Report of Cooperative Education

Removing Water from Triethylene Glycol Waste

Miss Orawan Sukchoy

A Report Submitted in Partial Fulfillment of the Requirements

for the Degree of Bachelor of Engineering (Petrochemical Engineering),

Department of Chemical Engineering, Faculty of Engineering,

King Mongkut's Institute of Technology Ladkrabang

Academic Year 2017

รายงานสหกิจศึกษาฉบับสมบูรณ์

การแยกน้ำออกจากของเสียไตรเอทิลีนไกลคอล

นางสาวอรวรรณ สุขช่วย

รายงานนี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรวิศวกรรมศาสตร์บัณฑิต
หลักสูตรวิศวกรรมปิโตรเคมี ภาควิชาวิศวกรรมเคมี คณะวิศวกรรมศาสตร์
สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง
ปีการศึกษา 2560

Cooperative Title: Removing Water from Triethylene Glycol Waste

By: Miss Orawan Sukchoy

Field of Study: Petrochemical Engineering

Advisor: Asst. Prof. Dr. Pornsawan Assawasaengrat

Affiliation: Department of Chemical Engineering, Faculty of Engineering

Mentor (Position): Miss Pattarahathai Onkaew (Process Engineer)

Company: Khanom Gas Separation Plant (PTT Public Company Limited)

ABSTRACT

The disposal cost of triethylene glycol (TEG) waste depended on its weight (5,000 baht/ton). In each year, Khanom gas separation plant paid for disposed of the TEG waste about 600,000 baht. Water was removed from TEG waste in order to decreased the weight of TEG waste and reduced the disposal cost. The appropriate temperature for water removing from TEG waste was studied in 2 parts using simulation by aspen plus V9 program and simple distillation experiments in a laboratory. In case of simulation, reduced disposal cost was 13,117 baht/year using appropriate temperature at 146.41 °C. In laboratory experiments, reduced disposal cost was 35,099 baht/year using appropriate temperature at 168.23 °C. In addition, the appropriate temperature in simulation part could be estimated from $T_{Appropriate} = 187.93 \times (\%\text{water content})^{-0.121}$.

Keywords: TEG, Triethylene glycol, TEG waste, Dehydration

ACKNOWLEDGEMENTS

I would like to express my deep appreciation and gratitude to my advisor, Asst. Prof. Dr. Pornsawan Assawasaengrat, Department of Chemical Engineering, King Mongkut's Institute of Technology Ladkrabang for her guidance, suggestions and assistance in this project. Without her supervision and constructive assistance, this project would not have been in its present shape.

Besides my advisor, I would like to thank Asst. Prof. Dr. Teeraporn Suteewong, Department of Chemical Engineering, King Mongkut's Institute of Technology Ladkrabang for her guidance and assistance which help me the internship opportunities in Khanom gas separation plant.

I respect and thank Miss Pattarahathai Onkaew for providing me an opportunity to do the project work in Khanom gas separation plant (PTT Public Company Limited) and giving me all support and guidance that made me complete the project. I am extremely thankful to her for providing such a nice support and guidance, although she had busy schedule managing the corporate affairs.

In addition, I am thankful to all staffs and technicians of Khanom gas separation plant for their help and technical support, which assisted me to complete this project.

Finally, my achievement would never be possible unless there is hearty support from my family. The deepest and sincere gratitude goes to my beloved parents for their endless love, encouragement and understanding throughout the entire period of my study.

Table of Contents

List of Figures

List of Tables

NOMENCLATURE

COD	Chemical oxygen demand
DEG	Diethylene glycol
GSP	Gas separation plant
LPG	Liquefied petroleum gas
MEG	Monoethylene glycol
MMSCFD	Million cubic feet per day
MSDS	Material safety data sheet
NGL	Natural gasoline
PTT	Petroleum Authority of Thailand
TEG	Triethylene glycol
wt	Net weight

CHAPTER I

INTRODUCTION

1.1 Khanom gas separation plant (PTT Public Company Limited)

Petroleum Authority of Thailand (PTT) is the largest gas separation operator in Thailand. The gas separation plants are run to separate various hydrocarbons from the natural gas which in turn maximizes value of the gas from the Gulf of Thailand. One of the PTT gas separation plants is located in Khanom district, Nakhon Si Thammarat province. It is known as Khanom gas separation plant.

Khanom gas separation plant was built in 1994 with the aim to satisfy the rising demand of liquefied petroleum gas (LPG) or cooking gas. It has a processing capacity of 230 million cubic feet per day (MMSCFD).

Products from Khanom gas separation include Sales gas, liquefied petroleum gas (LPG) and natural gasoline (NGL). Sales gas have a production capacity of 215 MMSCFD. It is sent through a pipeline to Khanom power plant. LPG and NGL have a production capacity of 205,000 ton/ year and 34,000 ton/ year, respectively. LPG and NGL are transported via ship to the customers.

Figure 1.1 Khanom gas separation plant

1.2 Background

Natural gas usually contains a large amount of water vapor which could combine with small hydrocarbons such as methane to form crystalline-structured solid hydrates. Hydrates can cause several problems for downstream processes and equipment. In order to prevent formation of hydrate, it is necessary to remove water from natural gas. The process often used in dehydration of natural gas is glycol dehydration by using triethylene glycol (TEG) as a dehydrating agent. TEG is very good absorbers for water because the hydroxyl groups in glycols form similar associations with water molecules.

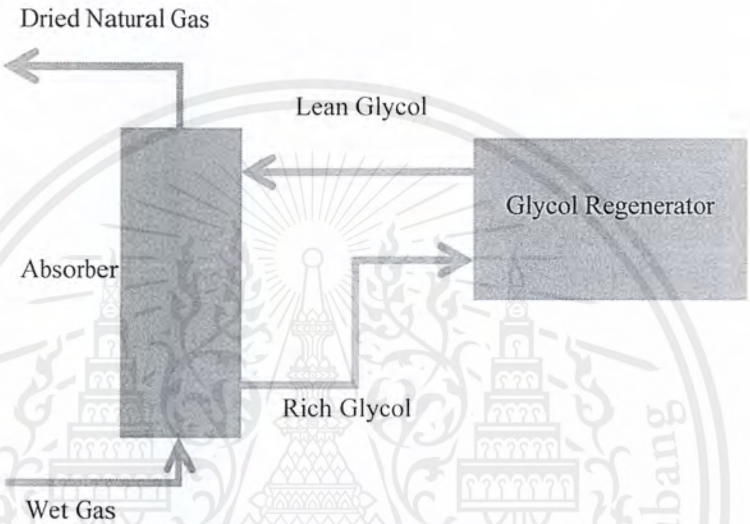

Figure 1.2 Dehydration process

Wet gas from the gas well is fed to the bottom of an absorber where it is contacted with the lean glycol stream. The glycol removes water from the natural gas by physical absorption and is carried out the bottom of the column. Upon exiting the absorber, the glycol stream is often referred to as rich glycol. After leaving the absorber, the rich glycol is fed to a glycol regeneration unit before being fed back into the absorber. Dehydrated natural gas or dried natural gas leaves the top of the absorption column and is fed to a gas separation plant.

The dried gas is sent to gas separation plant through the pipelines. It still contains some water and TEG from dehydration process, which is separated from natural gas by using slug catcher. The liquid that separated from slug catcher, which consists of TEG and water is sent to store in closed drain and called TEG waste. This waste will be sent to eliminate by using tank truck when there are about 20 tons. In each year Khanom gas separation plant have this waste about 120 tons and the disposal cost of this waste is 5,000 baht/ ton so Khanom gas separation plant must pay to dispose of this waste 600,000 baht/year.

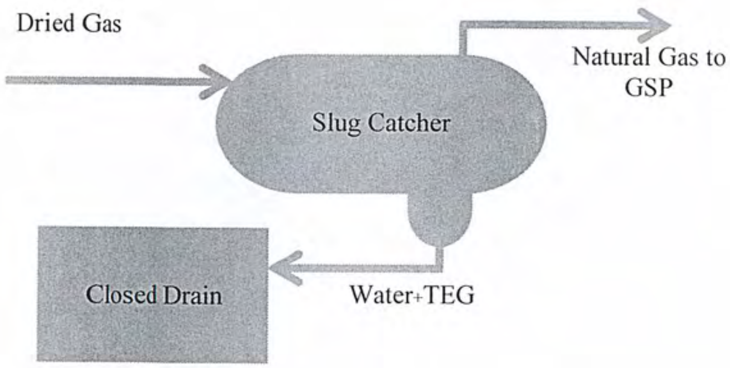

Figure 1.3 Separating slug from natural gas

From this problem, water need to be removed from TEG waste in order to decreased the weight of TEG waste and reduced the disposal cost. The appropriate temperature for water removal from TEG waste was studied in 2 parts using simulation by aspen plus V9 program and simple distillation experiments in a laboratory.

1.3 Objectives

1.2.1 To reduce the disposal cost of triethylene glycol waste

1.2.2 To determine the appropriate temperature for water removal from triethylene glycol waste

1.4 Scopes of work

1.3.1 Comparison of appropriate temperature for water removal from TEG waste using simulation by aspen plus V9 program and simple distillation in a laboratory.

1.3.2 Analyze the distillate of TEG waste by COD value.

1.3.3 Estimate the net reduced disposal cost.

1.5 Expected outputs

1.4.1 To reduce the disposal cost of triethylene glycol waste

CHAPTER II

THEORY AND LITERATURE REVIEW

2.1 Triethylene glycol characteristics

Triethylene glycol (also known as TEG, trigen and triglycol) is a member of a homologous series of dihydroxy alcohols with the formula $C_6H_{14}O_4$. It is often used to make chemical intermediates such as plasticizers and esters. It is well known for its hygroscopic quality and its ability to dehumidify fluids. TEG is also used as liquid desiccants for natural gas and in air conditioning systems.

Figure 2.1 Structure of triethylene glycol [1]

2.1.1 General properties

TEG is a colorless, odorless and stable liquid with high viscosity and a high boiling point. It is also soluble in ethanol, acetone, acetic acid, glycerin, pyridine and aldehydes and insoluble in oil, fat and hydrocarbons. The physical and chemical properties of TEG are shown in Table 2.1.

Table 2.1 Physical and chemical properties of TEG [2,3]

Parameter	Properties	Unit
Common Name	Triethylene glycol	-
CAS Registry Number	112-27-6	-
Synonym	2,2'-[1,2-Ethanediylbis(oxy)] bisethanol	-
Chemical Formula	$C_6H_{14}O_4$	-
Molecular Weight	150.18	g/mol
Density	1.10	g/cm^3
Boiling Point at 760 mm Hg	285 (545)	°C (°F)
Melting Point	-5 (23)	°C (°F)
Auto-Ignition Temperature	371 (699.8)	°C (°F)
Flash Points: Close Cup Open Cup	 177 (350.6) 165.5 (329.9)	 °C (°F) °C (°F)
Specific Gravity	1.1274	-
Solubility	Easily Soluble in Cold Water	-

2.1.2 Uses of triethylene glycol

TEG is mainly used as a dehydrating agent for dehydration process of natural gas. In addition, it is also a dehumidifying agent in air-conditioning units.

TEG is also used to make chemical intermediates such as polyester resins and polyester. Moreover, TEG is used as a solvent in many applications, including as a selective solvent for aromatics, and a solvent in textile dyeing and it is an additive in hydraulic fluids and brake fluids.

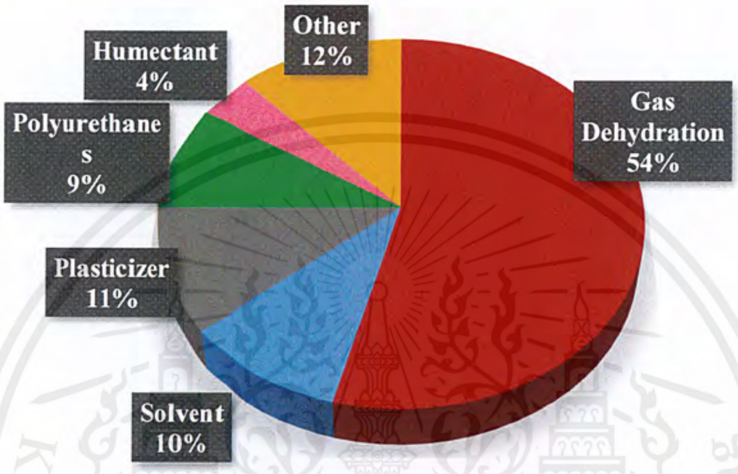

Figure 2.2 Major uses of triethylene glycol [3]

2.1.3 Toxic effects

TEG are very hazardous in human in case of eye contact (irritant) of ingestion and slightly hazardous in case of inhalation. Inflammation of the eye is characterized by redness, watering, and itching, which their primary method of prevention and medical care is showed in Table 2.2.

Table 2.2 The primary method of prevention and medical care of human [2,4]

Identification of hazards	Prevention
1. Potential Acute Health Effects Swallowed	- If swallowed do NOT induce vomiting. - If vomiting occurs, lean patient forward or place on left side (head-down position, if possible) to maintain open airway and prevent aspiration. - Observe the patient carefully. - Never give liquid to a person showing signs of being sleepy or with reduced awareness.

Identification of hazards	Prevention
Swallowed (cont.)	- Give water to rinse out mouth, then provide liquid slowly and as much as casualty can comfortably drink. - Seek immediate medical attention.
Eye contact (irritant)	- Check for and remove any contact lenses. - Wash out immediately with fresh running water. - Do not use an eye ointment. - Seek immediate medical attention.
Skin Contact	- Immediately remove all contaminated clothing. - Flush skin and hair with running water. - Seek medical attention in event of irritation.
Inhalation	- Allow the victim to rest in a well-ventilated area. - Seek immediate medical attention.
Ingestion	- Do not induce vomiting. - Loosen tight clothing such as a collar, tie, belt or waistband. - If the victim is not breathing, perform mouth-to-mouth resuscitation. - Seek immediate medical attention.
2. Potential Chronic Health Effects Carcinogenic effects	 Not available
Mutagenic effects	Not available
Affecting organs inside the body	The substance is toxic to kidneys, the nervous system

2.2 Aspen plus V9 program

Aspen Plus is the market-leading chemical process optimization software used for the design, operation, optimization of safe and profitable manufacturing facilities.

2.2.1 Separator (Flash2)

Figure 2.3 Flash2 (aspen plus V9 program)

Flash2 is used as a flashes, evaporators, knock-out drums and other single-stage separators. Flash2 performs vapor-liquid or vapor-liquid-liquid equilibrium calculations.

Use the following forms to enter specifications and view results for flash2

Use this form	To do this
Input	Enter flash specifications, flash convergence parameters, and entrainment specifications.
Block options	Override global values for physical properties, simulation options, diagnostic message levels, and report options for this block.
Results	View Flash2 simulation results.
Stream results	View stream results.
Summary	View and edit all scalar variables for this block.

2.2.2 Exchanger (Cooler)

Figure 2.4 Cooler (aspen plus V9 program)

Use the following forms to enter specifications and view results for cooler

Use this form	To do this
Input	Enter operating conditions and flash convergence parameters.
Block options	Override global values for physical properties, simulation options, diagnostic message levels, and report options for this block.
Results	View Heater results.
Stream results	View stream results.
Summary	View and edit all scalar variables for this block.

2.3 Distillation

An important separation process in the chemical industry is distillation. Distillation is a process which a liquid or vapor mixture of two or more substances is separated into its component fractions of desired purity, by the application and removal of heat. The process is based on vapor of a boiling mixture will be richer in the components that have lower boiling points. Therefore, when this vapor is cooled and condensed, it will contain more volatile components. At the same time, the original mixture will contain more of the less volatile material.

Distillation is the process of heating a liquid until some of its ingredients pass into the vapor phase, and then cooling the vapor to recover it in liquid form by condensation. The main purpose of distillation is to separate a mixture by taking advantage of different substances. If the difference in boiling points between two substances is great, complete separation may be easily accomplished by a single-stage distillation. If the boiling points differ only slightly, many re-distillations may be required.

2.4 Literature review

TEG is used to dehydrate natural gas, it must be concentrated to levels above 98.5-99.0% by weight available from atmospheric distillation of glycol-water mixtures at temperatures up to about 204°C. Polderman, L. D performed TEG-water distillation under vacuum, TEG can be regenerated up to 99.9 % by weight, but high operating costs and plant control complexity are serious drawbacks [5].

Willi Stahl used gas stripping method to remove water from TEG solutions, by using moderate quantities of stripping gas. This method has been used to concentrate TEG to very high level above 99.2-99.9% by weight [6]. However, as reserves have decreased and the price of gas has increased, dehydrating by using gas-stripped TEG can be expensive to operate so, alternative means have been sought.

F. Gironi used coldfinger process to regenerate TEG. Coldfinger is a method for exhausting water traces from organic liquid which are miscible with water. TEG purity can be increased up to 99.5-99.9% by weight operating at atmospheric pressure [7].

Purity of lean TEG exiting the still column can also be enhanced by using a circulating solvent (such as toluene or octane) to perform an azeotropic distillation instead of the simple TEG-water distillation. Khadijeh Paymooni enhanced TEG purity by adding 0.15wt% of isooctane, liquid hydrocarbon solvent vaporized rapidly in the reboiler and increased the water volatility which enhanced TEG concentration in the reboiler [8]. In this way lean TEG concentration can be increased up to 99.99 % by weight but plant complexity and costs are increased because of the need of a three-phase separator at the top of the distillator, the needs of treatments for the oily water discharged from this separator and devices for the solvent circulation line (such as a circulation pump and a heater).

CHAPTER III

RESEARCH METHODOLOGY

This study comprised of 2 parts which are simulation by aspen plus V9 program and simple distillation experiments in a laboratory. Figure 3.1 explains overall experimental study.

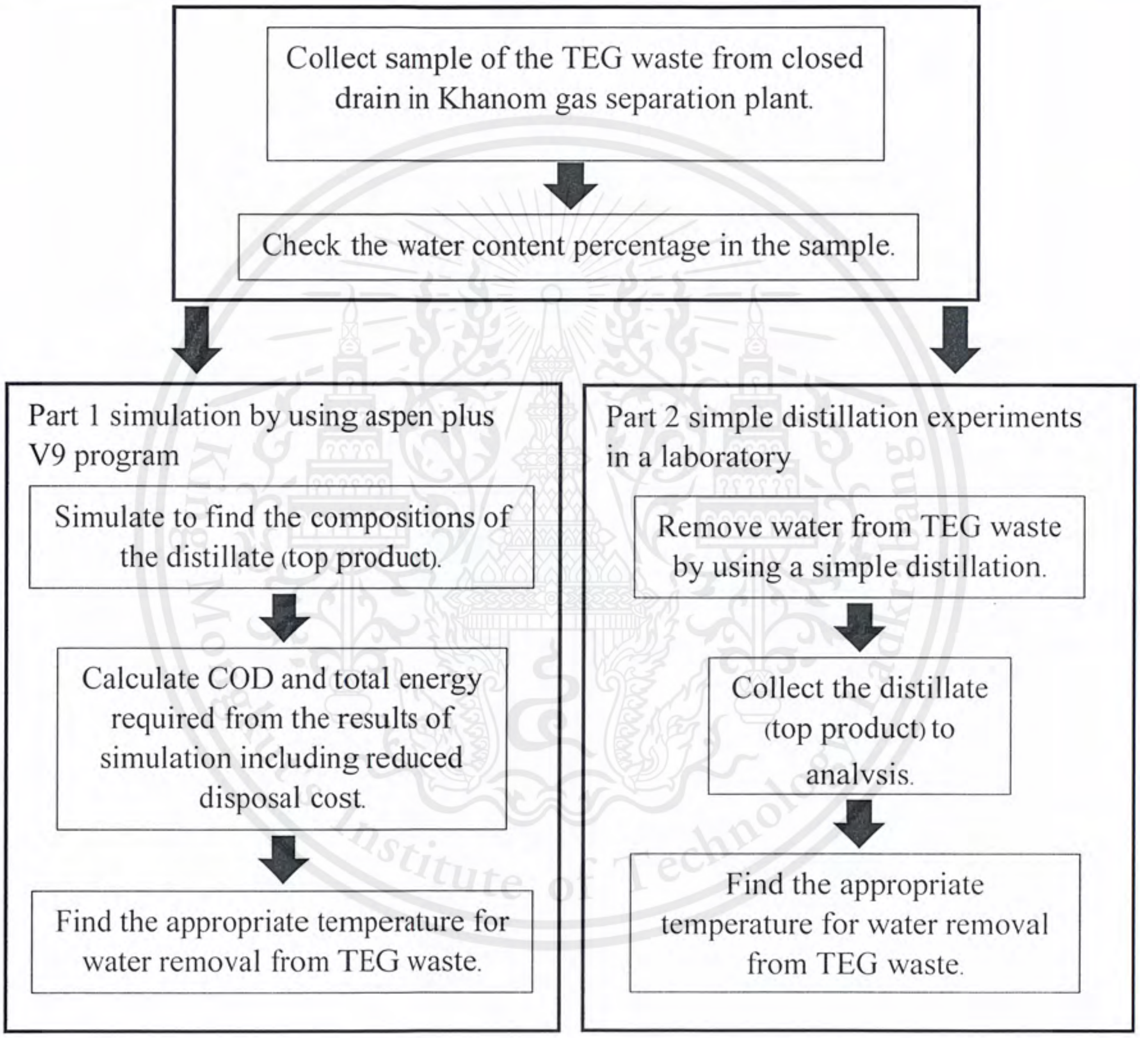

Figure 3.1 Experimental plan of study

The detail experiment of each part is presented in the subsequent sections.

3.1 Part 1: Simulation by aspen plus V9 program

3.1.1 Flowsheet

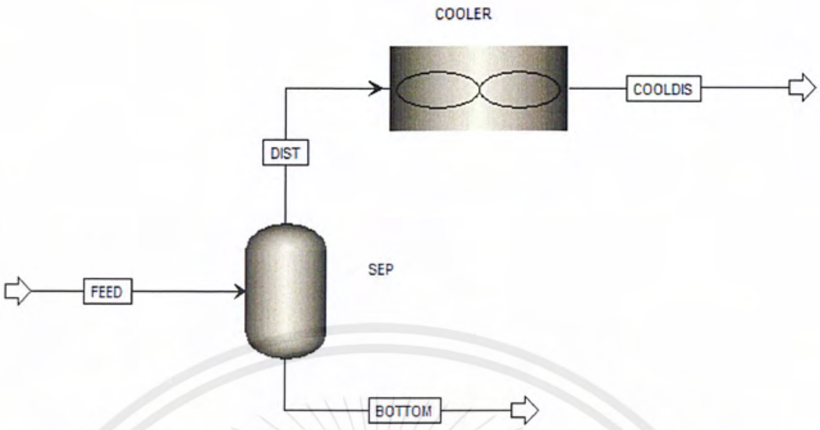

Figure 3.2 Flowsheet of simple distillation from aspen plus V9 program

In simulation by using aspen plus V9 program, NRTL equation of state (EOS) is used. distillation unit is replaced by separator and cooler because there are similarities in behavior, the mixture is heated to vaporization and separated from another substance. After separation by using a separator, the distillate stream is condensed by a cooler.

3.1.2 Compositions and conditions

Feed

Temperature	30	°C
Pressure	1	atm
Mass flow rate	100	kg/hr
Mass fraction TEG Water	 0.9153 0.0847	 - -

Separator

Temperature	100-180	°C
Pressure	1	atm

Cooler

Vapor fraction	0	-
Pressure	1	atm

Percentage of distillate was calculated as follows:

$$\%D = \frac{m_D}{m_F} \times 100 \tag{3.1}$$

Where $\%D$ = Percentage distillate
m_D = Mass of distillate, kg
m_F = Mass of feed, kg

Percentage of TEG in distillate was calculated as follows:

$$\%TEG_D = \frac{m_{TEG}}{m_F} \times 100 \tag{3.2}$$

Where TEG_D = Triehylene glycol content in distillate, kg
m_{TEG} = Mass of TEG in distillate, kg
m_F = Mass of feed, kg

Reduced disposal cost was calculated as follows:

$$R = \%D \times M \times C \tag{3.3}$$

Where R = Reduced disposal cost, baht/year
%D = Percentage of distillate
M = Total triethylene glycol waste, ton/year
C = Disposal cost, baht/ton

Note 1. Total TEG waste in Khanom gas separation plant is 120 ton/year
2. Disposal cost for remove TEG waste is 5,000 baht/ton

In the process of water removal from TEG waste require energy to heat the TEG waste to vapor. This energy come from hot oil system, which is used in Khanom gas separation plant. Fuel cost is derived from the price of fuel entering the heater to heat the hot oil. The hot oil is used as a medium to provide heat for water removal from TEG.

Fuel cost was calculated as follows:

$$F_C = \frac{E \times M \times F}{\%eff} \tag{3.4}$$

Where F_C = Fuel cost, baht/year
E = Energy per unit, Btu/kg
M = Total triethylene glycol waste, kg/year
F = Fuel cost per unit, baht/Btu
%eff = Efficiency of heater

Note 1. The price of fuel is 190 baht/MMBtu

2. The efficiency of heater referenced from heater in Khanom gas separation plant which is 75%

The distillate from separator is condensed by using fan. Thus, electrical power is required to rotate the fan blades. Utility cost was calculated as follows:

$$U_C = P \times t \times U \tag{3.5}$$

Where U_C = Utility cost, baht/year
P = Power of motor of fan, kWh
t = Time, hr
U = Utility cost per unit, baht/kW

Note 1. Utility cost is 5 baht/kW (reference from utility cost of Khanom gas separation plant

From material safety data sheet (Santa Cruz Biotechnology)

$$COD_{TEG} = 1.57\ g_{Oxygen}/g_{TEG} \tag{3.6}$$

Which mean, when weight 1 g of TEG and dissolve in water until volume equal 1 litter, this solution will have COD equal 1,570 mg/L. Thus,

$$\frac{1\ g_{TEG}}{1\ L} = 1{,}570 \tag{3.7}$$

$$\frac{X\ g_{TEG}}{L} = COD \tag{3.8}$$

COD of distillate was calculated as follows:

$$COD = \frac{1{,}570 \times \frac{X\ g_{TEG}}{L}}{\frac{1\ g_{TEG}}{L}} \tag{3.9}$$

Where X = Weight of triethylene glycol divided by volume of distillate, g/L

Because the COD of distillate is higher than the legal limit (COD must less than 120 mg/L). Thus, the COD of distillate is reduced by blending with reserve water.

$$(COD_D \times M_D)+(COD_W \times M_W) = COD_B \times (M_D+M_W) \tag{3.10}$$

$$COD_B = \frac{(COD_D \times M_D)+(COD_W \times M_W)}{(M_D+M_W)} \tag{3.11}$$

Where COD_D = COD of distillate, mg/L
COD_W = COD of reserve water, mg/L
COD_B = COD of blended distillate, mg/L
M_D = Mass of distillate, kg
M_W = Mass of reserve water, kg

3.2 Part 2: Simple distillation experiments in a laboratory

3.2.1 Materials

- TEG waste from closed drain in Khanom gas separation plant

3.2.2 Equipment

- Simple distillation unit	1
- Beaker 500 ml	1
- Beaker 50 ml	1
- Erlenmeyer flask 100 ml	1
- Glass funnel	1
- Sample bottle	5
- Heating mantle	1
- Thermocouple	1
- Weight Balance	1

3.2.2 Simple distillation unit

700 g of TEG waste is poured into a 1000 ml of round bottom flask. After that, the round bottom flask is connected to a simple distillation unit. Thermocouple is connected with the simple distillation unit by setting the thermocouple to measure at the temperature of TEG waste in round bottom flask. Heater and cooling water pump are turned on then, wait until the temperature of the TEG waste increase to set temperature. Distillation is stopped when no distillate come out. Finally, the heater and the cooling water pump are turned off. The distillate sample is collected to analysis.

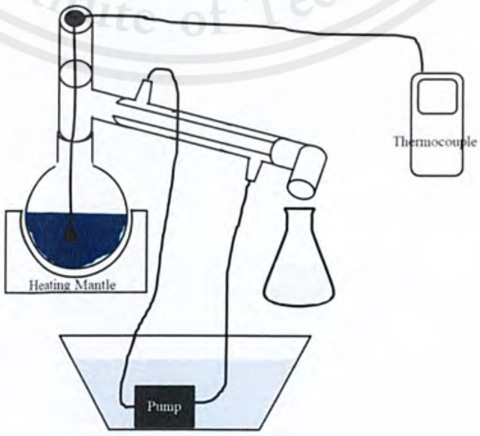

Figure 3.3 Diagram of simple distillation experimental set up

Percentage of distillate was calculated as follows:

$$\%D = \frac{m_D}{m_F} \times 100 \qquad (3\text{-}12)$$

Where $\%D$ = Percentage distillate
m_D = mass of distillate, g
m_F = mass of feed, g

CHAPTER IV

RESULTS AND DISCUSSION

Experimental results of water removing from TEG waste by aspen plus V9 program and simple distillation experiments in a laboratory were presented in this chapter.

TEG waste from closed drain in September, 2017 was analyzed by Intertek Testing Services (Thailand) Ltd. to find the amount of water contamination in TEG waste by using Karl Fischer titration method. The TEG waste that contained 8.47wt% water was showed in table 4.1.

Table 4.1 Test report contamination of water in TEG waste

Test item	Test method	Unit	Result
Water content	ASTM E 203-16	wt%	8.47

Test report from Intertek Testing Services (Thailand) Ltd. (September, 2017)

The amount of water that contaminated in the TEG waste was used as a basic information in simulation program. Assuming that the system consists of 2 components were TEG and water with NRTL thermodynamic model. This study focused on distillate (top product) only. The simulation results from aspen plus V9 program were showed in Figure 4.1.

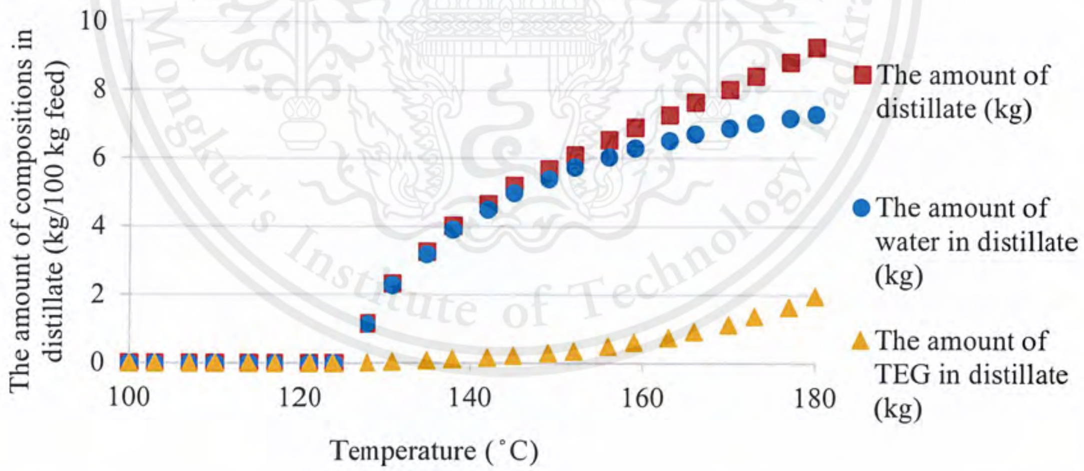

Figure 4.1 The influence of temperature on amount of distillate at 8.47wt% water in TEG waste by aspen plus V9

Figure 4.1 showed relationship between temperature and the amount of compositions in distillate at 8.47 wt% water (by aspen plus V9 program). The distillate contained 2 components, mostly water and slightly TEG. Distillate started to split from TEG waste at temperature of 125℃. The amount of distillate increased continuously when temperature was increased. The amount of water in distillate raised rapidly between 125 to

160℃. After that the amount of water increased gradually. The amount of TEG in distillate increased slowly in the range of 125 to 160℃ and increased rapidly when temperature higher than 160℃. This was probably because of the water molecules and TEG molecules were gathered strongly. Therefore, TEG could be found in distillate.

Simple distillation experiments in a laboratory were done to confirm precision of the simulation. Figure 4.1 showed that the most of water was separated at 130 to 170℃. Therefore, 130, 140, 150, 160 and 170 ℃ ware selected to perform the experiment. The results of the comparison of the amount of distillate between simulation and simple distillation experiments in a laboratory were showed in Figure 4.2.

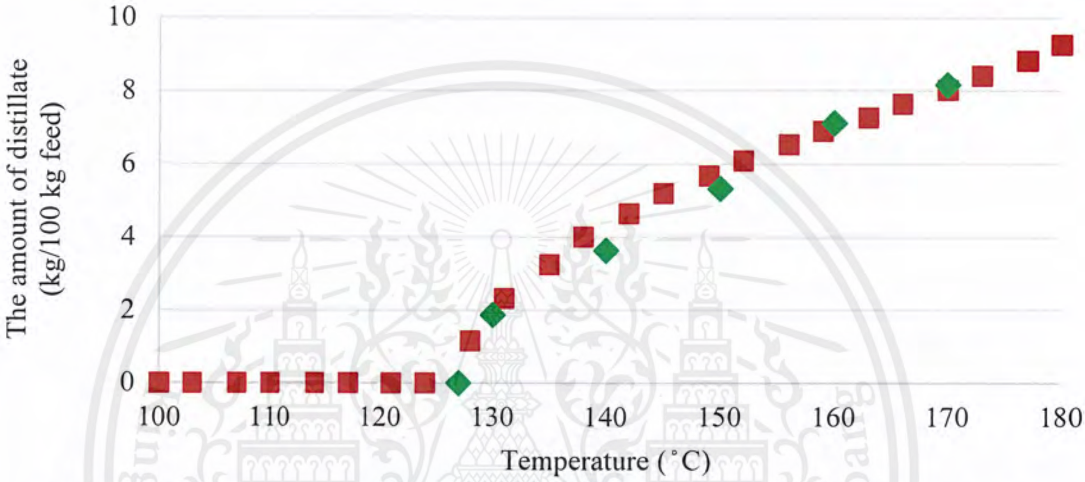

Figure 4.2 The influence of temperature on amount of distillate at 8.47wt% water content in TEG waste by simulation (■) and experiments (◆)

Figure 4.2 showed comparison of the amount of distillate between simulation and simple distillation experiments in a laboratory at 8.47wt% water. The amount of distillate from simple distillation experiments in a laboratory raised rapidly as same as the results from simulation. However, the distillate from experiments started to split from TEG waste with higher temperature than simulation. This was probably as the results of the real TEG waste consisted of other components such as mercury, mixture of mercury water and TEG that had higher boiling point than mixture of water and TEG. For this reason, the temperature that water was separated from TEG waste of real TEG waste higher than the simulation.

The disposal cost could be reduced by decreasing the amount of TEG waste. Therefore, using a higher temperature for separation could reduce the disposal cost. The disposal cost of the TEG waste was 5,000 baht/ton. Reduced disposal cost of water removal from TEG waste at temperature of 130 to 170℃ are showed in Table 4.2.

Table 4.2 Reduced disposal cost for water removal from TEG waste (baht/year)

Temperature (°C)	Percentage of distillate (%)	Total amount of distillate (kg/year)	Reduced disposal cost (baht/year)
130	1.91	2,296.08	11,480.38
140	4.34	5,208.26	26,041.32
150	5.85	7,017.02	35,085.10
160	6.99	8,393.94	41,969.68
170	8.07	9,680.25	48,401.27

By aspen plus V9 program at 8.47wt% water content in TEG waste

Water removal from TEG waste had operating costs from fuel for heating and utility for cooling. Fuel cost and utility cost of water removal from TEG waste were showed in Table 4.3.

Table 4.3 Fuel cost and utility cost for water removal from TEG waste (baht/year)

Temperature (°C)	Separator		Cooler	
	Duty of separator (Btu/kg)	Fuel cost (baht/year)	Duty of fan (kJ/kg)	Utility cost (baht/year)
130	268.26	8,155.08	43.80	610.25
140	340.63	10,355.03	99.05	1,379.93
150	392.21	11,923.07	132.08	1,840.07
160	434.15	13,198.17	154.82	2,156.88
170	471.39	14,330.12	172.71	2,406.13

By aspen plus V9 program at 8.47wt% water content in TEG waste

Net reduced disposal cost was the reduced disposal cost after deducting the cost of fuel and the cost of utility which were showed in Table 4.4.

Table 4.4 Net reduced disposal cost for water removal from TEG waste (baht/year)

Temperature (°C)	Reduced disposal cost (baht/year)	Fuel cost (baht/year)	Utility cost (baht/year)	Net reduced disposal cost (baht/year)
130	11,480.38	8,155.08	610.25	2,715.05
140	26,041.32	10,355.03	1,379.93	14,306.35
150	35,085.10	11,923.07	1,840.07	21,321.95
160	41,969.68	13,198.17	2,156.88	26,614.63
170	48,401.27	14,330.12	2,406.13	31,665.03

By aspen plus V9 program at 8.47wt% water content in TEG waste

It was found that higher temperature reduced more amount of TEG waste and reduced more disposal cost.

TEG dissolved in water and made the solution that had higher COD value. COD of TEG was equal to 1.57 grams of oxygen per a gram of TEG that mean weight 1 g of TEG and dissolved in water until volume equal 1 litter, this solution had COD equal 1,570 mg/L. In theory, higher temperature makes higher COD value because of more contaminating of TEG in the distillate. COD of distillate by simulation and by simple distillation experiments in a laboratory were compared in Figure 4.3.

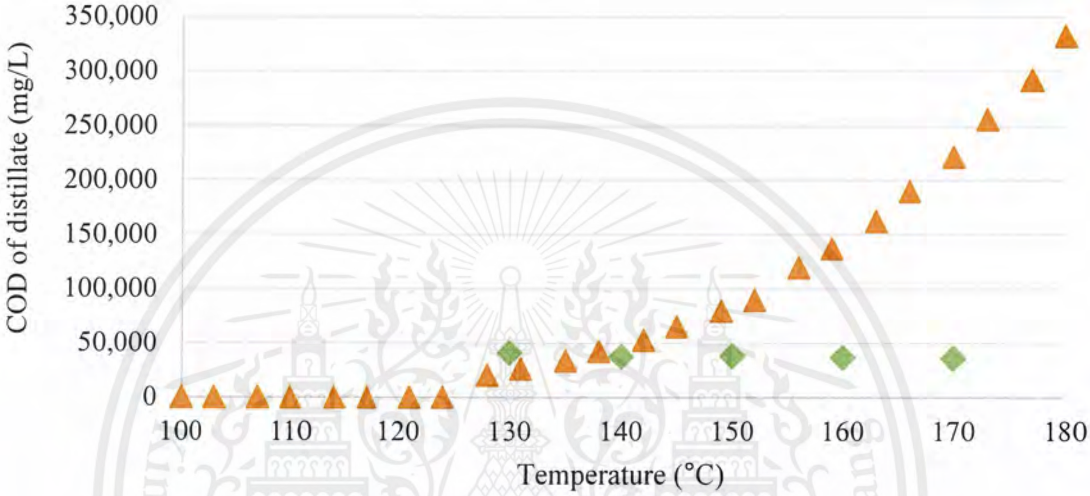

Figure 4.3 The influence of temperature on COD of distillate at 8.47wt% water content in TEG waste by simulation (▲) and experiments (◆)

Figure 4.3 showed comparison of COD of distillate between simulation and simple distillation experiments in a laboratory at 8.47wt% water. The COD value of distillate from simulation continuously increased when a temperature was increased whereas the COD value from experiments decreased when a temperature was increased. It might be increased temperature broken the bonding between TEG and water then the amount of TEG in distillate was decreased then COD value of distillate decreased when a temperature was increased. In addition, the COD value of distillate from simulation was higher than the COD from experiments. In fact, the TEG waste had other component such as mercury, monoethylene glycol (MEG) and diethylene glycol (DEG). TEG could absorbed mercury instead of water. Therefore, the amount of TEG content in the distillate was decreased. Moreover, MEG and DEG could absorbed water instead of TEG, both of them affected the value of COD less than TEG. As a result, the COD of distillate from experiments was less than the COD from the simulation.

Figure 4.3 showed that COD of distillates (both from simulation and simple distillation experiments in a laboratory) were high values. Therefore, COD of the distillate was reduced by blending with 1,000 cubic meters of reserved water. Assumed that COD of reserved water was zero and COD of water after blending was 60 mg/L. The appropriate temperature for water removal from TEG waste was found by using the equation of temperature, amount of distillate and COD of distillate, which were showed in 4.1-4.6.

Simulation by aspen plus V9 program

Temperature-Weight: $W = -0.0103T^3+4.3891T^2-587.48T+25{,}129$ (4.1)
Temperature-COD: $COD = 0.5388T^3-151.52T^2+14{,}007T-425{,}102$ (4.2)
Weight-COD: $COD = 60\times(10^6 + W)/W$ (4.3)

Simple distillation experiments in a laboratory

Temperature-Weight: $W = 0.0118T^3-5.667T^2+935.26T-51{,}416$ (4.4)
Temperature-COD: $COD = -0.4232T^3+158.69T^2-18{,}692T+703{,}262$ (4.5)
Weight-COD: $COD = 60\times(10^6 + W)/W$ (4.6)

The relationship between temperature and amount of distillate obtained from the graph in Figure 4.2 (using amount of feed was 20,000 kg) and relationship between temperature and COD of distillate obtained from the graph in Figure 4.3. The results from polymath program were showed in Table 4.5.

Table 4.5 Optimized value of water removal from TEG waste (by polymath)

	Appropriate temperature (°C)	COD of distillate (mg/L)	Reduced waste (wt%)	Net reduced disposal cost (baht/year)
Simulation by aspen plus V9 program	146.41	6.868×10^4	4.37	13,117.52
Simple distillation experiments in a laboratory	168.23	3.493×10^4	8.60	35,099.13

Table 4.5 showed the optimum value for water removal from TEG waste. Then appropriate temperatures were 146.41°C and 168.23 °C from simulation and simple distillation experiments in a laboratory, respectively. The reduced disposal cost from water removal from TEG waste was 13,117.52 baht/year by simulation and 35,099.13 baht/year from simple distillation experiments in a laboratory.

The water content in TEG waste is not constant. Therefore, 5,10,20,30,40 and 50 wt% water contents were applied to estimate the appropriate temperature for water removal from TEG waste. The relationship between temperature and amount of distillate at 5,10,20,30,40 and 50 wt% water contents in TEG waste were showed in Figure 4.4.

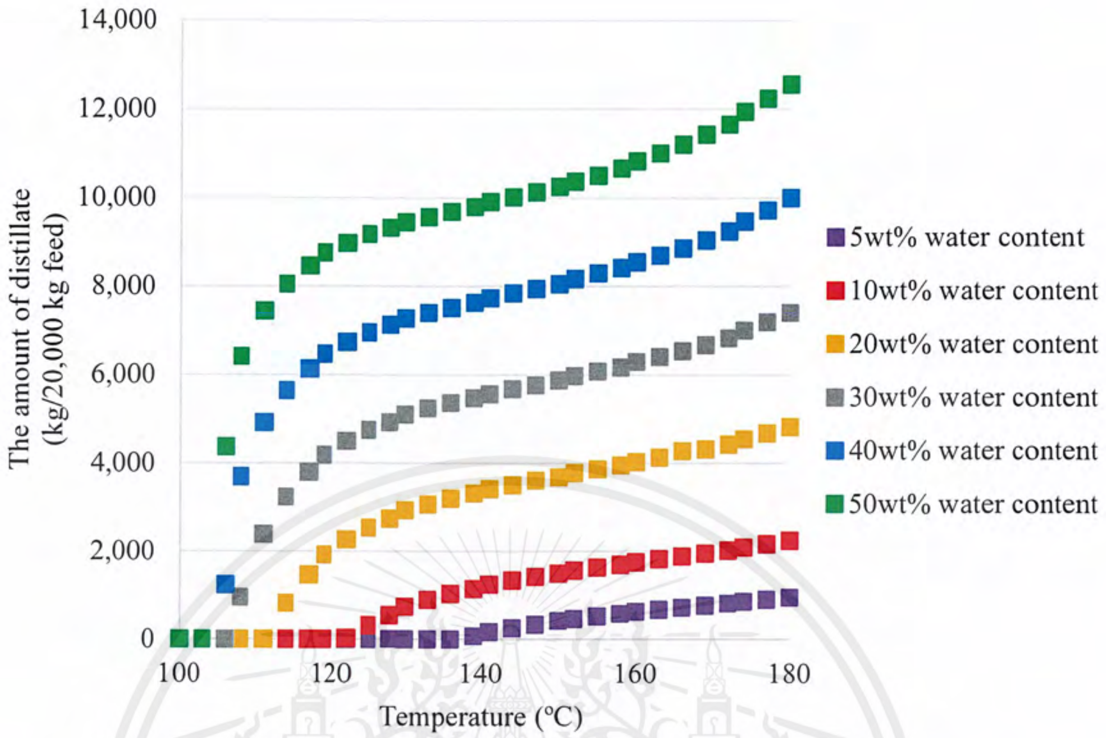

Figure 4.4 The influence of temperature on amount of distillate at various water contents in TEG waste by aspen plus V9 program

The equations for temperature and the amount of distillate were showed in 4.7-4.12

Water content 5wt%:

$$W = -0.0039T^3+1.8561T^2-272.19T+12,648 \quad (4\text{-}7)$$

Water content 10wt%:

$$W = -0.0112T^3+4.6779T^2-606.68T+25,025 \quad (4\text{-}8)$$

Water content 20wt%:

$$W = 0.0081T^3-4.2119T^2+756.98T-42,358 \quad (4\text{-}9)$$

Water content 30wt%:

$$W = 0.0401T^3-18.289T^2+2801.9T-138,240 \quad (4\text{-}10)$$

Water content 40wt%:

$$W = 0.0704T^3-31.401T^2+4678.1T-224,512 \quad (4\text{-}11)$$

Water content 50wt%:

$$W = 0.0976T^3-43.112T^2+6338T-299,724 \quad (4\text{-}12)$$

The relationship between temperature and COD of distillate at 5,10,20,30,40 and 50 wt% water contents in TEG waste were showed in Figure 4.5.

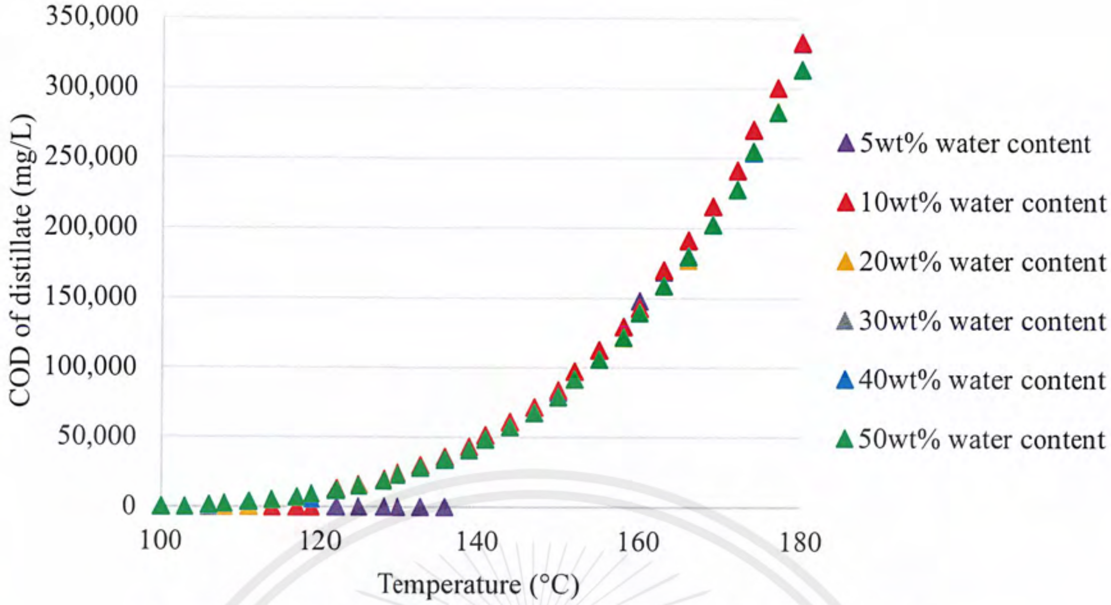

Figure 4.5 The influence of temperature on COD of distillate at various water contents in TEG waste by aspen plus V9 program

The equations for temperature and COD of distillate were showed in 4.13-4.18

Water content 5wt%:

$$COD = 0.268T^3 - 29.915T^2 - 3{,}749.4T + 413{,}075 \quad (4\text{-}13)$$

Water content 10wt%:

$$COD = 0.623T^3 - 187.14T^2 + 18{,}960T - 649{,}641 \quad (4\text{-}14)$$

Water content 20wt%:

$$COD = 0.6528T^3 - 204.11T^2 + 21{,}682T - 781{,}616 \quad (4\text{-}15)$$

Water content 30wt%:

$$COD = 0.6462T^3 - 201.19T^2 + 21{,}246T - 759{,}752 \quad (4\text{-}16)$$

Water content 40wt%:

$$COD = 0.6321T^3 - 195.05T^2 + 20{,}374T - 719{,}460 \quad (4\text{-}17)$$

Water content 50wt%:

$$COD = 0.6475T^3 - 201.58T^2 + 21{,}274T - 759{,}631 \quad (4\text{-}18)$$

The optimized values were showed in Table 4.6.

Table 4.6 Optimized values for water removal from TEG waste

% Water content	Appropriate temperature (°C)	COD of distillate (mg/L)	Reduced waste (kg/20,000kg feed)	Reduced waste (wt%)
5	155.22	1.126×10^{5}	533.13	2.67
10	142.00	5.302×10^{4}	1,132.87	5.66
20	130.34	2.238×10^{4}	2,688.63	13.44
30	124.17	1.351×10^{4}	4,459.35	22.30
40	120.49	9.399×10^{3}	6,424.49	32.12
50	117.57	7.446×10^{3}	8,123.04	40.62

The appropriate temperature from simulation tests were plotted with water content percentage were showed in Figure 4.6.

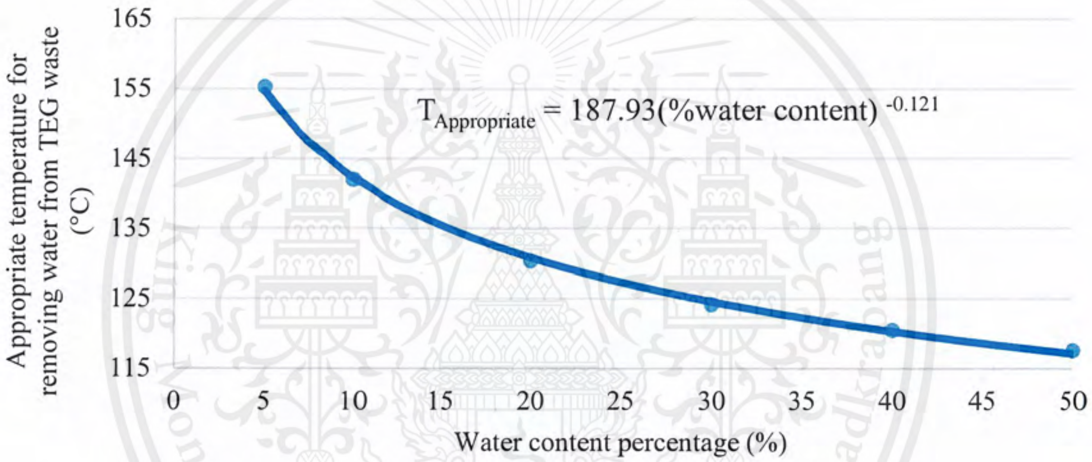

Figure 4.6 The influence of water content percentage on appropriate temperature by aspen plus V9 program

The equation for appropriate temperature estimation from various water content percentage was 4.19

$$T_{Appropriate} = 187.93\times(\%\text{water content})^{-0.121} \quad (4\text{-}19)$$

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study comprised of 2 parts which are simulation by aspen plus V9 program and simple distillation experiments in a laboratory. The results are concluded as following

1. Simulation by aspen plus V9 program

Water content (wt%)	Appropriate temperature (°C)	Reduced disposal cost (bath/year)
8.47	146.41	13,117.52

2. Simple distillation experiments in a laboratory

Water content (wt%)	Appropriate temperature (°C)	Reduced disposal cost (bath/year)
8.47	168.23	35,099.13

3. The appropriate temperature in simulation part can be estimated from $T_{Appropriate} = 187.93 \times (\%\text{water content})^{-0.121}$

5.2 Recommendations

5.2.1. The samples from other months should be analyzed and compared with simulation to confirm the precision of simulation.

5.2.2. The samples from other months should be collected and find the amount of water in that waste for the investment analysis.

5.2.3. The distillate sample should be replaced analysis to provide precision and accuracy values.

REFERENCES

[1] Pimchanok Khachonbun. *Membrane Based Triethylene Glycol Separation and Recovery from Gas Separation Plant Wastewater*. Thesis, Asian Institute of Technology, Thailand, May, 2013

[2] Santa Cruz Biotechnology, Inc. *Material Safety Data Sheet: Triethylene glycol.* https://www.scbt.com/scbt/product/triethylene-glycol-112-27-6 (accessed Aug 15,2017)

[3] Dow Chemical Company. *DOW Ethylene Glycols: Physical Properties.* https://www.dow.com/ethyleneglycol/about/properties.htm (accessed Aug 14,2017)

[4] Dow Chemical Company. *Product Safety Assessment documents: Triethylene glycol.* http://msdssearch.dow.com (accessed Aug 20,2017)

[5] Polderman, L.D. *The Performance of Vacuum-regenerated Glycol-type Natural Gas Dehydration Plants*, Proceedings of the University of Oklahoma Gas Conditioning Conference, March 6-7, 1957

[6] Willi Stahl. *Method and System for Drying Gas and Reconcentrating the Drying Absorbent.* US Patent 3105748, October 1, 1963

[7] F. Gironi; M. Maschietti, V. Piemonte; D. Diba; S. Gallegati; S. Schiavo. *Triethylene Glycol Regeneration in Natural Gas Dehydration Plants: A Study on the Coldfinger Process.* Presented by the OMC 2007 Programme Committee at the Offshore Mediterranean Conference and Exhibition in Ravenna, Italy, March 28-30, 2007

[8] Khadijeh Paymooni, Mohammad Reza Rahimpour, Sona Raeissi, Mohsen Abbasi and Mohammad Saviz Baktash. *Enhancement in Triethylene Glycol (TEG) Purity via Hydrocarbon Solvent Injection to a TEG + Water System in a Batch Distillation Column.* October 17, 2011

[9] Laurence S. Reid. *Method of Removing Water from Glycol Solutions*. US Patent 4332643, January 1, 1982

[10] Petroleum Authority of Thailand. *Gas Separation Plant*: Khanom gas separation plant. www.pttplc.com/th/Media-Center/Energy-Knowledge/ (accessed Aug 08,2017)

[11] Chemical&Laboratory Equipment. Material Safety Data Sheet: Triethylene Glycol MSDS. http://www.sciencelab.com/msds (accessed Aug 20,2017)

APPENDIX

APPENDIX A

EXPERIMENTAL SETUP

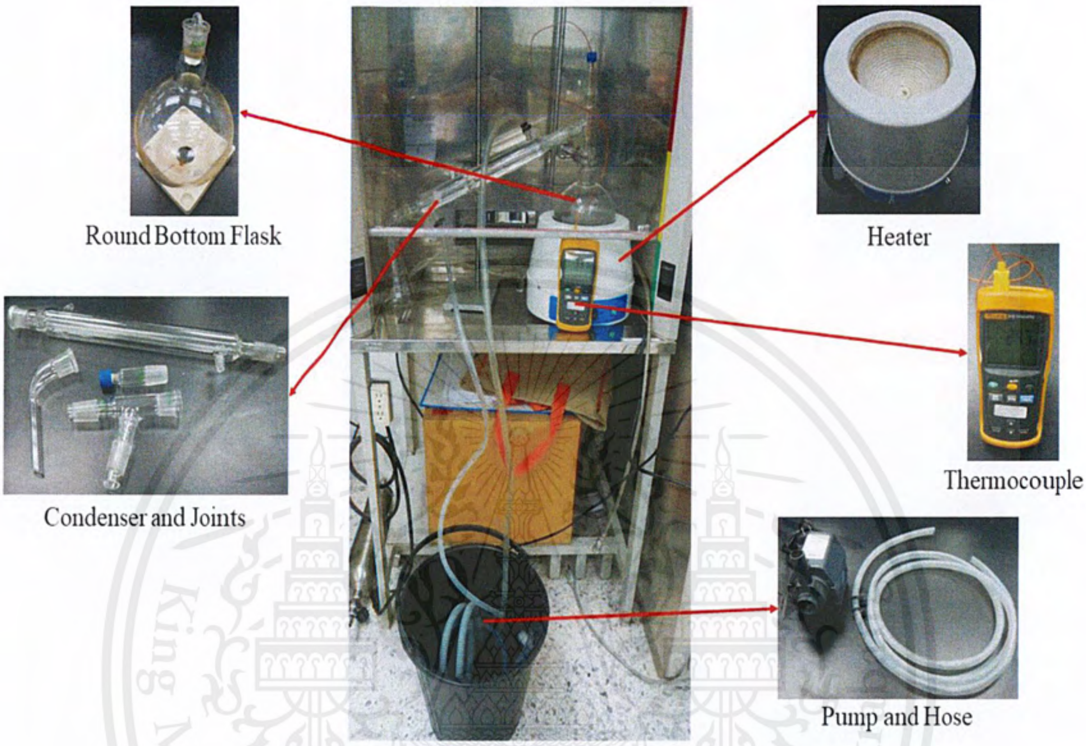

Figure A-1 Simple distillation experimental setup

APPENDIX B

EXPERIMENTAL RESULTS FROM SIMULATION

Table B-1 The amount of compositions in distillate at 8.47wt% water content in TEG waste

Temperature (°C)	The amount of distillate (kg/100kg feed)	The amount of water in distillate (kg/100kg feed)	The amount of TEG in distillate (kg/100 kg feed)
100	0.00	0.00	0.00
103	0.00	0.00	0.00
107	0.00	0.00	0.00
110	0.00	0.00	0.00
114	0.00	0.00	0.00
117	0.00	0.00	0.00
121	0.00	0.00	0.00
124	0.00	0.00	0.00
128	1.15	1.14	0.01
131	2.32	2.28	0.04
135	3.25	3.18	0.07
138	4.01	3.90	0.11
142	4.65	4.49	0.16
145	5.20	4.98	0.22
149	5.68	5.39	0.29
152	6.09	5.74	0.35
156	6.54	6.04	0.50
159	6.90	6.30	0.60
163	7.27	6.52	0.75
166	7.64	6.72	0.92
170	8.02	6.89	1.13
173	8.41	7.04	1.37
177	8.82	7.18	1.64
180	9.26	7.30	1.96

Table B-2 The amount of distillate with the temperature

Temperature (°C)	The amount of distillate (kg/20,000kg feed)					
	5wt% water content	10wt% water content	20wt% water content	30wt% water content	40wt% water content	50wt% water content
100	0.00	0.00	0.00	0.00	0.00	0.00
103	0.00	0.00	0.00	0.00	0.00	0.00
106	0.00	0.00	0.00	0.00	1,237.14	4,364.04
108	0.00	0.00	0.00	957.52	3,685.84	6,410.14
111	0.00	0.00	0.00	2,385.72	4,911.80	7,437.88
114	0.00	0.00	818.80	3,231.04	5,639.28	8,047.60
117	0.00	0.00	1,460.80	3,797.66	6,128.60	8,459.40
119	0.00	0.00	1,917.80	4,185.80	6,463.80	8,753.80
122	0.00	20.16	2,257.96	4,495.80	6,733.60	8,971.40
125	0.00	313.16	2,525.40	4,747.80	6,950.00	9,172.20
128	0.00	546.90	2,734.40	4,922.00	7,129.60	9,317.20
130	0.00	737.46	2,925.40	5,099.20	7,273.00	9,446.80
133	0.00	897.02	3,058.20	5,239.40	7,400.40	9,561.60
136	0.00	1,031.60	3,193.40	5,363.00	7,512.60	9,682.00
139	66.02	1,145.60	3,311.20	5,470.80	7,630.00	9,790.00
141	166.68	1,247.00	3,412.00	5,563.00	7,734.00	9,904.00
144	253.90	1,338.00	3,496.20	5,680.00	7,844.00	10,008.00
147	333.18	1,420.80	3,604.20	5,764.00	7,942.00	10,122.00
150	409.40	1,495.80	3,676.40	5,874.00	8,050.00	10,246.00
152	464.80	1,565.00	3,774.00	5,970.00	8,166.00	10,362.00
155	523.60	1,633.00	3,856.00	6,074.00	8,294.00	10,492.00
158	577.60	1,695.80	3,944.00	6,168.00	8,414.00	10,658.00
160	629.20	1,753.00	4,020.00	6,292.00	8,546.00	10,820.00
163	676.60	1,825.40	4,122.00	6,408.00	8,694.00	11,000.00
166	724.00	1,888.00	4,272.00	6,536.00	8,858.00	11,200.00
169	769.60	1,952.00	4,312.00	6,676.00	9,040.00	11,424.00
172	815.40	2,020.00	4,422.00	6,832.00	9,244.00	11,654.00
174	862.20	2,092.00	4,542.00	7,006.00	9,468.00	11,940.00
177	909.80	2,166.00	4,676.00	7,196.00	9,718.00	12,240.00
180	956.00	2,248.00	4,822.00	7,408.00	10,000.00	12,560.00

Table B-3 The relationship between temperature and amount of distillate

% Water content	Relationship between temperature and amount of distillate	R^2
5	$W = -0.0039T^3+1.8561T^2-272.19T+12,648$	0.8922
10	$W = -0.0112T^3 + 4.6779T^2 - 606.68T + 25,025$	0.9805
20	$W = 0.0081T^3 - 4.2119T^2 + 756.98T - 42,358$	0.9718
30	$W = 0.0401T^3 - 18.289T^2 + 2,801.9T - 138,240$	0.9796
40	$W = 0.0704T^3 - 31.401T^2 + 4,678.1T - 224,512$	0.9715
50	$W = 0.0976T^3 - 43.112T^2 + 6,338T - 299,724$	0.9414

Table B-4 The amount of TEG in distillate with the temperature

Temperature (°C)	The amount of TEG in distillate (kg/20,000kg feed)					
	5wt% water content	10wt% water content	20wt% water content	30wt% water content	40wt% water content	50wt% water content
100	0.00	0.00	0.00	0.00	0.00	0.00
103	0.00	0.00	0.00	0.00	0.00	0.00
106	0.00	0.00	0.00	0.00	1.14	4.04
108	0.00	0.00	0.00	1.52	5.84	10.14
111	0.00	0.00	0.00	5.72	11.80	17.88
114	0.00	0.00	2.80	11.04	19.28	27.60
117	0.00	0.00	6.80	17.66	28.60	39.40
119	0.00	0.00	11.80	25.80	23.80	53.80
122	0.00	0.16	17.96	35.80	53.60	71.40
125	0.00	3.16	25.40	47.80	70.00	92.20
128	0.00	6.90	34.40	62.00	89.60	117.20
130	0.00	11.46	45.40	79.20	113.00	146.80
133	0.00	17.02	58.20	99.40	140.40	181.60
136	0.00	23.60	73.40	123.00	172.60	222.00
139	1.82	31.60	91.20	150.80	210.00	270.00
141	5.48	41.00	112.00	183.00	254.00	324.00
144	9.90	52.00	136.20	220.00	304.00	388.00
147	15.18	64.80	164.20	264.00	362.00	462.00
150	21.40	79.80	196.40	314.00	430.00	546.00
152	28.80	97.00	234.00	370.00	506.00	642.00
155	37.60	117.00	276.00	434.00	594.00	752.00
158	47.60	139.80	324.00	508.00	694.00	878.00
160	59.20	159.00	380.00	592.00	806.00	1,020.00
163	72.60	197.40	442.00	688.00	934.00	1,180.00

Temperature (°C)	The amount of TEG in distillate (kg/20,000kg feed)					
	5wt% water content	10wt% water content	20wt% water content	30wt% water content	40wt% water content	50wt% water content
166	88.00	230.00	512.00	796.00	1,078.00	1,360.00
169	105.6	268.00	592.00	916.00	1,240.00	1,564.00
172	125.40	310.00	682.00	1,052.00	1,424.00	1,794.00
174	148.20	360.00	782.00	1,206.00	1,628.00	2,060.00
177	173.80	414.00	896.00	1,376.00	1,858.00	2,340.00
180	202.00	476.00	1,022.00	1,568.00	2,120.00	2,660.00

Table B-5 The COD of distillate with the temperature at 8.47wt% water content in TEG waste

Temperature (°C)	The amount of TEG in distillate (kg/100kg feed)	The amount of distillate (kg/100kg feed)	The amount of TEG in distillate (g/20,000kg feed)	Volume of distillate (L/20,000kg feed)	COD (mg/L)
100	0.00	0.00	0.00	0.00	0.00
103	0.00	0.00	0.00	0.00	0.00
107	0.00	0.00	0.00	0.00	0.00
110	0.00	0.00	0.00	0.00	0.00
114	0.00	0.00	0.00	0.00	0.00
117	0.00	0.00	0.00	0.00	0.00
121	0.00	0.00	0.00	0.00	0.00
124	0.00	0.00	0.00	0.00	0.00
128	0.01	1.15	2,960.00	230.96	20,121.23
131	0.04	2.32	7,740.00	463.74	26,203.91
135	0.07	3.25	13,860.00	649.86	33,484.44
138	0.11	4.01	21,600.00	801.60	42,305.39
142	0.16	4.65	31,200.00	929.20	52,716.32
145	0.22	5.20	43,000.00	1,039.00	64,975.94
149	0.29	5.68	57,400.00	1,135.40	79,371.15
152	0.35	6.09	69,400.00	1,217.40	89,500.57
156	0.50	6.54	99,400.00	1,307.40	119,365.15
159	0.60	6.90	120,600.00	1,380.60	137,144.72
163	0.75	7.27	150,000.00	1,454.00	161,966.99
166	0.92	7.64	184,800.00	1,528.80	189,780.22
170	1.13	8.02	226,000.00	1,604.00	221,209.48

Temperature (°C)	The amount of TEG in distillate (kg/100kg feed)	The amount of distillate (kg/100kg feed)	The amount of TEG in distillate (g/20,000kg feed)	Volume of distillate (L/20,000kg feed)	COD (mg/L)
173	1.37	8.41	274,000.00	1,682.00	255,755.05
177	1.64	8.82	328,000.00	1,764.00	291,927.44
180	1.96	9.26	392,000.00	1,852.00	332,311.02

Methodology to calculation the COD of distillate

The amount of TEG in distillate (g/20,000kg feed) was calculated as follows:

$$\text{COD} = \frac{1{,}570 \times \frac{X\ g_{TEG}}{L}}{\frac{1\ g_{TEG}}{L}}$$

Where X = Weight of TEG divided by volume of distillate, g/L

For the example

The temperature at 180°C

1. Calculate the amount of TEG in distillate

$$\text{Amount of TEG in distillate (g/20,000kg feed)} = \frac{1.96kg_{TEG}}{100kg_{Feed}} \times 20{,}000kg_{Feed} \times \frac{1000g_{TEG}}{1kg_{TEG}}$$

$$= 392{,}000\ g$$

2. Calculate volume of distillate

Assume density of the distillate equal to 1 g/mL

Volume of distillate (L/20,000kg feed)

$$= \frac{9.26kg_{D}}{100kg_{Feed}} \times 20{,}000kg_{Feed} \times \frac{mL}{1g_{D}} \times \frac{1000g_{D}}{1kg_{D}} \times \frac{1L}{1000mL}$$

$$= 1{,}852\ L$$

3. Calculate COD of distillate

$$\text{COD} = \frac{1{,}570 \times \frac{(392{,}000/1{,}852)\ g_{TEG}}{L}}{\frac{1\ g_{TEG}}{L}}$$

$$= 332{,}311.02\ g/mL$$

Table E-3 COD of distillate with the temperature

Temperature (°C)	COD of distillate (mg/L)					
	5wt% water content	10wt% water content	20wt% water content	30wt% water content	40wt% water content	50wt% water content
100	0.00	0.00	0.00	0.00	0.00	0
103	0.00	0.00	0.00	0.00	0.00	0
106	0.00	0.00	0.00	0.00	1,366.07	1,367.61
108	0.00	0.00	0.00	2,338.95	2,340.70	2,336.89
111	0.00	0.00	0.00	3,541.97	3,549.03	3,551.30
114	0.00	0.00	5,051.83	5,047.72	5,050.70	5,066.54
117	0.00	0.00	6,876.80	6,869.79	6,894.03	6,880.58
119	0.00	0.00	9,089.65	9,105.63	5,439.48	9,079.34
122	0.00	12,800.18	11,750.56	11,763.72	11,759.42	11,757.27
125	0.00	15,842.38	14,858.40	14,873.19	14,879.28	14,849.98
128	0.00	19,808.01	18,585.10	18,608.81	18,565.70	18,582.78
130	0.00	24,397.53	22,926.57	22,945.19	22,952.68	22,956.72
133	0.00	29,789.08	28,114.19	28,026.79	28,027.25	28,057.81
136	0.00	35,917.02	33,955.59	33,881.75	33,940.56	33,873.22
139	43,234.57	43,306.56	40,689.09	40,721.06	40,659.62	40,742.68
141	51,617.47	51,619.89	48,492.83	48,597.12	48,517.46	48,328.46
144	61,217.01	61,016.44	57,550.54	57,219.35	57,253.83	57,273.40
147	71,530.70	71,604.73	67,302.75	67,662.57	67,335.99	67,428.61
150	82,066.44	83,758.52	78,920.03	78,970.38	78,911.65	78,723.94
152	97,280.55	97,309.90	91,597.26	91,557.92	91,539.74	91,529.27
155	112,742.55	112,486.22	105,740.31	105,556.14	105,801.29	105,883.45
158	129,383.66	129,429.18	121,360.30	121,671.23	121,849.99	121,699.09

Temperature (°C)	COD of distillate (mg/L)					
	5wt% water content	10wt% water content	20wt% water content	30wt% water content	40wt% water content	50wt% water content
160	147,717.74	142,401.60	139,645.22	138,995.75	139,328.73	139,264.83
163	168,462.90	169,780.87	158,410.08	158,611.43	158,706.89	158,473.94
166	190,828.73	191,260.59	177,054.62	179,915.91	179,784.24	179,386.36
169	215,426.20	215,553.28	202,820.33	202,697.17	202,638.42	202,249.33
172	241,449.60	240,940.59	227,842.21	227,476.44	227,571.88	227,413.35
174	269,860.82	270,172.08	254,347.90	254,299.62	254,018.12	254,877.46
177	299,918.66	300,083.10	283,075.35	282,485.28	282,447.25	282,424.90
180	331,736.40	332,437.72	313,106.60	312,689.73	313,187.49	312,867.56

Table E-4 The relationship between temperature and COD of distillate by aspen plus V9 program

% Water content	Relationship between temperature and COD	R^2
5	$COD = 0.268T^3 - 29.915T^2 - 3{,}749.4T + 413{,}075$	0.9952
10	$COD = 0.623T^3 - 187.14T^2 + 18960T - 649{,}641$	0.9993
20	$COD = 0.6528T^3 - 204.11T^2 + 21682T - 781{,}616$	0.9997
30	$COD = 0.6462T^3 - 201.19T^2 + 21246T - 759{,}752$	0.9997
40	$COD = 0.6321T^3 - 195.05T^2 + 20374T - 719{,}460$	0.9997
50	$COD = 0.6475T^3 - 201.58T^2 + 21274T - 759{,}631$	0.9997

Table B-3 Fuel cost of water removal from TEG waste at 8.47wt% water content in TEG waste

Temperature (°C)	Energy of separator per unit (Btu/kg)	Fuel cost (baht/year)
130	268.26	8,155.08
140	340.63	10,355.03
150	392.21	11,923.07
160	434.15	13,198.17
170	471.39	14,330.12

Methodology to calculation the fuel cost

Fuel cost was calculated as follows:

$$F_C = \frac{E \times M \times F}{\%eff}$$

Where F_C = Fuel cost, baht/year
E = Energy per unit, Btu/kg
M = Total triethylene glycol waste, kg/year (Total waste is 120,000 kg/year)
F = Fuel cost per unit, baht/Btu (Fuel cost = 190 Baht/MMBtu)
%eff = Efficiency of heater
(75%: reference from heater of Khanom gas separation plant)

For the example
The temperature at 130°C

$$F_C = \frac{268.26 \times 120{,}000 \times (190 \times 10^{-6})}{0.75} = 8{,}155.08$$

Table B-4 Utility cost of water removal from TEG waste at 8.47wt% water content in TEG waste

Temperature (°C)	Duty of fan (kJ/kg)	Total duty of fan (kJ/year)	Total time (hr)	Utility cost (baht/year)
130	43.80	5,256,255.35	16.27	610.25
140	99.05	11,885,827.99	36.80	1,379.93
150	132.08	15,849,135.34	49.07	1,840.07
160	154.82	18,577,919.11	57.52	2,156.88
170	172.71	20,724,786.91	64.16	2,406.13

Methodology to calculation the utility cost

Utility cost was calculated as follows:

$$U_C = P \times t \times U$$

Where U_C = Utility cost, baht/year

P = Power of motor of fan, kWh (7.5 kWh, can remove heat 323 MJ/hr: reference from pentane side draw cooler at Khanom gas separation plant)

t = Time, hr

U = Utility cost per unit, baht/kW (5 Baht/kW: reference from utility cost of Khanom gas separation plant)

For the example

The temperature at 130°C

$$U_C = 7.5 \times 16.27 \times 5 = 610.25$$

APPENDIX C

EXPERIMENTAL RESULTS FROM EXPERIMENTS

Table C-1 The amount of distillate with the temperature at 8.47wt% water content in TEG waste

Run	Temperature (°C)									
	130		140		150		160		170	
	Feed (g)	The amount of distillate (g)	Feed (g)	The amount of distillate (g)	Feed (g)	The amount of distillate (g)	Feed (g)	The amount of distillate (g)	Feed (g)	The amount of distillate (g)
1	705.98	13.04	668.59	18.04	735.39	45.21	685.73	48.75	721.19	58.96
2	718.25	13.45	667.28	21.78	688.71	35.33	715.63	53.40	691.45	53.21
3	672.82	11.55	674.82	24.12	692.18	36.90	698.21	48.48	731.56	63.15
4	747.75	14.98	686.04	28.82	687.30	29.49	679.98	44.64	701.59	56.80
5	700.35	13.10	708.22	30.83	712.25	39.95	724.32	54.01	705.45	57.58
Average	709.03	13.22	680.99	24.72	703.17	37.38	700.77	49.86	710.25	57.94
%Distillate	1.87		3.63		5.32		7.11		8.16	

Methodology to calculation the percentage of distillate

Percentage of distillate (%D) was calculated as follows:

$$\%D = \frac{m_D}{m_F} \times 100$$

Where m_D = mass of distillate, g
m_F = mass of feed, g

For the example

The temperature at 130°C

$$\%D = \frac{(13.04+13.45+11.55+14.98+13.10)/5}{(705.98+718.25+672.82+747.75+700.35)/5} \times 100 = 1.87$$

Table C-2 The COD of distillate with the temperature at 8.47wt% water content in TEG waste

Temperature (°C)	**Characteristics of the sample**	**COD (mg/L)**
130	Colorless liquid	40,880
140	Colorless liquid	37,400
150	Colorless liquid	38,040
160	Colorless liquid	36,680
170	Colorless liquid	35,920

By The center for Scientific and Technological Equipment, Walailak University

APPENDIX D

POLYMATH RESULTS

Table D-1 The relationship between temperature, amount of distillate and COD by aspen plus V9 program at 8.47wt% water content in TEG waste

	Simulation by Aspen plus V9 program	R^2
Temperature-Weight	$W = -0.0103T^3+4.3891T^2-587.48T+25,129$	0.9854
Temperature-COD	$COD = 0.5388T^3-151.52T^2+14,007T-425,102$	0.9988
Weight-COD	$COD = 60\times(10^6 + W)/W$	-

Table D-2 The relationship between temperature, amount of distillate and COD by simple distillation experiments in a laboratory at 8.47wt% water content in TEG waste

	Simple Distillation Experiments in a Laboratory	R^2
Temperature-Weight	$W = 0.0118T^3-5.667T^2+935.26T-51,416$	0.9883
Temperature-COD	$COD = -0.4232T^3+158.69T^2-18,692T+703,262$	0.7590
Weight-COD	$COD = 60\times(10^6 + W)/W$	-

Table D-3 The result of solving the equation by using Polymath 6.1 at 8.47wt% water content in TEG waste

	Appropriate temperature (°C)	COD of distillate (mg/L)	Reduced waste (kg/20,000kg feed)	Reduced waste (wt%)
Simulation by aspen plus V9 program	146.41	6.868×10^4	874.44	4.37
Simple distillation experiments in a laboratory	168.23	3.493×10^4	1,720.53	8.60

Table D-4 Reduced and operating cost of water removal from TEG waste at 8.47wt% water content

	Reduced disposal cost (baht/year)	Energy of separator per unit (Btu/kg)*	Fuel cost (baht/year)	Duty of fan (kJ/kg)*	Utility cost (baht/year)	Net reduced disposal cost (baht/year)
Simulation by Aspen plus V9 program	26,220.00	375.18	11,405.39	121.81	1,697.09	13,117.52
Simple Distillation Experiments in a Laboratory	51,600.00	465.00	14,136.10	169.74	2,364.77	35,099.13

*By aspen plus V9 program

Table E-5 The results of solving the equation by Polymath 6.1

% Water Content	Appropriate temperature (°C)	COD of distillate (mg/L)	Reduced waste (kg/20,000kg feed)	Reduced waste (wt%)
5	155.22	1.126×10^{5}	533.13	2.67
10	142.00	5.302×10^{4}	1,132.87	5.66
20	130.34	2.238×10^{4}	2,688.63	13.44
30	124.17	1.351×10^{4}	4,459.35	22.30
40	120.49	9.399×10^{3}	6,424.49	32.12
50	117.57	7.446×10^{3}	8,123.04	40.62

APPENDIX E

PHOTO OF THE EXPERIMENTS WITH REAL WASTE

Figure F-1 Real waste from closed drain in Khanom gas separation plant

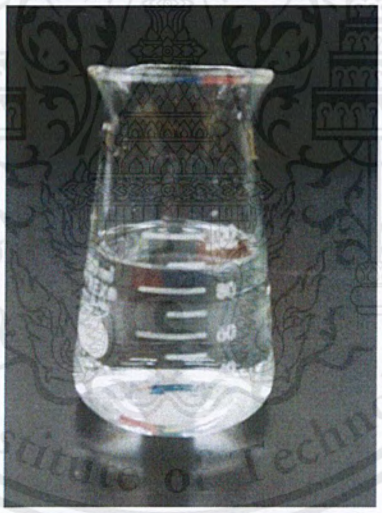

Figure F-2 Distillate from simple distillation experiment in a laboratory

BIOGRAHPY

Name: Miss Orawan Sukchoy

Date of Birth (DD/MM/YY): 14/03/95

Address: 11/56 Phraya Suren Rd, Sam Wa Tawan Tok sub district, Khlong Sam Wa district, Bangkok 10510

E-mail: orawan.sukchoy@hotmail.com

Academic Background:

2008-2013	Bodindecha (Sing Singhaseni) 2 School, Bangkok
2014-Present	Degree of Bachelor of Engineering (Petrochemical Engineering), Department of Chemical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok

Working Experience:

June-November 2017	Student trainee at Khanom gas separation plant (PTT Public Company Limited), Nakhon Si Thammarat