การวัดค่าความหนาแน่นและความหนืดของสารละลายเอมีนประเภทอะมิโนเอทานอลสำหรับกระบวนการการดูดซึมก๊าซคาร์บอนไดออกไซด์

นางสาวณัฐกานต์ ภูมิโคกรักษ์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมทรัพยากรธรณี ภาควิชาวิศวกรรมเหมืองแร่และปิโตรเลียม
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ปีการศึกษา 2558

DENSITY AND VISCOSITY MEASUREMENT OF AQUEOUS AMINE SOLUTION OF AMINO ETHANOL FOR CARBON DIOXIDE ABSORPTION PROCESS

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Georesources Engineering
Department of Mining and Petroleum Engineering
Faculty of Engineering
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Thesis Title	DENSITY AND VISCOSITY MEASUREMENT OF AQUEOUS AMINE SOLUTION OF AMINO ETHANOL FOR CARBON DIOXIDE ABSORPTION PROCESS
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Field of Study	Georesources Engineering
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ณัฐกานต์ ภูมิโคกรักษ์ : การวัดค่าความหนาแน่นและความหนืดของสารละลายเอมีนประเภทอะมิโนเอทานอลสำหรับกระบวนการการดูดซึมก๊าซคาร์บอนไดออกไซด์ (DENSITY AND VISCOSITY MEASUREMENT OF AQUEOUS AMINE SOLUTION OF AMINO ETHANOL FOR CARBON DIOXIDE ABSORPTION PROCESS) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร. เกรียงไกร มณีอินทร์, 94 หน้า.

ก๊าซคาร์บอนไดออกไซด์เป็นสาเหตุหนึ่งของการเปลี่ยนแปลงภูมิอากาศและสภาวะโลกร้อนในปัจจุบัน โดยแหล่งกำเนิดของก๊าซส่วนใหญ่มาจากโรงไฟฟ้าพลังงานเชื้อเพลิงซากดึกดำบรรพ์ ด้วยเหตุนี้จึงมีการพัฒนาเทคโนโลยีการดูดซึมก๊าซคาร์บอนไดออกไซด์ด้วยสารละลายเอมีนประเภทอะมิโนแอลกอฮอล์ ได้แก่ 2-(Diethylamino)ethanol (DEAE), 2-(Dimethylamino)ethanol (DMAE) and 2-(Methylamino)ethanol (MAE) ที่ช่วยลดปริมาณก๊าซคาร์บอนไดออกไซด์จากแหล่งกำเนิดนี้ นอกจากนี้ การศึกษาความหนาแน่นและความหนืดของสารละลายดังกล่าวเพื่อใช้เป็นข้อมูลพื้นฐานในการออกแบบเครื่องมือและกระบวนการการดูดซึมก๊าซคาร์บอนไดออกไซด์ ซึ่งวัตถุประสงค์ของการศึกษานี้คือ (1) เพื่อวัดค่าความหนาแน่นและความหนืดของสารละลายเอมีนประเภทอะมิโนแอลกอฮอล์และประเมินผลอัตราความเข้มข้นของสารและอุณหภูมิที่มีผลต่อคุณสมบัติเหล่านี้ (2) เพื่อพัฒนาสมการความสัมพันธ์สำหรับใช้พยากรณ์ข้อมูลในอนาคตและ (3) เพื่อพิจารณาผลของหมู่ฟังก์ชันต่างๆ ที่เกาะกับหมู่เอมีนและอะมิโนแอลกอฮอล์ที่มีผลต่อคุณสมบัติข้างต้น ผลจากการศึกษาพบว่าค่าความหนาแน่นของ DEAE, DMAE และ MAE ลดลงเมื่ออุณหภูมิเพิ่มสูงขึ้น นอกจากนี้ ผลของค่าความหนืดของสารละลายดังกล่าวมีค่าเพิ่มขึ้นตามค่าอุณหภูมิที่เพิ่มสูงขึ้นจนถึงอัตราความเข้มข้นของสารละลายของ DEAE, DMAE และ MAE ที่ประมาณ 0.4, 0.4 และ 0.6 โดยเศษส่วนโมลตามลำดับ จากนั้นค่าความหนืดจะเริ่มลดลงตามอุณหภูมิที่เพิ่มสูงขึ้น อย่างไรก็ตามสมการความสัมพันธ์ของ Redlich-Kister ถูกพัฒนาขึ้นเพื่อแสดงข้อมูลของค่าความหนาแน่นและความหนืด อีกทั้งยังใช้เพื่อพยากรณ์ค่าของคุณสมบัติดังกล่าวเพื่อการออกแบบเครื่องมือและกระบวนการการดูดซึมก๊าซคาร์บอนไดออกไซด์ ซึ่งสมการความสัมพันธ์ดังกล่าวเป็นสมการที่มีความเหมาะสมที่สุด เนื่องจากให้ค่าร้อยละของส่วนเบี่ยงเบนมาตรฐานที่ต่ำที่สุด โดยค่าร้อยละของส่วนเบี่ยงเบนมาตรฐานของความหนาแน่นของ DEAE, DMAE และ MAE คือร้อยละ 0.1590 ร้อยละ 0.112 และ ร้อยละ 0.0261 ตามลำดับ และค่าร้อยละของส่วนเบี่ยงเบนมาตรฐานของความหนืดของ DEAE, DMAE และ MAE คือร้อยละ 1.9413 2.0312 และ 1.4912 ตามลำดับ

ภาควิชา วิศวกรรมเหมืองแร่และปิโตรเลียม ลายมือชื่อนิสิต ....
สาขาวิชา วิศวกรรมทรัพยากรธรณี ลายมือชื่อ อ.ที่ปรึกษาหลัก ....
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NUTTHAKARN PHUMKOKRUX: DENSITY AND VISCOSITY MEASUREMENT OF AQUEOUS AMINE SOLUTION OF AMINO ETHANOL FOR CARBON DIOXIDE ABSORPTION PROCESS. ADVISOR: ASST. PROF. KREANGKRAI MANEEINTR, Ph.D., 94 pp.

Carbon dioxide (CO_2) causes the global issues on climate change and global warming. The sources of CO_2 are from fossil fuel power plants. The chemical absorption by aqueous amine solution of amino ethanol of 2-(Diethylamino)ethanol (DEAE), 2-(Dimethylamino)ethanol (DMAE) and 2-(Methylamino)ethanol (MAE) are promising method to remove CO_2 from fuel gases. Measurement of density and viscosity are the fundamental data for designing and modeling the absorption process. The objectives of this study are (1) to measure the density and viscosity of aqueous amino ethanol solutions and evaluate the effect of mole fraction and temperature on density and viscosity of amines. (2) to develop the correlation for prediction the data in the future. And (3) to investigate the effect of the various function groups attached to back-bone of amino ethanol. The results for the densities of DEAE, DMAE and MAE decrease with an increase of mole fraction and temperature. Also, the viscosities of all of the range of mole fraction of DEAE, DMAE and MAE decrease as temperature increases up to mole fraction of 0.4, 0.4 and 0.6, respectively and becomes lower. Moreover, the correlations by Redlich-Kister equation is the most suitable model which have been developed to represent the data and predict the data for equipment design. This equation gave the lowest percent absolute deviation (%AAD). The %AAD of density of DEAE, DMAE and MAE is 0.1590%, 0.0112% and 0.0261%, respectively. The %AAD of viscosity of DEAE, DMAE MAE is 1.9413%, 2.0312%, 1.4912, respectively.

Department:	Mining and Petroleum Engineering	Student's Signature	....
		Advisor's Signature	....
Field of Study:	Georesources Engineering		
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CONTENTS

Page

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Currently, carbon dioxide (CO_2) causes the global issues on climate change and global warming. (IPCC, 2012) The main sources of carbon dioxide are human sources and natural sources but carbon dioxide emissions from human sources especially, from burning of fossil fuels have been growing. (IEA., 2015; Le Quéré et al., 2013) Human activities are the primary causes of the increased carbon dioxide concentrations in the atmosphere. The burning of fossil fuels such as coal, oil and natural gas accounting of 87% of human carbon dioxide emissions. Coal is the most carbon intensive fossil fuel and produces the most carbon dioxide because it has high rate of use therefore, coal is the largest fossil fuel source of carbon dioxide emissions. (IPCC, 2012)

An increase of global temperature by comparing with carbon dioxide levels in 1960-2008 is presented in the Figure 1.1: The temperature increases with the amount of CO_2 in the atmosphere. The activities that produce carbon dioxide emission in USA as presented in the Figure 1.2: The main activity that produced the carbon dioxide emission come from power generation sector around 39.8%. Other activities are transportation sector (33.5%), industrial sector (15.9%), residential sector (6.4%) and commercial sector (4.3%) (EIA, 2013)

1.1 Uses and effect of CO_2

CO_2 can be used in various ways. It has great potential as a chemical feedstock for variety of commodity chemicals. Moreover, CO_2 can be used in industrial section to produce dry ice for using in various activities such as cold grinding process to grind the hard material, low temperature refrigerant process, inerting and cooling process. (Freezco, 2016) For food industry, CO_2 can be used in carbonated beverages industry and food preservation process. It is an essential ingredient in medical oxygen, where, in low concentrations, it acts as a breathing stimulant, and in the growth of plants or algae. (Freezco, 2016; Uttanavanit, 2011)

Currently, there are also extensive uses of CO_2 in enhanced oil recovery processes (EOR) to recover more oil from petroleum reservoirs (Gupta, Coyle, & Thambimuthu, 2003)

However, CO_2 has adverse effects as well. CO_2 is a significant factor in climate change and global warming. Increasing temperatures will lead to changes in many aspects such as wind pattern and tides pattern in the ocean. (Uttanavanit, 2011) It affects to many parts such as ecological, social, economic, hydrological and healthy. Carbon dioxide capture is the part of carbon capture and storage (CCS) technology to remove the total of carbon dioxide emission from the atmosphere around 80-90% by various techniques. (Gupta et al., 2003; K. Maneeintr, 2009)

1.2 Flue gas from coal-fired power plant

The combustion process of coal from coal-fired power plants gives the pollutant involve production of $CO_{2.}$ The table 1.1, present the composition of flue gas evolved in burning bituminous coal from western Kentucky. (Slack & Hollinden, 1975)

From the table, the concentration of CO_2 is around 12%, which is similar to flue gas that has typically of concentration of CO_2 at 10-18% (Gupta et al., 2003)

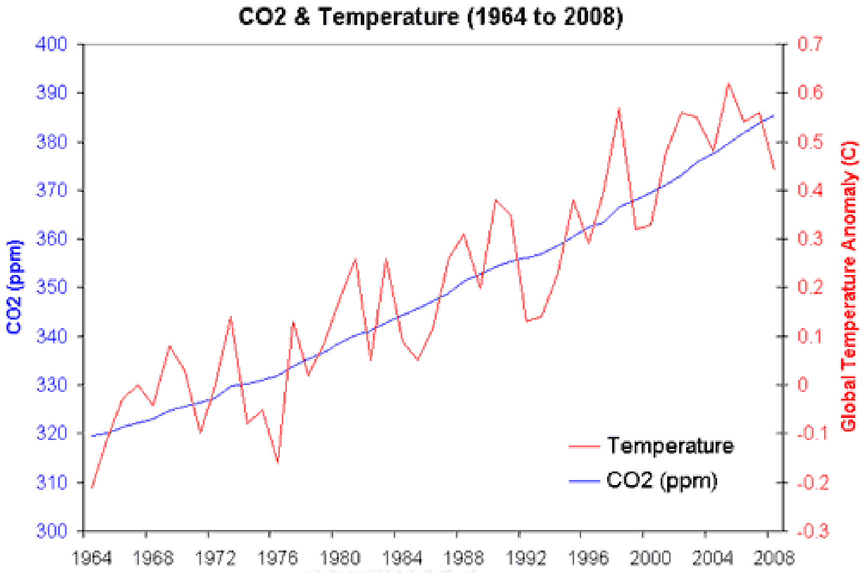


Figure 1.1 CO_2 and World's Temperature (SkepticalScience, 2015)

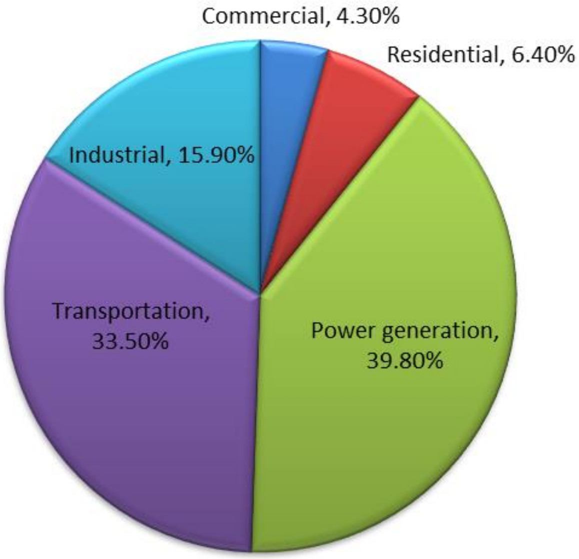


Figure 1.2 2013 U.S. CO_2 Emissions (EIA, 2013)

Table 1.1 Composition of flue gas evolved in burning bituminous coal (Slack & Hollinden, 1975)

Constituent	**Typical flue gas from western Kentucky coal*(%Vol)**
Nitrogen (N_2)	74.56
Carbon dioxide (CO_2)	12.55
Oxygen (O_2)	4.87
Water vapor (H_2O)	7.76
Sulfur oxides (SO_x)	
- Sulfur dioxide (SO_2)	0.22
- Sulfur trioxide (SO_3)	0.001
Nitrogen oxide (NO_x)	0.04
Particulate matter	
- Percent by weight	0.66
- Grains per standard cu. ft. (scf)	3.59

*Composition (%wt): 66.0% C; 3.3% S; 12.0% ash; 1.3% N.

The distribution of CO2 concentration produced from industrial sources in the area of the Western Canadian Sedimentary Basin (WCSB) is shown in the Figure 1.3, 75% of CO2 emission has low concentration at around 10-20%.

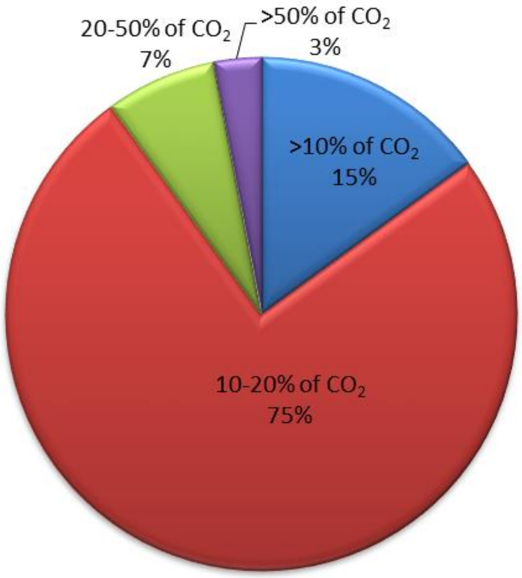


Figure 1.3 Distribution of CO_2 concentrations in WCSB

(Fischer, Shah;, & Velthuizen, 2002)

1.3 Carbon capture and storage

1.3.1 Overview of carbon capture and storage

Carbon capture and storage or carbon capture and sequestration (CCS) is the capture process of the waste carbon dioxide (CO_2) from large sources such as fossil fuel power plants then, transporting to suitable site and injecting it into deep underground geological formations where the CO_2 will be trapped and it cannot be emitted to the atmosphere. From the initial evaluation, CCS process can reduce the total CO_2 in the atmosphere up to 80-90% compared with normalcy. (IPCC, 2005)

CCS process has 3 main processes involve 1) CO_2 Capture and separation from other gases, 2) transporting CO_2 to storage site by ship or pipeline and 3) injecting and trapping it to underground in the geological rock that are typically located 3,000-5,000 meters below the earth's surface as shown in the Figure 1.4

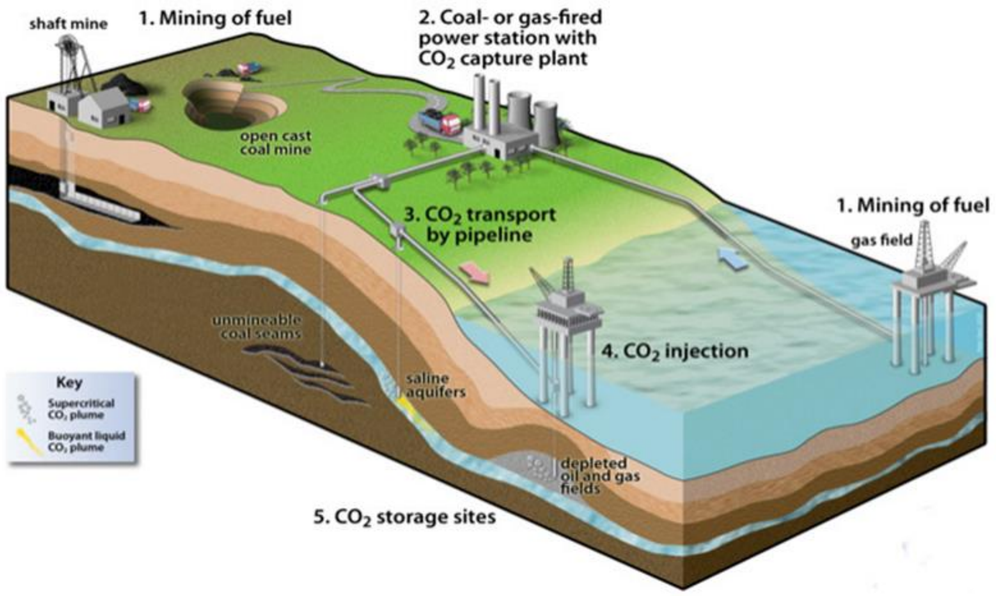


Figure 1.4 Carbon capture and storage process (Pool, 2011)

1.3.2 CO_2 Capture processes

Waste CO_2 comes from burning of fossil fuels for producing energy and electricity. Therefore, it can be captured in 3 processes such as post combustion, pre combustion and oxy-fuel combustion.

1.3.2.1 Post-Combustion process

As shown in the Figure 1.5, fuel and air are combusted. The energy is occurred for producing the electricity. The low pressure exhaust gas is passed through a separation process for separating CO_2 from other gas. The concentration of CO_2 is around 12-15% while N is rich to 70%. (Gupta et al., 2003)

CO_2 from post combustion process can be captured by many techniques such as amine absorption method, adsorption method, cryogenic separation method and membrane separation method. Currently, amine absorption is the suitable method because of economically viable technologies. (Ebenezer, 2005; Gupta et al., 2003)

1.3.2.2 Pre-Combustion process

As shown in the Figure 1.6, for pre-combustion, fuel is not burnt but reacted with high pressure and high temperature to form the synthesis gas which contains carbon monoxide (CO) and hydrogen (H_2). Then, these gases are reacted with water to convert CO to CO_2 and H_2. The concentration of CO_2 product is around 25-40% and total pressure is typically in range of 2.5-5MPa (Gupta et al., 2003), so partial pressure of CO_2 in pre-combustion process is higher than post-combustion process Thus, the suitable method for separating the CO_2 from this process is absorption process (Ebenezer, 2005; Gupta et al., 2003). Then, transporting it to storage site and hydrogen is sent to burn to produce energy.

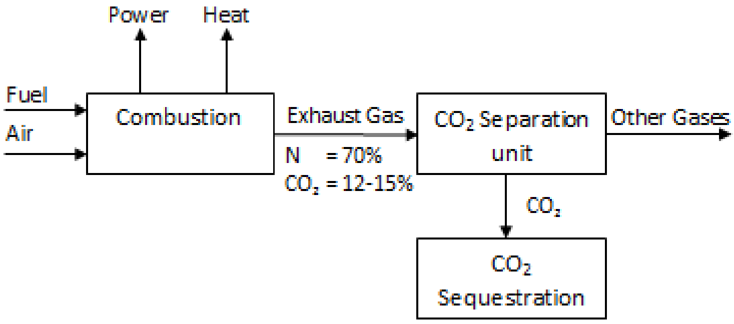


Figure 1.5 Post-Combustion process

(Modify from; (Figueroa, Fout, Plasynski, McIlvried, & Srivastava, 2008))

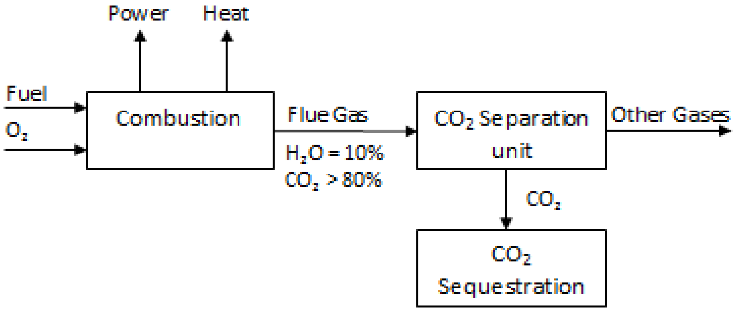


Figure 1.6 Pre-Combustion process (Modify from; (Figueroa et al., 2008))

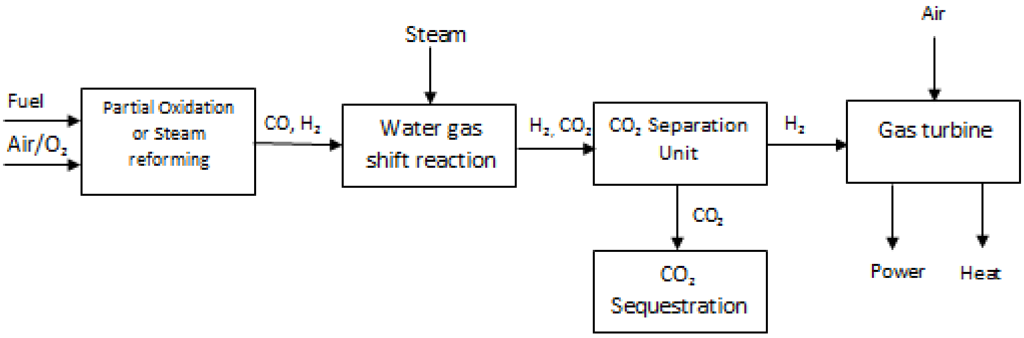


Figure 1.7 Oxy- fuel Combustion process (Modify from; (Figueroa et al., 2008))

1.3.2.3 Oxy-Fuel Combustion process

This process is developed from Post combustion capture. As shown in Figure 1.7, fuel and pure oxygen are combusted then, getting the energy, CO_2 and water. The result is in a flue gas with the high concentration of CO_2 (greater than 80% by volume) (Gupta et al., 2003) The steam is removed by cooling and compressing the gas stream.

The advantage and disadvantage can be classified and compared with any processes as shown in the table 1.2

1.3.3 CO_2 Separation technology

Separation of CO_2 from other gases is necessary. Several technologies can be used to separate CO_2 from other gases in the gas stream such as adsorption, adsorption, membrane separation and cryogenics as shown in the Figure 1.8 The selection of technology depends on many factors such as pressure of the gas stream, partial pressure of CO_2 in the gas stream, purity of CO_2 product, extent of CO_2 recovery required, capital and costs, environmental impact and corrosion. (Gupta et al., 2003; K. Maneeintr, 2009)

Table 1.2 The advantage and disadvantage of capturing CO_2 in any combustion processes

Combustion process	**Advantage**	**Disadvantage**
Post-Combustion process	The technique can be applied for capturing the CO_2 with the fossil fuel power plants	Necessary for using the high effective technology because of lean CO_2 concentration in the gas stream
Pre-Combustion process	High CO_2 concentration in the gas stream, so it can be used many technologies to apply	Study more information and reforming the plant to apply with this techniques are necessary
Oxy-fuel Combustion process	N_2 free, small flue gas volume, highly rich in CO_2, easy to purification and low cost	Many pure oxygen is required in the process

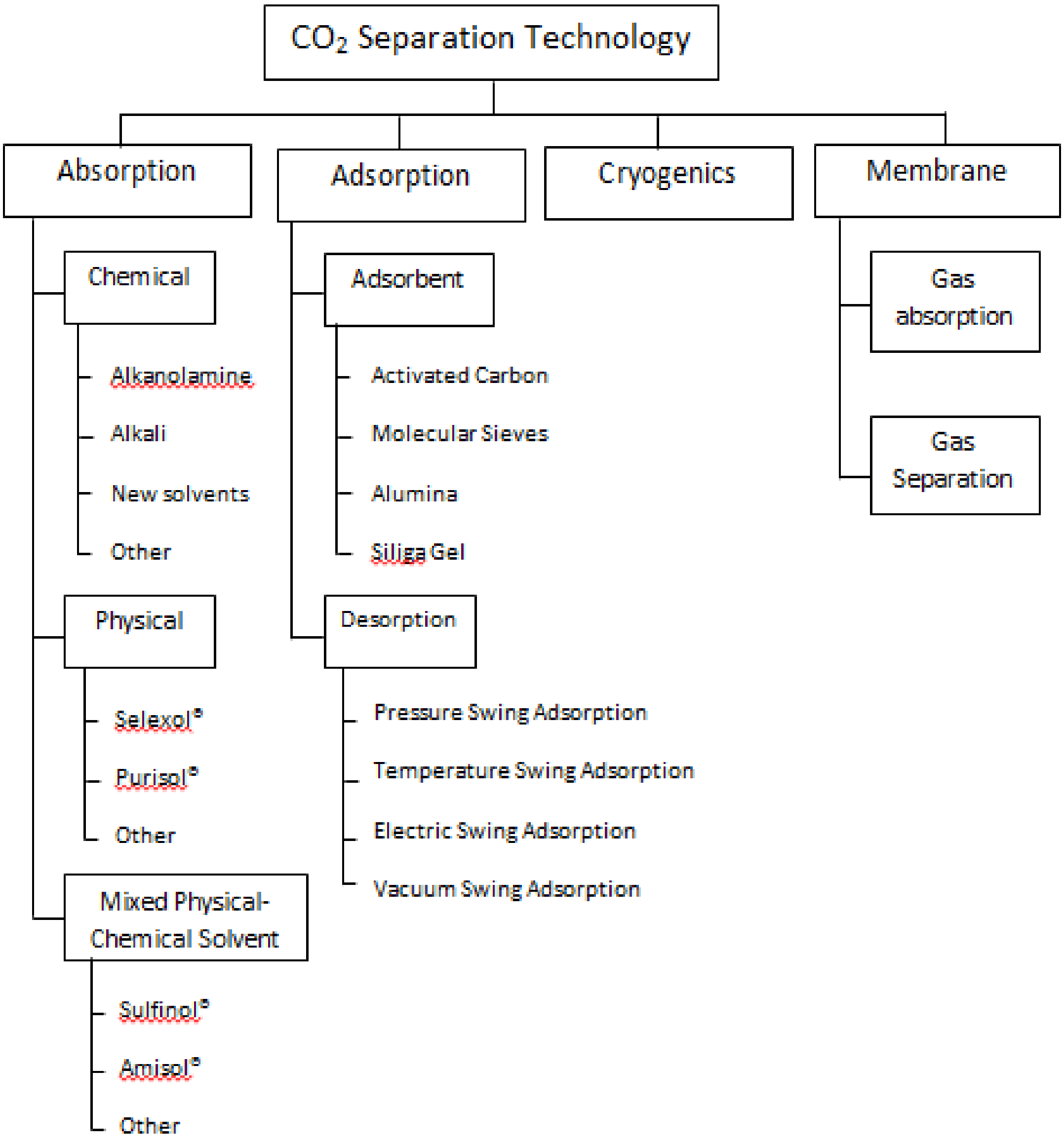


Figure 1.8 CO_2 Separation technology (K. Maneeintr, 2009)

1.3.3.1 Absorption

Currently, absorption technology is commonly used to separate of CO_2. Chemical absorption is widely used in the industrial to capture CO_2 which contain the dilute CO_2 concentration from flue gas stream.

Absorption occurs when gas solute moves from gas phase into liquid solvent across gas-liquid interphase. In a physical absorption process, the adsorption is a function of solubility of the solute in solvent; Thus, physical solvents are usually used when the partial pressure of the solute in flue gas is high (Gupta et al., 2003). Regeneration process is achieved by increase the temperature, reduce the pressure or both.

Unlike physical absorption, in chemical absorption process, chemical reaction makes the absorption rate increase, thus making chemical solvents more suitable for processes that have low solute partial pressure. This is usually the case in coal-fired power plants, where the flue gas is emitted at atmospheric pressure and typically contains the concentration of CO_2 around 10-15% (Gupta et al., 2003)

The chemical solvents wildly used in commercial for CO_2 separation are Monoethanolamine (MEA), Diethanolamine (DEA) and Methuldiethanolamine (MDEA). In regeneration process, the solvent can be regenerated by apply the temperature, CO_2 can be purified and produced. The absorption process detail will be discussed extensively in the next chapter.

1.3.3.2 Adsorption

Adsorption relies on a cyclical process of adsorption and desorption (Regeneration) process. CO_2 from flue gas in the gas stream is adsorbed on surface of solid called adsorbent which made from Metal organic Frameworks (MOF), Zeolites, Mesoporous carbons, silica gel (Oliver & Jadot, 1997) and alumina (Yong & Rodrigues, 2000).

Desorption process is achieved by many methods; thermal swing adsorption (TSA) by increasing the temperature, vacuum swing adsorption (VSA) by creating a near vacuum, pressure swing adsorption (PSA) by reducing the pressure. Electrical Swing Adsorption (ESA) by applying voltage.

The advantage of adsorption technology is this process gives the high purity of product. A recovery of CO_2 is around 90%. (Gupta et al., 2003) For the disadvantage, this technology is not attractive for the large scale of CO_2 separation in currently.

1.3.3.3 Membranes

Membrane technology is used as an effective technique of remove the CO_2 from the gas stream. Membrane material is specifically designed for separating the CO_2 molecule from other gases in mixture under suitable conditions, made from polymer, ceramic and combination of both. Currently, the membrane technology is not operated on large scale. There are two types of membrane system processes; Membrane

1.3.3.3.1 Gas separation membrane

Gas separation membrane is rely on the solubility and diffusion rate of molecule of the gas in membrane and using differences pressure of one side across to other as a driving force for gas separation. Membrane is acted as a semi-permeable barrier. As shown in the Figure 1.9, the CO_2 can pass easily through the membrane more than other gases in mixture. In generally, rate of moving gas is depended on size of gas molecule, difference pressure across, concentration of gas and affinity of the gas for membrane material.

The advantage of gas membrane separation technology is the equipment which is smaller and there are no solvent in the process. But the weak point is high cost required for energy to create the large difference pressure across to drive separation. (CO2CRC, 2015; Gupta et al., 2003; K. Maneeintr, 2009)

1.3.3.3.2 Gas absorption membrane

Gas absorption membrane is micro porous solid. CO_2 is diffused through porous of membrane and it is absorbed by effective solvent. Gas absorption membranes is used when the CO_2 has low partial pressure such as CO_2 from flue gas because of small driving force but this technology can be used in large scale, much development is needed before membrane can be used in the large scale such as capturing CO_2 from power plants. (CO2CRC, 2015; Ebenezer, 2005; Gupta et al., 2003; K. Maneeintr, 2009)

As shown in the Figure 1.10, membrane is made from specific material. It does not separate CO_2 from the other gases but it is used as the barrier between liquid phase and gas phase. Membrane allows the CO_2 to pass through the pore then, contact with solvent. Only CO_2 is absorbed selectively by the solvent.

In the absorption process, when liquid and gas are together, the foaming and channeling problems can be occurred. Physical separation can be solved these problems. (CO2CRC, 2015; Ebenezer, 2005; Gupta et al., 2003; K. Maneeintr, 2009)

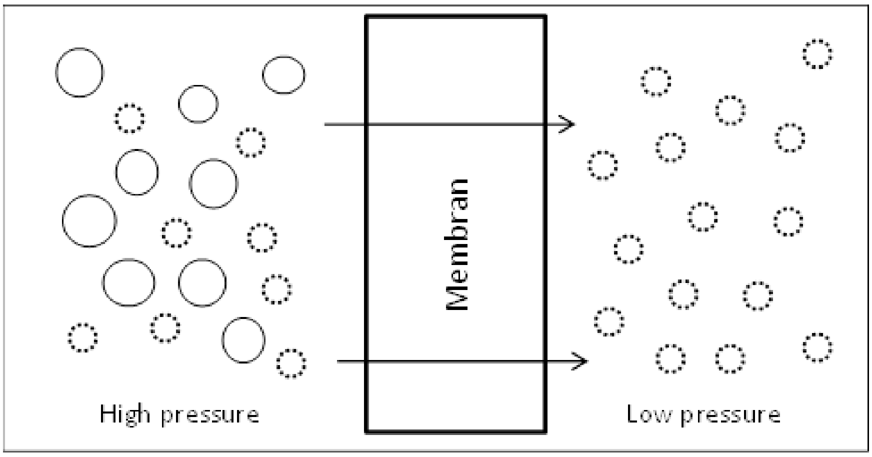


Figure 1.9 Gas separation membrane process (Modify from; (CO2CRC, 2015))

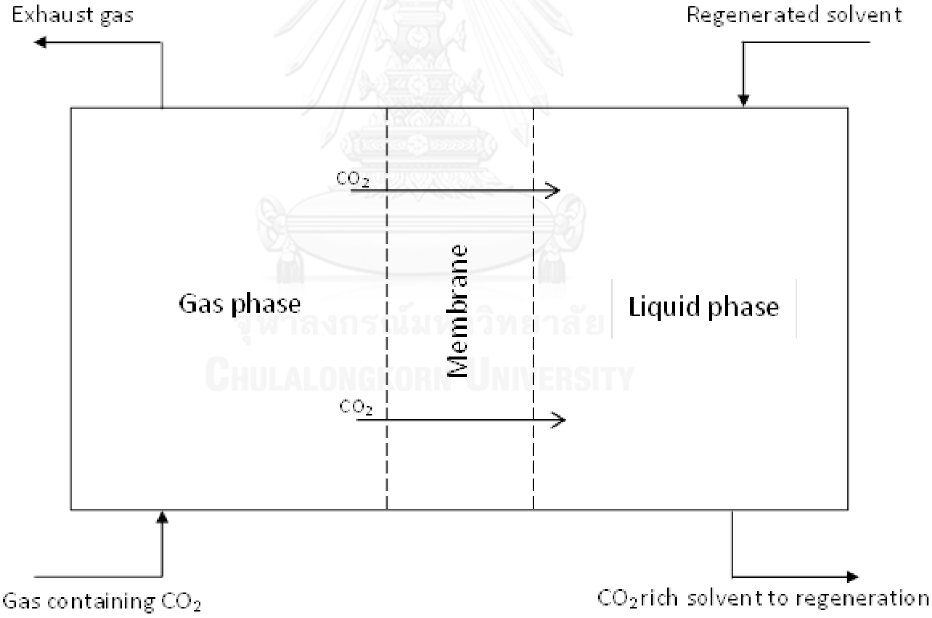


Figure 1.10 Gas absorption membrane process (Modify from; (CO2CRC, 2015))

1.3.3.4 Cryogenics

Cryogenics technology is wildly used in commercial to separate CO_2 in pre-combustion process and oxy-fuel combustion process which contains the high pressure of gases and high concentration of CO_2 (typically >50 %). Cryogenics technology is not normally used to separate CO_2 which contain the lean concentration inside such as CO_2 from flue gas because this technology require much energy in freezing process thus, it is not economical. For the advantage of this technology is directly product of CO_2 liquid, it would be easily to transport to storage field by ship or pipeline.

As shown in the Figure 1.11, CO_2 and water are frozen together to form ice (like crystal with CO_2 trapped inside) called hydrated by chilled water that passed through the flue gas to give the suitable temperature and pressure, other gases are moved out. The CO_2 can be released from hydrates by heating and hydrates are removed.

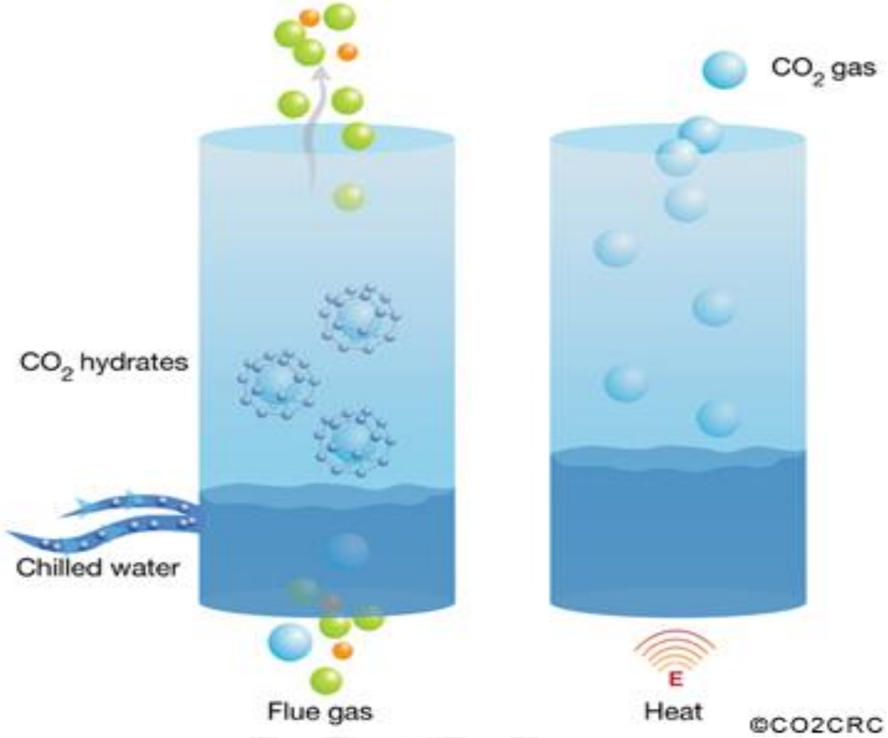


Figure 1.11 Cryogenics process (CO2CRC, 2015)

Table 1.3 The advantage and disadvantage of the CO_2 separation technologies

Process		**Advantage**	**disadvantage**
Absorption	-Chemical	-The efficiency for removing the acid gas such as CO_2 is high, around 98%. -The purity of product can be excess of 99% -It can be captured while the concentrate is low -General and wild use.	-High energy consumption
	-Physical	- Lower energy consumption	- The capacity of CO_2 removal is less than Chemical absorption.
Adsorption		-High purity of product around 90% of CO_2 recovery	-The capacity and CO_2 selectivity of available adsorbents is low. -It is not attractive for large scale for CO_2 Separation. -Recovery of products is lower

Table 1.3 The advantage and disadvantage of the CO_2 separation technologies (Continued)

Process	**Advantage**	**disadvantage**
Membrane	-Simplicity, versatility, low investment and operation cost. -Stability at high pressure -High recovery of products -Less environmental impact.	-Not much the purity of product -Cannot be used in the large scale
Cryogenic	-The direct production is CO_2 liquid, which is necessary for transportation by ship or pipe line.	-High energy required. -Not economical for regeneration. -It is not normally used for dilute CO_2

From the advantages and disadvantages of these technologies as shown above, it can be concluded that chemical absorption technology is a more economical and suitable process for capturing the CO_2 from low CO_2 concentration such as flue gas from fossil power plant (Astarita, Savage, & Bisio, 1983; Fischer et al., 2002; Kohl & Nielsen, 1997) The chemical solvents that are wildly used in commercial such as alkanolamine; Monoethanolamine (MEA), Diethanolamine (DEA) and Methuldiethanolamine (MDEA) are the effective solvents for CO_2 capturing. However, these solvents also have the disadvantage such as corrosion and other impurities, high solvent degradation rates from reaction with SO_2 and NO_2 and more than 80% of the total of energy consumption using for regeneration process. (White, Strazisar, J.;, & Hoffman, 2003) From these disadvantages, improvement of the solvents or new solvents is important to develop the absorption capacity, enhance CO_2 absorption rates, high degradation resistance and low corrosiveness. Reducing the energy consumption is necessary.

The three new solvents are selected to study in this research are

2-(Diethylamino)Ethanol (DEAE)
2-(Dimethylamino)Ethanol (DMAE)
2-(Methylamino)Ethanol (MAE)

These solvents are amino alcohols which contain both an amine and an alcohol group. All of these solvents provided the higher performance for CO_2 absorption than Monoethanolamine (MEA) because they have higher cyclic capacity than MEA. The cyclic capacity is used to consider the performance of the new solvents. (K.; Maneeintr, Boonpipattanapong, Assabumrungrat, & Charinpanitkul, 2014; K.; Maneeintr, Iamareerat, Manonukul, Assabumrungrat, & Charinpanitkul, 2015; K.; Maneeintr, Luemunkong, & Charinpanitkul, 2014)

Density and viscosity are physical and transport properties of aqueous solution which are the basic properties and necessary to study because these properties are important to analyze heat and mass transfer. There are required to modeling and design the equipment in absorption process.

1.4 Objective of this research

According to the information as presented above, fundamental data such as understanding of acid gas treating process, gas absorption by chemical absorption, physical properties of the new solvents and physical and transport properties are required to study for modeling and design the economical and efficiency for absorption process. The objectives of this research are presented below;

1. To measure the density and viscosity of aqueous amino ethanol solutions and evaluate the effect of mole fraction and temperature on density and viscosity of amines for carbon dioxide absorption process
2. To develop the correlation for prediction the data in the future.
3. To investigate the effect of the various function groups attached to back-bone of amino ethanol.

This research provides the contribution to carbon dioxide absorption process include (1) evaluate behavior of the binary mixture of water and amine. And (2) provide the fundamental data for estimating other data and the design of other processes.

1.5 Outline of research

Scope of this research study the density and viscosity which are the basic physical and transport properties of the new solvents; DEAE, DMAE and MAE, required in absorption process Parameters and conditions of this research are the temperature and the concentration of the solvents. Correlation of experimental data between parameters, conditions and these properties would be developed to predict the density and viscosity data.

The chapter 1 introduces the uses and effect of CO_2, the information of fuel gas from coal-fired power plant, the detail of carbon capture and storage technology including the separation technology of CO_2 and objective of this research including the benefits. The chapter 2 presents the theory of absorption process and interesting literatures related with this research. The chapter 3 presents the methodology, conditions and parameters which using in this research. The chapter 4 presents results and discussion of density and viscosity with various conditions and the correlation to predict the experimental density and viscosity data. And the chapter 5 presents the conclusion and recommendation of this research.

CHAPTER 2

THEORY AND LITERATURE REVIEW

Chemical absorption technology is the most suitable method for CO_2 removal from the low partial pressure of CO_2 from fuel gas. The basic knowledge and theory of the absorption process as well as physical properties are presented in the chapter 2 as shown below.

2.1 Absorption process

2.1.1 Absorption types

2.1.1.1 Chemical absorption

Chemical absorption involves the chemical reaction between gaseous components like CO_2 absorbed with the component of liquid phase (absorbent) to form reaction products. The chemical absorption process is the cycle process between absorption process and regenerate process. The examples of this process are Alkanolamine process and Alkali process

The advantages of this process are the capacity absorption is high, the recovery rate and purity of product is high and the solvents (absorbent) can be regenerated to use in the process again

2.1.1.2 Physical absorption

Physical process based is on Henry's law. CO_2 is absorbed under the high partial pressure and low temperature and regenerated (desorbed) by decrease pressure and increasing temperature. This technology is commonly use in the industries with natural gas, synthesized gas and high concentration of CO_2 removal. (Olajire, 2010)

For physical process, the solute (absorbate) CO_2 is soluble in the liquid phase (absorbent) but it does not reacted with absorbent. The equilibrium concentration of solute in the liquid phase is strongly and depended on partial pressure of the component in the gas phase. (K. Maneeintr, 2009) The examples of physical process are Selexol process, Rectisol process, Morphysorb process and Fluor process.

The advantages of this process are low vapor pressure, low toxicity, less corrosive and required lower energy consumption. (Yu, Huang, & Tan, 2012)

2.1.2 Absorption process description

The basic flow diagram of an acid gas absorption process system can be concluded as shown in the Figure 2.1, the absorption process is commonly used in post-combustion capture process and the adsorbents are liquid solvent. In post combustion, the fuel gases are containing CO_2 and other gases are fed to the first tower called absorber tower. The fuel gases enter to the bottom of the tower while the solvent is feeding to the top of this tower then, fuel gases flows up to contact with the solvent and it is absorbed by the solvents then, it is felt down to the bottom. The gas which contain little CO_2 and other gases goes up to the top, the CO_2 rich solvent at the bottom of the absorption tower transports to another tower called desorber tower. (K. Maneeintr, 2009)

The desorber tower where it is heated with steam to reverse the CO_2 absorption reactions. The CO_2 is desorbed then, the CO_2 flows up to the top of tower. The vapor mixture is fed to the condenser where water and solvent are recovered and returned to desorber tower. The lean solvent that use for absorption process from the bottom of the desorption system is cooled and recycled by temperature change method and other methods include pressure change and the use of membrane with solvents. The solvent is to be back to the absorber tower to complete the cycle. (CO2CRC, 2015)

Absorption process is economically and suitable for CO_2 capture process. It can be captured the CO_2 while the concentration of CO_2 is low, the capacity for CO_2

removal is high about 98% and the purity of product is excess than 99% but as shown in the process, it consume high energy consumption especially, in desorption process and corrosion problem can be occurred. (Gupta et al., 2003)

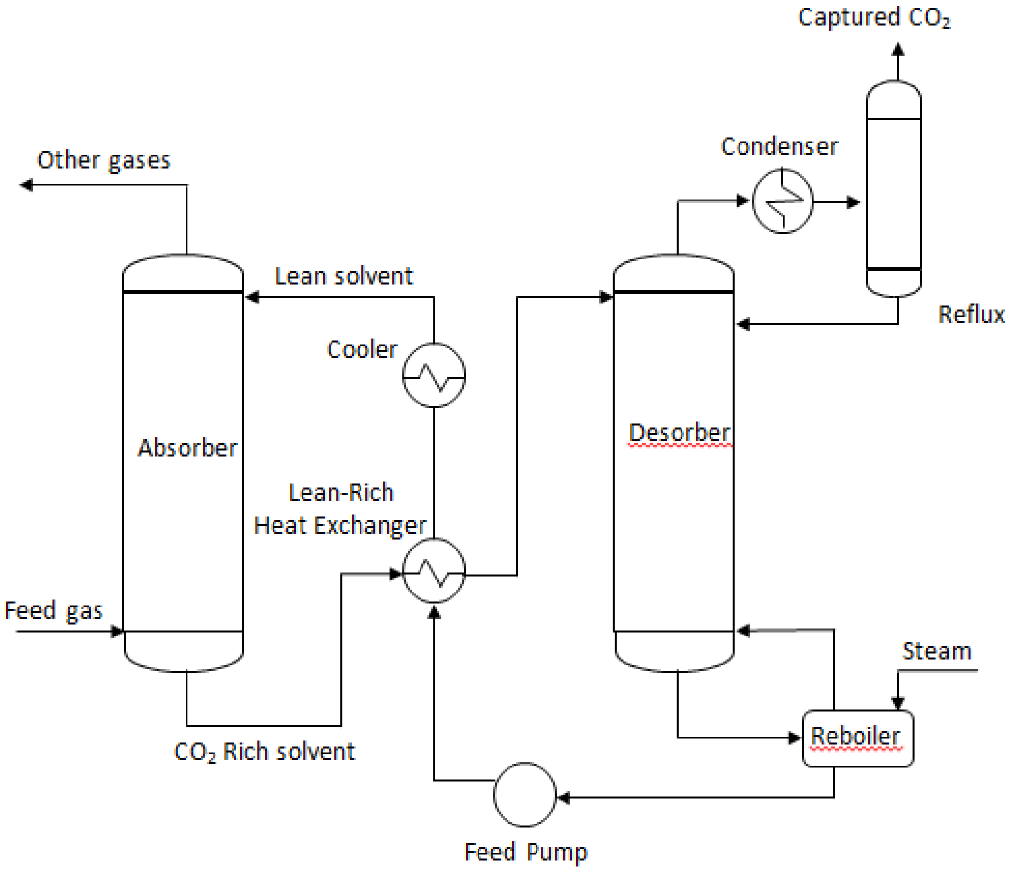


Figure 2.1 Flow diagram of an acid gas absorption process system

(Modifying from; (CO2CRC, 2015; K. Maneeintr, 2009)

2.2 Absorbing solutions for aid gas absorption

In absorption process, the effective absorbing solutions are the important keys to be success for this process. The desirable characteristics of the solvents are high solubility or cyclic capacity of acid gas, high reactivity such as brief contact time, high water solubility (allowing the use of highly concentrated absorbing solution), low vapor pressure, high thermal and chemical stability, less corrosion of construction materials, low cost and low environmental impact (Kohl & Nielsen, 1997; K. Maneeintr, 2009) Selection of the absorbing agent which has all of the desirable characteristics is impossible but the absorbing agent using in absorption process should have maximum number of these properties and minimum number of undesirable characteristics. (Kohl & Nielsen, 1997; K. Maneeintr, 2009)

In this section, the absorbing solutions can be classified into 3 groups; Chemical solvents, Physical solvents and Mixed chemical-physical solvents. Each group has own advantages, disadvantages and characteristics.

2.2.1 Chemical solvents

The list of commercial CO_2 scrubbing solvents used in the industry is presented in the Table 2.1 The majority of absorbing solutions in chemical solvents are organic amine based. However, this solvents group also has the limitations and disadvantage such as low absorption capacity, corrosion, impurity and high energy consumption especially, in the regeneration process. From these undesirable properties, research and development of sterically hindered amine and new amine solvents become to be important to reduce the limitations, undesirable properties and enhance the high absorption capacity.

Table 2.1 Commercial CO_2 Scrubbing solvents used in the industry (Gupta et al., 2003)

Absorption process	Solvent	Process conditions	Develop/licensor
<u>Chemical Solvent</u>			
<u>Organic</u> (Amine based)			
MEA	2.5 M MEA and chemical inhibitors	40 °C, ambient-intermediate pressures	Dow Chemical, USA
Amine Guard (MEA)	5 M MEA and chemical inhibitors	40 °C, ambient-intermediate pressures	Union Carbide, USA
Econamine	6 M DGA	80-120 °C, 6.3 MPa	SNEA version by Societe National Elf Aquitane, France
ADIP	2-4 M DIPA and 2M MDEA	35-40 °C, >0.1 MPa	Shell, Netherlands
MDEA	2 M MDEA		
Flexsorb/KS-1, KS-2, KS-3	Hindered amine		Exxon, USA; M.H.I.

Alkanolamine process

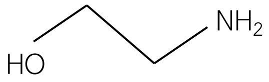
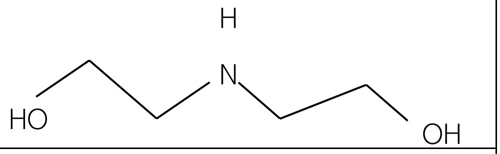
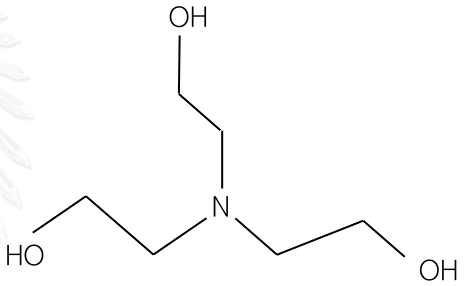
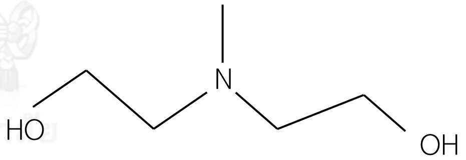
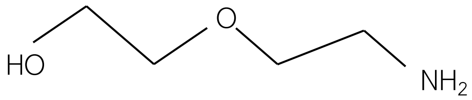
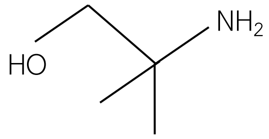
Amine scrubbing technology is used for more than 60 years in the chemical and oil industries for removal acid gas such as hydrogen sulfide (H_2S) and Carbon dioxide (CO_2) from gas stream. This technology is used the most on natural gas streams but nowadays, it can be also used to capture CO_2 from fuel gas stream. (Gupta et al., 2003)

The amine solvents that an available in commercial for gas treatment are monoethanolamine (MEA), diethanolamine (DEA) and methyldiethanolamine (MDEA). Among these, MEA is more effective and hence dominate the market of CO_2 Capture. According to structural formulas that presented in the Table 2.2 their structural formulas contain at least one hydroxyl group, which can help to reduce vapor pressures and increase the solubility in an aqueous solution.

The disadvantages of MEA and other amine solvents are corrosion in the presence of oxygen and other impurities, high degradation rate of solvent and the large total energy consumption required in the absorption process. Around 80% of the total energy is required for solvent regeneration process (Chakravarty, Phukan, & Weiland, 1985; White et al., 2003). From these disadvantages contribute to high solvent consumption, large energy loss and a need for large equipment thus, improving the solvents and the new solvents which have higher CO_2 absorption rates, faster absorption rate and high degradation resistances, low corrosion and low energy consumption are needed to reduce the size of equipment and reduce the capital and operating costs. (Haszeldine, 2009; Yu et al., 2012)

In many researchers synthesize the new solvents such as sterically hindered amine. For the example, 2-amino-2-methyl-1-propanol (AMP) is one of the new solvents which have the higher CO_2 absorption capacity. The detail of the new solvents will be discussed in the next section.

Table 2.2 Conventional alkanolamines (Kohl & Nielsen, 1997)

Name	Type of amine	Chemical Structure
Monoethanolamine (MEA)	Primary amine	
Diethanolamine (DEA)	Secondary amine	
Triethanolamine (TEA)	Tertiary amine	
Methyldiethanolamine (MDEA)	Tertiary amine	
Diglycolamine (DGA)	Primary amine	
2-Amino-2-Methyl-1-Propanol (AMP)	Sterically hindered amine	

2.3 Literature review of new solvents

Amines have been using in the commercial for acid gas removal especially CO_2 for more over 70 years (Gupta et al., 2003) because of the advantages but they are also have the drawbacks such as they required large energy consumption in the process, low cyclic capacity, corrosive thus, the new solvents are considered to solve the drawbacks of current amine and to be the alternative choice for CO_2 removal process.

The current demands for being incentives for several modifications are that the solvents have to required lower energy in the removal process, lower corrosion on the material, higher absorption performance rate, higher cyclic capacity, decreasing solvents losses and environmental friendly concerns, such as air and water quality.

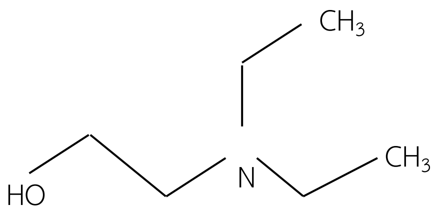
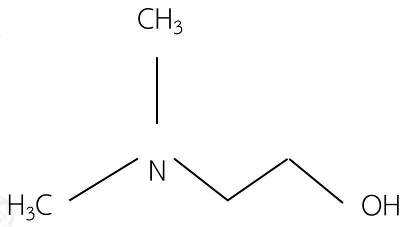
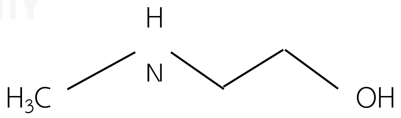
Therefore, the new solvents that were considered to be the absorbent in CO_2 removal process based on the concept of molecular design and the placement of functional groups that promote CO_2 capture on suitable backbones. It is important to determine the effects of placements on performance of amines for CO_2 capture. (Tontiwachwuthikul et al., 2007)

The new three solvents are selected to study in this research are

2-(Diethylamino)Ethanol (DEAE),
2-(Dimethylamino)Ethanol (DMAE)
2-(Methylamino)Ethanol (MAE)

These solvents are amino alcohols which contain both an amine and an alcohol group. The formulas are presented in the Table 2.3. The information of these solvents is presented below.

Table 2.3 The formulas of new solvents which using in this study for CO_2 absorption process

Name		Chemical Structure
2-(Diethylamino)Ethanol (DEAE)	Formula: $C_6H_{15}NO$ Molecular Weight: 117.19 Tertiary amine	
2-(Dimethylamino)Ethanol (DMAE)	Formula: $C_4H_{11}NO$ Molecular Weight: 89.14 Tertiary amine	
2-(Methylamino)Ethanol (MAE)	Formula: C_3H_9NO Molecular Weight: 75.11 Secondary amine	

2.3.1 Literature review of 2-(Diethylamino)Ethanol (DEAE)

K.; Maneeintr, Boonpipattanapong, et al. (2014) studied about CO_2 absorption in 5M aqueous solution of 2-(Diethylamino)Ethanol (DEAE). The conditions of this work are the temperature ranging from 30-80°C and partial pressure ranging from 15-100 kPa which are the conditions of fuel gas from power plant. Comparison of the results of CO_2's solubility in DEAE with the values of Monoethanolamine (MEA) from the literature review at the same conditions. (Aronu et al., 2011; J. I. Lee, Otto, & Mather, 1974; Shen & Li, 1992; Yamada, Chowdhury, Goto, & Higashii, 2013)

According to the Figure 2.2, CO_2 loading which is the amount of CO_2 dissolved in the DEAE per mole of amine can increase while partial pressure increase and decrease at higher temperature.

Figure 2.3, the results of CO_2 solubility in DEAE compared with in MEA at 15 kPa and 100 kPa which the temperature ranging from 30-80°C. For comparison of the results with MEA at the temperature of 30°C and partial pressure at 15 kPa, DEAE has greater absorption capacity up to 37.06% but at the temperature of 80°C, DEAE has lower absorption capacity at 66.39%. The cyclic capacity is the gap between solubility at absorption and desorption conditions. From the results, DEAE has higher cyclic capacity than MEA for 360.11% (at 15 kPa) and 861% (at 100 kPa) thus, DEAE has greater performance to absorb CO_2 than MEA.

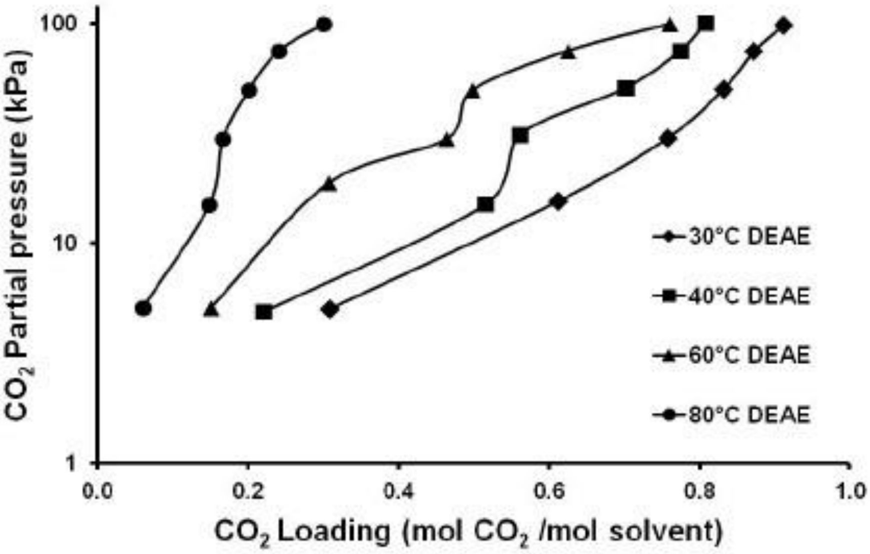


Figure 2.2 The solubility results of CO$_2$ in 5M DEAE solution at various conditions

(K.; Maneeintr, Boonpipattanapong, et al., 2014)

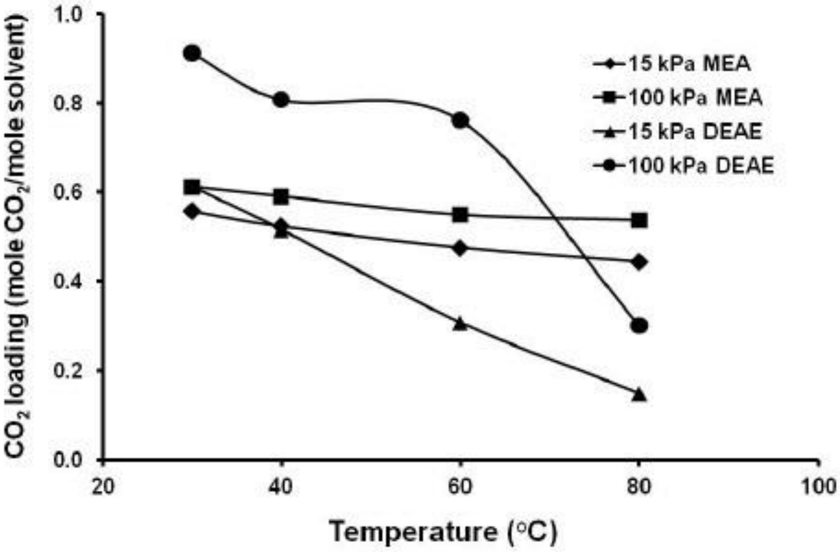


Figure 2.3 The CO$_2$ loading of 5M MEA and DEAE solutions at 15 kPa and 100 kPa.

(K.; Maneeintr, Boonpipattanapong, et al., 2014)

2.3.2 Literature review of 2-(Dimethylamino)Ethanol (DMAE)

K.; Maneeintr, Luemunkong, et al. (2014) studied about vapor-liquid equilibrium of carbon dioxide in a 5M aqueous solution of 2-(Dimethylamino)Ethanol (DMAE). The conditions of this work are the temperature ranging from 303.15, 313.15, 333.15 and 353.15 K, for partial pressure ranging from 5-100 kPa with 5M of DMAE. Comparison of the solubility results of CO_2 in DMAE with the values of Monoethanolamine (MEA) from the literature review at the same conditions. (Aronu et al., 2011; J. I. Lee et al., 1974; Shen & Li, 1992; Yamada et al., 2013) Solubility of CO_2 in DMAE decrease with an increase in temperature and at higher partial pressure, the solubility was increasing as shown in the Figure 2.4

Figure 2.5, the results of CO_2 solubility in DMAE compared with in MEA at 15 kPa and 100 kPa which the temperature ranging from 303.15-353.15 K. For comparison of the results with MEA partial pressure at 100 kPa, DMAE has greater absorption capacity up to 713%. At the partial pressure below 15 kPa, the absorption capacity of DMAE is lower at all temperature but the cyclic capacity is higher around 174%. It mean DMAE cannot be absorb very well in desorption process. From the results, DMAE has higher cyclic capacity than MEA thus, DMAE has greater performance to absorb CO_2 than MEA.

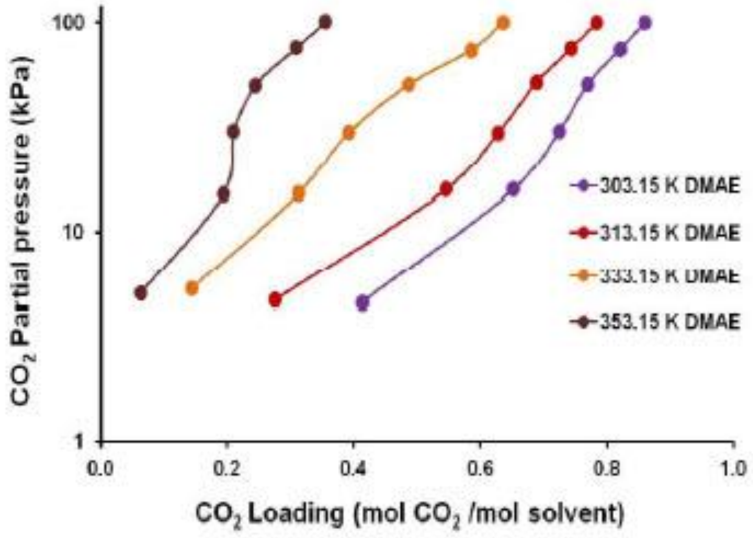


Figure 2.4 The solubility results of CO_2 in 5M DMAE solution at various conditions

(K.; Maneeintr, Luemunkong, et al., 2014)

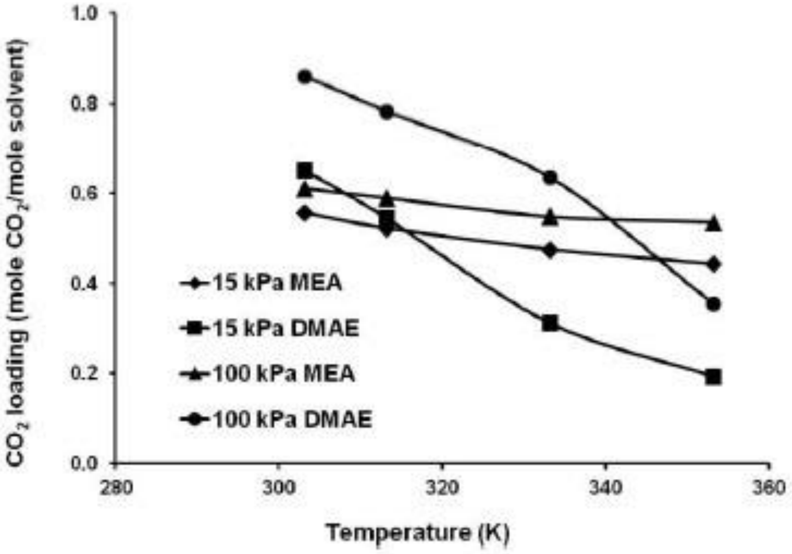


Figure 2.5 The CO_2 loading of 5M MEA and DMAE solutions at 15 kPa and 100 kPa.

(K.; Maneeintr, Luemunkong, et al., 2014)

2.3.2 Literature review of 2-(Methylamino)Ethanol (MAE)

K.; Maneeintr et al. (2015) studied about carbon dioxide removal by using absorption process in a 5M aqueous solution of 2-(Methylamino)Ethanol (MAE). The conditions of this work are the temperature ranging from 30-80°C, for CO_2 partial pressure ranging from 5-100 kPa with 5M of MAE. Comparison of the solubility results of CO_2 in MAE with the values of Monoethanolamine (MEA) from the literature review at the same conditions. (Aronu et al., 2011; J. I. Lee et al., 1974; Shen & Li, 1992; Yamada et al., 2013)

The solubility results of CO_2 in MAE are presented in the Figure 2.6 Solubility of CO_2 in MAE increases with the partial pressure but it is decreased as the temperature increase because gas cannot dissolve well in the higher temperature.

According to the Figure 2.7, the results of CO_2 solubility in MAE are compared with in MEA at 15 kPa and 100 kPa at the temperature ranging from 30-80°C. For the partial pressure at 100 kPa, DMAE has greater absorption capacity 86.8%. But at the partial pressure 15 kPa, the absorption capacity of DMAE is not great especially at higher temperature compared with MEA but the cyclic capacity is higher up to 150.9%. From the results, MAE has higher cyclic capacity than MEA thus, MAE has greater performance to absorb CO_2 than MEA.

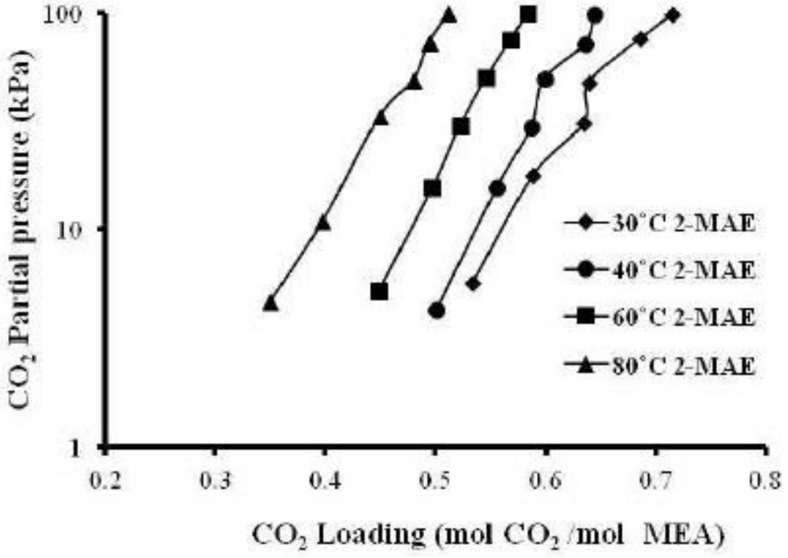


Figure 2.6 The solubility results of CO_2 in 5M MAE solution at various conditions (K.; Maneeintr et al., 2015)

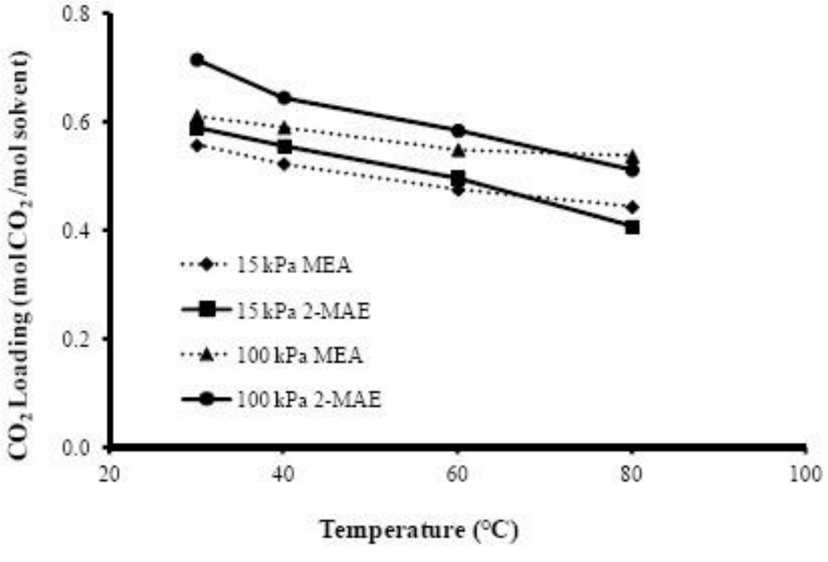


Figure 2.7 The CO_2 loading of 5M MEA and MAE solutions at 15 kPa and 100 kPa. (K.; Maneeintr et al., 2015)

2.4 Physical and transport properties

Physical and transport properties of aqueous amines solution are the important and necessary to study because these properties affect to efficient design and operation of gas treating process plants. Density and viscosity are the basic properties of physical and transport properties which an important to analyze heat and mass transfer of fluids.

Density and viscosity of aqueous amines solution are important to modeling and design the equipment in the absorption process like absorber and desorber tower because these properties affect to hydrodynamics and mass transfer coefficients. (Hagewiesche, Ashour, & Sandall, 1995; Li & Lie, 1994; Rinker, Oelschlager, Colussi, Henry, & Sandall, 1994) Moreover, these properties are required to predict other properties such as diffusivities and reaction rate of constants. (Chauhan, Yoon, & Lee, 2003; Mandal, Biswas, & Bandyopadhyay, 2003; K. Maneeintr, 2009)

This research measure the density and viscosity of the new solvents in amino alcohol groups which concentration at 0.0-1.0 by mole fraction with the temperature ranging from 30-80°C

2.5 Literature review of physical and transport properties of new solvents for CO_2 absorption process

2-(Dietylamino)Ethanol (DEAE), 2-(Dimethylamino)Ethanol (DMAE) and 2-(Methylamino)Ethnol are the new solvents that an selected and considered to be the absorbents in the CO_2 removal process. However, no physical and transport data values are available. The literature review of this research based on Monoethanolamine (MEA) and water, many researches of density and viscosity of MEA have been done. The objectives of using the MEA in this research are to confirm the density and viscosity measurement data values with the other work in literature and to verify the density and viscosity measurement equipment before measured the new solvents. Many research studied about density and viscosity of Monoethanolamine (MEA) and water with the range of temperature at 20-80^{o}C which the conditions from power plants. The literature review of physical and transport properties as presented in the Table 2.4 and 2.5

Kestin, Sokolov, and Wakeham (1978) measured the viscosities of pure water at the temperature from -8 ^{o}C-150^{o}C and Arachchige, Aryal, Eimer, and Melaaen (2013) studied about pure MEA at 293.15-423.15K., both of these research studied about only viscosity property.

The research that studied just the density are Tseng and Thompson (1964) measured the densities of MEA and water with the concentration of MEA at 0.0-99.92% mass with the temperature 20-30^{o}C. Diguillo (1992) measured pure MEA at 21-158^{o}C and Stec, Tatarczuk, Śpiewak, and Wilk (2014) measured pure water at 283.15-343.15K.

Many researchers reported about the densities and viscosities of pure water. Henni (2001) measured these properties of pure water at the temperature from 25-80^{o}C. Mundhwa, Alam, and Henni (2006) and K. Maneeintr (2009) measured pure water at 25-70^{o}C (298.15-343.15K).

Several researches measured the densities and viscosities of MEA and water. Li and Lie (1994) measured pure MEA and water at the temperature of 30-80°C. M. J. Lee and Lin (1995) measured MEA mixed with water with the concentration 0.0-1.0 by mole fraction at 30-50°C. Song, Yoon, Lee, and Lee (1996) measured 0-30%mass of MEA mixed with water at 30-70°C. Mandal et al. (2003) measured 30%mass of MEA at 25-50°C. Geng et al. (2008) measured pure MEA at 25-80°C. Amundsen, Øi, and Eimer (2009) measured 20-100%mass of MEA mixed with water at 25-80°C. and Sobrino, Concepción, Ángel Gómez-Hernández, M.; Martín, and Segovia (2016) measured 10-40%mass of MEA mixed with water at 293.15-323.15K.

Table 2.4 Literature review of density of MEA and Water

Reference	Chemical	Concentration	Temperature
Tseng and Thompson (1964)	MEA+H_2O	0.0-99.92 mass% of MEA and H_2O	20,25 and 30°C
Diguillo (1992)	MEA	Pure MEA	21, 40, 60, 80, 100, 119, 139, 158°C
Li and Lie (1994)	MEA and H_2O	20% mass and pure MEA and pure H_2O	30-80°C
M. J. Lee and Lin (1995)	MEA and H_2O	0.0-1.0 mole fraction of MEA and H_2O	30-50°C
Song et al. (1996)	MEA	15, 30 %mass and Pure MEA and Pure H_2O	30-70°C
Henni (2001)	H_2O	Pure H_2O	25-70°C
Mandal et al. (2003)	MEA	30 %mass of MEA	25-50°C
Mundhwa et al. (2006)	H_2O	Pure H_2O	25-70°C
K. Maneeintr (2009)	H_2O	Pure H_2O	298.15-343.15 K
Geng et al. (2008)	MEA	Pure MEA	283.15-343.15 K
Amundsen et al. (2009)	MEA+ H_2O	20-100 %mass of MEA and H_2O	25-80°C
Stec et al. (2014)	H_2O	Pure H_2O	283.15-343.15 K
Sobrino et al. (2016)	MEA+H_2O	10-40% Amine mass	293.15-323.15K

Table 2.5 Literature review of Viscosity of MEA and Water

Reference	Chemical	Concentration	Temperature
Kestin et al. (1978)	H_2O	Pure H_2O	-8°C-150°C
Li and Lie (1994)	MEA and H_2O	Pure MEA and Pure H_2O	30-80°C
M. J. Lee and Lin (1995)	MEA and H_2O	0.0-1.0 mole fraction of MEA and H_2O	30-50°C
Song et al. (1996)	MEA	15, 30 %mass and Pure MEA and Pure H_2O	30-70°C
Henni (2001)	H_2O	Pure H_2O	25-70°C
Mandal et al. (2003)	MEA	30 %mass of MEA	25-50°C
Mundhwa et al. (2006)	H_2O	Pure H_2O	25-70°C
K. Maneeintr (2009)	H_2O	Pure H_2O	298.15-343.15 K
Geng et al. (2008)	MEA	Pure MEA	288.15-323.15
Amundsen et al. (2009)	MEA+ H_2O	20-100 %mass of MEA and H_2O	25-80°C
Arachchige et al. (2013)	MEA	Pure MEA	293.15-423.15 K
Sobrino et al. (2016)	MEA+H_2O	10-40% Amine mass	293.15-323.15K

CHAPTER 3

EXPERIMENT

The experimental information includes material, equipment, experimental conditions, correlation information for prediction of physical and transport properties of binary and previous relevant researches are presented below in the chapter 3.

3.1 Materials

There are three chemical solvents which using in this study. 2-(Diethylamino)ethanol (DEAE) has a purity of ≥99% obtaining from Merck. 2-(Dimethylamino)ethanol (DMAE) has a purity of ≥98% and 2-(Mthylamino)ethanol (MAE) has a purity of ≥98%, which purchased by Sigma-Aldrich. All of them are prepared by mixing with distilled water to the desired concentration from 0.0-1.0 by mole fraction. Monoethanolamine (MEA) is using for calibration the equipment has a purity of ≥99%, which purchased from Sigma-Aldrich.

3.2 Equipment

All chemical are prepared to the desired the concentration from 0.0-1.0 by mole fraction with mixing distilled water. The weights of material were measured by using analytical balance; model SI-234 from Denver Instrument, NY with ±0.0001g. accuracy.

There are 2 types of equipment which using in this study to measure the densities and viscosities of binary mixture as presented below.

Density measurements of binary mixture are measured by using Anton Paar density meter, Model DMA-4500 with 0.00001 g/cm^3 resolution. Calibration the equipment by using distilled water and MEA. The density of distilled water and MEA are measured in the temperature range 30-80°C and compared with the data values from the instruction manual of equipment and literature. All of samples are measured 3 times. The accuracy of the equipment is ±0.00005 g/cm^3 with the temperature ±0.03°C

Kinematic viscosity measurements of binary mixture are measured by using appropriate U-tube glass viscometers from SI Analytics, GmbH, Mainz which the different size for measurement MEA, distilled water and all samples. MEA and water are used to verify the equipment and compare the data with literature. The information of each viscometer is presented in the Table 3.1. All of the sizes are used to cover the temperature ranging from 30-80°C.

The kinematic viscosity measurements are performed in water baht; model CT72/2 from SI analytics with ±0.20°C uncertainly. The efflux time are measured with digital stopwatch with ±0.01 s. accuracy. All of samples are measured 3 times at each temperature. The equation of kinematic viscosity is

$$\nu = K \times t \qquad (3.1)$$

Where t = the flow time in seconds which corrected.

K = the instrument constant

ν = kinematic viscosity value

The absolute viscosity values as shown in equation 3.2 were obtained by measurement of kinematic viscosity and density at the same conditions. The uncertainly in absolute viscosity values were at ±0.003 mPa●s.

$$\eta = \nu \times \rho \qquad (3.2)$$

Whereby η = absolute viscosity value

ρ = density value

Table 3.1 The information of appropriate U-tube glass viscometers from SI Analytics

No.	The instrument constant (K.)
No. 527 00/o	0.0008653 mm^2/s^2
No. 527 01/ob	0.005905 mm^2/s^2
No. 527 03/oc	0.002696 mm^2/s^2
No. 527 10/l	0.009487 mm^2/s^2
No. 527 13/ic	0.02701 mm^2/s^2
No. 527 20/ll	0.09045 mm^2/s^2
No. 525 23/llc	0.2786 mm^2/s^2

3.3 Experimental conditions

The conditions which using for physical and transportation property experiment are shown in the Table 3.2 below;

Table 3.2 The experimental conditions

Sample	DEAE, DMAE, MAE
Concentration (mole fraction)	0.0-1.0
Temperature (^{o}C)	30-80

3.4 Correlations

Various equations are applied for excess molar volume for the correlation of the physical and transportation properties such as density and viscosity of binary liquid mixtures. There are many correlations which using to represent the experimental data such as the Redlich-Kister, the Wilson model, the Grunberg and Nissan Equation and the strictly empirical polynomial correlation by Chauhan (2003). The information of each equation is presented below;

3.4.1 The Redlich-Kister equation (Redlich & Kister, 1984)

The Redlich-Kister equation can be applied for correlation of density and viscosity properties of binary liquid mixture. For the density, the correlation is in the form of excess molar volume as presented in equation 3.3-3.6. And for the viscosity, the correlation is in the form of viscosity deviation as presented in equation 3.7-3.8

$$\Delta P = x_1 x_2 \sum_{i=0}^{n} A_i \,(x_1 - x_2)^i \qquad (3.3)$$

$$V^E = x_1 x_2 \sum_{j=0}^{n} A_i \left(x_1 - x_2\right)^j \qquad (3.4)$$

$$V^E = V_m - \sum x_i V_i \qquad (3.5)$$

$$V_m = \frac{\sum x_i M_i}{\rho_m} \qquad (3.6)$$

$$\Delta\eta = x_1 x_2 \sum_{j=0}^{n} A_i \,(x_1 - x_2)^j \qquad (3.7)$$

$$\Delta\eta = \eta - x_1\eta_1 - x_2\eta_2 \qquad (3.8)$$

Whereby ΔP refer to excess molar volume (V^E) or viscosity deviation (**$\Delta\eta$**)

A_i, A, B, C and D refer to coefficients

x_1 and x_2 refer to mole fraction of component 1 and 2

V^E refer to excess molar volume (cm^3/mol)

V_m refer to the measured mixture properties

V_i refer to molar volume of pure component in the mixture

ρ refer to density value

$\Delta\eta$ refer to viscosity deviation (mPa●s)

η , η_1 and η_2 refer to viscosity of mixture and pure component 1 and 2

According to the Table 3.3 Redlich-Kister equation is convenient method which can be used for representing the excess properties of aqueous solutions and it can be used for different types of liquid solution. This equation gives the lowest error as presenting by %average absolute deviation (%AAD) The Redlich-Kister equation is the most suitable method for calculating the experimental values. (K. Maneeintr, 2009)

Table 3.3 Literature review of the Richdlich-Kister equation for physical and transport properties

Reference	Chemicals	Temperature	%AAD$_s$
Li and Lie (1994)	MEA+ H_2O	30-80°C	Density = 0.020% Viscosity= 0.53%
	MDEA+ H_2O	30-80°C	Density = 0.05% Viscosity= 1.49%
	AMP+ H_2O	30-80°C	Density = 0.03% Viscosity= 1.50%
	MEA+MDEA+H_2O	30-80°C	Density = 0.02% Viscosity= 0.72%
	MEA+AMP+H_2O	30-80°C	Density = 0.02% Viscosity= 1.41%
Lee et al. (1997)	MEA+1-Propanol	303.15-323.15K	Density = 0.020% Viscosity= 0.03%
	MEA+1-Hexanol	303.15-323.15K	Density = 0.022% Viscosity= 0.05%
	MEA+1-Octanol	303.15-323.15K	Density = 0.026% Viscosity= 0.09%
Maneeintr et al. (2008)	4-Diethylamino-2-butanol (DEAB)+ H_2O	298.15-343.15K	Density = 0.029% Viscosity= 0.885%
Amundesen et al. (2009)	MEA+H_2O	25-80°C	Density=0.017%
Stec et al. (2014)	Aminoethylethanolamine+H_2O	283.15-343.15K	Density=0.013%

%AAD is %average absolute deviation

3.4.2 The Wilson model (Prausnitz, Lichtenthaler, & Azevedo, 1999)

The Wilson model can be used to represent the experimental data and calculated data for the physical and transported properties of binary mixture. The equation are shown below,

$$\Delta \mathrm{P} = \mathrm{RT}(-\mathrm{X}_1 \ln(\mathrm{X}_1 + \mathrm{AX}_2) - \mathrm{X}_2 \ln(\mathrm{X}_2 + \mathrm{BX}_1)) \qquad (3.9)$$

Where **Δ**P refers to excess molar volume (V^E)

A and B refer to coefficients.

x_1 and x_2 refer to mole fraction of component 1 and 2

T is the temperature of the mixture in Kelvin

R is the molar refraction of the mixture

3.4.3 The Grunberg and Nissan Equation (Poling, Prausnitz, & O'Connell, 2001)

The Grunberg and Nissan Equation can be applied for correlation of density and viscosity properties of binary liquid mixture. The information as shown below,

$$\mathrm{lnP_m} = \mathrm{X_1 lnP_1} + \mathrm{X_2 lnP_2} + \mathrm{X_1 X_2 G_{12}} \qquad (3.10)$$

Where P_m refer to the measured mixture properties

x_1 and x_2 refer to mole fraction of component 1 and 2

Gij is the interaction parameter while T is the temperature of the mixture in Kelvin

P_i is property of pure component in the mixture

3.4.4 The strictly empirical polynomial correlation by Chauhan (Chauhan et al., 2003)

The strictly empirical polynomial correlation by Chauhan also can be used to predict the density and viscosity data of binary mixture. The information as shown below,

$$\mathrm{G_{ij}} = \mathrm{A} + \mathrm{B}\left(\frac{\mathrm{T}}{\mathrm{K}}\right) + \mathrm{C}\left(\frac{\mathrm{T}}{\mathrm{K}}\right)^2 + \mathrm{D}\left(\frac{\mathrm{T}}{\mathrm{K}}\right)^3 \qquad (3.11)$$

Where Gij is the interaction parameter while T is the temperature of the mixture in Kelvin

A, B, C and D refer to coefficients.

T is the temperature of the mixture in Kelvin.

The average absolute deviation (AADs)

The average absolute deviation ($\mathrm{AAD_s}$) between data from the calculated values and the data from the experimental is estimated from this equation

$$\%\mathrm{AAD} = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{P_{exp}-P_{cal}}{P_{exp}}\right| \qquad (3.12)$$

Where n is the number of data points.

The suitable correlation equation for prediction the results of the experimental data for binary mixture is the Redlich-Kister because it gave the lowest percent absolute deviation (%AAD).

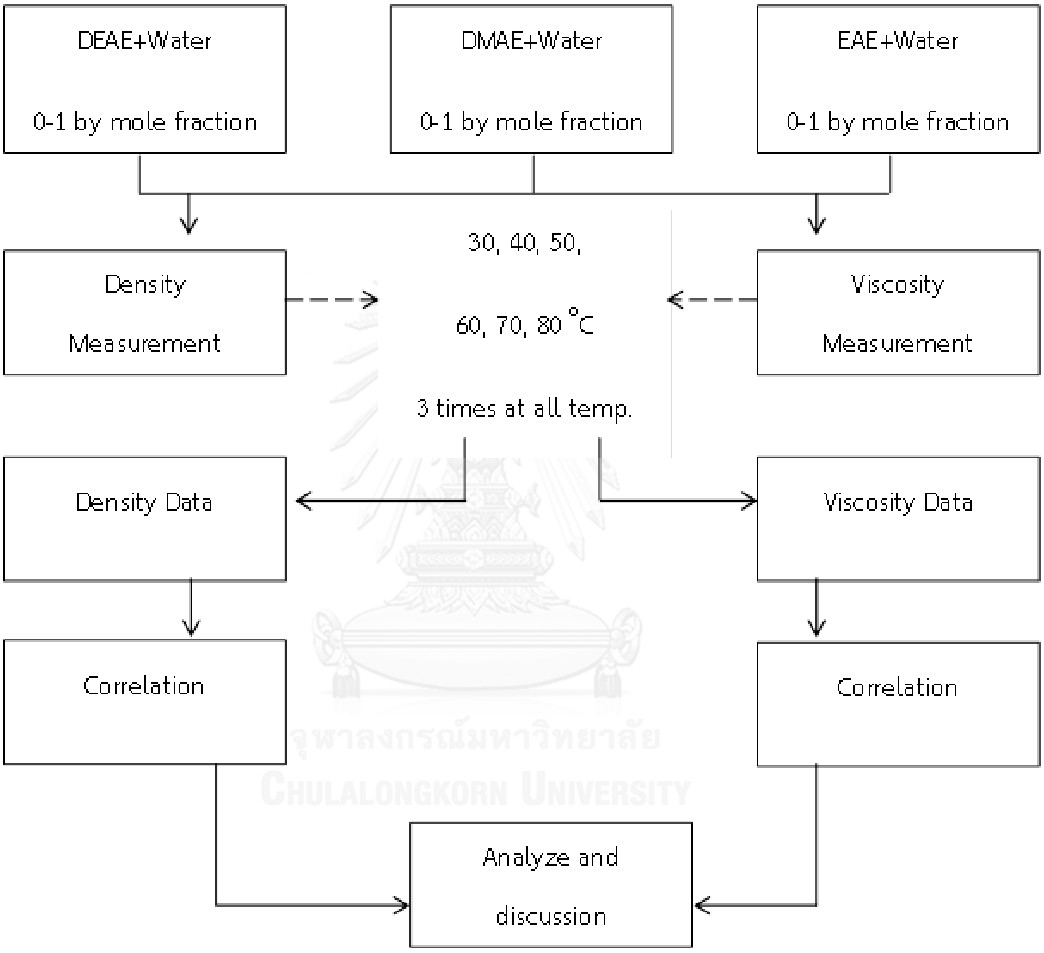


Figure 3.1 Flow chart of methodology

CHAPTER 4
RESULTS AND DISCUSSION

Density and viscosity are important physical and transport properties. They play a significant role with the modeling of absorber and desorber tower in chemical absorption process. The results of density and viscosity measurement of the new solvents and the correlations of these properties are presented in the chapter 4.

4.1 Verifying of the equipment and procedure

4.1.1 Density measurement

Anton Paar density meter, Model DMA-4500 is used to measure the density. The equipment and procedure are verified by MEA and water measured at the temperature ranging from 30-80°C. Then, the experimental data are compared those from literature review. The results as presented in the Figure 4.1 and 4.2 are agreed with the density data of previous research. The percent difference of density between experimental and literature are 0.0133% for MEA and 0.0157% for distilled water 0.0157%, respectively. Therefore, the density measurement equipment and procedure could be applied further for this study.

4.1.2 Viscosity measurement

Appropriate U-tube glass viscometers from SI Analytics, GmbH, Mainz which have different size of tube are used to measure the kinematic viscosity. The equipment and procedures are verified by MEA and water measured at the temperature ranging from 30-80°C. The absolute viscosity can be calculated by using the kinematic equation as presented in equation 3.2 in the previous chapter. The absolute viscosities from experiment are compared with those from the literature. The results are presented in the Figure 4.3 and 4.4. The experimental data are agreed with the viscosity data of previous research. The percent difference of viscosity between experimental and literature are 2.24% for MEA, 1.71% for distilled water. Thus, the density measurement equipment and procedure could be applied for this study.

4.2 Density experimental results

4.2.1 Density experimental results of 2-(Diethylamino)Ethanol (DEAE)

The experimental results of density of 2-Diethylamino-ethanol (DEAE) mixed with distilled water by mole fraction from 0.0-1.0 at the temperature of 30 - 80°C and the calculated values by the Redich-Kister equation are presented in Figure 4.5 and Table 4.1 the density values of DEAE decrease with an increase in mole fraction and temperature. The calculated values agree well with the measured data. The Redlich-Kister equation coefficients and average absolute deviation of excess molar volume of DEAE and water are presented in the Table 4.2. The percent average absolute deviation for densities is 0.1590%. The comparison of measured and calculated data based on effect of mole fraction for DEAE mixed with water at temperature of 30-80°C is presented in the Figure 4.6

4.2.2 Density experimental results of 2-(Dimethylamino)Ethanol (DMAE)

The density experimental results of 2-(Dimethylamino)Ethanol (DMAE) mixed with distilled water at the concentration of 0.0-1.0 by mole fraction and the temperature from 30 - 80°C as presented in the Figure 4.7 and Table 4.3. The calculated values are calculated and presented by the Redlich-Kister equation. The Redlich-Kister equation coefficients and average absolute deviation of excess molar volume of DMAE and water are presented in the Table 4.4. The density data of DMAE decrease with an increase in mole fraction and temperature. The calculated values agree well with the measured data. The percent average absolute deviation for densities is 0.0112% The comparison of measured and calculated data based on the effect of mole fraction for DMAE mixed with water at temperature of 30-80°C are presented in the Figure 4.8

4.2.3 Density experimental results of 2-(Methylamino)Ethanol (MAE)

The experimental results of density of 2-(Methylamino)Ethanol (MAE) mixed with distilled water by mole fraction from 0.0-1.0 at the temperature of 30 - 80°C and the calculated values by the Redich-Kister equation are presented in Figure 4.9 and Table 4.5. The density values of MAE decrease with an increase in mole fraction and temperature. The calculated values agree well with the measured data. The Redlich-Kister equation coefficients and average absolute deviation of excess molar volume of MAE and water are presented in the Table 4.6. The percent average absolute deviation for densities is 0.0261%. The comparison of measured and calculated data based on effect of mole fraction for MAE mixed with water at temperature of 30-80°C as presented in the Figure 4.10

Densities of all mixture depend on temperature and concentration of mixture. The densities decrease with increasing temperature because kinetic energy of substance molecule is higher and the volume of substance expands; therefore, the density is decreased. For effect of concentration, increasing in concentration of agent results in decreasing in density. Because density of the pure distilled water is higher than pure agent thus, the density of mixture is in between the densities of both pure substances.

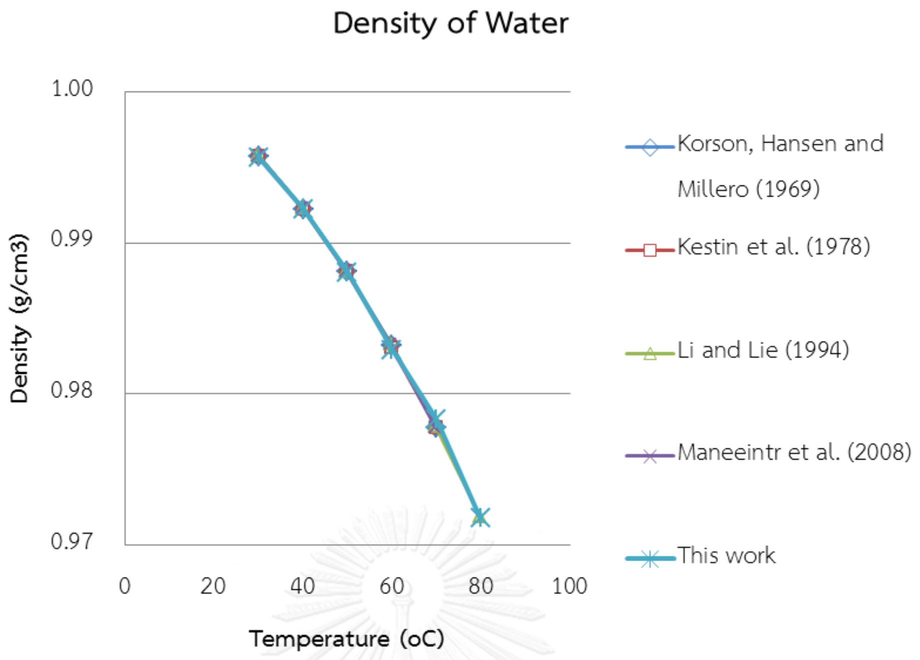


Figure 4.1 Comparison of density of water

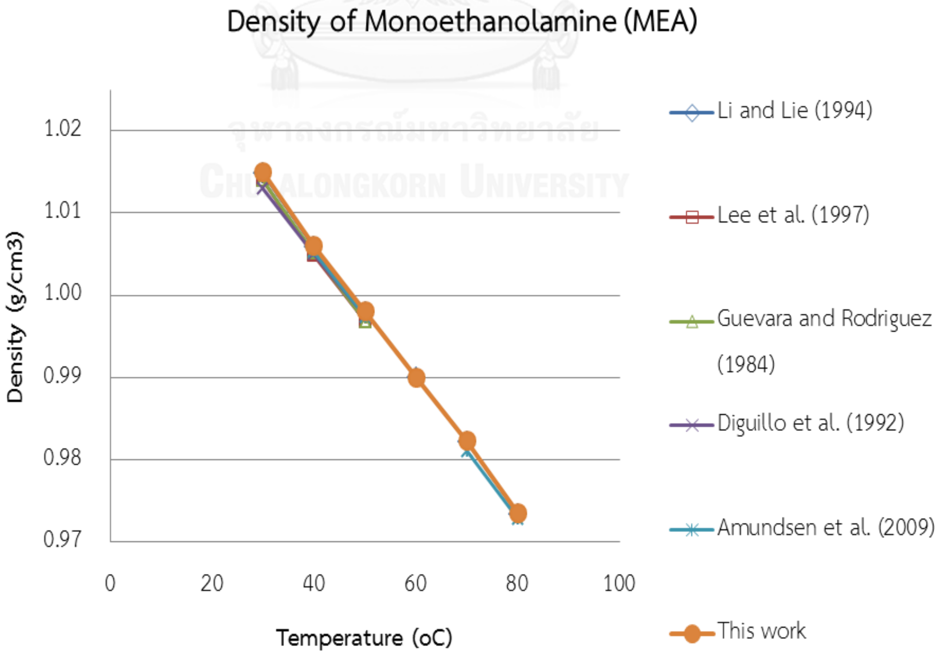


Figure 4.2 Comparison of density of MEA

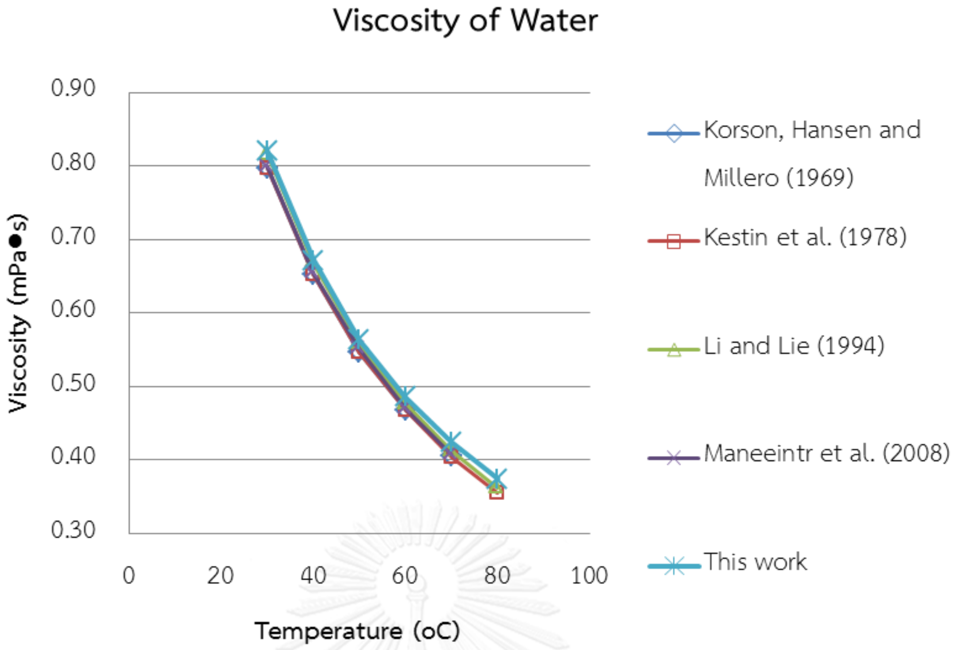


Figure 4.3 Comparison of viscosity of water

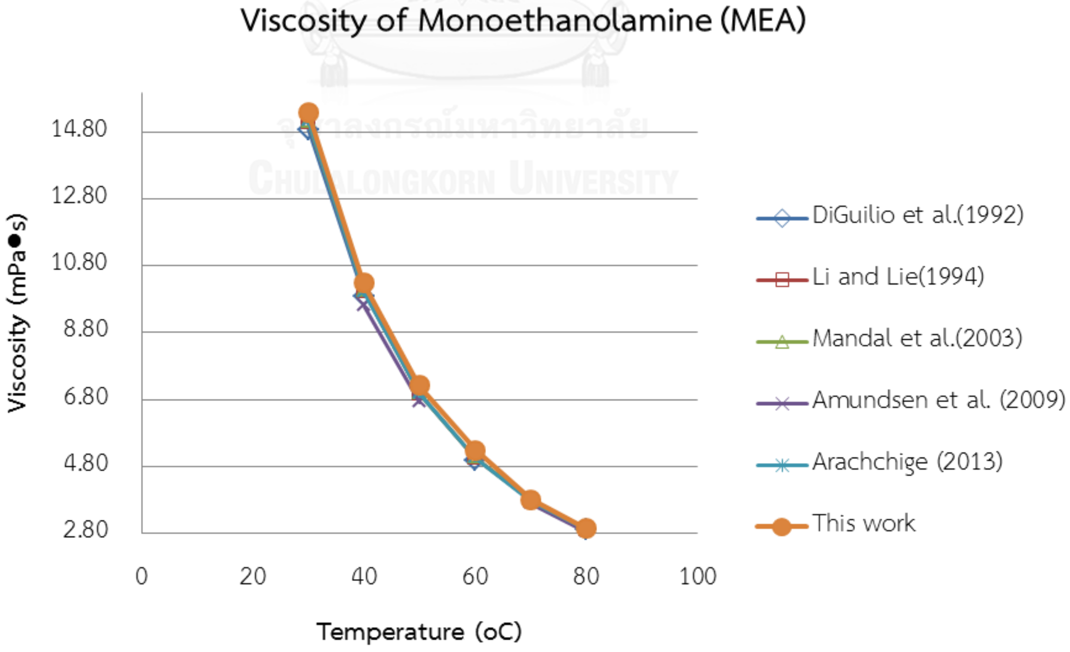


Figure 4.4 Comparison of viscosity of MEA

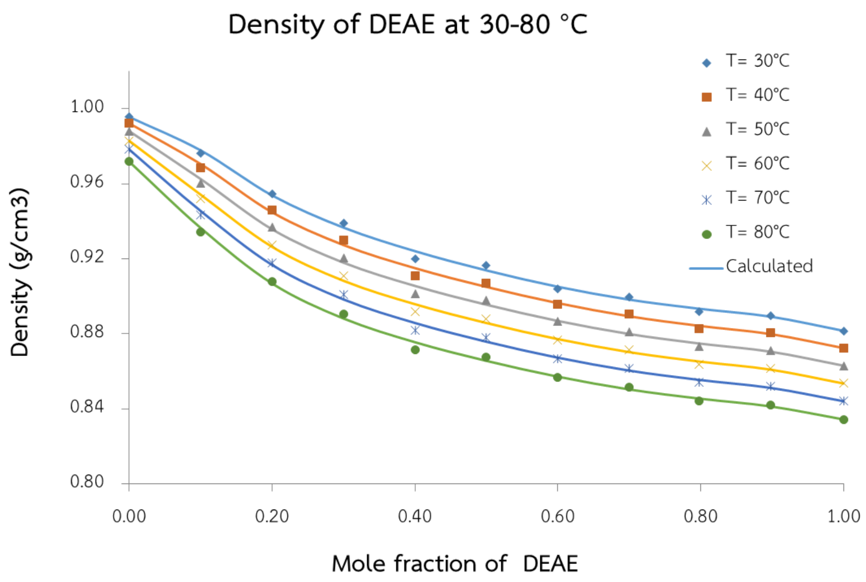


Figure 4.5 Density of DEAE+water at various mole fraction and temperature of 30-80°C

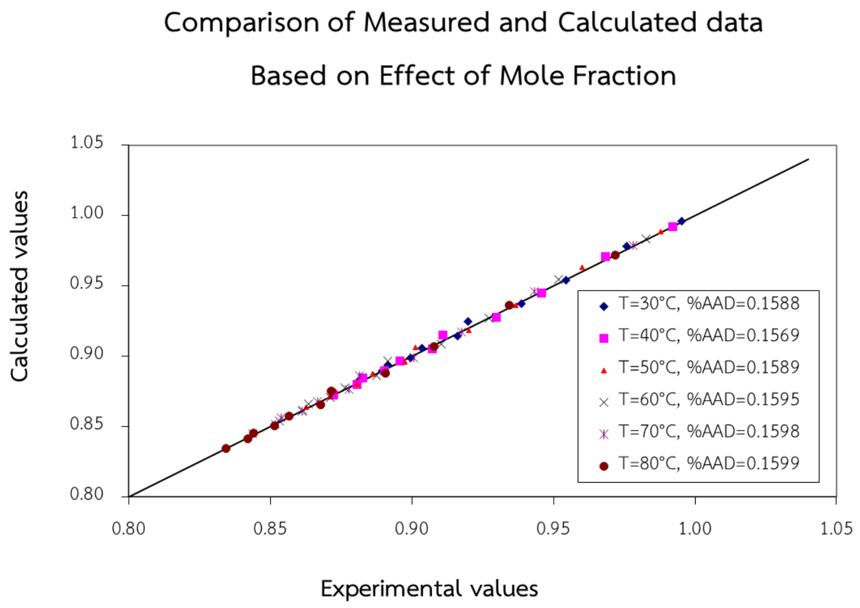


Figure 4.6 Comparison of measured and calculated data based on effect of mole fraction for DEAE+water at temperature of 30-80°C

Table 4.1 Measured and calculated density values of DEAE+water at temperature of 30-80°C

x/Temp.	30°C		40°C		50°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.99566	0.99566	0.99224	0.99224	0.98806	0.98806
0.1001	0.97610	0.97782	0.96841	0.97052	0.96040	0.96254
0.2002	0.95464	0.95377	0.94590	0.94477	0.93684	0.93570
0.2999	0.93890	0.93667	0.92980	0.92736	0.92040	0.91796
0.4001	0.92015	0.92408	0.91090	0.91501	0.90140	0.90553
0.4998	0.91642	0.91383	0.90715	0.90503	0.89767	0.89553
0.5996	0.90392	0.90513	0.89592	0.89640	0.88644	0.88691
0.6996	0.89968	0.89824	0.89049	0.88936	0.88102	0.87991
0.7981	0.89192	0.89337	0.88272	0.88424	0.87331	0.87483
0.8979	0.88984	0.88916	0.88063	0.87986	0.87124	0.87047
1.0000	0.88160	0.88160	0.87238	0.87238	0.86300	0.86300

x/Temp.	60°C		70°C		80°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.98291	0.98291	0.97829	0.97829	0.97181	0.97181
0.1001	0.95206	0.95418	0.94339	0.94549	0.93438	0.93644
0.2002	0.92746	0.92635	0.91780	0.91670	0.90786	0.90680
0.2999	0.91073	0.90829	0.90079	0.89837	0.89060	0.88818
0.4001	0.89166	0.89577	0.88169	0.88577	0.87147	0.87551
0.4998	0.88791	0.88578	0.87792	0.87580	0.86770	0.86559
0.5996	0.87674	0.87721	0.86682	0.86730	0.85668	0.85717
0.6996	0.87137	0.87026	0.86150	0.86041	0.85144	0.85036
0.7981	0.86371	0.86522	0.85393	0.85541	0.84398	0.84544
0.8979	0.86166	0.86090	0.85192	0.85117	0.84202	0.84128
1.0000	0.85349	0.85349	0.84405	0.84405	0.83432	0.83432

Table 4.2 Redlich-Kister equation coefficients of excess molar volume for DEAE+water at temperature of 30-80°C

T (°C)	A_0	A_1	A_2	A_3	A_4	%AAD
30	-6.1306	2.7606	-0.0473	-1.8729	-9.3494	1.9094
40	-6.1858	2.1812	0.6564	-1.0961	-9.9863	1.8914
50	-6.0896	2.0574	0.7778	-1.2291	-10.1797	1.9236
60	-5.9855	1.9450	0.8529	1.2514	-10.3428	2.3947
70	-5.7497	1.8720	0.9816	-1.1798	-10.1512	1.7739
80	-5.5922	1.8112	1.0240	-1.0992	-10.2680	1.7548

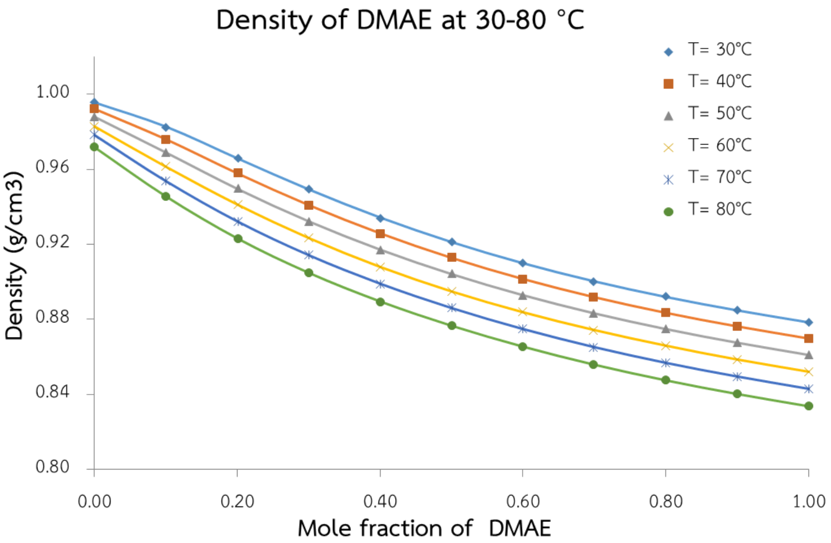


Figure 4.7 Density of DMAE+water at various mole fraction and temperature of 30-80°C

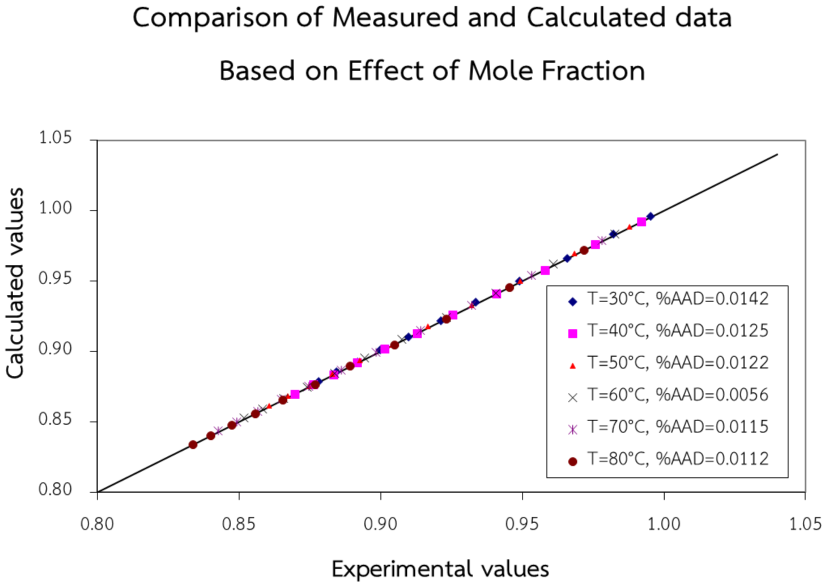


Figure 4.8 Comparison of measured and calculated data based on effect of mole fraction for DMAE+water at temperature of 30-80°C

Table 4.3 Measured and calculated density values of DMAE+water at temperature of 30-80°C

x/Temp.	30°C		40°C		50°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.99566	0.99566	0.99224	0.99224	0.98806	0.98806
0.1001	0.98253	0.98278	0.97583	0.97603	0.96878	0.96895
0.2009	0.96605	0.96573	0.95797	0.95772	0.94965	0.94944
0.3000	0.94927	0.94930	0.94091	0.94091	0.93227	0.93226
0.4003	0.93394	0.93426	0.92552	0.92582	0.91683	0.91713
0.5002	0.92146	0.92118	0.91303	0.91276	0.90437	0.90410
0.5996	0.90996	0.90995	0.90154	0.90154	0.89289	0.89291
0.6988	0.90021	0.90035	0.89178	0.89192	0.88314	0.88327
0.7997	0.89206	0.89197	0.88358	0.88350	0.87492	0.87482
0.9000	0.88473	0.88475	0.87621	0.87623	0.86749	0.86752
1.0000	0.87837	0.87837	0.86977	0.86977	0.86100	0.86100
x/Temp.	60°C		70°C		80°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.98291	0.98291	0.97829	0.97829	0.97181	0.97181
0.1001	0.96136	0.96139	0.95359	0.95372	0.94547	0.94557
0.2009	0.94109	0.94108	0.93224	0.93209	0.92312	0.92301
0.3000	0.92341	0.92337	0.91428	0.91424	0.90487	0.90481
0.4003	0.90790	0.90792	0.89870	0.89898	0.88923	0.88950
0.5002	0.89476	0.89487	0.88626	0.88601	0.87682	0.87657
0.5996	0.88401	0.88384	0.87487	0.87489	0.86546	0.86548
0.6988	0.87426	0.87439	0.86514	0.86528	0.85576	0.85590
0.7997	0.86603	0.86599	0.85693	0.85682	0.84758	0.84747
0.9000	0.85858	0.85859	0.84946	0.84950	0.84013	0.84017
1.0000	0.85206	0.85206	0.84292	0.84292	0.83361	0.83361

Table 4.4 Redlich-Kister equation coefficients of excess molar volume for DMAE+water at temperature of 30-80°C

T (°C)	A_0	A_1	A_2	A_3	A_4	%AAD
30	-6.5115	3.0064	-1.0731	0.0062	-0.0167	0.0142
40	-6.4987	2.8050	-0.8938	0.0129	-0.1659	0.0125
50	-6.4895	2.6152	-0.7410	0.0752	-0.3237	0.0122
60	-6.4077	2.4625	-1.3010	0.1773	0.4358	0.0056
70	-6.4558	2.2999	-0.5389	0.1463	-0.4800	0.0115
80	-6.4591	2.2040	-0.4373	0.2713	-0.7065	0.0112

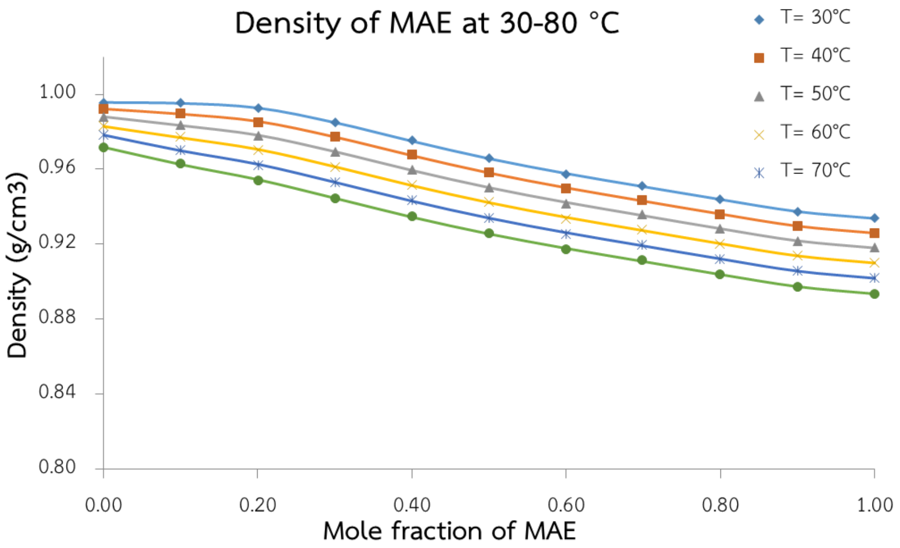


Figure 4.9 Density of MAE+water at various mole fraction and temperature of 30-80°C

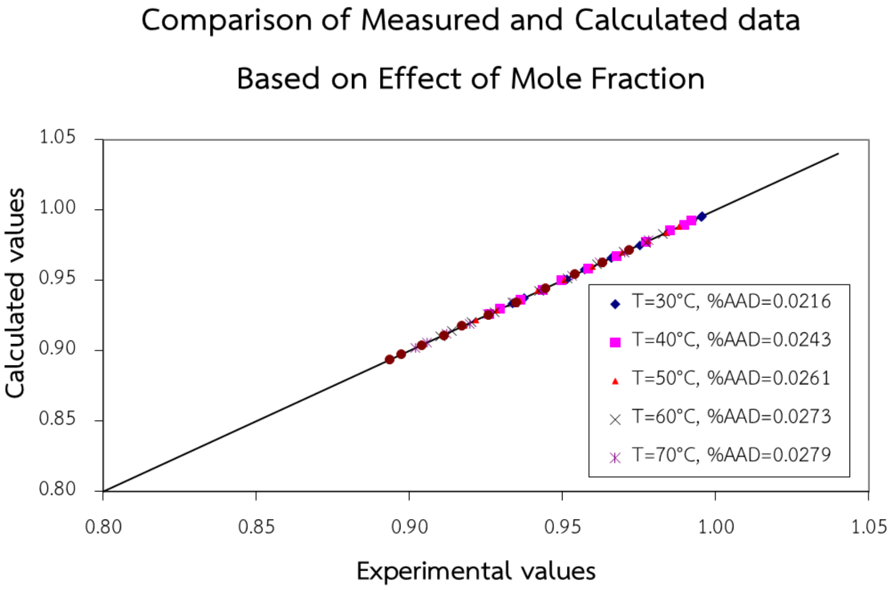


Figure 4.10 Comparison of measured and calculated data based on effect of mole fraction for MAE+water at temperature of 30-80°C

Table 4.5 Measured and calculated density values of MAE+water at temperature of 30-80°C

x/Temp.	30°C		40°C		50°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.99566	0.99566	0.99224	0.99224	0.98806	0.98806
0.1002	0.99545	0.99519	0.98987	0.98949	0.98382	0.98338
0.2001	0.99252	0.99276	0.98518	0.98559	0.97776	0.97824
0.3002	0.98479	0.98492	0.97718	0.97724	0.96936	0.96942
0.3999	0.97528	0.97502	0.96763	0.96732	0.95980	0.95944
0.4997	0.96592	0.96570	0.95827	0.95809	0.95043	0.95027
0.5995	0.95718	0.95780	0.94954	0.95019	0.94175	0.94241
0.6984	0.95133	0.95087	0.94367	0.94320	0.93588	0.93541
0.7992	0.94386	0.94398	0.93615	0.93625	0.92833	0.92842
0.8996	0.93748	0.93749	0.92973	0.92975	0.92185	0.92189
1.0000	0.93380	0.93380	0.92599	0.92599	0.91809	0.91809

x/Temp.	60°C		70°C		80°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.98291	0.98291	0.97829	0.97829	0.97181	0.97181
0.1002	0.97733	0.97686	0.97042	0.96994	0.96312	0.96258
0.2001	0.97014	0.97065	0.96219	0.96272	0.95392	0.95452
0.3002	0.96133	0.96139	0.95306	0.95311	0.94455	0.94458
0.3999	0.95174	0.95136	0.94344	0.94305	0.93491	0.93450
0.4997	0.94241	0.94225	0.93417	0.93401	0.92570	0.92555
0.5995	0.93376	0.93444	0.92558	0.92627	0.91718	0.91789
0.6984	0.92792	0.92744	0.91977	0.91929	0.91143	0.91095
0.7992	0.92035	0.92043	0.91222	0.91229	0.90392	0.90397
0.8996	0.91385	0.91389	0.90571	0.90576	0.89741	0.89746
1.0000	0.91005	0.91005	0.90191	0.90191	0.89360	0.89360

Table 4.6 Redlich-Kister equation coefficients of excess molar volume for MAE+water at temperature of 30-80°C

T (°C)	A_0	A_1	A_2	A_3	A_4	%AAD
30	-4.1869	2.1754	-2.3510	0.0493	4.9539	0.0216
40	-4.1349	1.9665	-2.0801	0.2222	4.5712	0.0243
50	-4.0860	1.7765	-1.9471	0.4238	4.3965	0.0261
60	-4.0539	1.6218	-1.8527	0.6205	4.1904	0.0273
70	-3.9744	1.4512	-1.7599	0.6900	4.1695	0.0279
80	-3.9452	1.3235	-1.7079	0.8898	3.9877	0.0294

4.3 Viscosity experimental results

4.3.1 Viscosity experimental results of 2-(Diethylamino)Ethanol (DEAE)

The experimental results of viscosity of 2-(Diethylamino)Ethanol (DEAE) mixed with distilled water by mole fraction from 0.0-1.0 at the temperature of 30-80°C and the calculated values by the Redich-Kister equation are presented in Figure 4.11 and Table 4.7 The viscosities increase with the mole fraction of DEAE up to a mole fraction of approximately 0.4. Then, the viscosities decrease with an increase mole fraction. The calculated values agree well with the measured data. The Redlich-Kister equation coefficients and average absolute deviation of viscosity deviation of DEAE and water are presented in the Table 4.8. The percent average absolute deviation for viscosities is 1.941%. The comparison of measured and calculated data based on effect of mole fraction for DEAE+water at temperature of 30-80°C is presented in the Figure 4.12

4.3.2 Viscosity experimental results of 2-(Dimethylamino)Ethanol (DMAE)

The viscosity experimental results of 2-(Dimethylamino)Ethanol (DMAE) mixed with distilled water at the concentration of 0.0-1.0 by mole fraction, measured at the temperature of 30-80°C and the calculated values presented by the Redlich-Kister equation are presented in Figure 4.13 and Table 4.9. The Redlich-Kister equation coefficients and average absolute deviation of viscosity deviation of DMAE and water are presented in the Table 4.10 The comparison of measured and calculated data based on effect of mole fraction for DEAE+water at temperature of 30-80°C is presented in the Figure 4.14 The experimental results of viscosity of DMAE increase with the mole fraction of DEAE up to a mole fraction of approximately 0.4 then, the viscosities decrease with an increase mole fraction. The calculated viscosity values get along well with the measured data. The percent average absolute deviation for viscosities is 2.031%.

4.3.3 Viscosity experimental results of 2-(Methylamino)Ethanol (MAE)

The experimental results of viscosity of 2-(Methylamino)Ethanol (MAE) mixed with distilled water at the concentration of 0.0-1.0 by mole fraction which the temperature of 30-80°C and the calculated values presented by Redlich-Kister equation are presented in Figure 4.15 and Table 4.11. The viscosities increase with the mole fraction of DEAE up to a mole fraction of approximately 0.6 then. The viscosities decrease with an increase mole fraction. The calculated values agree well with the measured data. The Redlich-Kister equation coefficients and average absolute deviation of viscosity deviation of MAE and water are presented in the Table 4.12. The percent average absolute deviation for viscosities is 1.491%. The comparison of measured and calculated data based on effect of mole fraction for MAE+water at temperature of 30-80°C is presented in the Figure 4.16

According to the results, the maximum of the viscosity of DEAE, DMAE and MAE occur at a specific mole fraction; approximately 0.4, 0.4 and 0.6 respectively because hydrogen bonds are formed following interactions between amine and distilled water when an amine is dissolved in the distilled water. This feature reflects the maximum attraction in the interaction between the solute DEAE, DMAE, MAE and the distilled water. The appearance of such a maximum has been reported in the literature (Assarsson & Eirich, 1968; Fort & Moore, 1966; García, Alcalde, Leal, & Matos, 1997) for systems of polar unlike molecules such as the ethanol–water system. These authors also suggested that there exists the highest degree of association at those specific compositions leading to complex formation between nitrogen or oxygen and water. They further suggested that, at these specific compositions of the amines, the water molecule is associated strongly with the unshared pair of electrons on the oxygen, while water molecule is held on a lone pair of electrons on nitrogen. (K.; Maneeintr, Henni, Idem, Tontiwachwuthikul, & Wee, 2008)

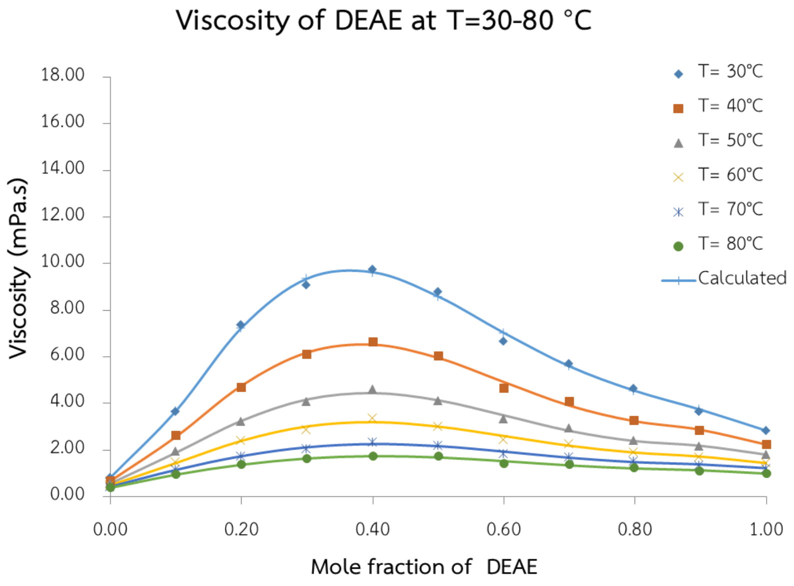


Figure 4.11 Viscosity of DEAE+water at various mole fraction and temperature of 30-80°C

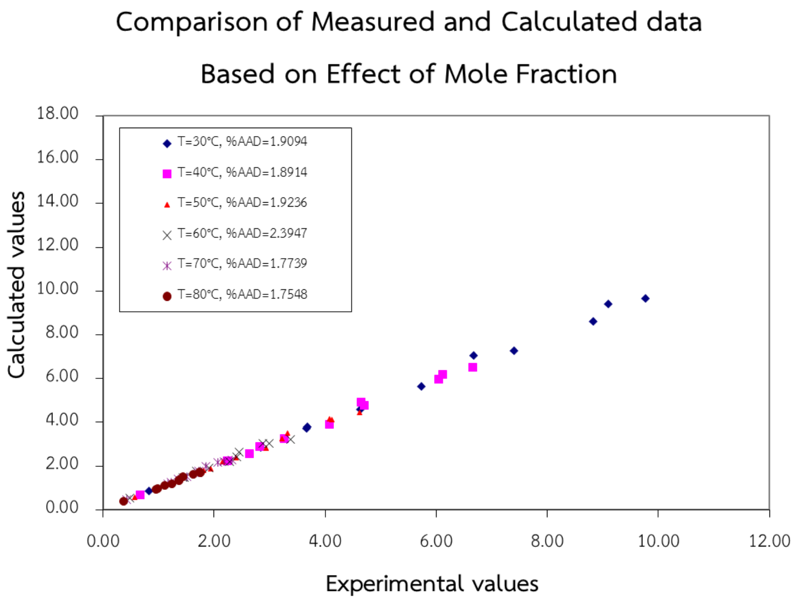


Figure 4.12 Comparison of measured and calculated data based on effect of mole fraction for DEAE+water at temperature of 30-80°C

Table 4.7 Measured and calculated viscosity values of DEAE+water at temperature of 30-80°C

x/Temp.	30°C		40°C		50°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.8211	0.8211	0.6715	0.6715	0.5632	0.5632
0.1001	3.6621	3.6873	2.6367	2.5724	1.9350	1.8877
0.2002	7.3941	7.2549	4.7000	4.7665	3.2205	3.2579
0.2999	9.0927	9.3596	6.1193	6.1856	4.0787	4.1717
0.4001	9.7665	9.6304	6.6520	6.5230	4.6166	4.4435
0.4998	8.8198	8.5893	6.0388	5.9541	4.1216	4.1348
0.5996	6.6676	7.0330	4.6415	4.9213	3.3224	3.4902
0.6996	5.7274	5.5963	4.0753	3.9066	2.9406	2.8225
0.7981	4.6330	4.5543	3.2603	3.2417	2.3977	2.3867
0.8979	3.6709	3.7452	2.8252	2.8758	2.1501	2.1861
1.0000	2.8311	2.8311	2.2335	2.2335	1.8019	1.8019

x/Temp.	60°C		70°C		80°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.4862	0.4862	0.4245	0.4245	0.3744	0.3744
0.1001	1.4707	1.4450	1.1709	1.1500	0.9525	0.9424
0.2002	2.4051	2.3965	1.7254	1.7380	1.3644	1.3686
0.2999	2.8781	3.0132	2.0708	2.1177	1.6175	1.6373
0.4001	3.3777	3.1962	2.3231	2.2544	1.7410	1.7363
0.4998	2.9981	3.0050	2.1848	2.1666	1.7459	1.6798
0.5996	2.4450	2.6036	1.8481	1.9336	1.4314	1.5214
0.6996	2.2855	2.1837	1.7019	1.6694	1.3645	1.3390
0.7981	1.9090	1.8918	1.5135	1.4803	1.2349	1.2059
0.8979	1.6871	1.7226	1.3528	1.3827	1.1064	1.1301
1.0000	1.4383	1.4383	1.2191	1.2191	0.9878	0.9878

Table 4.8 Redlich-Kister equation coefficients of viscosity deviation for DEAE+water at temperature of 30-80°C

T (°C)	A_0	A_1	A_2	A_3	A_4	%AAD
30	27.0414	-32.6797	2.0657	34.1020	-18.2513	1.9094
40	17.9995	-20.8789	-5.4006	22.3019	-1.1405	1.8914
50	11.8048	-13.0554	-5.3409	12.8612	2.6331	1.9236
60	8.1684	-8.4947	-2.4916	7.9953	0.7519	2.3947
70	5.3776	-5.1552	-2.0638	3.6717	2.1233	1.7739
80	3.9939	-3.6180	-1.2362	2.3550	1.7882	1.7548

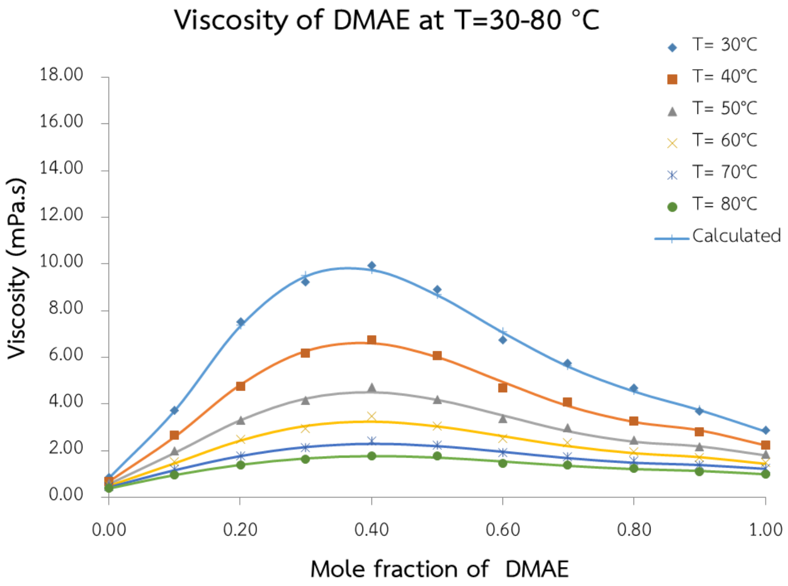


Figure 4.13 Viscosity of DMAE+water at various mole fraction and temperature of 30-80°C

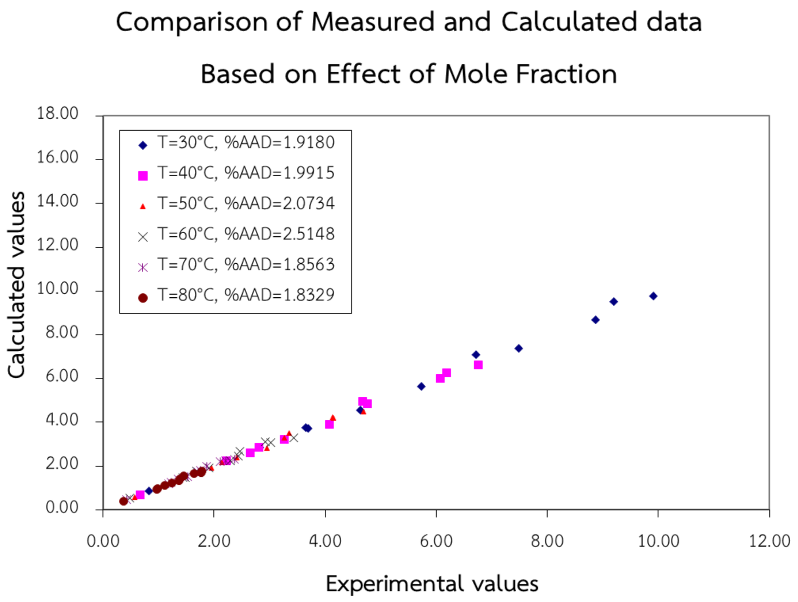


Figure 4.14 Comparison of measured and calculated data based on effect of mole fraction for DMAE+water at temperature of 30-80°C

Table 4.9 Measured and calculated viscosity values of DMAE+water at temperature of 30-80°C

x/Temp.	30°C		40°C		50°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.8211	0.8211	0.6715	0.6715	0.5632	0.5632
0.1001	3.6862	3.7030	2.6569	2.5857	1.9519	1.8996
0.2009	7.4825	7.3508	4.7600	4.8343	3.2646	3.3070
0.3000	9.1931	9.4741	6.1925	6.2677	4.1313	4.2317
0.4003	9.9128	9.7419	6.7587	6.6039	4.6956	4.5031
0.5002	8.8683	8.6632	6.0779	6.0095	4.1523	4.1775
0.5996	6.7122	7.0694	4.6706	4.9499	3.3466	3.5141
0.6988	5.7308	5.6115	4.0812	3.9187	2.9477	2.8339
0.7997	4.6338	4.5380	3.2635	3.2314	2.4022	2.3813
0.9000	3.6498	3.7345	2.8110	2.8698	2.1408	2.1829
1.0000	2.8207	2.8207	2.2268	2.2268	1.7977	1.7977

x/Temp.	60°C		70°C		80°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.4862	0.4862	0.4245	0.4245	0.3744	0.3744
0.1001	1.4850	1.4558	1.1835	1.1603	0.9638	0.9519
0.2009	2.4405	2.4351	1.7525	1.7673	1.3873	1.3929
0.3000	2.9181	3.0599	2.1018	2.1529	1.6434	1.6662
0.4003	3.4392	3.2420	2.3679	2.2892	1.7765	1.7648
0.5002	3.0213	3.0382	2.2056	2.1932	1.7642	1.7020
0.5996	2.4653	2.6231	1.8652	1.9504	1.4460	1.5359
0.6988	2.2931	2.1942	1.7091	1.6790	1.3714	1.3477
0.7997	1.9141	1.8903	1.5188	1.4807	1.2402	1.2075
0.9000	1.6811	1.7207	1.3489	1.3821	1.1039	1.1301
1.0000	1.4359	1.4359	1.2174	1.2174	0.9869	0.9869

Table 4.10 Redlich-Kister equation coefficients of viscosity deviation for DMAE+water at temperature of 30-80°C

T (°C)	A_0	A_1	A_2	A_3	A_4	%AAD
30	27.3811	-33.5039	1.8705	35.3754	-18.3414	1.9180
40	18.2489	-21.4479	-5.5694	23.1199	-1.1968	1.9915
50	11.9926	-13.4421	-5.4640	13.3760	2.5891	2.0734
60	8.3116	-8.7788	-2.5411	8.3595	0.6775	2.5148
70	5.4902	-5.3489	-2.1043	3.8888	2.0873	1.8563
80	4.0862	-3.7680	-1.2582	2.5090	1.7574	1.8329

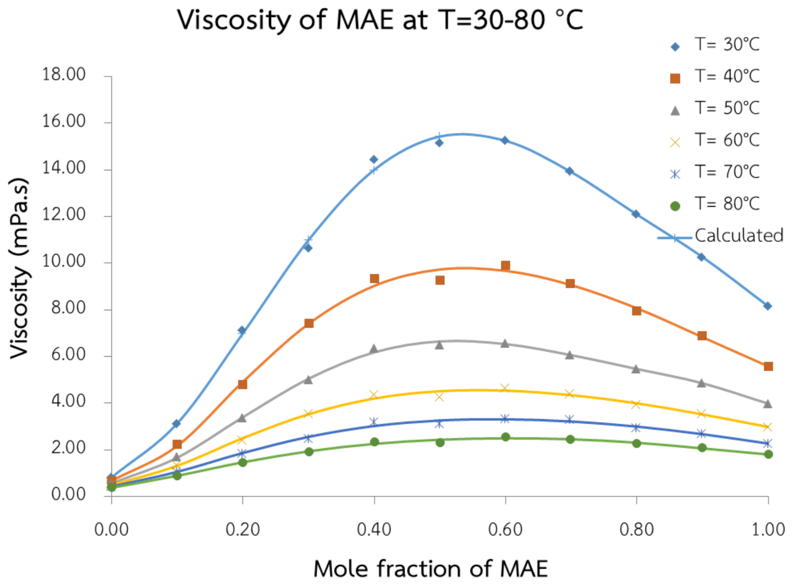


Figure 4.15 Viscosity of MAE + water at various mole fraction and temperature of 30-80°C

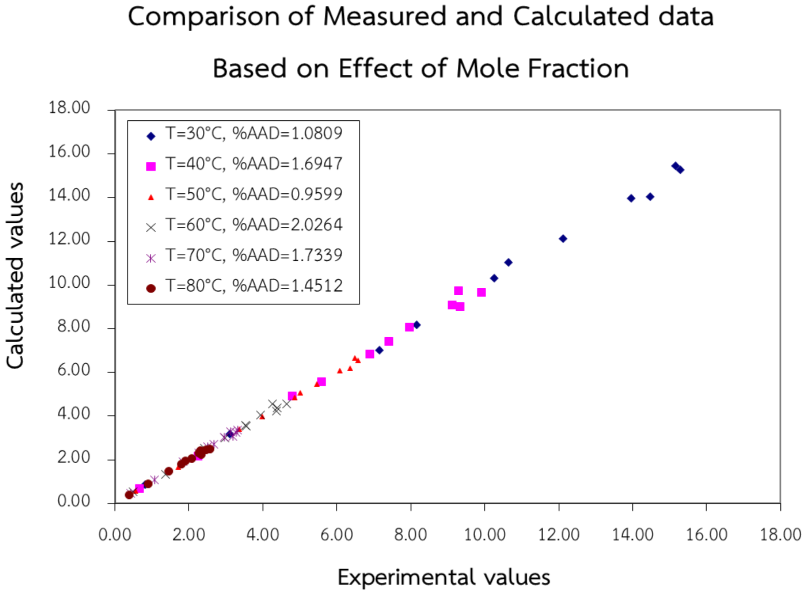


Figure 4.16 Comparison of measured and calculated data based on effect of mole fraction for MAE+water at temperature of 30-80°C

Table 4.11 Measured and calculated viscosity values of MAE+water at temperature of 30-80°C

x/Temp.	30°C		40°C		50°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.8211	0.8211	0.6715	0.6715	0.5632	0.5632
0.1002	3.1129	3.1369	2.2395	2.1731	1.7015	1.6672
0.2001	7.1469	7.0021	4.8011	4.9197	3.3612	3.4013
0.3002	10.6422	11.0051	7.4042	7.4067	5.0004	5.0508
0.3999	14.4646	14.0072	9.3344	9.0292	6.3515	6.1796
0.4997	15.1592	15.4316	9.2810	9.7313	6.4881	6.6480
0.5995	15.2797	15.2514	9.9155	9.6750	6.5763	6.5347
0.6984	13.9645	13.9330	9.1162	9.0759	6.0861	6.0670
0.7992	12.1128	12.1000	7.9637	8.0768	5.4652	5.4699
0.8996	10.2500	10.2715	6.8861	6.8336	4.8490	4.8558
1.0000	8.1553	8.1553	5.5777	5.5777	3.9787	3.9787

x/Temp.	60°C		70°C		80°C	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0.0000	0.4862	0.4862	0.4245	0.4245	0.3744	0.3744
0.1002	1.3603	1.3158	1.0782	1.0582	0.8929	0.8886
0.2001	2.4233	2.5026	1.8500	1.8656	1.4637	1.4673
0.3002	3.5339	3.5287	2.4937	2.5561	1.9121	1.9380
0.3999	4.3715	4.1989	3.1794	3.0201	2.3408	2.2542
0.4997	4.2679	4.5117	3.1217	3.2586	2.3150	2.4316
0.5995	4.6469	4.5360	3.3192	3.3097	2.5612	2.4940
0.6984	4.3926	4.3500	3.2822	3.2156	2.4600	2.4530
0.7992	3.9287	3.9978	2.9486	2.9971	2.2724	2.3046
0.8996	3.5485	3.5197	2.6848	2.6711	2.0785	2.0616
1.0000	2.9806	2.9806	2.2681	2.2681	1.7989	1.7989

Table 4.12 Redlich-Kister equation coefficients of viscosity deviation for MAE+water at temperature of 30-80°C

T (°C)	A_0	A_1	A_2	A_3	A_4	%AAD
30	43.7804	-3.1342	-38.7990	18.6401	13.6603	1.0809
40	26.4302	-4.1008	-11.7378	14.3853	-8.9226	1.6947
50	17.5101	-3.8840	-12.2760	11.0245	3.2247	0.9599
60	11.1151	-1.9047	-3.3689	5.2388	-3.3692	2.0264
70	7.6506	-0.9487	-1.7415	2.9809	-1.9387	1.7339
80	5.3812	-0.5188	-0.3261	1.1735	-2.1214	1.4512

4.4 Comparison of the results

For comparison of three components, the trend of density and viscosity of DEAE and DMAE are similar but MAE is different, because the molecular structure of DEAE and DMAE resemble each other. Both of DEAE and DMAE have the two functional groups which are tertiary amine and hydroxyl group. Differently, functional groups of MAE are secondary amine and hydroxyl group.

For the impact of hydrogen bond, DEAE and DMAE have 2 types of hydrogen bond (OH---:O and OH---:N) but MAE have 4 types of hydrogen bond (OH---:O , OH---:N , NH---:O and NH---:N). For that reason, MAE has different density and viscosity trend, as shown in the figure 4.17 - figure 4.28, the density and viscosity of MAE are obviously higher than the others. For example, the densities of pure DEAE, DMAE and MAE at 30 degree Celsius (figure 4.17) are 0.8816, 0.8784 and 0.9338 g/cm^3. The maximum viscosities of DEAE, DMAE and MAE at 30 degree Celsius (figure 4.18) are 9.77, 9.91 and 15.28 MPa.s (at mole fraction of 0.4, 0.4 and 0.6) respectively.

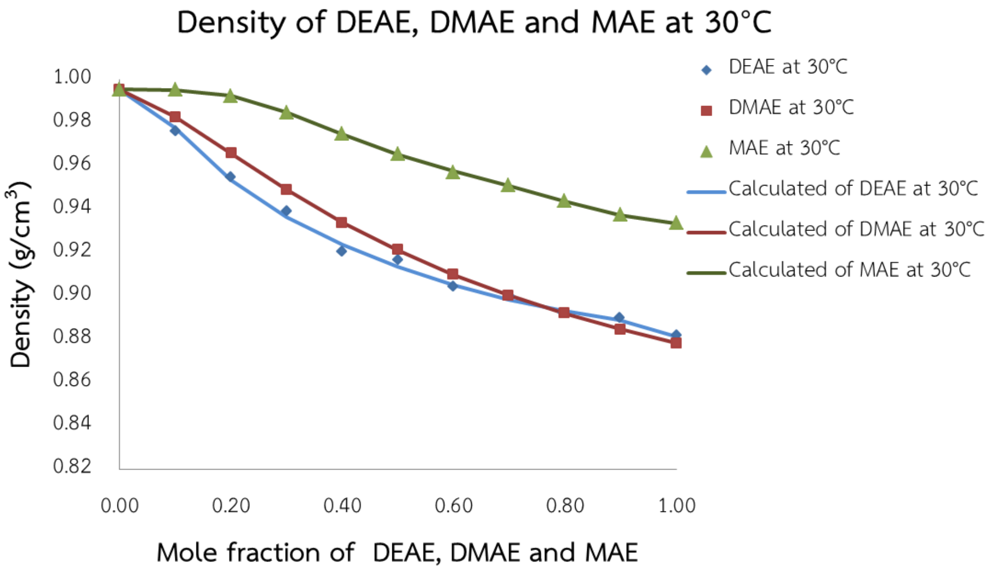


Figure 4.17 Comparison of the density results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 30°C

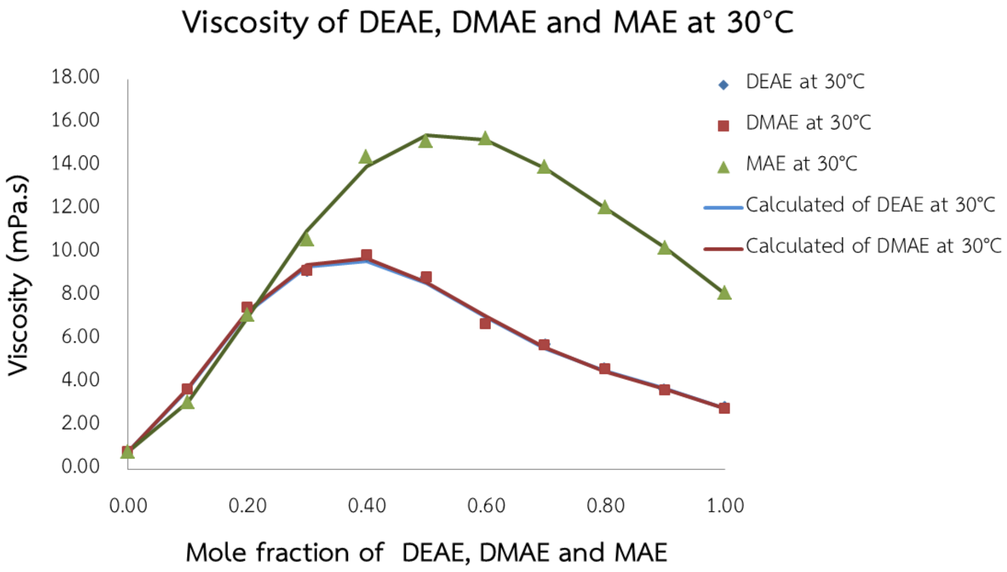


Figure 4.18 Comparison of the viscosity results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 30°C

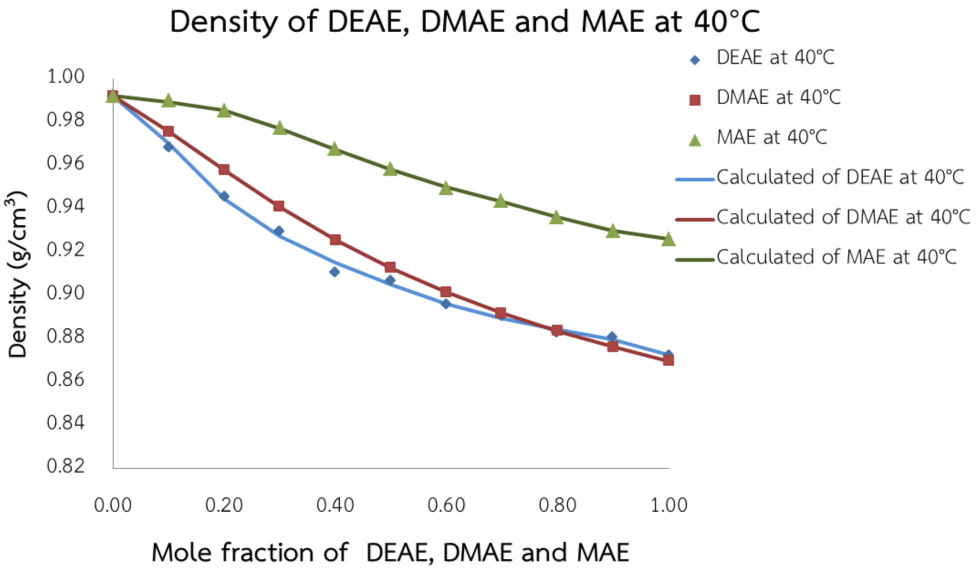


Figure 4.19 Comparison of the density results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 40°C

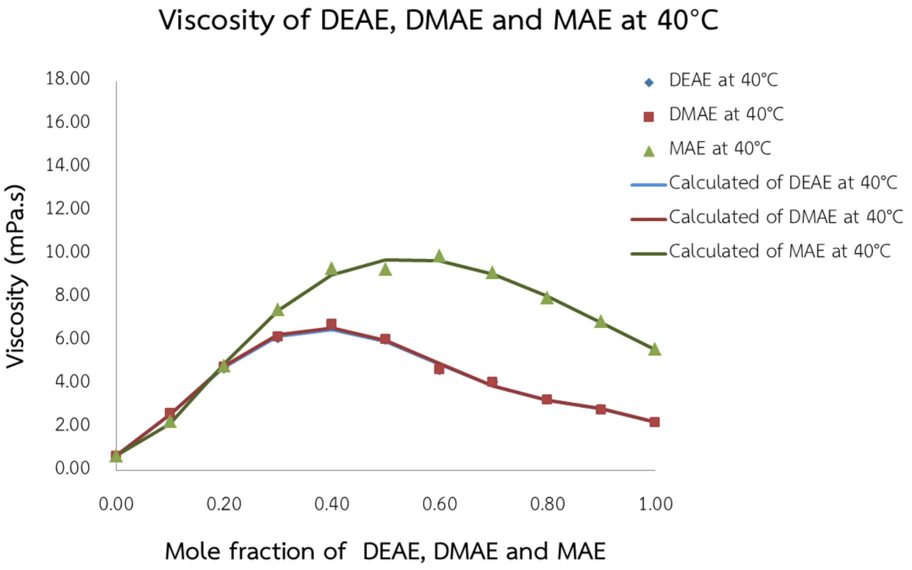


Figure 4.20 Comparison of the viscosity results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 40°C

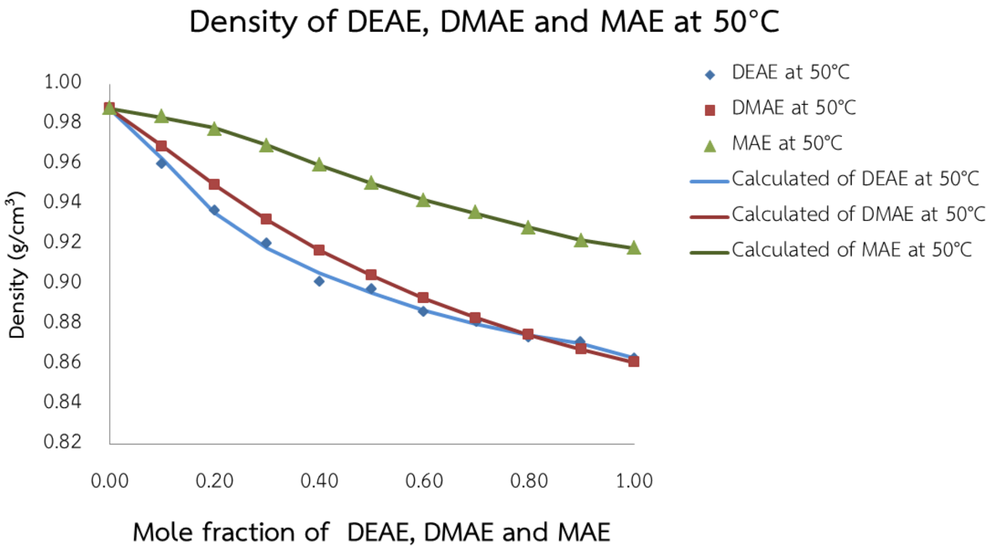


Figure 4.21 Comparison of the density results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 50°C

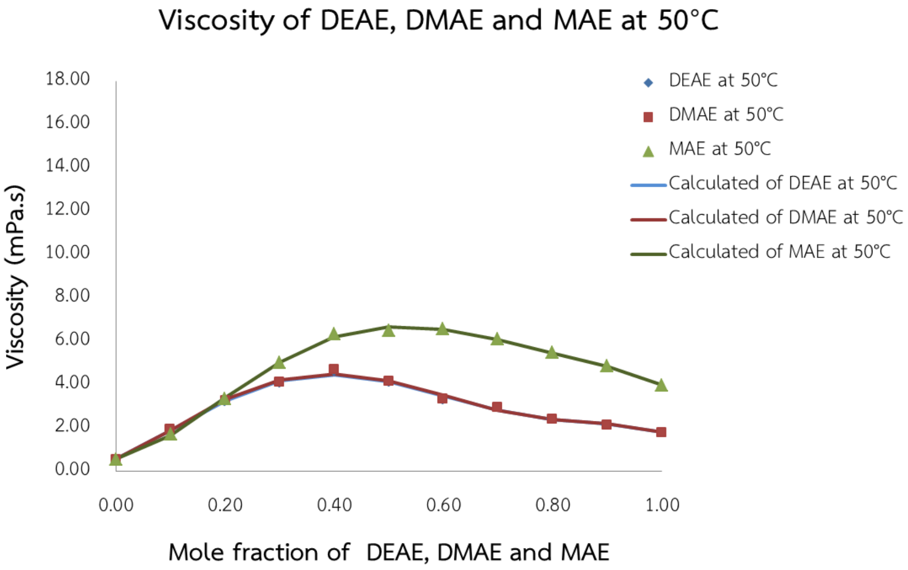


Figure 4.22 Comparison of the viscosity results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 50°C

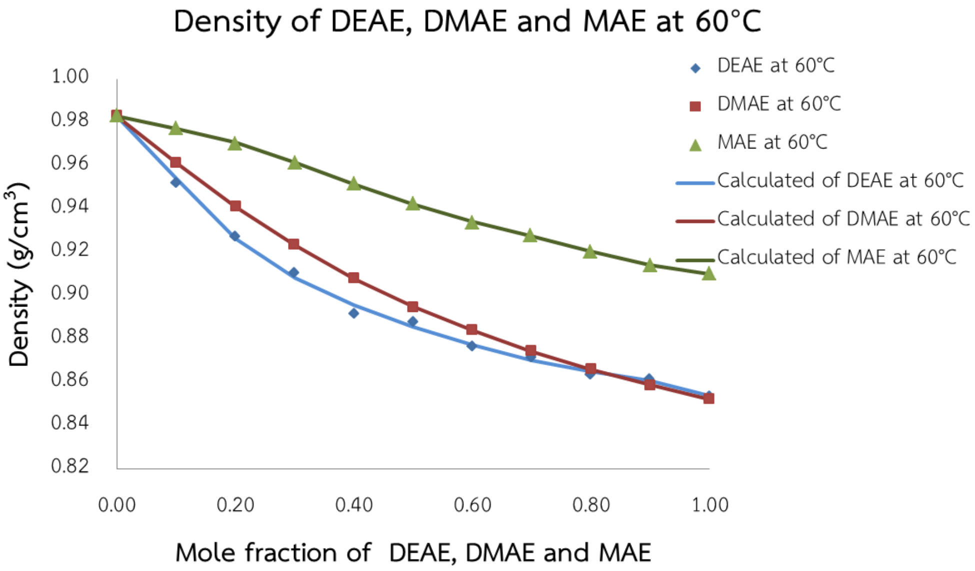


Figure 4.23 Comparison of the density results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 60°C

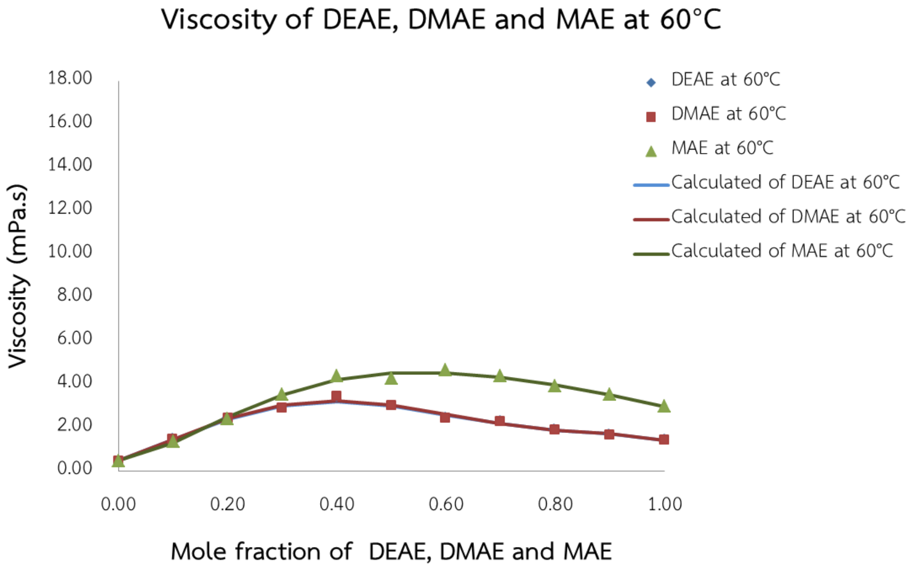


Figure 4.24 Comparison of the viscosity results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 60°C

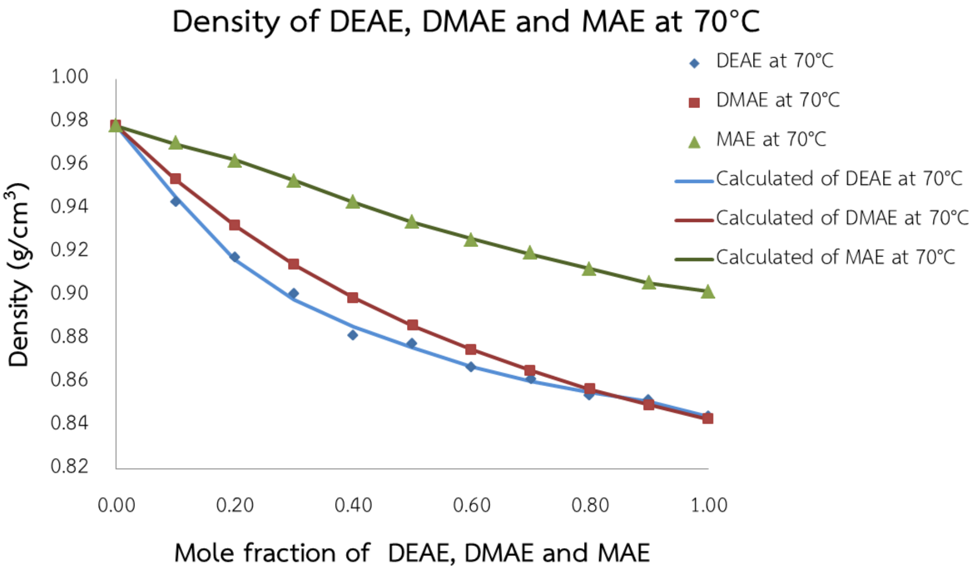


Figure 4.25 Comparison of the density results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 70°C

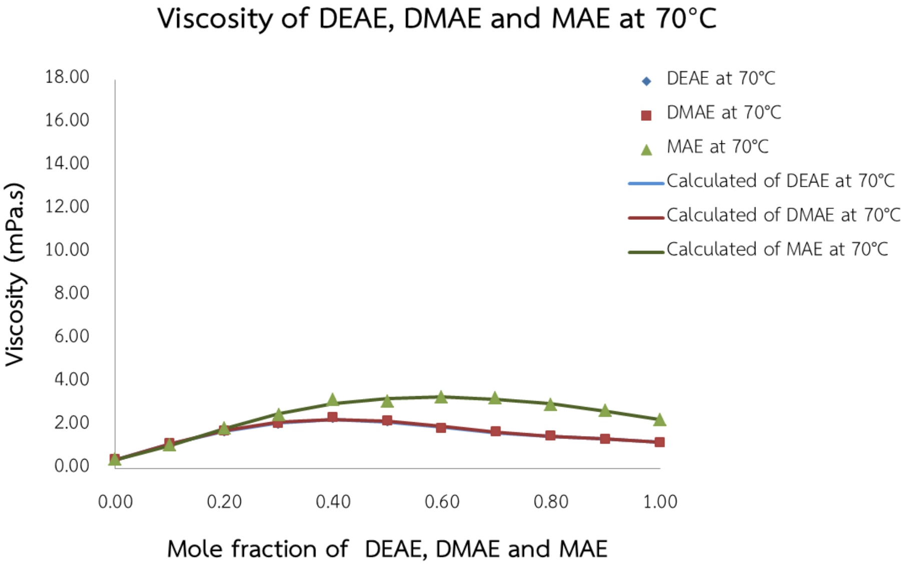


Figure 4.26 Comparison of the viscosity results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 70°C

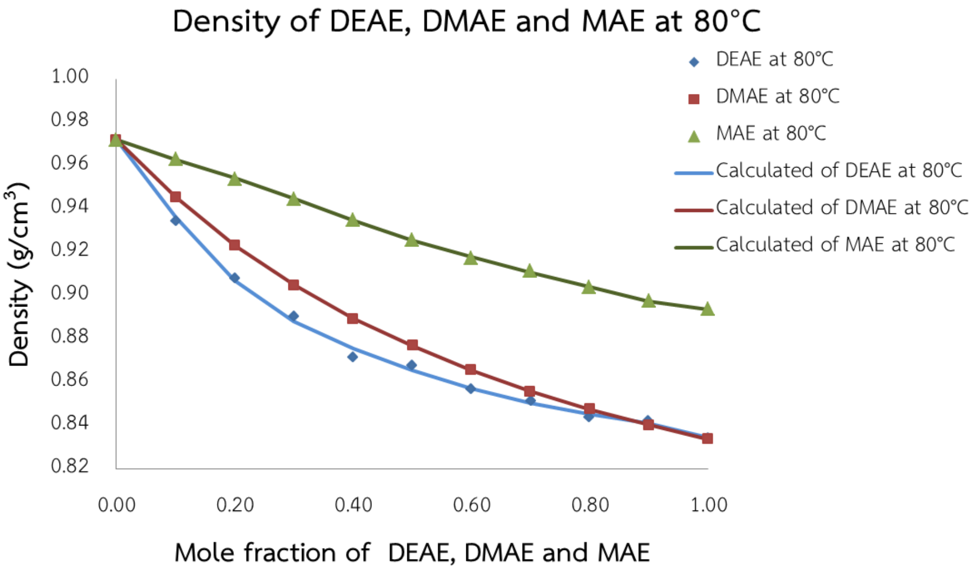


Figure 4.27 Comparison of the density results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 80°C

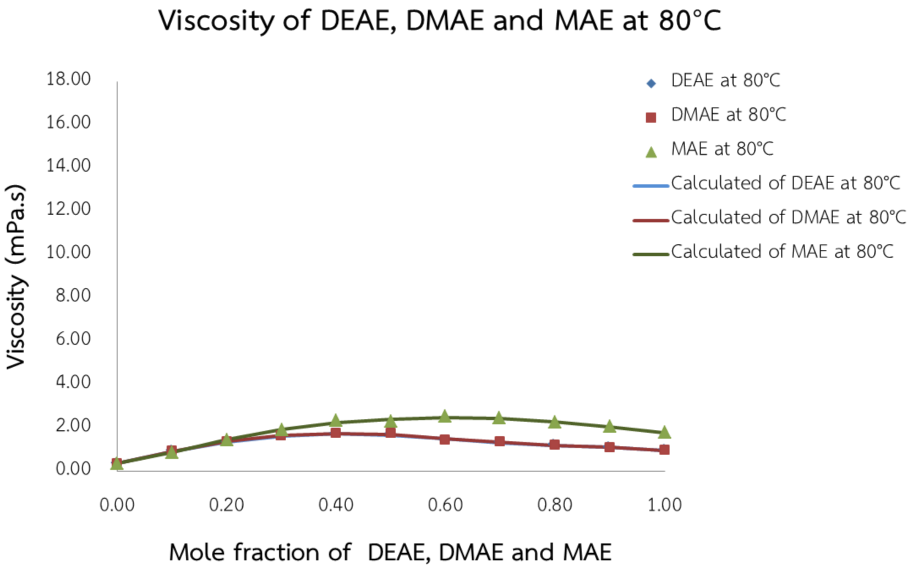


Figure 4.28 Comparison of the viscosity results of DEAE+water, DMAE+water, MAE+water at various mole fraction and temperature of 80°C

CHAPTER 5
CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

According to the results of the density and viscosity measurement of aqueous amine solution of amino ethanol for carbon dioxide absorption process, the amino alcohol solution which using in this study are DEAE, DMAE and DAME, are prepared by mixing with the distilled water at the concentration of 0.0-1.0 by mole fraction. These solvents are measured the density and viscosity at the temperature of 30-80°C which is the condition in fossil fuel power plants to evaluate the effect of mole fraction and temperature on density and viscosity of amines for carbon dioxide absorption process and to investigate the effect of the various function groups attached to back-bone of amino ethanol. Moreover, to the develop correlation for prediction of density and viscosity property. The following conclusion and recommendation can be presented below;

The physical and transport properties of aqueous amines solution such as density and viscosity are important to study because these properties affect to efficient design and operation of gas treating process plants. Otherwise, these properties can be used to predict other properties such as diffusivity and reaction rate constant.

The densities and viscosities of binary mixture like DEAE, DMAE and MAE mixed with distilled water at the concentration of 0.0-1.0 by mole fraction are measured at the temperature ranging from 30-80°C. These properties data are correlated as a function of mole fraction and temperature. The Redlich-Kister equation is the suitable model to represent the results of the experimental data of density and viscosity of binary mixture which using in this study, with the lowest percent average absolute deviation (%AAD). The percent average deviation of DEAE is

0.1590% and 1.9413% for density and viscosity, respectively. For DMAE is 0.0112% and 2.0312% for density and viscosity, respectively. And for MAE is 0.0261%, 1.4912% for density and viscosity, respectively.

Densities of all mixture depend on temperature and concentration of mixture. The densities decrease with increasing temperature because kinetic energy of substance molecule is higher and the volume of substance expands. For effect of concentration, increasing in concentration of agent results in decreasing in density. Because density of the pure distilled water is higher than pure agent thus, the density is lower when the increasing in composition of agent mixture.

According to the viscosity results, the maximum of the viscosity of DEAE, DMAE and MAE occur at a specific mole fraction; approximately 0.4, 0.4 and 0.6 respectively because of hydrogen bonds are formed following interactions between amine and distilled water.

For comparison of three components, the density and viscosity trend of DEAE and DMAE are similar but MAE is different. The densities and viscosities of MAE are higher than DEAE and MAE because the molecular structure of DEAE and DMAE resemble each other. Both of DEAE and DMAE have same two functional groups which are tertiary amine and hydroxyl group. Differently, functional groups of MAE are secondary amine and hydroxyl group. For other reason, DEAE and DMAE have 2 types of hydrogen bond but MAE has 4 types of it so, the maximum attraction occur at the higher and specific mole fraction.

5.2 Recommendation

1. Study other properties of DEAE, DMAE and MAE to be the fundamental data such as specific heat capacity because this property plays significant with heat transfer in the chemical absorption process.

2. Study other correlations to get the lowest percent of average absolute deviation (%AAD).

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APPENDIX

VITA

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