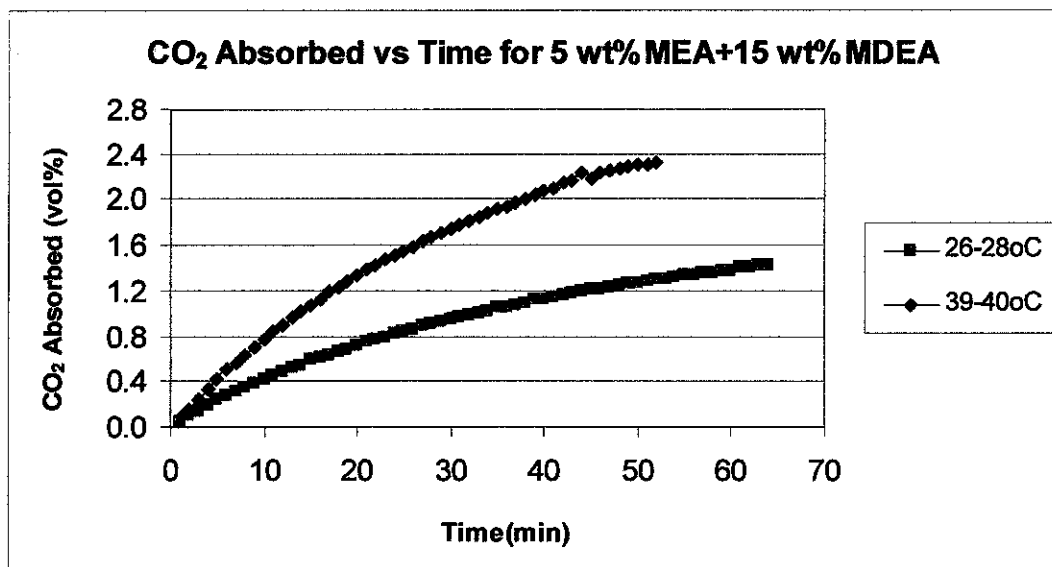
Figure 4.2.3: Graph of CO_2 Absorbed versus Time at two different temperatures for 5 wt% MEA+15 wt% MDEA
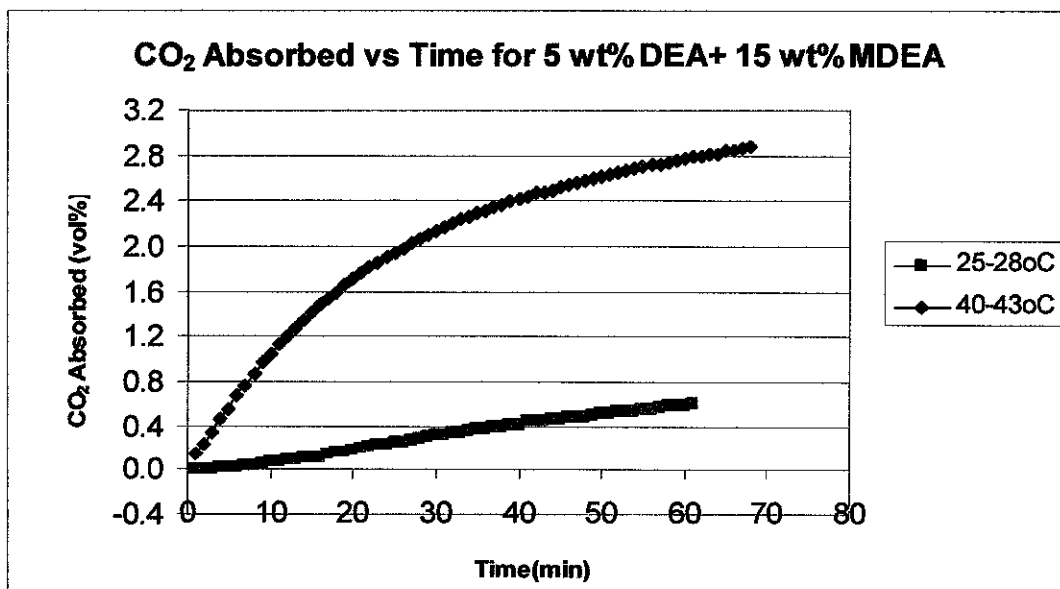
Figure 4.2.4: Graph of CO_2 Absorbed versus Time at two different temperatures for 5 wt% DEA+ 15 wt% MDEA

25

Based on the above graphs, the effect of temperatures on the solubility for single and mixed amines can be seen clearly. At higher temperature more CO_2 being absorbed by the amine solution. This results seem to violate the theory of absorption which stated that absorption favors low temperature. CO_2 absorption in aqueous alkanolamines has two steps; the first is CO_2 molecules physically dissolve in water and then these CO_2 molecules chemically react with the alkanolamines species in the solution. Therefore it should be noted that increasing the temperature will decrease the CO_2 solubility because the physical absorption (first step) will decrease resulting in a decrease in the total absorption.

However, since CO_2 absorption is kinetically controlled, a hotter solution increases the reaction rate until certain extent. Thus, increasing the amine solution temperature and contact time increase the CO_2 absorbed, however there is limit to the maximum temperature. This temperature depends on amine concentration, inlet gas composition, and the amount of CO_2 pickup. The temperature limit for the amines solution normally 49°C (322K). Exceeding this upper temperature results in increase the kinetic effect to a greater extent relative to the decrease of solubility. Therefore for the above graphs more CO_2 being absorbed at higher temperature as the maximum temperature is 43°C that does not exceed the upper temperature limit[7].

In the temperature range 293-313K, the rates of absorption of CO_2 increased marginally with the increase in temperature[11]. Although the temperature was kept constant, temperature variable of the solution were unavoidable. The trends of the temperature variations are the same for all solution, the temperature gradually increases to its maximum temperature and then decreases to the room temperature[3]. The increase in the temperature during the experiment indicates that the CO_2-alkanolamines reactions are typically exothermal reaction process.

26

For the operating temperature above the upper limit of 49°C, the solubility will marginally decrease. The reason for this gas solubility relationship with temperature is very similar to the reason that vapor pressure increases with temperature. Increase temperature causes an increase in kinetic energy. The higher kinetic energy causes more motion in molecules which break intermolecular bonds and escape from solution.

4.3   Effect of amine concentration on the absorption of CO_2
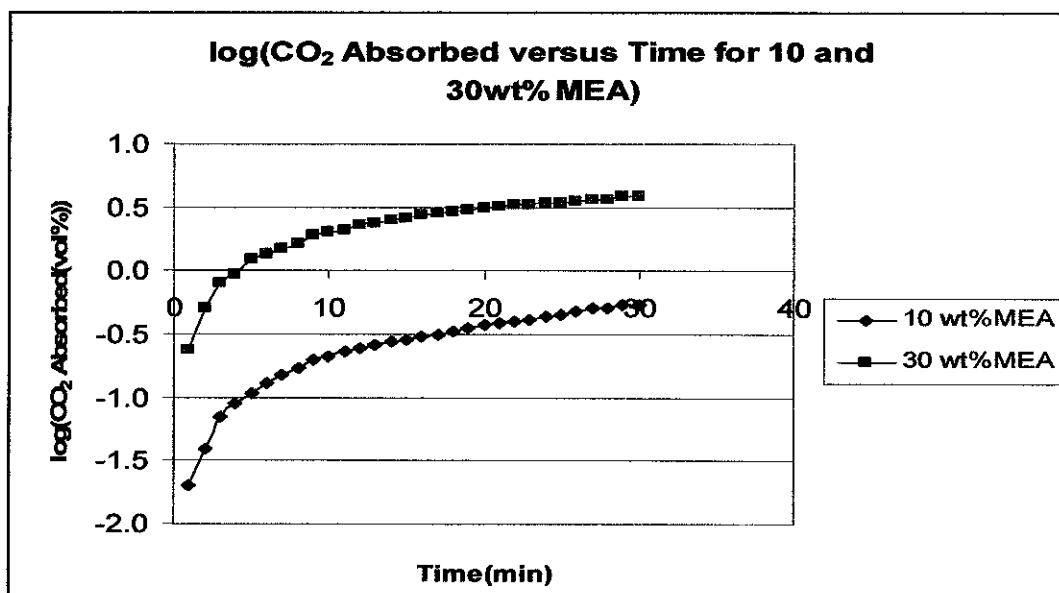
Figure 4.3.1: Graph of log (CO_2 Absorbed) versus Time for Different Concentration of MEA

log(CO_2 Absorbed) versus Time for 10,20,30 wt% DEA
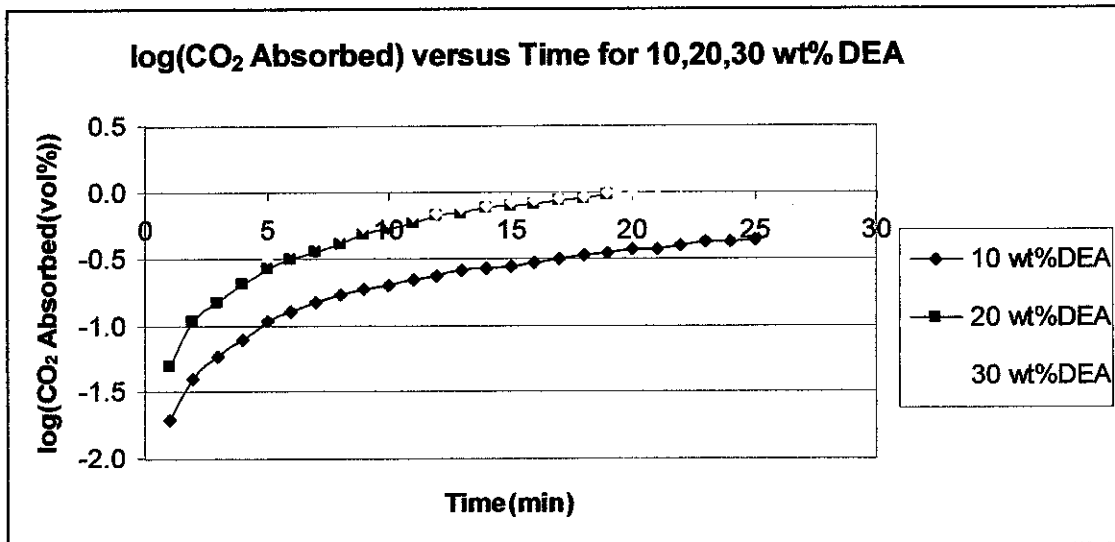
Figure 4.3.2: Graph of log (CO_2 Absorbed) versus Time for Different Concentration of DEA

From the above figures, the CO_2 loading capacity increases as the concentration increases ranging from 10 to 30wt%. Within this amines concentration range, the rate of absorption of CO_2 is seen to increase rapidly with the increases in amine concentration. This is results from the increase in number of molecules in the solution that capable to absorb more CO_2. However, from Yeh et.al (1999) study on the effect of solvent concentration on CO_2 removal efficiency shows that there is limit in increasing the solution concentration in order to increase the absorption capacity. The graph in Figure 1 in Appendix 1 shows that for MEA solvent concentration are greater than 28 wt%, the increasing rate of CO_2 removal efficiency decreases[3].

Therefore the CO_2 absorption capacity increases as the solvent concentration increases only applicable for certain range of concentration. However care should be taken not exceed corrosion limits when increasing the solvent concentration especially for MEA and DEA to avoid excessive corrosion effect during operation.

28

4.4 Effect of amines ratio on CO_2 loading capacity

CO₂ Absorbed versus Time for Mixed DEA and MDEA at 25°C
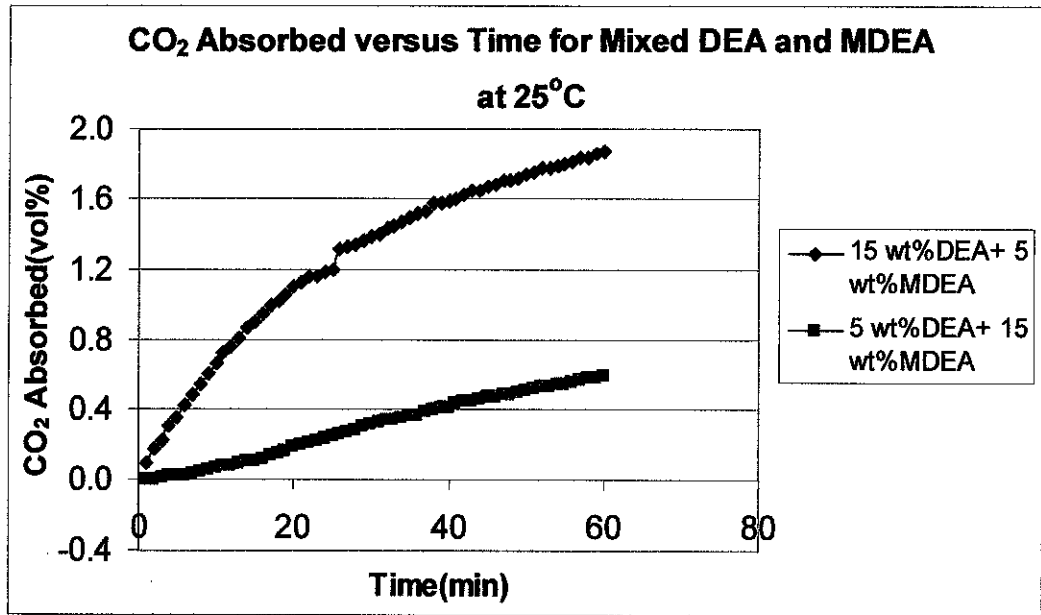
Figure 4.4.1: CO_2 Absorbed versus Time for Different Ratio of Mixed DEA and MDEA

Figure 4.4.1 indicates that 15 wt% DEA+ 5wt% MDEA has higher loading capacity compared to 5 wt% DEA+ 15wt% MDEA although at the same total weight percent. This shows that varying the concentration of mixed amine affects the loading capacity. From the graph above, it can be seen that by increasing DEA/MDEA ratio results in increase in the CO_2 loading. Similar result was be found in MEA+MDEA blended solvents.

These phenomena were also mentioned by Daneshvar et. al. 2004, Rebolledo-Libreros and Trejo, 2004. This is because, the secondary alkanolamines, DEA reacts with CO_2 in alkaline solutions, to produce stable carbamate as reaction (1) in section 2.3. Tertiary alkanolamines, MDEA in contrary with primary and secondary ones, are unable to produce carbamate and so, only react with CO_2 via acid-base reaction mechanism(reaction(4)). MEA and DEA is more alkaline than MDEA and so, the

equilibrium constant of reaction(4) will be less than those for MEA and DEA in reaction(1). Therefore, increasing MEA and DEA to MDEA ratio in absorbing solution, increases CO_2 loading[16].

Figure 2 in the Appendix 2 shows the calculated results for CO_2 concentration in the sweet gas by BR&E Technical Papers, for DEA/MDEA mixture. The figure clearly indicates the relationship between the DEA and the additional MDEA. As the ratio of DEA/MDEA decreases the CO_2 concentration being absorbed decreases.

4.5   Effect of foaming on CO_2 absorption
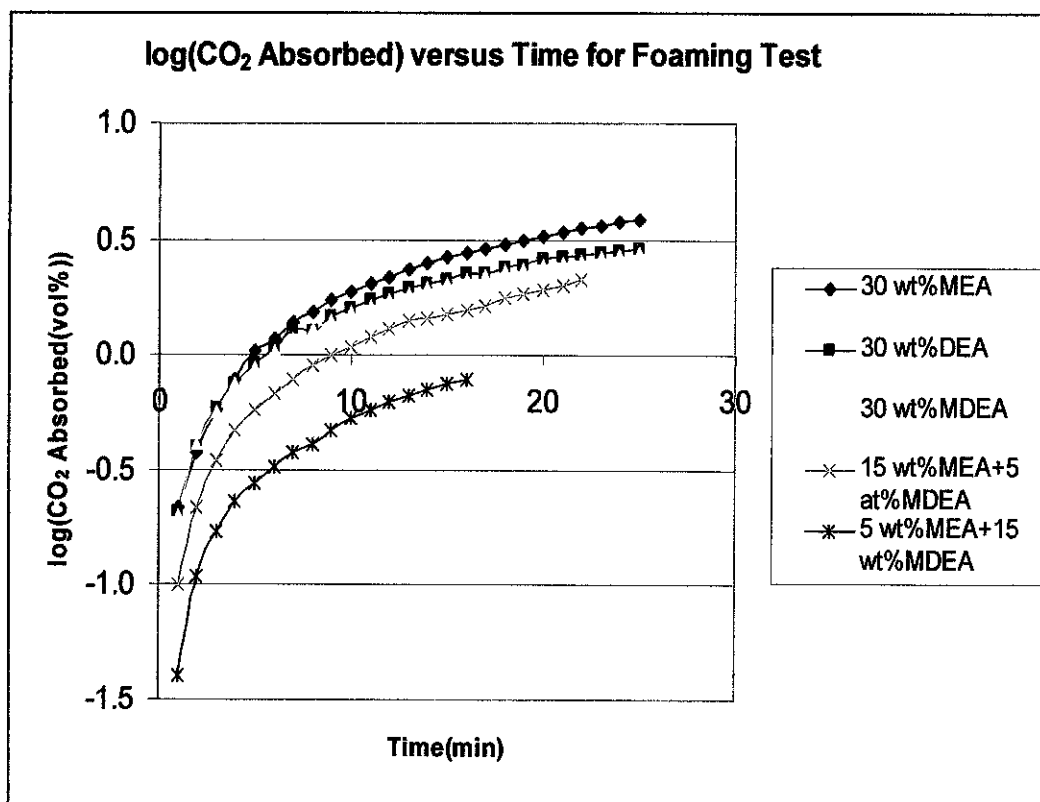
Figure 4.5.1: CO_2 Absorbed versus Time for Foaming Test for Single Amines

30

Table 4.5.1: Observation During the CO_2 Foaming Experiment – conducted at ambient temperature and constant stirrer speed.

Amine Concentration	Range of Foam Height(mm)	Time the Foaming Starts(min)	Observations
30 wt% MEA	3-15	0	• The foaming occurred was too vigorous. • At the end of the experiment there were lumps of impurities on the surface of the solution.
30 wt% DEA	1-2	4	• Thin layer of uniform foaming was formed during the experiment. • At the end of the experiment there was a thin visible layer on the surface of the solution.
30 wt% MDEA	1-2	4	• Thin layer of uniform and stable foaming was formed during the experiment. • At the end of the experiment there was a thin visible layer on the surface of the solution.

15wt% MEA + 5wt% MDEA	1-4	6	• Big bubbles and unstable foaming was formed. • At the end of the experiment the foaming collapsed after 1 minute. The experiment stopped before the thin visible layer on the surface of solution appeared
5wt% MEA+ 15wt% MDEA	1-2	5	• A layer of foaming was formed • At the end of the experiment there was a thin visible layer on the surface of the solution

From the experimental results, it was observed that foaming can only occur with the influence of the stirrer speed. For better comparison the stirrer speed is kept constant throughout the experiment. However it is difficult to measure the height of foam since they occur uniformly. Therefore only the highest peak of the foam was considered. In most of the experiments, the foam were collapsed immediately after the stirrer was stopped. When the foam collapsed, they form visible layer on the solution surface.

Figure 4.5.1 shows that 30 wt% MEA absorbed the highest CO_2 although it has the highest foaming height. This result violates the theory that foaming will reduce the solubility since it limits the physical absorption into the solution and thus reduce the

overall absorption. Supposedly 30wt% DEA and 30 wt% MDEA will absorb more CO_2 compared to the 30 wt% MEA since they have less restriction to the physical absorption. This error might due to the fact that the experimental time was too short. Therefore this experiment must be extended for longer time for clearer results.

From the observations, 30 wt% MEA gave the highest foaming height compared to other solutions. The foaming occurred vigorously and there were lumps on the visible layer at the end of the experiment. This might be due to the properties of the MEA that is easily degraded. By referring to Table 2.2 the corrosion rate of 30 wt% MEA is very high which is about 0.81mm/a. This value is 90% higher than the corrosion rate of 50wt% MDEA. This corrosive environment might be due to the present of some degradation products and the thermally stable salt from the chemical reaction between the CO_2 and aqueous alkanolamines. Since MEA get more degradation products and stable salt presence, the foaming formed become stable, so MEA has the highest foaming.

In industries, MEA solvent easily degraded by the presence of SO_2 and O_2 in the flue gas. Oxygen is capable of oxidizing MEA solvent, and SO_2 may react with MEA to form irreversible by-products thus reducing the reaction rate of the absorption as well as MEA absorption capacity. Besides, it may also make the solvent more difficult to be recovered[3]. To overcome this foaming problem they have introduced special antifoam to reduce foaming in the system. However this antifoam will accumulate in the system and thus increase the viscosity of the solution and reduces its strength. Increase in viscosity of the solution will reduce the mass transfer of gas into the solution thus decrease the absorption efficiency[8].

33

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

In the meantime, aqueous alkanolamines solutions are the most widely used solvents for the removal of acid gases (CO_2 and H_2S). Most commonly conventional alkanolamines used are MEA, DEA and MDEA. In view of this, many research works has been done to determine and model the gas solubility in different types of amine solutions and their mixtures. This study on the solubility and foaming of CO_2 in aqueous amines solutions in small scale results in the determination of the CO_2 loading capacity in different types of amines and the effects of varying the temperatures and solvent concentration on the CO_2-akanolamines absorption.

From the experiments, the absorption of CO_2 in mixed amines has specific advantages over the use of single amine such as to improve the absorption capacity. Solutions containing mixture of amines have the combined properties of the constituent amines. 15 wt% DEA+5 wt% MDEA has the highest loading capacity among the samples. MDEA has the highest loading capacity among the single amines. The CO_2 absorption is kinetically controlled, thus increase in solution temperature will increase the CO_2 absorption capacity. However, the temperature limit for the amine solution is normally 49°C (322K). The higher temperature increases the kinetic effect to a greater extent relative to the decrease in solubility.

34

For 10-30 wt% of amine solution, the CO_2 absorption increases as the solution concentration increases. However this might be applicable only for certain range of solvent concentration and depend on the types of solvent. There are limited data on the effects of solvent concentration on the absorption of CO_2. Therefore proper comparison can not be made. For the plant application, there are several factors that need to be considered in deciding the solvent concentration such as the corrosion rate, degradation rate, heat of reaction and amount of gas loading. For concentration of mixed amines, the higher the ratio of primary and secondary amines to tertiary amines (MEA/MDEA and DEA/MDEA), the greater the absorption.

Foaming is caused by the presence of particulates that can be either produced internally or introduced into the system which contaminated the solution. Foaming will reduce the efficiency of the absorption and may lead to the corrosion problem. MEA has the greatest foaming phenomena as compared to other solutions. Therefore further and details study and research must be done in order to improve the CO_2 absorption and to reduce the operating problems for the CO_2-alkanolamine absorption.

5.2   Recommendations

1.   The CO_2 loading capacity will be more effective if this experiment is conducted using other equipments with larger surface contact between the gas and the solution such as the wetted wall or absorption column. This experiment setup only allows the contact of gas with the bulk solution which may reduce the effectiveness of absorption.

2.   To determine the effects of temperatures on the CO_2 absorption, the upper limit of $49^{\circ}C$ must be considered. To ensure that the solubility increases as temperature increases below this limit and vice versa for beyond this limit, the experiment must be done by taking this temperature limit..

3. Since it is difficult to determine the effect of solvent concentration, more variations the concentration of amines solutions must be conducted for better results.

4. Experiments to determine the effects of foaming on the absorption must be conducted at longer time for better or clearer results. Moreover the effect of degradation on formation of other particulates in the solvent only can be seen after a certain period. The effects of foaming can be discussed in details since it becomes an importance problem to the industries.

5. The laboratory must provide the adequate equipments such as portable rotameter or flowmeter for the final year project (FYP). To avoid the FYP students to do their experiments in rush, the laboratory should be opened during the weekend since the schedule of the student and the laboratory itself is packed. On the weekdays the FYP student must share the equipments with the other Chemical Engineering Laboratory students.

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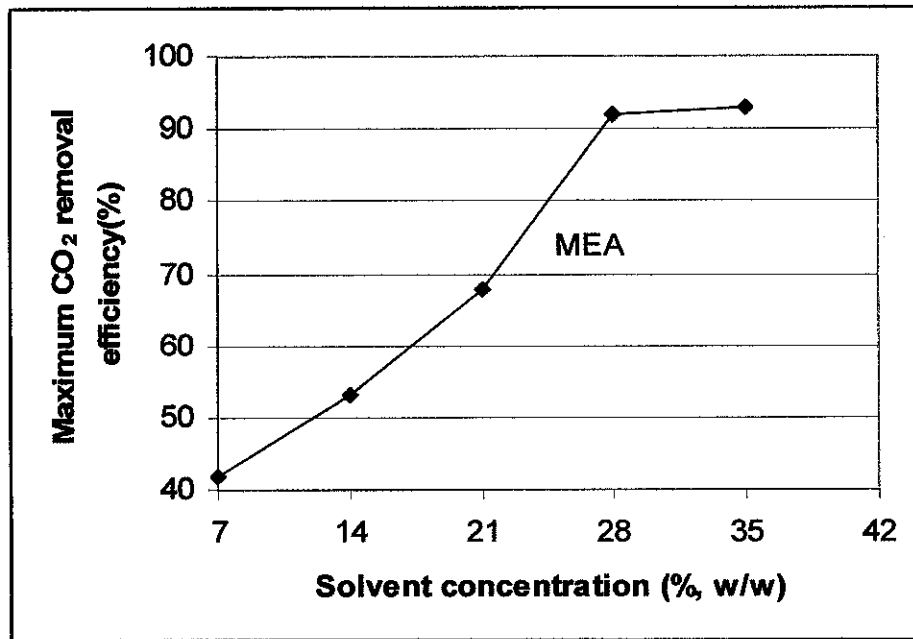
Figure 1: The effects of solvent concentration on CO_2 removal efficiency[3]
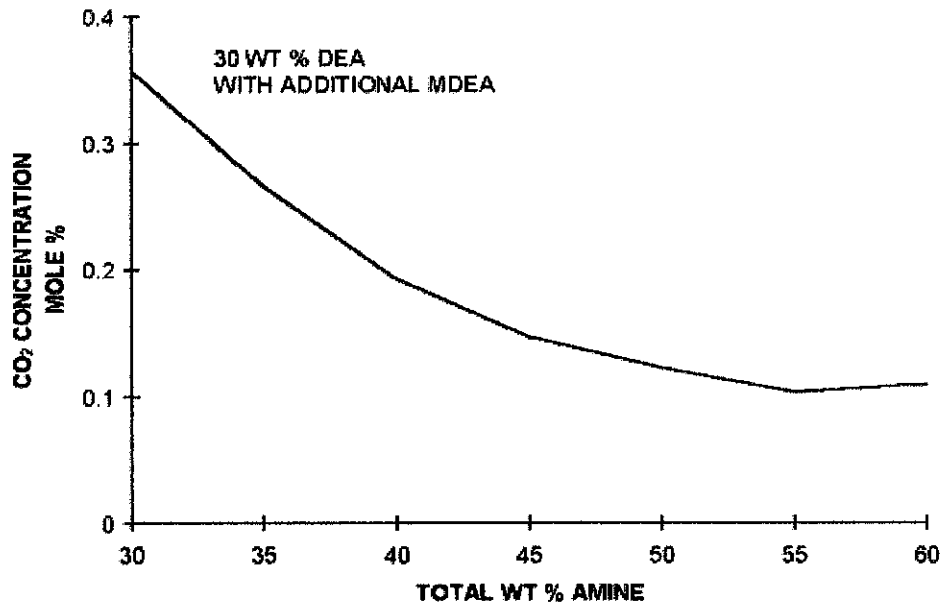
Figure 2: Calculated results for CO_2 in the sweet gas for DEA/MDEA mixture[7]

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	10 wt%MEA 12.8 23-26oC 1	Time in minute CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	12.16	0.02	-1.699
2	12.14	0.04	-1.398
3	12.11	0.07	-1.155
4	12.09	0.09	-1.046
5	12.07	0.11	-0.959
6	12.05	0.13	-0.886
7	12.03	0.15	-0.824
8	12.01	0.17	-0.770
9	11.98	0.20	-0.699
10	11.97	0.21	-0.678
11	11.95	0.23	-0.638
12	11.93	0.25	-0.602
13	11.92	0.26	-0.585
14	11.90	0.28	-0.553
15	11.89	0.29	-0.538
16	11.87	0.31	-0.509
17	11.86	0.32	-0.495
18	11.84	0.34	-0.469
19	11.82	0.36	-0.444
20	11.80	0.38	-0.420
21	11.79	0.39	-0.409
22	11.78	0.40	-0.398
23	11.76	0.42	-0.377
24	11.74	0.44	-0.357
25	11.72	0.46	-0.337
26	11.69	0.49	-0.310
27	11.67	0.51	-0.292
28	11.66	0.52	-0.284
29	11.64	0.54	-0.268
30	11.63	0.55	-0.260

Sample composition:	10 wt%DEA	Time in minute
CO2 vol% inlet:	8.16	CO2 in vol%
Temperature:	24-25oC	
Stirrer speed:	1	

Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.13	0.03	-1.523
2	8.11	0.05	-1.301
3	8.09	0.07	-1.155
4	8.07	0.09	-1.046
5	8.06	0.10	-1.000
6	8.04	0.12	-0.921
7	7.99	0.17	-0.770
8	7.97	0.17	-0.770
9	7.96	0.19	-0.721
10	7.94	0.20	-0.699
11	7.92	0.22	-0.658
12	7.90	0.24	-0.620
13	7.89	0.26	-0.585
14	7.88	0.27	-0.569
15	7.86	0.28	-0.553
16	7.84	0.30	-0.523
17	7.82	0.32	-0.495
18	7.81	0.34	-0.469
19	7.79	0.35	-0.456
20	7.78	0.37	-0.432
21	7.76	0.38	-0.420
22	7.74	0.40	-0.398
23	7.73	0.42	-0.377
24	7.72	0.43	-0.367
25	7.71	0.44	-0.357
26	7.70	0.45	-0.347
27	7.68	0.46	-0.337
28	7.67	0.48	-0.319
29	7.66	0.49	-0.310

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	10 wt%MDEA 8.14 24-25oC 1	Time in minute CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.12	0.02	-1.699
2	8.11	0.03	-1.523
3	8.04	0.10	-1.000
4	7.96	0.18	-0.745
5	7.94	0.20	-0.699
6	7.90	0.24	-0.620
7	7.86	0.28	-0.553
8	7.82	0.32	-0.495
9	7.78	0.36	-0.444
10	7.74	0.40	-0.398
11	7.71	0.43	-0.367
12	7.67	0.47	-0.328
13	7.63	0.51	-0.292
14	7.60	0.54	-0.268
15	7.57	0.57	-0.244
16	7.54	0.60	-0.222
17	7.50	0.64	-0.194
18	7.48	0.66	-0.180
19	7.46	0.68	-0.167
20	7.42	0.72	-0.143
21	7.40	0.74	-0.131
22	7.38	0.76	-0.119
23	7.36	0.78	-0.108
24	7.34	0.80	-0.097
25	7.31	0.83	-0.081
26	7.29	0.85	-0.071
27	7.28	0.86	-0.066
28	7.25	0.89	-0.051
29	7.23	0.91	-0.041
30	7.21	0.93	-0.032
31	7.20	0.94	-0.027
32	7.19	0.95	-0.022
33	7.18	0.96	-0.018
34	7.16	0.98	-0.009
35	7.15	0.99	-0.004
36	7.13	1.01	0.004
37	7.10	1.04	0.017
38	7.10	1.04	0.017
39	7.10	1.04	0.017
40	7.09	1.05	0.021
41	7.07	1.07	0.029
42	7.05	1.09	0.037
43	7.04	1.10	0.041

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	30 wt%MEA 8.34 24-25oC 1	Time in minute CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)

Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.10	0.24	-0.620
2	7.82	0.52	-0.284
3	7.53	0.81	-0.092
4	7.39	0.95	-0.022
5	7.09	1.25	0.097
6	6.98	1.36	0.134
7	6.82	1.52	0.182
8	6.68	1.66	0.220
9	6.41	1.93	0.286
10	6.32	2.02	0.305
11	6.21	2.13	0.328
12	6.01	2.33	0.367
13	5.94	2.40	0.380
14	5.84	2.50	0.398
15	5.71	2.63	0.420
16	5.60	2.74	0.438
17	5.49	2.85	0.455
18	5.39	2.95	0.470
19	5.28	3.06	0.486
20	5.20	3.14	0.497
21	5.10	3.24	0.511
22	5.01	3.33	0.522
23	5.02	3.32	0.521
24	4.93	3.41	0.533
25	4.86	3.48	0.542
26	4.79	3.55	0.550
27	4.71	3.63	0.560
28	4.65	3.69	0.567
29	4.51	3.83	0.583
30	4.44	3.90	0.591
31	4.35	3.99	0.601
32	4.28	4.06	0.609
33	4.26	4.08	0.611
34	4.23	4.11	0.614
35	4.20	4.14	0.617
36	4.15	4.19	0.622
37	4.10	4.24	0.627
38	4.05	4.29	0.632
39	4.01	4.33	0.636
40	3.96	4.38	0.641
41	3.92	4.42	0.645
42	3.89	4.45	0.648
43	3.85	4.49	0.652

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	20 wt%DEA 8.1 24-25oC 1	Time in minute CO2 in vol%	
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.05	0.05	-1.301
2	7.99	0.11	-0.959
3	7.95	0.15	-0.824
4	7.89	0.21	-0.678
5	7.83	0.27	-0.569
6	7.78	0.32	-0.495
7	7.74	0.36	-0.444
8	7.69	0.41	-0.387
9	7.62	0.48	-0.319
10	7.57	0.53	-0.276
11	7.51	0.59	-0.229
12	7.44	0.66	-0.180
13	7.40	0.70	-0.155
14	7.35	0.75	-0.125
15	7.32	0.78	-0.108
16	7.28	0.82	-0.086
17	7.23	0.87	-0.060
18	7.19	0.91	-0.041
19	7.15	0.95	-0.022

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	30 wt%DEA 8.16 23-26oC 1	Time in minute CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.09	0.07	-1.155
2	8.02	0.14	-0.854
3	7.95	0.21	-0.678
4	7.89	0.27	-0.569
5	7.83	0.33	-0.481
6	7.77	0.39	-0.409
7	7.72	0.44	-0.357
8	7.67	0.49	-0.310
9	7.60	0.56	-0.252
10	7.56	0.60	-0.222
11	7.49	0.67	-0.174
12	7.46	0.70	-0.155
13	7.41	0.75	-0.125
14	7.37	0.79	-0.102
15	7.33	0.83	-0.081
16	7.29	0.87	-0.060
17	7.25	0.91	-0.041
18	7.22	0.94	-0.027
19	7.18	0.98	-0.009
20	7.14	1.02	0.009
21	7.11	1.05	0.021
22	7.08	1.08	0.033
23	7.04	1.12	0.049
24	7.01	1.15	0.061
25	6.98	1.18	0.072
26	6.96	1.20	0.079
27	6.93	1.23	0.090
28	6.90	1.26	0.100
29	6.88	1.28	0.107
30	6.86	1.30	0.114
31	6.83	1.33	0.124
32	6.80	1.36	0.134
33	6.78	1.38	0.140
34	6.76	1.40	0.146
35	6.73	1.43	0.155
36	6.71	1.45	0.161
37	6.69	1.47	0.167
38	6.67	1.49	0.173
39	6.65	1.51	0.179
40	6.63	1.53	0.185
41	6.61	1.55	0.190
42	6.57	1.59	0.201
43	6.57	1.59	0.201

47

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	30 wt%MDEA 8.16 23-26oC 1	Time in minute CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.15	0.01	-2.000
2	8.14	0.02	-1.699
3	8.13	0.03	-1.523
4	8.11	0.05	-1.301
5	8.09	0.07	-1.155
6	8.07	0.09	-1.046
7	8.05	0.11	-0.959
8	8.03	0.13	-0.886
9	8.01	0.15	-0.824
10	7.99	0.17	-0.770
11	7.98	0.18	-0.745
12	7.96	0.20	-0.699
13	7.95	0.21	-0.678
14	7.93	0.23	-0.638
15	7.92	0.24	-0.620
16	7.90	0.26	-0.585
17	7.89	0.27	-0.569
18	7.88	0.28	-0.553
19	7.86	0.30	-0.523
20	7.85	0.31	-0.509
21	7.84	0.32	-0.495
22	7.83	0.33	-0.481
23	7.82	0.34	-0.469
24	7.81	0.35	-0.456
25	7.80	0.36	-0.444
26	7.78	0.38	-0.420
27	7.77	0.39	-0.409
28	7.75	0.41	-0.387
29	7.75	0.41	-0.387
30	7.74	0.42	-0.377
31	7.72	0.44	-0.357
32	7.71	0.45	-0.347
33	7.70	0.46	-0.337
34	7.69	0.47	-0.328
35	7.68	0.48	-0.319
36	7.68	0.48	-0.319
37	7.66	0.50	-0.301
38	7.66	0.50	-0.301
39	7.65	0.51	-0.292
40	7.64	0.52	-0.284
41	7.64	0.52	-0.284
42	7.63	0.53	-0.276
43	7.63	0.53	-0.276

48

Sample composition:		15 wt% DEA + 5wt% MDEA	
CO2 vol% inlet:		8.13	
Temperature:		23-26oC	Time in minute
Stirrer speed:		1	CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.03	0.10	-1.000
2	7.95	0.18	-0.745
3	7.90	0.23	-0.638
4	7.82	0.31	-0.509
5	7.77	0.36	-0.444
6	7.70	0.43	-0.367
7	7.64	0.49	-0.310
8	7.58	0.55	-0.260
9	7.52	0.61	-0.215
10	7.47	0.66	-0.180
11	7.41	0.72	-0.143
12	7.37	0.76	-0.119
13	7.32	0.81	-0.092
14	7.27	0.86	-0.066
15	7.23	0.90	-0.046
16	7.18	0.95	-0.022
17	7.14	0.99	-0.004
18	7.11	1.02	0.009
19	7.07	1.06	0.025
20	7.03	1.10	0.041
21	7.00	1.13	0.053
22	6.97	1.16	0.064
23	6.97	1.16	0.064
24	6.95	1.18	0.072
25	6.93	1.20	0.079
26	6.81	1.32	0.121
27	6.80	1.33	0.124
28	6.79	1.34	0.127
29	6.77	1.36	0.134
30	6.75	1.38	0.140
31	6.73	1.40	0.146
32	6.70	1.43	0.155
33	6.68	1.45	0.161
34	6.66	1.47	0.167
35	6.64	1.49	0.173
36	6.62	1.51	0.179
37	6.60	1.53	0.185
38	6.56	1.57	0.196
39	6.55	1.58	0.199
40	6.54	1.59	0.201
41	6.53	1.60	0.204
42	6.51	1.62	0.210
43	6.49	1.64	0.215

Sample composition:		5 wt% DEA + 15wt% MDEA	
CO2 vol% inlet:	8.19		
Temperature:	23-26oC	**Time in minute**	
Stirrer speed:	1	**CO2 in vol%**	
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.19	0.00	#NUM!
2	8.19	0.00	#NUM!
3	8.18	0.01	-2.000
4	8.17	0.02	-1.699
5	8.17	0.02	-1.699
6	8.16	0.03	-1.523
7	8.15	0.04	-1.398
8	8.14	0.05	-1.301
9	8.13	0.06	-1.222
10	8.12	0.07	-1.155
11	8.11	0.08	-1.097
12	8.10	0.09	-1.046
13	8.09	0.10	-1.000
14	8.08	0.11	-0.959
15	8.08	0.11	-0.959
16	8.07	0.12	-0.921
17	8.05	0.14	-0.854
18	8.03	0.16	-0.796
19	8.02	0.17	-0.770
20	8.00	0.19	-0.721
21	7.99	0.20	-0.699
22	7.98	0.21	-0.678
23	7.96	0.23	-0.638
24	7.95	0.24	-0.620
25	7.94	0.25	-0.602
26	7.93	0.26	-0.585
27	7.92	0.27	-0.569
28	7.90	0.29	-0.538
29	7.88	0.31	-0.509
30	7.87	0.32	-0.495
31	7.86	0.33	-0.481
32	7.85	0.34	-0.469
33	7.84	0.35	-0.456
34	7.83	0.36	-0.444
35	7.82	0.37	-0.432
36	7.82	0.37	-0.432
37	7.80	0.39	-0.409
38	7.79	0.40	-0.398
39	7.78	0.41	-0.387
40	7.77	0.42	-0.377
41	7.75	0.44	-0.357
42	7.74	0.45	-0.347
43	7.74	0.45	-0.347

50

Sample composition:		15 wt% MEA + 5wt% MDEA	
CO2 vol% inlet:		8.16	
Temperature:		23-26oC	**Time in minute**
Stirrer speed:		1	**CO2 in vol%**
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.16	0.00	#NUM!
2	8.15	0.01	-2.000
3	8.15	0.01	-2.000
4	8.14	0.02	-1.699
5	8.14	0.02	-1.699
6	8.13	0.03	-1.523
7	8.12	0.04	-1.398
8	8.12	0.04	-1.398
9	8.11	0.05	-1.301
10	8.10	0.06	-1.222
11	8.10	0.06	-1.222
12	8.09	0.07	-1.155
13	8.08	0.08	-1.097
14	8.07	0.09	-1.046
15	8.06	0.10	-1.000
16	8.06	0.10	-1.000
17	8.05	0.11	-0.959
18	8.04	0.12	-0.921
19	8.03	0.13	-0.886
20	8.02	0.14	-0.854
21	8.02	0.14	-0.854
22	8.01	0.15	-0.824
23	8.00	0.16	-0.796
24	7.99	0.17	-0.770
25	7.98	0.18	-0.745
26	7.98	0.18	-0.745
27	7.96	0.20	-0.699
28	7.96	0.20	-0.699
29	7.95	0.21	-0.678
30	7.94	0.22	-0.658
31	7.93	0.23	-0.638
32	7.93	0.23	-0.638
33	7.92	0.24	-0.620
34	7.91	0.25	-0.602
35	7.90	0.26	-0.585
36	7.90	0.26	-0.585
37	7.89	0.27	-0.569
38	7.88	0.28	-0.553
39	7.87	0.29	-0.538
40	7.87	0.29	-0.538
41	7.86	0.30	-0.523
42	7.85	0.31	-0.509
43	7.84	0.32	-0.495

Sample composition:		5 wt% MEA + 15wt% MDEA	
CO2 vol% inlet:		8.19	
Temperature:		23-26oC	Time in minute
Stirrer speed:		1	CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.19	0.00	#NUM!
2	8.19	0.00	#NUM!
3	8.18	0.01	-2.000
4	8.17	0.02	-1.699
5	8.17	0.02	-1.699
6	8.16	0.03	-1.523
7	8.15	0.04	-1.398
8	8.14	0.05	-1.301
9	8.13	0.06	-1.222
10	8.12	0.07	-1.155
11	8.11	0.08	-1.097
12	8.10	0.09	-1.046
13	8.09	0.10	-1.000
14	8.08	0.11	-0.959
15	8.08	0.11	-0.959
16	8.07	0.12	-0.921
17	8.05	0.14	-0.854
18	8.03	0.16	-0.796
19	8.02	0.17	-0.770
20	8.00	0.19	-0.721
21	7.99	0.20	-0.699
22	7.98	0.21	-0.678
23	7.96	0.23	-0.638
24	7.95	0.24	-0.620
25	7.94	0.25	-0.602
26	7.93	0.26	-0.585
27	7.92	0.27	-0.569
28	7.90	0.29	-0.538
29	7.88	0.31	-0.509
30	7.87	0.32	-0.495
31	7.86	0.33	-0.481
32	7.85	0.34	-0.469
33	7.84	0.35	-0.456
34	7.83	0.36	-0.444
35	7.82	0.37	-0.432
36	7.82	0.37	-0.432
37	7.80	0.39	-0.409
38	7.79	0.40	-0.398
39	7.78	0.41	-0.387
40	7.77	0.42	-0.377
41	7.75	0.44	-0.357
42	7.74	0.45	-0.347
43	7.74	0.45	-0.347

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	10 wt%MEA 9.7 23-40oC 1	Time in minute CO2 in vol%	
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.10	1.60	0.204
2	7.83	1.87	0.272
3	6.01	3.69	0.567
4	4.46	5.24	0.719
5	3.71	5.99	0.777
6	2.19	7.51	0.876
7	0.92	8.78	0.943
8	0.33	9.37	0.972
9	0.17	9.53	0.979
10	0.12	9.58	0.981
11	0.07	9.63	0.984
12	0.05	9.65	0.985
13	0.04	9.66	0.985
14	0.02	9.68	0.986
15	0.01	9.69	0.986
16	0.01	9.69	0.986
17	0.01	9.69	0.986
18	0.01	9.69	0.986
19	0.01	9.69	0.986
20	0.01	9.69	0.986
21	0.01	9.69	0.986

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	10 wt%DEA 8.16 40-42oC 1	Time in minute CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.10	0.06	-1.222
2	8.04	0.12	-0.921
3	8.02	0.14	-0.854
4	8.00	0.16	-0.796
5	7.95	0.21	-0.678
6	7.90	0.26	-0.585
7	7.88	0.28	-0.553
8	7.85	0.31	-0.509
9	7.81	0.35	-0.456
10	7.78	0.38	-0.420
11	7.74	0.42	-0.377
12	7.71	0.45	-0.347
13	7.67	0.49	-0.310
14	7.64	0.52	-0.284
15	7.61	0.55	-0.260
16	7.57	0.59	-0.229
17	7.55	0.61	-0.215
18	7.52	0.64	-0.194
19	7.50	0.66	-0.180
20	7.46	0.70	-0.155
21	7.44	0.72	-0.143
22	7.41	0.75	-0.125
23	7.40	0.76	-0.119
24	7.37	0.79	-0.102
25	7.35	0.81	-0.092
26	7.33	0.83	-0.081
27	7.31	0.85	-0.071
28	7.28	0.88	-0.056
29	7.26	0.90	-0.046
30	7.24	0.92	-0.036
31	7.22	0.94	-0.027
32	7.20	0.96	-0.018
33	7.18	0.98	-0.009
34	7.16	1.00	0.000
35	7.14	1.02	0.009
36	7.12	1.04	0.017
37	7.11	1.05	0.021
38	7.09	1.07	0.029
39	7.07	1.09	0.037
40	7.05	1.11	0.045
41	7.03	1.13	0.053
42	7.01	1.15	0.061
43	7.00	1.16	0.064

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	10 wt%MDEA 8.16 40-42oC 1	Time in minute CO2 in vol%	
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.07	0.09	-1.046
2	8.00	0.16	-0.796
3	7.92	0.24	-0.620
4	7.88	0.28	-0.553
5	7.81	0.35	-0.456
6	7.77	0.39	-0.409
7	7.68	0.48	-0.319
8	7.65	0.51	-0.292
9	7.60	0.56	-0.252
10	7.55	0.61	-0.215
11	7.50	0.66	-0.180
12	7.45	0.71	-0.149
13	7.39	0.77	-0.114
14	7.35	0.81	-0.092
15	7.29	0.87	-0.060
16	7.27	0.89	-0.051
17	7.25	0.91	-0.041
18	7.18	0.98	-0.009
19	7.14	1.02	0.009
20	7.10	1.06	0.025
21	7.06	1.10	0.041
22	7.02	1.14	0.057
23	6.99	1.17	0.068
24	6.95	1.21	0.083
25	6.90	1.26	0.100
26	6.88	1.28	0.107
27	6.85	1.31	0.117
28	6.82	1.34	0.127
29	6.79	1.37	0.137
30	6.76	1.40	0.146
31	6.73	1.43	0.155
32	6.70	1.46	0.164
33	6.67	1.49	0.173
34	6.64	1.52	0.182
35	6.62	1.54	0.188
36	6.60	1.56	0.193
37	6.57	1.59	0.201
38	6.54	1.62	0.210
39	6.51	1.65	0.217
40	6.50	1.66	0.220
41	6.47	1.69	0.228
42	6.44	1.72	0.236
43	6.42	1.74	0.241

Sample composition:	30 wt%MEA	Time in minute
CO2 vol% inlet:	8.23	CO2 in vol%
Temperature:	40-45oC	
Stirrer speed:	1	

Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.17	0.06	-1.222
2	8.11	0.12	-0.921
3	8.01	0.22	-0.658
4	7.99	0.24	-0.620
5	7.93	0.30	-0.523
6	7.88	0.35	-0.456
7	7.84	0.39	-0.409
8	7.79	0.44	-0.357
9	7.74	0.49	-0.310
10	7.77	0.46	-0.337
11	7.65	0.58	-0.237
12	7.61	0.62	-0.208
13	7.57	0.66	-0.180
14	7.52	0.71	-0.149
15	7.48	0.75	-0.125
16	7.43	0.80	-0.097
17	7.40	0.83	-0.081
18	7.37	0.86	-0.066
19	7.34	0.89	-0.051
20	7.31	0.92	-0.036
21	7.28	0.95	-0.022
22	7.25	0.98	-0.009
23	7.21	1.02	0.009
24	7.18	1.05	0.021
25	7.14	1.09	0.037
26	7.12	1.11	0.045
27	7.09	1.14	0.057
28	7.06	1.17	0.068
29	7.01	1.22	0.086
30	7.03	1.20	0.079
31	6.97	1.26	0.100
32	6.94	1.29	0.111
33	6.92	1.31	0.117
34	6.89	1.34	0.127
35	6.87	1.36	0.134
36	6.84	1.39	0.143
37	6.81	1.42	0.152
38	6.79	1.44	0.158
39	6.78	1.45	0.161
40	6.74	1.49	0.173
41	6.73	1.50	0.176
42	6.71	1.52	0.182
43	6.69	1.54	0.188

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	30 wt%DEA 8.14 39-42oC 1	Time in minute CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.02	0.12	-0.921
2	7.95	0.19	-0.721
3	7.86	0.28	-0.553
4	7.79	0.35	-0.456
5	7.71	0.43	-0.367
6	7.66	0.48	-0.319
7	7.56	0.58	-0.237
8	7.50	0.64	-0.194
9	7.43	0.71	-0.149
10	7.37	0.77	-0.114
11	7.31	0.83	-0.081
12	7.25	0.89	-0.051
13	7.19	0.95	-0.022
14	7.14	1.00	0.000
15	7.08	1.06	0.025
16	7.03	1.11	0.045
17	6.98	1.16	0.064
18	6.93	1.21	0.083
19	6.89	1.25	0.097
20	6.86	1.28	0.107
21	6.82	1.32	0.121
22	6.77	1.37	0.137
23	6.73	1.41	0.149
24	6.69	1.45	0.161
25	6.66	1.48	0.170
26	6.63	1.51	0.179
27	6.60	1.54	0.188
28	6.56	1.58	0.199
29	6.53	1.61	0.207
30	6.51	1.63	0.212
31	6.49	1.65	0.217
32	6.44	1.70	0.230
33	6.41	1.73	0.238
34	6.38	1.76	0.246
35	6.35	1.79	0.253
36	6.33	1.81	0.258
37	6.31	1.83	0.262
38	6.28	1.86	0.270
39	6.25	1.89	0.276
40	6.23	1.91	0.281
41	6.21	1.93	0.286
42	6.19	1.95	0.290
43	6.16	1.98	0.297

57

Sample composition: CO2 vol% inlet: Temperature: Stirrer speed:	30 wt%MDEA 8.22 39-42oC 1	Time in minute CO2 in vol%	
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.18	0.04	-1.398
2	8.15	0.07	-1.155
3	8.12	0.10	-1.000
4	8.05	0.17	-0.770
5	8.01	0.21	-0.678
6	7.97	0.25	-0.602
7	7.93	0.29	-0.538
8	7.89	0.33	-0.481
9	7.84	0.38	-0.420
10	7.81	0.41	-0.387
11	7.76	0.46	-0.337
12	7.72	0.50	-0.301
13	7.69	0.53	-0.276
14	7.65	0.57	-0.244
15	7.61	0.61	-0.215
16	7.57	0.65	-0.187
17	7.54	0.68	-0.167
18	7.51	0.71	-0.149
19	7.48	0.74	-0.131
20	7.45	0.77	-0.114
21	7.43	0.79	-0.102
22	7.40	0.82	-0.086
23	7.37	0.85	-0.071
24	7.34	0.88	-0.056
25	7.31	0.91	-0.041
26	7.29	0.93	-0.032
27	7.27	0.95	-0.022
28	7.24	0.98	-0.009
29	7.22	1.00	0.000
30	7.20	1.02	0.009
31	7.18	1.04	0.017
32	7.16	1.06	0.025
33	7.15	1.07	0.029
34	7.13	1.09	0.037
35	7.11	1.11	0.045
36	7.09	1.13	0.053
37	7.06	1.16	0.064
38	7.04	1.18	0.072
39	7.01	1.21	0.083
40	6.99	1.23	0.090
41	6.97	1.25	0.097
42	6.95	1.27	0.104
43	6.93	1.29	0.111

Sample composition:		15 wt% MEA + 5wt% MDEA	
CO2 vol% inlet:		8.17	
Temperature:		39-42oC	Time in minute
Stirrer speed:		1	CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.17	0.00	#NUM!
2	8.17	0.00	#NUM!
3	8.17	0.00	#NUM!
4	8.17	0.00	#NUM!
5	8.16	0.01	-2.000
6	8.16	0.01	-2.000
7	8.15	0.02	-1.699
8	8.15	0.02	-1.699
9	8.14	0.03	-1.523
10	8.14	0.03	-1.523
11	8.13	0.04	-1.398
12	8.12	0.05	-1.301
13	8.12	0.05	-1.301
14	8.11	0.06	-1.222
15	8.11	0.06	-1.222
16	8.11	0.06	-1.222
17	8.10	0.07	-1.155
18	8.10	0.07	-1.155
19	8.09	0.08	-1.097
20	8.08	0.09	-1.046
21	8.08	0.09	-1.046
22	8.07	0.10	-1.000
23	8.06	0.11	-0.959
24	8.05	0.12	-0.921
25	8.05	0.12	-0.921
26	8.04	0.13	-0.886
27	8.04	0.13	-0.886
28	8.03	0.14	-0.854
29	8.03	0.14	-0.854
30	8.02	0.15	-0.824
31	8.02	0.15	-0.824
32	8.02	0.15	-0.824
33	8.01	0.16	-0.796
34	8.01	0.16	-0.796
35	8.00	0.17	-0.770
36	8.00	0.17	-0.770
37	8.00	0.17	-0.770
38	7.98	0.19	-0.721
39	7.98	0.19	-0.721
40	7.97	0.20	-0.699
41	7.97	0.20	-0.699
42	7.96	0.21	-0.678
43	7.96	0.21	-0.678

Sample composition:		5 wt% MEA + 15wt% MDEA	
CO2 vol% inlet:		7.3	
Temperature:		39-41oC	Time in minute
Stirrer speed:		1	CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	7.21	0.09	-1.046
2	7.15	0.15	-0.824
3	7.05	0.25	-0.602
4	6.96	0.34	-0.469
5	6.87	0.43	-0.367
6	6.79	0.51	-0.292
7	6.73	0.57	-0.244
8	6.66	0.64	-0.194
9	6.60	0.70	-0.155
10	6.53	0.77	-0.114
11	6.46	0.84	-0.076
12	6.40	0.90	-0.046
13	6.33	0.97	-0.013
14	6.28	1.02	0.009
15	6.23	1.07	0.029
16	6.17	1.13	0.053
17	6.11	1.19	0.076
18	6.06	1.24	0.093
19	6.01	1.29	0.111
20	5.96	1.34	0.127
21	5.91	1.39	0.143
22	5.87	1.43	0.155
23	5.82	1.48	0.170
24	5.79	1.51	0.179
25	5.75	1.55	0.190
26	5.71	1.59	0.201
27	5.67	1.63	0.212
28	5.63	1.67	0.223
29	5.59	1.71	0.233
30	5.56	1.74	0.241
31	5.52	1.78	0.250
32	5.49	1.81	0.258
33	5.45	1.85	0.267
34	5.42	1.88	0.274
35	5.38	1.92	0.283
36	5.36	1.94	0.288
37	5.33	1.97	0.294
38	5.29	2.01	0.303
39	5.26	2.04	0.310
40	5.23	2.07	0.316
41	5.21	2.09	0.320
42	5.16	2.14	0.330
43	5.13	2.17	0.336

Sample composition:		15 wt% DEA + 5wt% MDEA	
CO2 vol% inlet:		8.14	
Temperature:		40-43oC	Time in minute
Stirrer speed:		1	CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	8.06	0.08	-1.097
2	8.00	0.14	-0.854
3	7.94	0.20	-0.699
4	7.84	0.30	-0.523
5	7.81	0.33	-0.481
6	7.75	0.39	-0.409
7	7.69	0.45	-0.347
8	7.73	0.41	-0.387
9	7.57	0.57	-0.244
10	7.51	0.63	-0.201
11	7.48	0.66	-0.180
12	7.42	0.72	-0.143
13	7.37	0.77	-0.114
14	7.31	0.83	-0.081
15	7.27	0.87	-0.060
16	7.22	0.92	-0.036
17	7.18	0.96	-0.018
18	7.14	1.00	0.000
19	7.10	1.04	0.017
20	7.06	1.08	0.033
21	7.04	1.10	0.041
22	7.01	1.13	0.053
23	6.98	1.16	0.064
24	6.97	1.17	0.068
25	6.95	1.19	0.076
26	6.92	1.22	0.086
27	6.89	1.25	0.097
28	6.85	1.29	0.111
29	6.83	1.31	0.117
30	6.81	1.33	0.124
31	6.78	1.36	0.134
32	6.76	1.38	0.140
33	6.73	1.41	0.149
34	6.70	1.44	0.158
35	6.68	1.46	0.164
36	6.66	1.48	0.170
37	6.63	1.51	0.179
38	6.61	1.53	0.185
39	6.58	1.56	0.193
40	6.57	1.57	0.196
41	6.55	1.59	0.201
42	6.53	1.61	0.207
43	6.52	1.62	0.210

Sample composition:		5 wt% DEA + 15wt% MDEA	
CO2 vol% inlet:		8.1	
Temperature:		40-43oC	Time in minute
Stirrer speed:		1	CO2 in vol%
Time	CO2 Outlet	CO2 Absorbed	log(CO2 Absorbed)
1	7.96	0.14	-0.854
2	7.86	0.24	-0.620
3	7.75	0.35	-0.456
4	7.64	0.46	-0.337
5	7.54	0.56	-0.252
6	7.43	0.67	-0.174
7	7.33	0.77	-0.114
8	7.23	0.87	-0.060
9	7.13	0.97	-0.013
10	7.05	1.05	0.021
11	6.97	1.13	0.053
12	6.90	1.20	0.079
13	6.82	1.28	0.107
14	6.75	1.35	0.130
15	6.68	1.42	0.152
16	6.62	1.48	0.170
17	6.55	1.55	0.190
18	6.50	1.60	0.204
19	6.44	1.66	0.220
20	6.39	1.71	0.233
21	6.33	1.77	0.248
22	6.28	1.82	0.260
23	6.24	1.86	0.270
24	6.19	1.91	0.281
25	6.15	1.95	0.290
26	6.11	1.99	0.299
27	6.06	2.04	0.310
28	6.03	2.07	0.316
29	5.99	2.11	0.324
30	5.96	2.14	0.330
31	5.92	2.18	0.338
32	5.89	2.21	0.344
33	5.86	2.24	0.350
34	5.83	2.27	0.356
35	5.80	2.30	0.362
36	5.78	2.32	0.365
37	5.75	2.35	0.371
38	5.73	2.37	0.375
39	5.70	2.40	0.380
40	5.68	2.42	0.384
41	5.66	2.44	0.387
42	5.63	2.47	0.393
43	5.62	2.48	0.394

Sample composition:	30 wt%MEA		Time in minute	
CO2 vol% inlet:	15.85	CO2 Outlet and Absorbed in vol%		
Temperature:	23-28oC	Initial layer	6 cm	
Stirrer speed:	1	Final layer	2 cm	
Time	CO2 Outlet	CO2 Absorbed	Foam height(cm)	log(CO2 Absorbed)
1	15.63	0.22	10	-0.658
2	15.47	0.38	12	-0.420
3	15.27	0.58	13	-0.237
4	15.06	0.79	14	-0.102
5	14.81	1.04	12	0.017
6	14.67	1.18	13	0.072
7	14.47	1.38	12	0.140
8	14.30	1.55	14	0.190
9	14.10	1.75	14	0.243
10	13.96	1.89	13	0.276
11	13.80	2.05	13	0.312
12	13.66	2.19	10	0.340
13	13.50	2.35	13	0.371
14	13.35	2.50	14	0.398
15	13.21	2.64	15	0.422
16	13.09	2.76	12	0.441
17	12.94	2.91	16	0.464
18	12.81	3.04	15	0.483
19	12.69	3.16	14	0.500
20	12.57	3.28	13	0.516
21	12.45	3.40	12	0.531
22	12.32	3.53	12	0.548
23	12.22	3.63	15	0.560
24	12.10	3.75	11	0.574
25	11.99	3.86	13	0.587
26	11.89	3.96	14	0.598
27	11.79	4.06	15	0.609
28	11.70	4.15	14	0.618
29	11.58	4.27	14	0.630
30	11.51	4.34	14	0.637
31	11.42	4.43	12	0.646
32	11.34	4.51	11	0.654
33	11.26	4.59	10	0.662
34	11.18	4.67	11	0.669
35	11.10	4.75	9	0.677
36	11.02	4.83	10	0.684
37	10.95	4.90	9	0.690
38	10.87	4.98	8	0.697
39	10.76	5.09	5	0.707
40	10.70	5.15	6	0.712
41	10.63	5.22	6	0.718
42	10.58	5.27	5	0.722
43	10.51	5.34	4	0.728

Sample composition:	30 wt%DEA		Time in minute	
CO2 vol% inlet:	14.98		CO2 Outlet and Absorbed in vol%	
Temperature:	23-28oC	Initial layer	6 cm	
Stirrer speed:	1	Final layer	1 cm	
Time	CO2 Outlet	CO2 Absorbed	Foam height(cm)	log(CO2 Absorbed)
1	14.77	0.21	1	-0.678
2	14.58	0.40	1	-0.398
3	14.39	0.59	1	-0.229
4	14.23	0.75	1	-0.125
5	14.05	0.93	1	-0.032
6	13.89	1.09	1	0.037
7	13.67	1.31	1	0.117
8	13.69	1.29	1	0.111
9	13.50	1.48	1	0.170
10	13.37	1.61	1	0.207
11	13.25	1.73	1	0.238
12	13.13	1.85	1	0.267
13	13.01	1.97	1	0.294
14	12.92	2.06	1	0.314
15	12.84	2.14	1	0.330
16	12.73	2.25	1	0.352
17	12.70	2.28	1	0.358
18	12.59	2.39	1	0.378
19	12.50	2.48	1	0.394
20	12.39	2.59	1	0.413
21	12.33	2.65	2	0.423
22	12.26	2.72	1	0.435
23	12.21	2.77	2	0.442
24	12.14	2.84	1	0.453
25	12.06	2.92	1	0.465
26	12.01	2.97	1	0.473
27	11.97	3.01	1	0.479
28	11.93	3.05	1	0.484
29	11.90	3.08	1	0.489
30	11.83	3.15	1	0.498

Sample composition:	30 wt%MDEA		Time in minute	
CO2 vol% inlet:	15.08	CO2 Outlet and Absorbed in vol%		
Temperature:	23-28oC	Initial layer	6 cm	
Stirrer speed:	1	Final layer	1 cm	
Time	CO2 Outlet	CO2 Absorbed	Foam height(cm)	log(CO2 Absorbed)
1	14.88	0.20	0	-0.699
2	14.67	0.41	0	-0.387
3	14.51	0.57	0	-0.244
4	14.33	0.75	1	-0.125
5	14.19	0.89	2	-0.051
6	14.04	1.04	1	0.017
7	13.90	1.18	1	0.072
8	13.78	1.30	1	0.114
9	13.66	1.42	1	0.152
10	13.55	1.53	2	0.185
11	13.44	1.64	2	0.215
12	13.34	1.74	2	0.241
13	13.23	1.85	2	0.267
14	13.12	1.96	1	0.292
15	13.04	2.04	1	0.309
16	12.95	2.13	1	0.328
17	12.87	2.21	1	0.344
18	12.79	2.29	1	0.360
19	12.72	2.36	1	0.373
20	12.61	2.47	1	0.393
21	12.56	2.52	2	0.401
22	12.50	2.58	2	0.412
23	12.43	2.65	2	0.423
24	12.36	2.72	1	0.435
25	12.32	2.76	1	0.441
26	12.28	2.80	1	0.447
27	12.23	2.85	1	0.455
28	12.19	2.89	1	0.461
29	12.14	2.94	1	0.468
30	12.10	2.98	1	0.474
31	12.04	3.04	1	0.483
32	12.00	3.08	1	0.489
33	11.95	3.13	2	0.496
34	11.90	3.18	2	0.502
35	11.86	3.22	2	0.508
36	11.78	3.30	1	0.519
37	11.70	3.38	1	0.529

Sample composition:	15 wt% MEA + 5wt% MDEA		Time in minute	
CO2 vol% inlet:	15.77		CO2 Outlet and Absorbed in vol%	
Temperature:	23-28oC	Initial layer	6 cm	
Stirrer speed:	1	Final layer	1 cm	
Time	CO2 Outlet	CO2 Absorbed	Foam height(cm)	log(CO2 Absorbed)
1	15.67	0.10	-	-1.000
2	15.55	0.22	-	-0.658
3	15.42	0.35	-	-0.456
4	15.30	0.47	-	-0.328
5	15.19	0.58	-	-0.237
6	15.09	0.68	1	-0.167
7	14.98	0.79	1	-0.102
8	14.87	0.90	2	-0.046
9	14.76	1.01	2	0.004
10	14.68	1.09	2	0.037
11	14.57	1.20	3	0.079
12	14.47	1.30	3	0.114
13	14.36	1.41	3	0.149
14	14.31	1.46	3	0.164
15	14.26	1.51	3	0.179
16	14.21	1.56	3	0.193
17	14.15	1.62	3	0.210
18	13.99	1.78	4	0.250
19	13.93	1.84	4	0.265
20	13.86	1.91	4	0.281
21	13.75	2.02	4	0.305
22	13.64	2.13	4	0.328
23	12.43	2.65	2	0.423
24	12.36	2.72	1	0.435
25	12.32	2.76	1	0.441
26	12.28	2.80	1	0.447
27	12.23	2.85	1	0.455
28	12.19	2.89	1	0.461
29	12.14	2.94	1	0.468
30	12.10	2.98	1	0.474
31	12.04	3.04	1	0.483
32	12.00	3.08	1	0.489
33	11.95	3.13	2	0.496
34	11.90	3.18	2	0.502
35	11.86	3.22	2	0.508
36	11.78	3.30	1	0.519
37	11.70	3.38	1	0.529

Sample composition:	5 wt% MEA + 15 wt% MDEA		Time in minute	
CO2 vol% inlet:	15.08		CO2 Outlet and Absorbed in vol%	
Temperature:	23-28oC		Initial layer	6 cm
Stirrer speed:	1		Final layer	1 cm
Time	CO2 Outlet	CO2 Absorbed	Foam height(cm)	log(CO2 Absorbed)
1	15.35	0.04	-	-1.398
2	15.28	0.11	-	-0.959
3	15.22	0.17	-	-0.770
4	15.16	0.23	-	-0.638
5	15.11	0.28	1	-0.553
6	15.06	0.33	1	-0.481
7	15.01	0.38	2	-0.420
8	14.98	0.41	2	-0.387
9	14.92	0.47	2	-0.328
10	14.86	0.53	2	-0.276
11	14.81	0.58	2	-0.237
12	14.76	0.63	2	-0.201
13	14.72	0.67	2	-0.174
14	14.68	0.71	2	-0.149
15	14.63	0.76	2	-0.119
16	14.60	0.79	2	-0.102

Sample calculation for this project

Sample calculation for MEA

$V_{solvent} = 200$ mL $= 0.2$ L $= 0.0002$ m^3

$\rho_{H2O} = 1000$ kg/m^3

$\rho_{MEA} = 1020$ kg/m^3

x wt% $= (V_{MEA} \times \rho_{MEA}) / [(V_{MEA} \times \rho_{MEA}) + (V_{H2O} \times \rho_{H2O})]$

x wt% $= (V_{MEA} \times 1020) / [(V_{MEA} \times 1020) + [(0.0002 - V_{MEA}) + 1000]]$

x wt% $= (1020V_{MEA}) / [(1020V_{MEA}) + (0.2 - 1000V_{MEA})]$

x wt% $= (1020V_{MEA}) / (20V_{MEA} + 0.2)$

for x wt% =10wt% MEA

$0.10 (20V_{MEA} + 0.2) = 1020V_{MEA}$

$2 V_{MEA} + 0.02 = 1020V_{MEA}$

$1018V_{MEA} = 0.02$

$V_{MEA} = 1.96 \times 10^{-5}$ m^3

$V_{MEA} = 19.6$ mL

$V_{H2O} = 200 - 19.6 = 180.4$ mL

Sample calculation for mixture of MEA and MDEA

MEA-15wt% + MDEA-5wt%

$V_{solvent} = 200\ mL = 0.2\ L = 0.0002\ m^3$

$V_{MEA} = 10\ mL = 0.01\ L = 0.00001\ m^3$

$\rho_{H2O} = 1000\ kg/m^3$

$\rho_{MEA} = 1020\ kg/m^3$

$\rho_{MDEA} = 1040\ kg/m^3$

$x_{MDEA}\ wt\% = (V_{MDEA} \times \rho_{MDEA}) / [(V_{MEA} \times \rho_{MEA}) + (V_{MDEA} \times \rho_{MDEA}) + (V_{H2O} \times \rho_{H2O})]$

$x_{MDEA}\ wt\% = (V_{MEA} \times 1040) / [(V_{MEA} \times 1020) + (V_{MDEA} \times 1040) + [(0.0002 - 0.00001 - V_{MDEA}) \times 1000]]$

for $x_{MDEA}\ wt\% = 5\ wt\%MDEA$

$0.05 = (1040\ V_{MDEA}) / [\ (0.0102 + 1040 V_{MDEA} + 0.19 - 1000 V_{MDEA})\ ]$

$0.01001 + 2\ V_{MDEA} = 1040\ V_{MDEA}$

$V_{MDEA} = 9.64 \times 10^{-6}\ m^3$

$V_{MDEA} = 9.6\ mL$

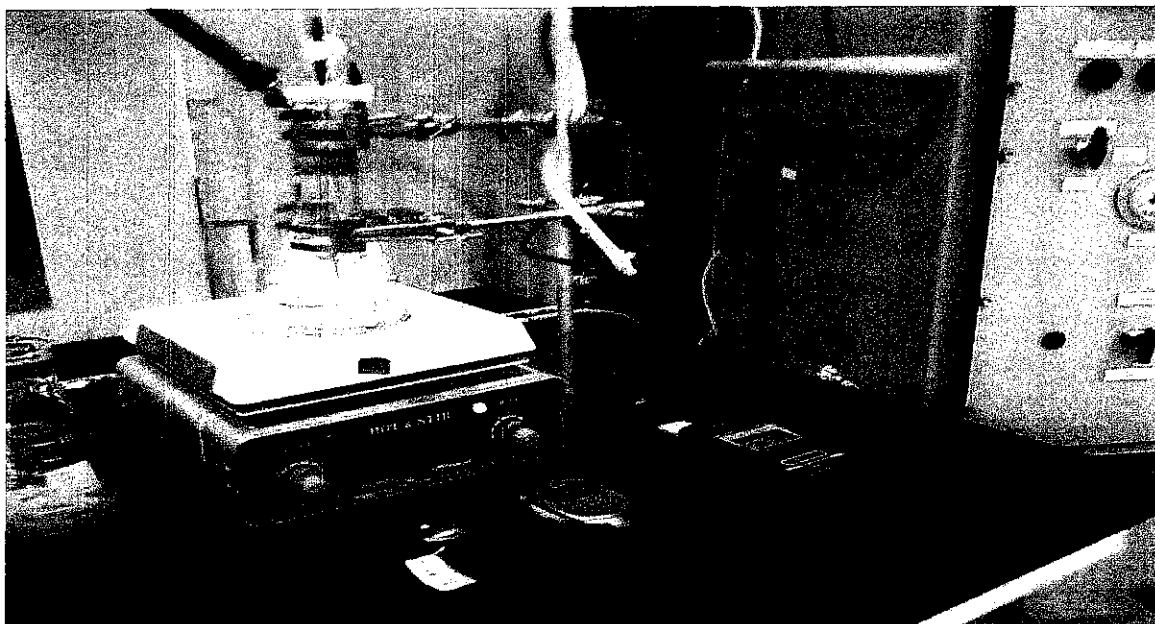$V_{MEA} = 10\ mL$

$V_{H2O} = 180.4 mL$

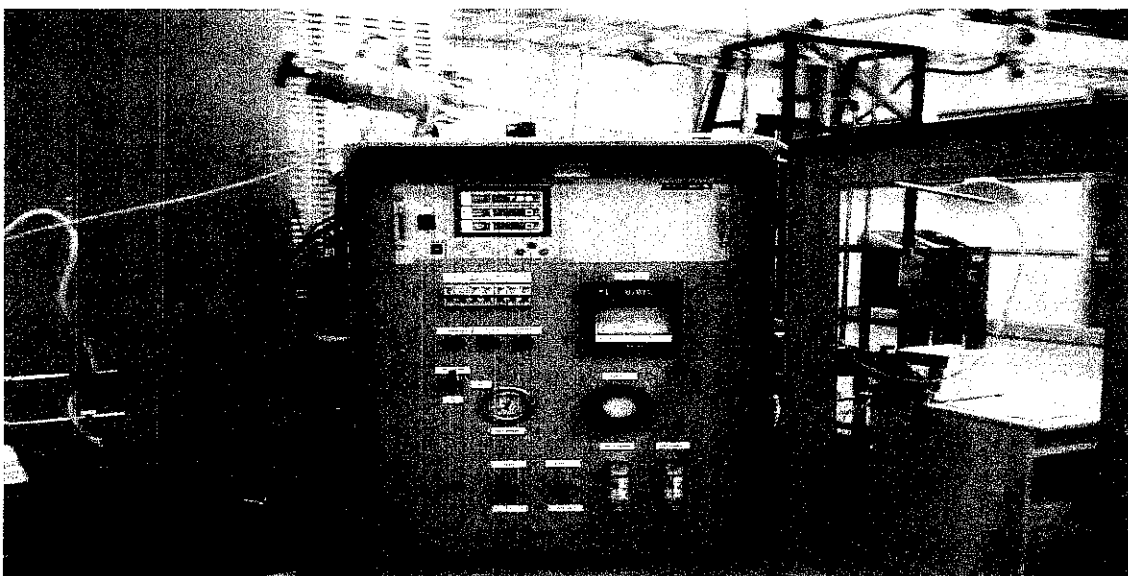Figure 3: experiment setup for solubility of CO_2 in aqueous amine solutions at different temperatures

Figure 4: IR Gas Analyzer

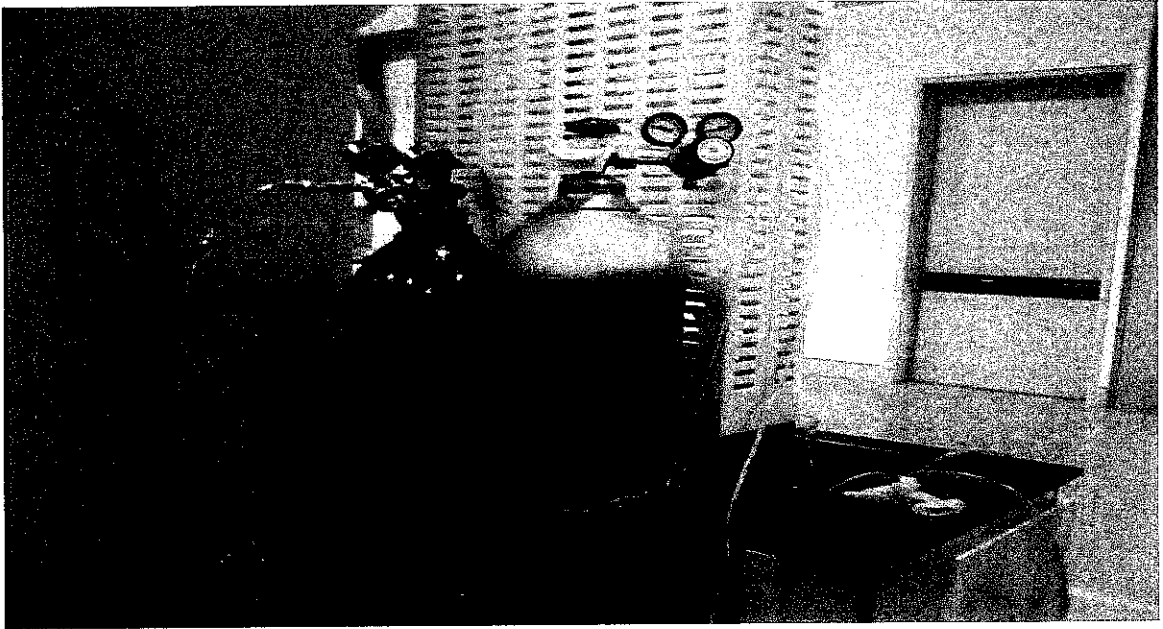Figure 5: H_2 and N_2 tanks