Desalinated water production
from solar thermal energy

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A Report Submitted in Partial Fulfillment of the Requirements
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Field of Study	Petrochemical Engineering
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Title Desalinated water production from solar thermal energy

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Field of Study Petrochemical Engineering

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Abstract

At present, many countries are suffering from the shortage of fresh water due to their arid landscape and economic conditions which are interrupting the freshwater production ability. Moreover, the limitation of freshwater resources in worldwide are gradually decrease in contrast to the increasing demand from the growing population. Consequently, the utilization of alternative resources is greatly interesting. The most abundant of solar thermal energy which is available as a renewable energy and the alternative source of salt water are going to be integrated in the desalination water production. In this research, the cheap system for desalinated water production from solar thermal energy is going to be presented. Moreover, the system can be operated by integrating an evacuated tube solar thermal collector (ETSC) with an evaporation bath and a heating medium storage tank. The temperature of palm oil inlet from a heating medium storage tank is represent as a solar radiation temperature substituting the ETSC and it can accelerate the evaporation process because of the heater system. The optimal angle of an inclined polycarbonate plate, 30° and the temperature of 100°C of inlet palm oil which can produce the most of distilled water from the total amount of condensed water were presented in the previous work. The application of this system is going to be developed and optimized for the desalination process by using the inlet palm oil temperature at 80°C, 100°C and 120°C. As a result, the inlet palm oil temperature at 120°C provides the maximum evaporation rate at 269 mL/h and 251 mL/h, 130 mL/h at 100°C and 80°C respectively.

Keywords: Solar thermal energy, Desalination, Salt water, Evaporator

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เรื่อง การกลั่นน้ำเกลือจากความร้อนพลังงานแสงอาทิตย์

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บทคัดย่อ

ในปัจจุบันหลายๆประเทศกำลังประสบปัญหาการขาดแคลนน้ำสะอาดเนื่องจากสภาพภูมิประเทศที่แห้งแล้งและสภาวะเศรษฐกิจที่ไม่ค่อยดีนักส่งผลให้ผู้คนในประเทศเหล่านั้นไม่สามารถผลิตน้ำสะอาดใช้ได้อย่างเพียงพอ อีกทั้งทรัพยากรน้ำในโลกของเรานั้นมีอย่างจำกัดและค่อยๆลดลงไปเรื่อยๆ ซึ่งตรงกันข้ามกับความต้องการที่เพิ่มขึ้นอย่างต่อเนื่องจากการเพิ่มขึ้นของประชากรโลก ดังนั้นการนำทรัพยากรทางเลือกมาใช้ประโยชน์จึงเป็นสิ่งที่น่าสนใจ การบูรณาการกันระหว่างพลังงานหมุนเวียนที่มีอย่างมากมายที่ใช้แล้วไม่หมดไปอย่างพลังงานแสงอาทิตย์และทรัพยากรทางเลือกอย่างน้ำเกลือที่มีอย่างมากมายเช่นเดียวกันนั้นกำลังจะถูกนำไปใช้ประโยชน์ในกระบวนการแยกน้ำออกจากเกลือในวิธีการกลั่น ปริญญานิพนธ์ฉบับนี้จึงต้องการที่จะนำเสนอการผลิตน้ำกลั่นจากความร้อนพลังงานแสงอาทิตย์อย่างง่ายและราคาย่อมเยา นอกจากนี้ระบบการกลั่นน้ำเกลือนี้ ยังสามารถบูรณาการได้โดยการทำงานร่วมกันของแผ่นรับแสงอาทิตย์แบบหลอดแก้วสุญญากาศกับอ่างระเหยและถังเก็บสารตัวกลางที่ให้ความร้อน ซึ่งอุณหภูมิของน้ำมันปาล์มขาเข้าจากถังเก็บสารตัวกลางที่ให้ความร้อนนั้นเปรียบเสมือนอุณหภูมิจากการแผ่รังสีจากแสงอาทิตย์ที่ทำหน้าที่แทนแผ่นรับแสงอาทิตย์แบบหลอดแก้วสุญญากาศ อีกทั้งยังสามารถเร่งกระบวนการระเหยได้โดยการเพิ่มอุณภูมิจากระบบให้ความร้อนที่ถูกติดตั้งไว้ในถังน้ำมันปาล์ม ซึ่งในงานก่อนหน้านี้ได้ทำการทดลองและเสนอมุมที่เหมาะสมที่สุดของแผ่นพอลิคาร์บอเนตคือมุม 30° และอุณหภูมิของน้ำมันปาล์มขาเข้าที่ 100°C ซึ่งเป็นภาวะที่ทำให้ได้ปริมาณน้ำกลั่นจากน้ำที่ควบแน่นได้มากที่สุด จากระบบที่กล่าวมานั้นจะถูกนำมาพัฒนาและเพิ่มประสิทธิภาพให้กับกระบวนการกลั่นน้ำเกลือจากความร้อนพลังงานแสงอาทิตย์ โดยการประยุกต์ใช้อุณหภูมิน้ำมันปาล์มขาเข้าที่ 80°C, 100°C และ 120°C

คำสำคัญ: ความร้อนพลังงานแสงอาทิตย์, การกลั่นน้ำเกลือ, น้ำเกลือ, เครื่องระเหย

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NOMENCLATURE

h_{cwg} Convective heat transfer coefficient from basin water to glass cover (W/m2 °C)

h_{ewg} Evaporative heat transfer coefficient from basin water to glass cover (W/m2 °C)

h_{twg} Total heat transfer coefficient from basin water to glass cover (W/m2 °C)

q_{cwg} Convective heat transfer from basin water to glass cover (W/m2)

q_{ewg} Evaporative heat transfer from basin water to glass cover (W/m2)

T_w Basin water temperature (°C)

T_g Glass cover temperature (°C)

P_w Partial saturated vapor pressure at a basin water temperature (N/m2)

P_g Partial saturated vapor pressures at glass cover temperature (N/m2)

$\boldsymbol{m_w}$ Mass of water in basin (Kg)

$\boldsymbol{M_w}$ Hourly distillate output per unit basin area (Kg/m2/h)

$\boldsymbol{L_{ev}}$ Latent heat of vaporization of water (J/kg)

Subscripts

EXP Experiment

g glass cover

w *basin water*

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CHAPTER 1
INTRODUCTION

1.1 Background

Recently, the freshwater consumption requirements in worldwide are gradually increasing along with the population growth especially in arid areas where are suffering from the limitation of freshwater resources, climate change and their environmental pollutions. The fresh water remaining on Earth is only 1%. So, there is impossible to be enough for human life, [1].

The investigation of desalination technologies which are feasible to provide fresh water such as thermal technology and membrane technology are going to be discussed in the matter of their advantages and disadvantages whether in terms of operation cost, water treatment required, energy required and the quality of produced water for each technique. Moreover, the environmental impact assessment (EIA) should be considered for the desalination technology selection to reduce costs and negative impacts of the desalination process.

Thermal desalination technology and membrane technology are frequently used in remote areas because it is far from conventional water sources and the limitation of freshwater transportation. Reverse osmosis (RO) is classified as a type of membrane technology which has low energy requirement, high production capacity, simple and fast operation but pretreatment of feed water is required and charges approximately 50% of the entire process is used for high-pressure pumps [1]. On the other hand, thermal desalination technology requires minimum feed water pretreatment, high quality of water can produce and high design capacity. However, intensive energy needed, and material corrosion problems is must be concerned, [2].

The renewable energy is the one of sustainable energy that's interesting to apply in thermal desalination technology, especially the solar energy which is the most abundant and cleanest renewable energy source available. Consequently, if renewable sources of energy can be used, desalination will be economical for other uses.

As mentioned above, this research proposal attends to present the desalinated water production from solar thermal energy integrating with nonconventional resources as saline to solve the scarcity on water demand, especially in remote areas where are facing of the inability to produce freshwater for their life.

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The solar thermal energy desalination system is consisting of 3 main parts including of evacuated tube solar thermal collector (ETSC), a heating medium storage tank, and an evaporation bath. The solar radiation provides thermal energy which can be absorbed by ETSC. Then, the heating storage tank pumps a heating medium fluid through the ETSC manifold to receive thermal energy and stored as a heat source by returning it into the heating medium storage tank preparing for evaporation bath supply, [3].

The purpose of this study is to assess the feasibility of integration between the solar thermal energy with saline as a nonconventional resource for the desalination technology development to solve the water scarcity problem in many arid areas. Moreover, to provide the simple and economical desalination system which can be scaled up to large scale in freshwater production from solar thermal energy as a renewable and sustainable energy.

1.2 Objectives

1.2.1 To investigate the effects of inlet palm oil temperature on desalinated water productivity.

1.2.2 To apply the solar thermal desalination system to produce desalinated water from synthetic seawater.

1.3 Scopes of work

1.3.1 Find the optimum inlet palm oil temperature at the specific of synthetic seawater concentration which is 35 grams/liter [1] by varying temperature in a range of 80-120 °C.

1.3.2 Evaluate the ability to maximize the desalinated water productivity by applying synthetic seawater with the solar thermal desalination system.

1.4 Expected Outputs

1.4.1 Freshwater from this thermal desalination system can be achieved.

1.4.2 The desalination system can reduce the negative impacts on the environment.

1.4.3 Solar thermal desalination systems can efficiently solve the problems of the scarcity on water demand and the shortage of conventional water resources.

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CHAPTER 2
LITERATURE REVIEW

2.1 Definition of seawater

Seawater, or salt water, is water from a sea or ocean. On average, seawater in the world's oceans has a salinity of about 3.5% (35 g/L, 35 ppt, 600 mM). That means every kilogram or one liter by volume of seawater has approximately 35 grams of dissolved salts (mainly sodium (Na^+) and chloride (Cl^-) ions). The average density at the surface is 1.025 kg/L. Seawater is denser than both fresh water and pure water (density 1.0 kg/L at 4°C) because the dissolved salts increase the mass by a larger proportion than the volume. Seawater pH is typically limited to a range between 7.5 and 8.4.

2.2 Water quality analysis

Water quality analysis is the utilization of chemical and physical methods to determine the content of various chemical components in water. Water quality monitoring is mainly a process of monitoring the desalinated water concentration changed after the desalination process to ensure that freshwater is achieved. Simple analysis is carried out in the desalination process with few analysis items which used to analyze these parameters:

2.2.1 Total Dissolved Solids (TDS)

TDS is a measure of the dissolved combined content of all inorganic and organic substances present in a liquid in molecular or ionized suspended form. TDS concentrations are often reported in parts per million (ppm). For the desalination systems, the level of total dissolved solids uses to analyze the desalinated water obtained from the process is freshwater. Water TDS concentrations can be determined using a digital meter which is TDS meter.

2.2.2 Salinity

Salinity is the dissolved salt present in water. It is typically measured with a salinity meter, which calculates the amount or weight of salt present in a specific volume of water. This can be expressed in units such as parts per million (ppm) and grams of salt per kilogram of water or as a simple percentage. For the desalination system, the seawater concentration of 35 gram/liter is going to be synthesized to investigate the ability to desalinate salt water to produce freshwater in the desalination process.

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2.3 Solar energy desalination

Solar energy is mostly used in the part of thermal desalination process, which is a huge intensity solar radiation receivable. Solar desalination is a technique to desalinate water using solar energy by connecting the solar collector with desalination system. In principle, the solar collector absorbs heat from the solar radiation which transforms to thermal energy to heat the heat transfer fluid stored inside the conductive pipe. The heat transfer fluid is responsible for receiving thermal energy from the outside, then exchanging with saltwater in the evaporation bath which is part of the desalination system [4].

2.4 Single slope solar still

Solar still is a device which is widely used in the solar thermal desalination process. Still is an airtight rectangular basin enclosed by transparent cover to trap the solar energy inside it and contains saltwater. When sunlight falls on transparent cover, saltwater is heated and gets evaporated. The water vapor condenses on the inner side of the cover and runs down along the cover surface due to gravity and gets collected gradually in a beaker through condensate channel [4].

2.5 Thermal energy calculations of solar still model

In order to simplify the thermal energy balance equations for various parts of a single basin single slop solar still, the following assumptions have been made:

- Solar still is assumed as a slightly vapor leakage.
- Water vapor and dry air are assumed to behave like an ideal gas.
- The physical properties of salt water used in experiments remain constant with different temperature range.

2.5.1 Basin water mass

Heat energy is absorbed by the basin water due to heat transfer taking place between hot fluid as palm oil transfer to cold fluid as salt water. Absorbed heat energy is consumed in three ways, one part is stored in water due to its specific heat, second part is the heat transfer from hot palm oil through the copper pipe to salt water and remaining part of heat energy is transferred from salt water surface to the inside glass cover by conduction, convection and evaporation respectively.

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2.5.2 Internal heat transfer process

The internal heat transfer takes place from the basin water to the inner surface of glass cover through the two modes of convection and evaporation by which the internal heat transfer process in the evaporation basin [5].

The convective heat transfer occurs between salt water surface and inner side of the glass cover. It is calculated by the following equation,

$$q_{cwg}=h_{cwg}(T_w - T_g) \tag{2.1}$$

where, the convective heat transfer coefficient is obtained from an empirical relation, which is given by Dunkle [6].

$$h_{cwg}=0.884\left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{(268.9 \times 10^3 - P_w)}\right]^{1/3} \tag{2.2}$$

The evaporative heat transfer occurs between the water surface and glass cover in the form of the water to the air-vapor mixture (humid air),

$$q_{ewg}=h_{ewg}(T_w - T_g) \tag{2.3}$$

where, the evaporative heat transfer coefficient between water and glass cover is found from [7].

$$h_{ewg}=(16.28\times10^{-3})h_{cwg}(P_w - P_g)/(T_w - T_g) \tag{2.4}$$

And the hourly distillate per unit basin area is obtained from the relation,

$$M_w=(h_{ewg}(T_w - T_g)\times3600)/(L_{ev}) \tag{2.5}$$

Total internal heat transfer coefficient of water surface to the inner surface of the glass cover is the sum of these entire heat transfer coefficients by all these modes thus,

$$h_{twg}=h_{cwg} + h_{ewg} \tag{2.6}$$

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2.6 Heat transfer

2.6.1 The overall heat transfer coefficient

Typically, a heat exchanger consists of two fluids separated by a solid wall. First, heat is transmitted by convection from the hot fluid to the wall, then by conduction through the wall, and finally by convection from the wall to the cold fluid. Typically, radiation effects are accounted for convective heat transfer coefficients [8].

The network of thermal resistances associated with this heat transfer process consists of two convection resistances and one conduction resistance. Here, and represent the inner and outer surfaces of the inner tube, respectively. The thermal resistance of the tube wall within a double-pipe heat exchanger is

$$R_{wall}=\frac{\ln(D_o/D_i)}{2\pi kL} \quad (2.7)$$

.

In the analysis of heat exchangers, it is practical to combine all thermal resistances in the path of heat flow from the hot fluid to the cold fluid into a single resistance R and to represent the rate of heat transfer between the two fluids as

$$\dot{Q}=\frac{\Delta T}{R}=UA_s\Delta T=U_iA_i\Delta T=U_oA_o\Delta T \quad (2.8)$$

Where; A_s is the surface area, (m^2)

A_i is the area of the inner surface of the wall, (m^2)

A_o is the area of the outer surface of the wall, (m^2)

U is the overall heat transfer coefficient, ($W/m^2 \cdot K$)

2.7 Evaporation

It is a vaporization that occurs on the surface of a liquid during the transition from the liquid to the gaseous phase. Because water vapor is constantly traveling back and forth from the sea surface, it is a net process. Evaporation occurs when more molecules leave the surface of the water than enter. When a liquid evaporates, the energy taken from it lowers its temperature, resulting in evaporative cooling [9].

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2.8 Condensation

Condensation and evaporation are conflicting processes that occur concurrently. The rate of evaporation, which is the number of water molecules that change phase from liquid to gas every second, is mostly determined by the liquid water's temperature. The higher the temperature of the liquid water, the faster the rate of evaporation. In contrast, the condensation rate, which is the number of water molecules that change phase from gas to liquid per second, is mostly determined by the vapor pressure. The greater the vapor pressure, the quicker the condensation rate. When a water vapor molecule collides with a liquid water surface and chemically links to liquid water molecules, condensation happens. Evaporation happens when a molecule of liquid water acquires enough energy to break its chemical interactions with surrounding water molecules.

In a closed system, dynamic equilibrium is achieved when the rates of evaporation and condensation are equal. When this occurs, the saturation vapor pressure may be determined, and the air within a closed system is said to be saturated with water vapor. At a given temperature, saturation may refer to the capacity or maximum amount of water vapor that can exist in the air. It is crucial to realize that the saturation vapor pressure increases with increasing air temperature. The saturation vapor pressure is strongly dependent on temperature.

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CHAPTER 3
EXPERIMENTAL

3.1 Plan installation the solar thermal energy desalination system

The solar thermal desalination system is going to be installed in two main sections, there are ETSC and the desalination system which are connected via pump, pipe, and valve. The desalination system consists of a heating medium storage tank, an evaporation bath, and a saltwater tank. At the evaporation bath, salt water was added to cover the copper pipe inside the bath and the heating medium fluid runs through a copper pipe to transfer heat between two fluids, allowing saltwater to evaporate. The sufficient energy will turn the water into vapor and rise to form a cloud. The evaporation will continue until an equilibrium is reached, which is when the evaporation of water is equal to its condensation at the inclined top plate of the bath. The condensate flows down a steep of the inclined plate to the gutter and is collected as desalinated water. The rest of the water is drained at the bottom as saline. This project will utilize the evaporation bath for connection to the ETSC by using ETSC data from the preceding project, [3].

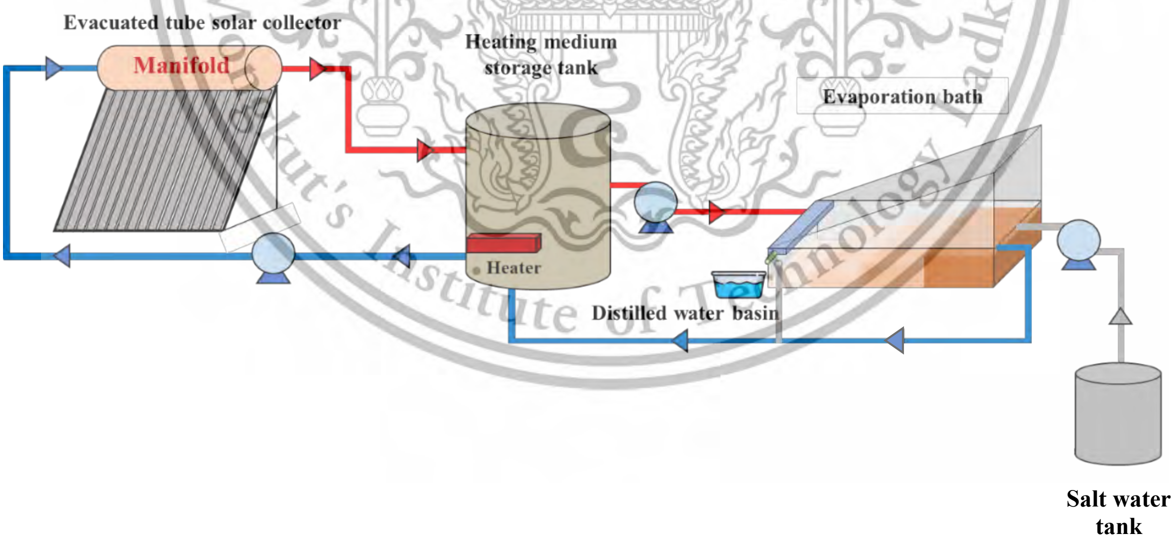

Figure 3.1 The solar desalination system

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Install measurement devices and control system.

The measurement devices and control system must be installed to use for the experiments. Figure 3.2 illustrates a desalination system with a control loop.

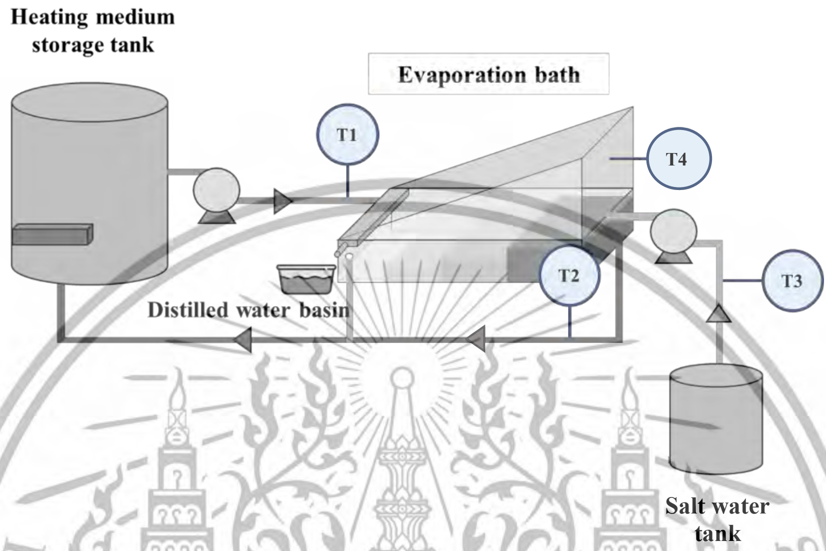

Figure 3.2 The desalination system with control loop

The experimental setup of the desalination system for this experiment is shown in Fig.3 below, there are four necessary pieces of apparatus. The primary component of this system is the evaporation bath, which evaporates saltwater to produce desalinated water. The second is a heating medium storage tank that supplies heat to the evaporation bath. The third is the saltwater tank, which is used to store saltwater solution as a raw material for the experiment. The final is temperature measurement devices which used to measure the temperature of the inlet and outlet palm oil, saltwater in basin and vapor inside the evaporation bath, [3].

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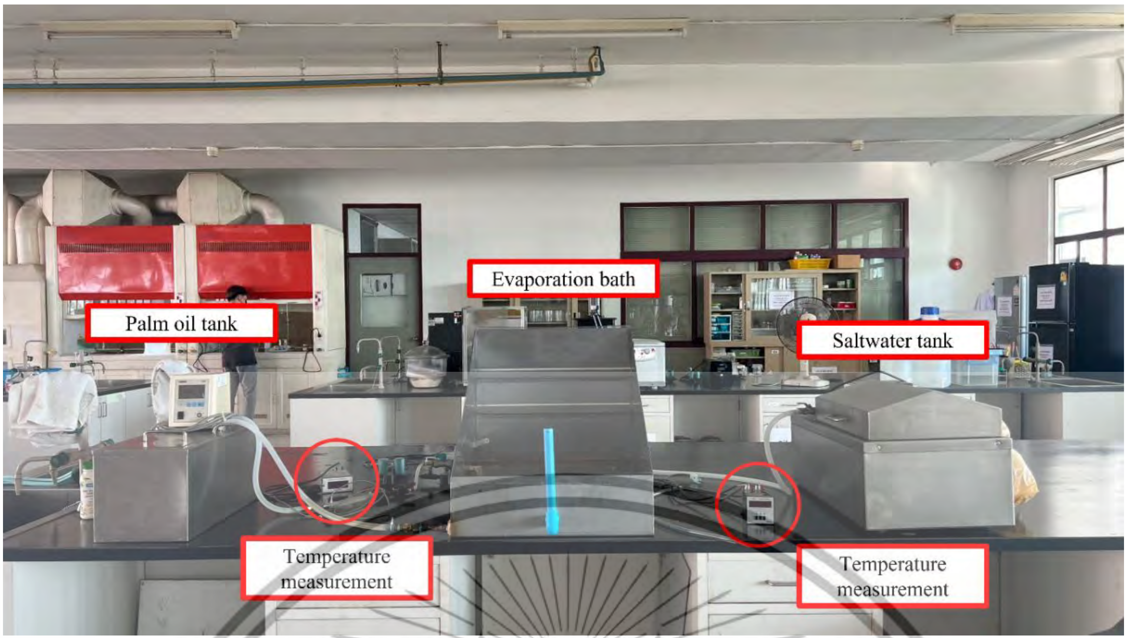

Figure 3.3 The experimental setup of the desalination system

3.2 Material selection

(1) Stainless steel

In this work, the 316-grade stainless steel (UNS S31600/S31603 - commonly termed "marine grade" stainless) incorporates 2-3% of molybdenum and 18% chromium is used to build the evaporation basin, on account of corrosion resistance especially chloride and other industrial solvents. As a sequence, this stainless steel is practicable for this work which uses saltwater to circulate the system.

(2) Copper pipe

Copper pipe is selected in this work because of its thermal conductivity strength, durability, and corrosion resistance. In addition, the size selected of this pipe is 0.019 m of inner diameter and 0.022 m of outer diameter due to its strength and optimum size which is suitable for this system.

(3) Polycarbonate sheet

A transparent solid polycarbonate sheet with 5 mm of thickness is used to cover the slope of the evaporation bath due to its strength and durability for extreme temperatures, additionally, the transparent material is necessary in this work because it was used to observe and analyze the phenomena of dropwise condensation.

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3.3 The operating conditions of the desalination system

In this work, the heat transfer between heating medium fluid in the copper pipe and saltwater is going to be investigated under the conditions of interest. Therefore, the manipulated variable for this experiment is temperature of the palm oil entering the evaporation bath in the range of 80-120°C.

To evaluate the ability to connect the desalination system to the ETSC, the variation temperature of the palm oil entering the evaporation bath must be investigated to determine that the desalinated water can be produced even though the temperature is below 100°C, which considers the temperature instability from solar radiation. The temperature range of incoming palm oil is determined by previous research which indicates that the ETSC can increase the temperature of 50 L of palm oil to 98.5°C, [3].

3.4 Water quality measurement

In this work, the homogeneity of saltwater solution and the quality of desalinated water are both important. The homogeneity of saltwater affects the solution concentration and ability of the evaporation process, and the quality of desalinated water must be acceptable to the WHO-2017 standards. Consequently, water quality measurement is required to analyze the saltwater solution before desalination process and to analyze the desalinated water as a distillate output after saltwater is evaporated. TDS and Salinity parameters are going to be measured by the following measurement below.

3.4.1 TDS/Salinity meter

Figure 3.4 TDS/Salinity meter

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The TDS/Salinity Meter can measure the TDS (Total Dissolved Solid), Salinity and Temperature for the water solution target. The TDS unit of measurement includes ppm and ppt, and the units of Salinity include ppt, % and specific gravity (S.G.). This only needs one touch to switch different units for different measuring purposes. It could be the best Water Quality tester for all professional measuring purposes, including the LAB, water treatment business, Aquaculture, Aqua farm, swimming pool or other related industry.

Materials and equipment

1. Sodium Chloride (NaCl) or Salt: 350 grams
2. Water: 10 liters
3. Evaporation bath
4. Heating medium storage tank with a heater inside
5. Saltwater tank
6. Mixing tank
7. TDS/Salinity meter
8. Desalinated water bath: Cylinder 250 mL
9. Palm oil (heating medium fluid)
10. Temperature measurement

Procedures

1. Synthesis of seawater at a salt concentration of 35 g/l by following this step:
    - Weigh 35 grams of salt.
    - Pour 1 liter of water into the mixing tank.
    - Add 35 grams of salt into the mixing tank which contains water.
    - Mix until salt is completely dissolved.
    - Repeat these steps until the volume of saltwater solution is 10 liters.
2. Measure the concentration of saltwater solution by using the Salinity meter.
3. Install the desalination system as shown in Figure 3.3
4. Set the angle of the inclined polycarbonate plate to 30 degrees [10].

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5. Fill the heating medium storage tank with palm oil and the saltwater tank with saltwater solution, respectively.
6. Open the heater inside the heating medium storage tank.
7. Start the pump to circulate palm oil and pump saltwater into the evaporation bath which is maintained as follows:

Table 3.1 The operating conditions for the experiment.

Mass concentration of NaCl solution (g/L)	The amount of saltwater in basin (L)	Flow of palm oil (mL/s)	Inlet palm oil temperature (°C)
35	10	21	80
	10	21	100
	10	21	120

8. Measure and record the variables every 0.5 hours until 4 hours as follows:
   - Palm oil temperature at entrance of evaporation bath ($T_{o,\ in}$)
   - Palm oil temperature at the exit of the evaporation bath ($T_{o,\ out}$)
   - Saltwater temperature inside of the evaporation bath ($T_{w,\ inside}$)
   - The temperature at the inner side of the glass cover ($T_{v,inside}$)
   - Quantity of the desalinated water
9. Analyze the desalinated water quality by using TDS/Salinity meter to measure the parameters which the distillate output was acceptable according to the WHO-2017 standards as follows:

Table 3.2 WHO-2017 standards for freshwater acceptable value.

TDS (mg/l)	≤1000
Salinity level (ppt)	<0.5

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CHAPTER 4
RESULTS AND DISCUSSION

4.1 Optimization of the conditions of the desalinated water system

The parameter of the inlet palm oil temperature of the evaporation bath ($T_{o,in}$) was investigated in this experiment. The variation of the inlet palm oil temperature represents the instability of the solar radiation intensity which is collected by ETSC in each period. The inlet palm oil temperature has effects directly on the productivity of the product.

The desalinated water system that used palm oil as a heat transfer medium was investigated to evaluate the possibility of connecting the ETSC. Three different temperatures of inlet palm oil, 120°C, 100°C, 80°C were used to determine whether the system could still produce freshwater despite the thermal energy from palm oil cannot raise the saltwater temperature up to the boiling point of water, which is 100°C.

Table 4.1 The results of desalinated water temperature and evaporation rate at each condition.

Palm oil temperature: $T_{o,\,in}$ (°C)	**Salt water temperature: $T_{w,\,inside}$ (°C)**	**Evaporation rate (mL/h)**
120	73	269
100	72	251
80	60	130

According to Table 4.1 the results of desalinated water temperature and evaporation rate at each condition, The greatest salt water temperature was reached at inlet palm oil temperature ($T_{o,in}$) of 120°C, followed by 100°C and 80°C. The variables of palm oil flow rate, the amount of salt water in basin (10 L) and the salinity of saltwater (35 g/L) are all constant. From the result, the heat transfer rate will vary with the inlet palm oil temperature ($T_{o,in}$), as investigated by the salt water temperature ($T_{w,inside}$) which can be described by the relation below.

$$Q \propto T_{o,in} \quad (4.1)$$

This points out that if the temperature of the inlet palm oil increased, the heat transfer rate will increase, resulting in the greater salt water temperature that influences an increase in the evaporation rate.

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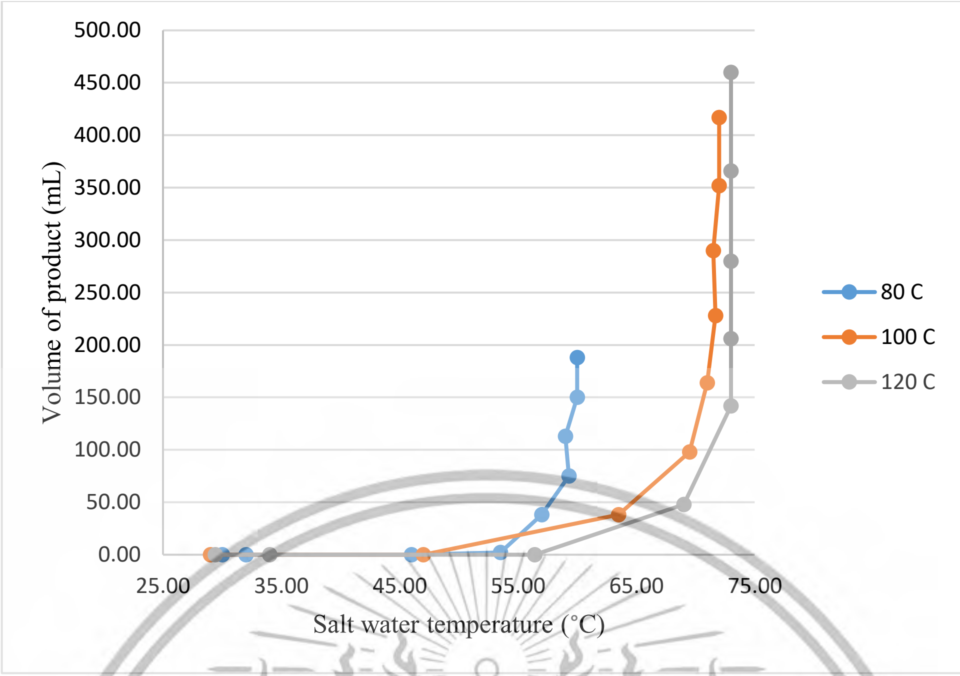

Figure 4.1 The relation between salt water temperature ($T_{w,inside}$) and volume of product at each inlet palm oil temperature

In this experiment, we assume that the boiling point of salt water is equal to pure water because most of the components are water that contains salt only 35 grams of 10 liters of water. Figure 4.1 indicates that even if the temperature of salt water is less than 100°C it can still produce desalinated water that is below the boiling point of water. Under the conditions of inlet palm oil temperature of 80°C, salt water in basin can be raised to 60°C and it can still produce desalinated water of 188 mL during 4 hours of experiment. This shows a trend that the evaporation bath can connect to the ETSC due to its ability to produce evaporation even at low inlet palm oil temperatures, but also produces a small amount of product.

Table 4.2 The results of evaporation rate and percentage of collected water at each condition.

Inlet palm oil temperature: $T_{o,in}$ (°C)	**Temperature of the inside glass cover: $T_{g,inside}$ (°C)**	**Evaporation rate (mL/h)**	**Collected water rate (mL/h)**	**Percentage of collected water from evaporation (%)**
120	67.50	269	153	57
100	66.50	251	127	51
80	54.50	130	63	49

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From Table 4.2 it can be shown that the percentage of collected water from total water evaporated is only 48%, 51% and 58%, which can indicate that not all the condensates can be collected. This problem may occur when condensate flows over the inside glass surface drop in the middle of the path before reaching the water storage chute and partially leaking vapor out of the evaporation bath. The highest percentage of collected water at 58% was achieved when inlet palm oil temperature is 120°C. This is due to the highest evaporation rate, which results in the most water vapor condenses into droplets and have the greater ability to touch, combine, and form a single larger drop consequences the most of products can be collected.

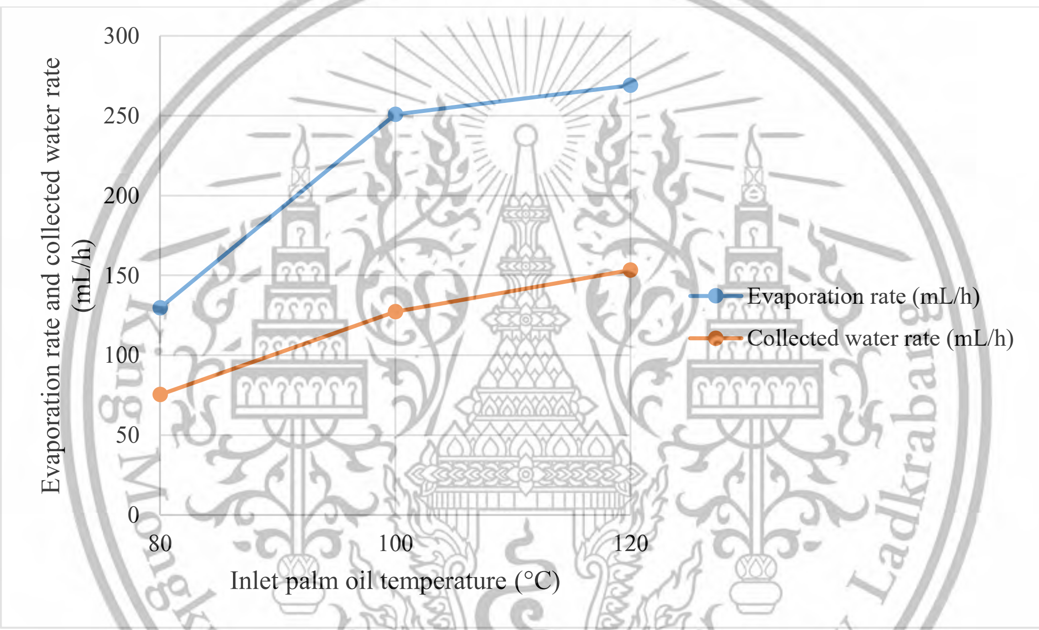

Figure 4.2 The relation between inlet palm oil temperature and evaporation rate and collected water rate.

Figure 4.2 shows the evaporation rate and collected water rate varying directly with the inlet palm oil temperature, which is the inlet palm oil temperature increases the evaporation rate and collected water rate also increases. From the figure, the space between the evaporation rate line and collected water rate line indicates that there are some vapor leaks and condensate drop in the middle of the path before reaching the water storage chute. The vapor leakage occurs at the top of the bath which the polycarbonate plate cannot be completely covered. This due to the polycarbonate sheet was continuously heated throughout the experiment causing the polycarbonate sheet to bend out of its original straight sheet. In addition, another problem that occurs during the experiment is condensate drop in the middle of the path before reaching the

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water storage chute. This can be related to the surface tension and gravitational force between the water droplets and the surface of the polycarbonate sheet. In case of water droplets combining and accumulating on the surface of the polycarbonate sheet in large quantities. The mass of the accumulated water increases, thus increasing the multiplier of the water mass (m_w) and the Earth's gravitational acceleration (g). As a result, $m_w g$ is greater than the surface tension causing the water to drop along the path before reaching the water storage chute. Consequently, the amount of collected water from the desalinated water evaporated can collect only 51-58% of total water that evaporated.

Table 4.3 The experimental result at the operating condition of 80ºC of inlet palm oil temperature

Temperature of 80ºC						
Time	Synthetic Seawater		Oil			Product
	$T_{w,inside}$ (ºC)	$T_{g,inside}$ (ºC)	Flow rate (mL/s)	$T_{o,in}$ (ºC)	$T_{o,out}$ (ºC)	Volume (mL)
14.30	30.00	30.50	21.00	31.00	30.00	0.00
15.00	32.00	32.00	21.00	67.00	31.00	0.00
15.30	46.00	39.30	21.00	80.00	48.00	0.00
16.00	53.50	45.00	21.00	80.00	57.00	2.00
16.30	57.00	53.50	21.00	80.00	61.00	38.00
17.00	59.30	53.00	21.00	80.00	63.00	75.00
17.30	59.00	54.30	21.00	80.00	63.00	113.00
18.00	60.00	54.50	21.00	80.00	64.00	150.00
18.30	60.00	54.50	21.00	80.00	64.00	188.00

According to Table 4.3, the desalinated water product begins to be collected at the salt water temperature ($T_{w,inside}$) of 53.50ºC and the glass cover temperature ($T_{g,inside}$) of 45.00ºC after 1.30 hours and keep increasing in product about 56.5 mL/h in average of three hours until steady at the salt water temperature ($T_{w,inside}$) of 60.00ºC and the glass cover temperature ($T_{g,inside}$) of 54.50ºC. Even though the temperature of salt water is below the boiling point of 100ºC, it can still produce desalinated water because of evaporation. It is caused by the differences in vapor pressure between the surface of heated salt water in basin and the inner side glass cover. Moreover, the water vapor that evaporated from the surface of salt water in basin is condensed at the inner side of the cooler polycarbonate sheet which contact with ambient air at the temperature of 33ºC. Consequently, the differences in temperature between the water vapor at the inner side glass cover and ambient air causing condensation.

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Table 4.4 The experimental result at the operating condition of 100ºC of inlet palm oil temperature

Temperature of 100ºC						
Time	Synthetic Seawater		Oil			Product
	$T_{w,inside}$ (ºC)	$T_{g,inside}$ (ºC)	Flow rate (mL/s)	$T_{o,in}$ (ºC)	$T_{o,out}$ (ºC)	Volume (mL)
13.00	29.00	32.00	21.00	34.00	29.00	0.00
13.30	47.00	37.50	21.00	87.50	43.00	0.00
14.00	63.50	55.30	21.00	100.00	68.00	38.00
14.30	69.50	64.00	21.00	100.00	73.00	98.00
15.00	71.00	65.00	21.00	100.00	76.00	164.00
15.30	71.70	66.20	21.00	100.00	76.00	228.00
16.00	71.50	66.50	21.00	100.00	77.00	290.00
16.30	72.00	66.50	21.00	100.00	77.00	352.00
17.00	72.00	66.50	21.00	100.00	77.00	417.00

From this table, the product begins to be collected at the first hour of the experiment at the salt water temperature ($T_{w,inside}$) of 63.50ºC and the glass cover temperature ($T_{g,inside}$) of 55.30ºC and keep increasing in product about 127 mL/h during 3 hours until steady at the salt water temperature ($T_{w,inside}$) of 72.00ºC and glass cover temperature ($T_{g,inside}$) of 66.50ºC. The molecules at the liquid surface absorb sufficient energy to overcome vapor pressure and the energy is greater than the intermolecular forces causing evaporation. The temperature is directly proportional to energy, meaning that the higher the temperature, the better the evaporation will occur. The higher temperature differences between the inner side of glass cover and ambient air causing higher condensation rate.

Table 4.5 The experimental result at the operating condition of 120ºC of inlet palm oil temperature

Temperature of 120ºC						
Time	Synthetic Seawater		Oil			Product
	$T_{w,inside}$ (ºC)	$T_{g,inside}$ (ºC)	Flow rate (mL/s)	$T_{o,in}$ (ºC)	$T_{o,out}$ (ºC)	Volume (mL)
15.00	29.40	31.20	21.00	31.50	27.00	0.00
15.30	34.00	31.50	21.00	79.60	31.00	0.00
16.00	56.40	45.80	21.00	110.00	53.00	0.00
16.30	69.00	64.30	21.00	120.00	77.00	48.00
17.00	73.00	68.30	21.00	120.00	82.00	142.00
17.30	73.00	67.50	21.00	120.00	82.00	206.00
18.00	73.00	68.00	21.00	120.00	82.00	280.00
18.30	73.00	67.50	21.00	120.00	82.00	366.00
19.00	73.00	67.50	21.00	120.00	82.00	460.00

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As you can see in the Table 4.5, the experiment at the operating condition of 120ºC of inlet palm oil temperature provides the highest production rate at approximately 153 mL/h throughout four hours of the experiment and the temperature of salt water ($T_{w,inside}$) can be reached at the highest temperature in all three experiments at 73.00ºC and also the glass cover temperature ($T_{g,inside}$) of 67.50ºC. As explained in the previous table, the temperature is directly proportional to energy and the higher energy causes the molecules at the surface of the liquid to evaporate more and faster. At the salt water temperature of ($T_{w,inside}$) 73.00ºC, the production rate can be increased up to 159 mL/h in average of the last two hours of the experiment.

The higher salt water temperature increases the temperature of the evaporated water vapor and the temperature difference between the ambient air and the inner side of the glass cover causes condensation. The greater the temperature difference, the higher condensation rate, resulting in higher production rates. At the glass cover temperature ($T_{g,inside}$) of 67.50ºC, the ambient air temperature at that time was 33ºC. It can be seen that the temperature difference is 34.5ºC which is quite a lot of different temperatures causes the higher condensation rate. As a result, the production rate is also higher.

Therefore, it can be seen in Table 4.5, the temperature of the salt water ($T_{w,inside}$) and the inner side of the glass cover ($T_{g,inside}$) are both high, causing the salt water in basin to higher evaporation rate and higher condensation rate consequences the production rate is the highest in all three experiments.

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CHAPTER 5
CONCLUSIONS

5.1 Conclusions

This project presents the application of desalination system for connecting to ETSC in the solar desalinated water system. From the results, the desalination system can produce the desalinated water from salt water with a concentration of 35 g/l. This tends to be able to apply to solve the water scarcity in worldwide. In addition, the desalination system can still produce desalinated water even if the salt water temperature is only 60°C with the evaporation rate approximately 130 mL/h by using inlet palm oil temperature of only 80°C. This suggests that the salt water can be used in the desalination system and can be applied to solar thermal desalination system by connecting to ETSC, but the production rate still need to be considered because of the variations of inlet palm oil temperature, which represents the instability of the solar radiation intensity in each time during the day that collected by ETSC. The evaporation rate is directly depending on the inlet palm oil temperature which is the heating medium fluid that serves as the heat source for the evaporation bath. There are some vapor leaks and the condensate drop in the middle of the path of the polycarbonate cover before reaching the water storage chute that results in the percentage of collected water from the total evaporation is approximately 51-58%.

5.2 Suggestions

- The polycarbonate plate should be completely covered at the top of the bath to prevent vapor leakage, consequently increasing the production rate.
- There are some welds leaks of the copper pipe holder between the steps that should be sealed to prevent the salt water at the higher step leaked down to the lower step that results in accumulation, consequently decreasing the heat transfer surface area.
- The evaporation bath can add more length and the length of the copper pipe will be long as well. This can maximize the heat transfer area between copper pipe and salt water surface resulting in the evaporation rate increases.

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APPENDIX

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Appendix A: Experimental results and calculation

Appendix A-1: Experimental results of the investigation of inlet palm oil temperature in the desalination system.

Table A-1-1: Data of 80ºC of inlet palm oil temperature

Table A-1-2: Data of 100ºC of inlet palm oil temperature

Table A-1-3: Data of 120ºC of inlet palm oil temperature

Appendix B: Experimental setup and results

Appendix B-1: The desalination system installation with measurements

Appendix C: Demonstration

Appendix C-1: Structure of droplet during the experiment

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Appendix A: Experimental results and calculation

Appendix A-1: Experimental results of the investigation of inlet palm oil temperature in the desalination system.

Table A-1-1: Data of 80ºC of inlet palm oil temperature

Temperature of 80ºC						
Time	Synthetic Seawater		Oil			Product
	$T_{w,inside}$ (ºC)	$T_{g,inside}$ (ºC)	Flow rate (mL/s)	$T_{o,in}$ (ºC)	$T_{o,out}$ (ºC)	Volume (mL)
14.30	30.00	30.50	21.00	31.00	30.00	0.00
15.00	32.00	32.00	21.00	67.00	31.00	0.00
15.30	46.00	39.30	21.00	80.00	48.00	0.00
16.00	53.50	45.00	21.00	80.00	57.00	2.00
16.30	57.00	53.50	21.00	80.00	61.00	38.00
17.00	59.30	53.00	21.00	80.00	63.00	75.00
17.30	59.00	54.30	21.00	80.00	63.00	113.00
18.00	60.00	54.50	21.00	80.00	64.00	150.00
18.30	60.00	54.50	21.00	80.00	64.00	188.00

Table A-1-2: Data of 100ºC of inlet palm oil temperature

Temperature of 100ºC						
Time	Synthetic Seawater		Oil			Product
	$T_{w,inside}$ (ºC)	$T_{g,inside}$ (ºC)	Flow rate (mL/s)	$T_{o,in}$ (ºC)	$T_{o,out}$ (ºC)	Volume (mL)
13.00	29.00	32.00	21.00	34.00	29.00	0.00
13.30	47.00	37.50	21.00	87.50	43.00	0.00
14.00	63.50	55.30	21.00	100.00	68.00	38.00
14.30	69.50	64.00	21.00	100.00	73.00	98.00
15.00	71.00	65.00	21.00	100.00	76.00	164.00
15.30	71.70	66.20	21.00	100.00	76.00	228.00
16.00	71.50	66.50	21.00	100.00	77.00	290.00
16.30	72.00	66.50	21.00	100.00	77.00	352.00
17.00	72.00	66.50	21.00	100.00	77.00	417.00

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Table A-1-3: Data of 120°C of inlet palm oil temperature

Temperature of 120°C						
Time	Synthetic Seawater		Oil			Product
	$T_{w,inside}$ (°C)	$T_{g,inside}$ (°C)	Flow rate (mL/s)	$T_{o,in}$ (°C)	$T_{o,out}$ (°C)	Volume (mL)
15.00	29.40	31.20	21.00	31.50	27.00	0.00
15.30	34.00	31.50	21.00	79.60	31.00	0.00
16.00	56.40	45.80	21.00	110.00	53.00	0.00
16.30	69.00	64.30	21.00	120.00	77.00	48.00
17.00	73.00	68.30	21.00	120.00	82.00	142.00
17.30	73.00	67.50	21.00	120.00	82.00	206.00
18.00	73.00	68.00	21.00	120.00	82.00	280.00
18.30	73.00	67.50	21.00	120.00	82.00	366.00
19.00	73.00	67.50	21.00	120.00	82.00	460.00

Calculation

1) Evaporation rate (For 120°C of inlet palm oil temperature)

The calculation of the evaporation rate is investigated between two parameters, there are temperature of synthetic seawater (T_w) and glass cover temperature (T_g). The calculation of the evaporation rate is depicted below.

The formulas of partial vapor with the function of temperature are as follows [5].

$$P_w = EXP\left\{25.317 - \frac{5144}{T_w + 273}\right\}$$

$$P_g = EXP\left\{25.317 - \frac{5144}{T_g + 273}\right\}$$

Where T_w obtained from the experiment of 120°C of inlet palm oil temperature is 73°C

$$P_w = EXP\left\{25.317 - \frac{5144}{73 + 273}\right\}$$

$$= 34542.5776 \text{ N/m}^2$$

And T_g is 67.50°C

$$P_g = EXP\left\{25.317 - \frac{5144}{67.50 + 273}\right\}$$

$$= 27168.2610 \text{ N/m}^2$$

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where, the convective heat transfer coefficient is obtained from an empirical relation, which is

$$h_{cwg}=0.884\left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{(268.9\times10^3 - P_w)}\right]^{1/3}$$

$$=0.884\left[(73.00 - 67.50) + \frac{(34542.5776 - 27168.2610\ )(73 + 273)}{(268.9\times10^3 - 34542.5776)}\right]^{1/3}$$

$$= 4.8288\ \mathrm{W/m^{2o}C}$$

where, the evaporative heat transfer coefficient between water and glass cover is found from

$$h_{ewg}=(16.28\times10^{-3})h_{cwg}(P_w - P_g)/(T_w - T_g)$$

$$=(16.28\times10^{-3})4.8288(34542.5776 - 27168.2610)/(73.00 - 67.50)$$

$$=105.4026\ \mathrm{W/m^{2o}C}$$

The latent heat of evaporation of water is calculated by the given expression [5].

$$L_{ev} = (2501.67 - 2.389\times T_w)\times10^3$$

And T_w is 73°C

$$L_{ev} = (2501.67 - 2.389\times73)\times10^3$$

$$= 2327273\ \mathrm{J/kg}$$

The hourly distillate per unit basin area is obtained from the relation,

$$M_w=(h_{ewg}(T_w - T_g)\times3600)/(L_{ev})$$

Substitute values into the relation

$$M_w=(105.4026\ (73.00 - 67.50)\times3600)/(2327273)$$

$$= 0.8967\ \mathrm{Kg/m^2h}$$

Area of vapor-liquid interface is 0.3 m^2 and assuming 1 kg of water is equal to 1000 mL.

Finally, the volume of evaporation rate at T_w = 73°C and T_g = 67.50°C is

$$V_{evap} = M_w\times \mathrm{Area}$$

$$= 0.8967\times0.3$$

$$= 269\ \mathrm{mL/h}$$

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The average rate of desalinated water output from experiment of 120°C of inlet palm oil temperature is

$$V_{output} = 180 \text{ mL/h}$$

And the rate of evaporation from calculation is

$$V_{evap} = 269 \text{ mL/h}$$

Then, the percentage of product collected from total vapor evaporated is

$$V_{collected} = \frac{V_{output}}{V_{evap}} \times 100$$

$$= \frac{180}{269} \times 100$$

$$= 66.91 \%$$

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Appendix B: Experimental setup and results

<u>Appendix B-1: The desalination system installation with measurements</u>

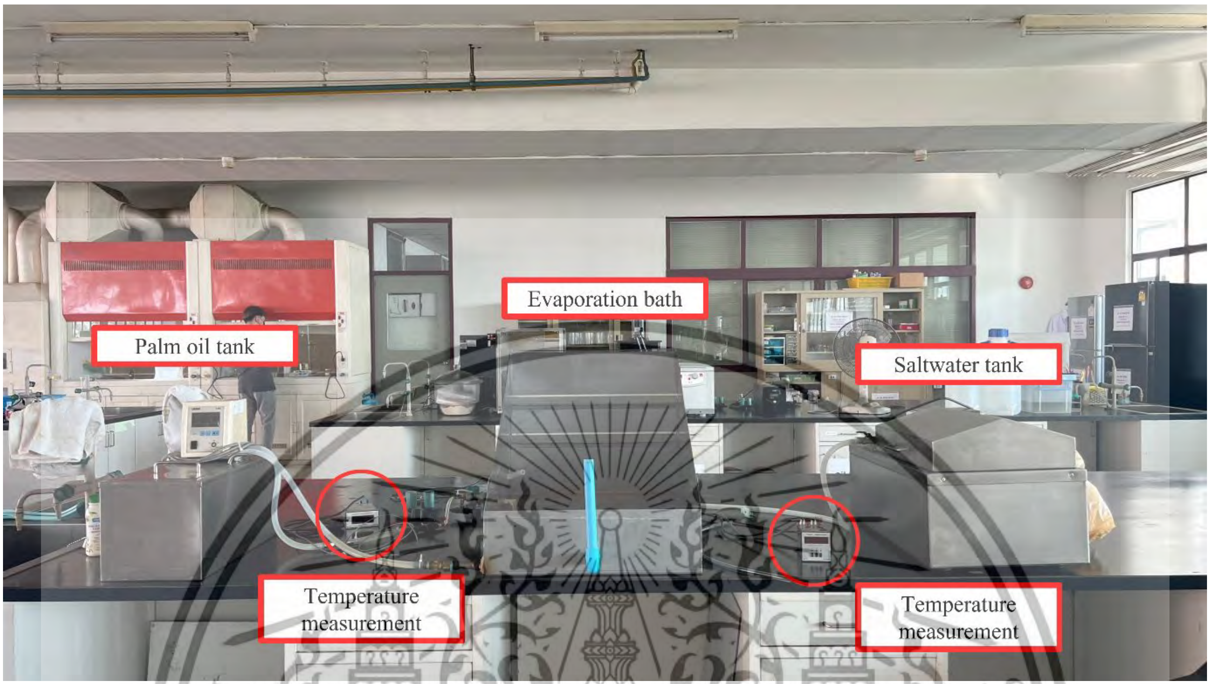

Figure B1-1 The desalination system installation with measurements

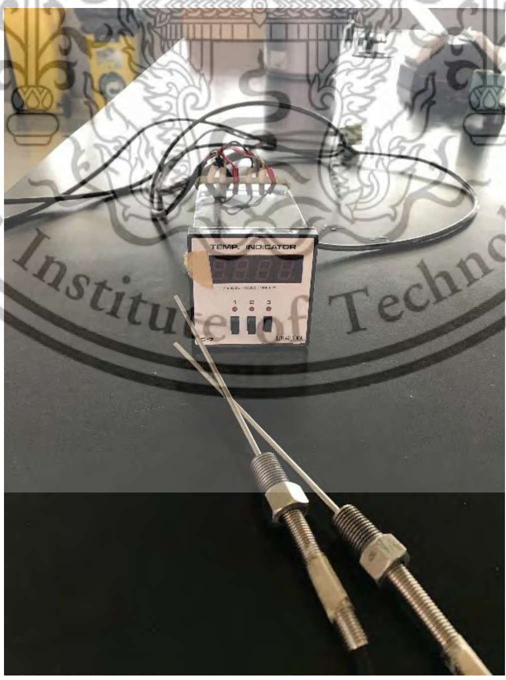

Figure B1-2 Thermocouple measures temperature of basin saltwater and inner side of glass cover.

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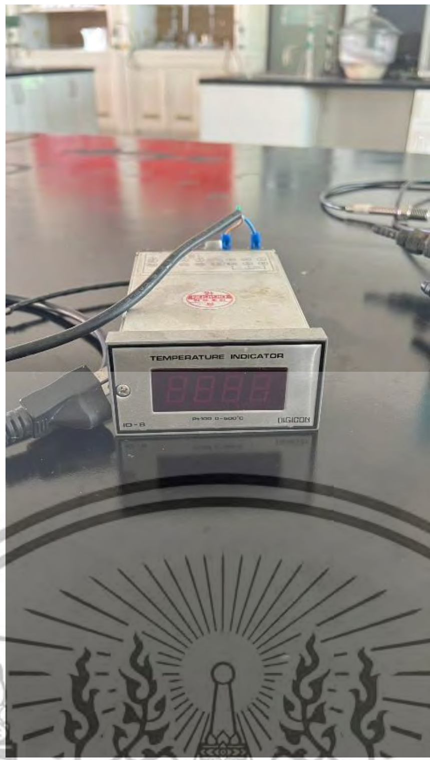

Figure B1-3 Thermocouple measures temperature of outlet palm oil

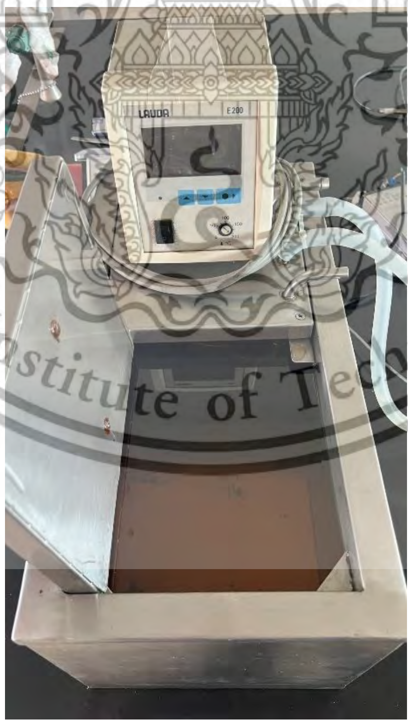

Figure B1-4 Palm oil tank with thermocouple measures temperature of inlet palm oil

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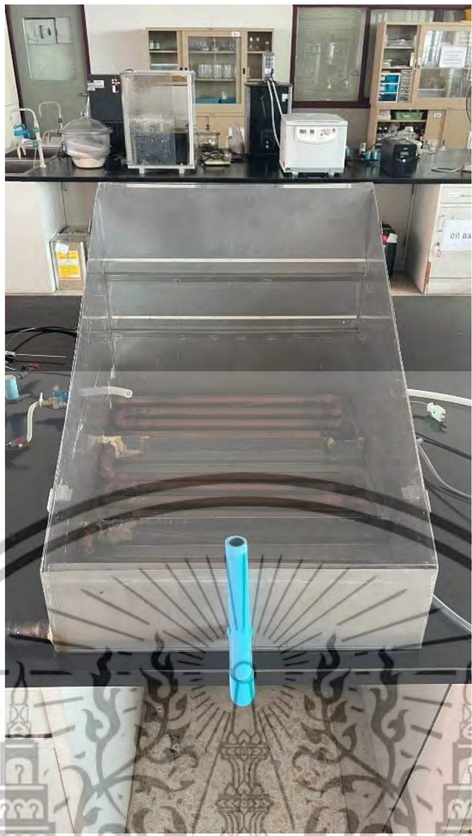

Figure B1-5 Evaporation bath with polycarbonate plate cover

Figure B1-6 Copper pipe laying structure in the evaporation bath

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Figure B1-7 Saltwater tank

Appendix C: Demonstration

<u>Appendix C-1: Structure of droplet during the experiment</u>

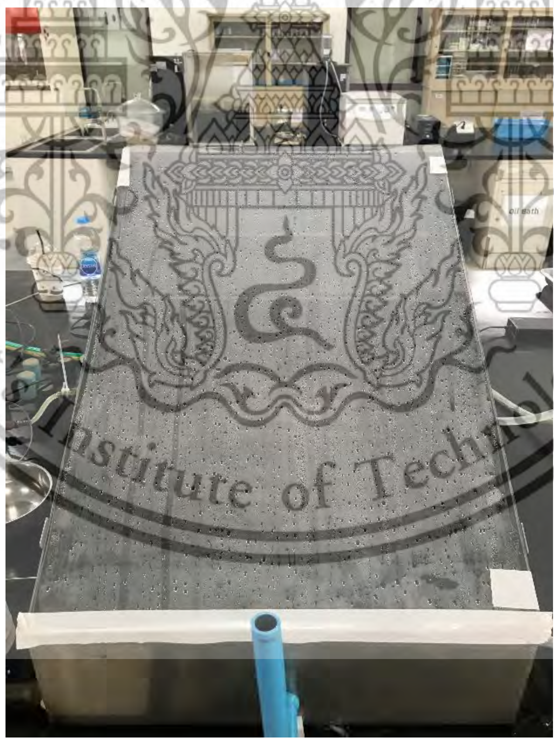

Figure C1-1 Structure of droplet in the case of 120°C of inlet palm oil temperature

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