Solar Ice Maker

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A Report Submitted in Partial Fulfillment of the Requirement
for the Degree of Bachelor of Engineering (Petrochemical Engineering)
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เครื่องทำน้ำแข็งพลังงานแสงอาทิตย์

ภานุลักษณ์ บุญเรือง

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Field of Study	Petrochemical Engineering
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บทคัดย่อ

โดยปกติแล้วตัวดูดซับและสารทำความเย็นที่มักจะถูกนำมาใช้กับระบบการทำความเย็นแบบดูดซับจากพลังงานแสงอาทิตย์คือถ่านกำมันต์ และเมทานอลตามลำดับ เมื่อวิเคราะห์ตามคุณสมบัติทางกายภาพของสารทำความเย็นพบว่าอะซิโตนที่สามารถนำมาใช้เป็นสารทำความเย็นได้เช่นกัน และจะสามารถลดอุณหภูมิได้ต่ำกว่าเมทนอลเมื่อระบบอยู่ที่ความดันเดียวกัน งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาและพัฒนาระบบการทำความเย็นแบบดูดซับจากพลังงานแสงอาทิตย์เพื่อนำมาใช้สร้างเครื่องผลิตน้ำแข็งพลังงานแสงอาทิตย์ เครื่องผลิตน้ำแข็งพลังงานแสงอาทิตย์จะประกอบไปด้วย 3 ส่วนคือ 1) แผงเก็บความร้อนพลังงานแสงอาทิตย์ 2) ถังเก็บสารทำความเย็น (ส่วนควบแน่น) และ 3) เครื่องระเหย ในส่วนของแผงเก็บความร้อนพลังงานแสงอาทิตย์จะมีขนาด 3600 ตารางเซนติเมตร ซึ่งภายในบรรจุถ่านกำมันต์ 1220 กรัม และสารทำความเย็น 244 กรัม ระบบนี้ถูกทดสอบในช่วงเดือนมีนาคม – เมษายน 2562 ที่ภาควิชาวิศวกรรมเคมี ณ สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง ผลลัพธ์จากการทดลองแสดงให้เห็นว่า เครื่องผลิตน้ำแข็งพลังงานแสงอาทิตย์สามารถผลิตน้ำแข็งได้ 15 กรัม และมีค่าประสิทธิภาพการทำความเย็นเท่ากับ 0.001 อย่างไรก็ตามระบบนี้ยังไม่สามารถทำงานเป็นวัฏจักร ได้อย่างสมบูรณ์

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Title Solar Ice Maker

By Mr. Panuluk Boonreung

Advisor Asst. Prof. Dr. Nuttapol Lerkkasemsan

Field of Study Petrochemical Engineering

Abstract

The adsorbent and refrigerant used in the solar adsorption refrigeration system are generally activated carbon and methanol, respectively. The analysis of physical properties of refrigerant indicates that acetone are also able to be refrigerant. Furthermore, it can more decrease temperature of system than methanol while the system is operated at the same pressure. The objective of this research is to study and develop the solar adsorption refrigeration system for construction of the solar ice maker. The solar ice maker consists of 3 main parts consisting of 1) Solar collector, 2) Refrigerant tank (condenser), and 3) Evaporator. The solar collector with a size of 3600 cm^2 is loaded 1220 g and 244 g of activated carbon and acetone, respectively. This system is experimented in March – April 2019 at Department of Chemical Engineering, King Mongkut's Institute of Technology Ladkrabang. The results shows that 15 g of ice and 0.001 of COP are produced by this system. However, this system cannot be completely operated as a cycle.

Keywords: Activated Carbon, Acetone, Solar Collector, Refrigerant tank, Evaporator, COP.

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Nomenclature

COP Coefficient of performance

Q_{ads} The amount of received heat from adsorbent bed, (kJ)

Q_{evap} The amount of removed heat from evaporator, (kJ)

A The exposure area, (m^2)

$\hat{m}_{Acetone}$ The mass flow rate of acetone, (kg)

V_{solar} The volume of solar collector, (m^3)

V_{AC} The volume of activated carbon, (m^3)

V_{evap} The volume of evaporator, (m^3)

V_{TANK} The volume of refrigerant tank, (m^3)

r_{evap} The time of refrigerant movement from evaporator to solar collector, (s)

r_{ads} The adsorption capacity of refrigerant on adsorbent

P The operating pressure of the system, (kPa)

T The desired temperature of the system, (K)

$\hat{v}$ The specific volume of refrigerant, (m^3/kg)

T_c The critical temperature of refrigerant, (K)

P_c The critical pressure of refrigerant, (kPa)

R Gas constant, (8.314 kJ/kg.K)

L_T The length of each edge of the refrigerant tank, (m)

$\rho_{Acetone}$ Density of acetone, (kg/m^3)

ρ_R Density of refrigerant, (kg/m^3)

ρ_{AC} Density of activated carbon, (kg/m^3)

ρ_{ads} Density of adsorbent, (kg/m^3)

$m_{Acetone}$ The mass of acetone, (kg)

m_R The mass of refrigerant, (kg)

m_{AC} The mass of activated carbon, (kg)

m_{ads} The mass of adsorbent, (kg)

L_C Thickness of acrylic plate, (m)

L_{mat} Thickness of cover material, (m)

L_G Height of gap between adsorbent and cover material, (m)

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L_{AC}	Thickness of activated carbon, (m)
L_{ads}	Thickness of adsorbent, (m)
L_S	The length of solar collector, (m)
Q_{solar}	Heat flux from solar energy, (W/m^2)
Q_{abs}	Heat flux absorbed by activated carbon, (W/m^2)
$Q_{release}$	Heat flux released to environment, (W/m^2)
R_{gap}	The thermal resistance of gap, (K/W)
$R_{material}$	The thermal resistance of material, (K/W)
k_{AC}	Thermal conductivity of activated carbon, (W/m.K)
k_G	Thermal conductivity of gap (acetone is between gap), (W/m.K)
k_C	Thermal conductivity of acrylic plate, (W/m.K)
k_{mat}	The thermal conductivity of material, (W/m.K)
k_{gap}	The thermal conductivity of gap, (W/m.K)
T_1	Surface temperature of activated carbon, (K)
T_2	Surface temperature of inner acrylic plate, (K)
T_3	Surface temperature of outer acrylic plate, (K)
$H_{vap,Acetone}$	Latent heat of acetone, (kJ/kg)
$H_{vap,R}$	The latent heat of refrigerant at the operating pressure, (kJ/kg)
$(H)_{fusion}$	The heat of fusion of cooling load, (kJ/kg)
m_c	The mass of cooling load (water), (kg)
$C_{P,l}$	The heat capacity of cooling load in liquid phase, (kJ/kg.K)
$C_{P,s}$	The heat capacity of cooling load in solid phase, (kJ/kg.K)
ΔT	The change in temperature, (K or ^oC)

Subscripts

ads	Adsorption	*C*	Acrylic plate
evap	Evaporation	*R*	Refrigerant
vap	Vaporization	*mat*	Material
solar	Solar	*G or gap*	Gap
TANK or T	Tank	*S*	Solar collector
AC	Activated carbon	*release*	Release
Acetone	Acetone	*fusion*	Fusion
c	Critical point or cooling load	*l*	Liquid
s	Solid		

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CHAPTER I
INTRODUCTION

1.1 Background

The adsorption refrigeration system has been discovered in 1960s [1]. It is different from the vapor compression refrigeration system. The vapor compression system transform electrical energy to be mechanical energy and drive compressor, respectively [2]. The compressor compress a refrigerant to increase its temperature and remove its heat to environment. Then, the refrigerant pass through an expansion device to reduce its temperature. Therefore, the refrigerant is able to absorb heat from environment and cooling effect will occur. After it absorbed, it will pass to compressor and repeat step as a cycle. Nevertheless, the adsorption system directly consumes heat from heat source to drive a refrigerant from absorbent bed to evaporator. After the absorbent bed has been heated, it cools down and then the refrigerant returns from evaporator to absorbent bed. Thus, the cooling effect will occur at the evaporator.

The solar energy can be used as heat source for the adsorption refrigeration system so, this system is suitable for tropical zone or remote areas in developing countries that electricity is not available [2]. In the remote areas, the refrigeration system is essential for various application such as preservation of agricultural crops and vaccine [2]. However, the vapor compression refrigeration system is unsuitable for this area where electricity is not available. Therefore, the adsorption refrigeration system with solar energy is more attractive than another system. The construction of solar adsorption refrigeration system consists of 4 main parts [2],[3]. The 1st part is absorbent bed or solar collector containing solid absorbent and refrigerant. The 2nd part is a condenser and refrigerant tank. The 3rd part is expansion device and the last one is evaporator. The efficiency of this system generally depends on solar collector, adsorbent, and refrigerant.

The previous researches show that the maximum coefficient of performance (COP) of adsorption refrigeration system was equal to 0.2 approximately [3]. This COP is very low compared with the vapor compression system. Furthermore, the adsorption refrigeration system can be operated only 1 cycle per day that means the cooling effect will occur at night time because at this time the absorbent bed does not receive heat from heat source. Although, the potentiality of the adsorption refrigeration system is lower than the vapor compression system when they are compared with the result of

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their cooling effect. However, the form of energy that is used in the vapor compression system is electrical energy form which is high cost energy and improbability for every areas. Meanwhile, another system consumes only heat from the sun for operation.

The aim of this work is study about the principle of solar adsorption refrigeration system for the design of solar ice maker. The solar ice maker is expected to produce 300 g of ice per day.

1.2 Objectives

1.2.1 To study and develop the principle of solar adsorption refrigeration system for design of the solar ice maker.

1.2.2 To construct the solar ice maker for ice making.

1.3 Scopes of work

1.3.1 A suitable solar collector, refrigerant tank, and evaporator will be designed.

1.3.2 A proper adsorbent and refrigerant will be selected.

1.3.3 A water is used as a cooling load in evaporator of this system. The cooling load is used for measuring the solar ice maker potentiality.

1.4 Expected Outputs

1.4.1 The each equipment of solar ice maker is completely designed.

1.4.2 The solar ice maker can produce 300 g of ice per day.

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CHAPTER II
THEORY AND LITERATURE REVIEW

2.1 Theory

2.1.1 The working principle of adsorption refrigeration system

The adsorption refrigeration system is a type of refrigeration system. It is different from another system because it directly consumes only heat for operation while another system consumes mechanical and electrical energy for operation. This system contains 4 main parts. The 1st part is absorbent bed containing solid adsorbent and refrigerant inside. The 2nd part is condenser and refrigerant tank. The 3rd part is expansion device and the last one is evaporator. In addition, the operation of this system can be explained by Clapeyron diagram shown in the Figure 1.

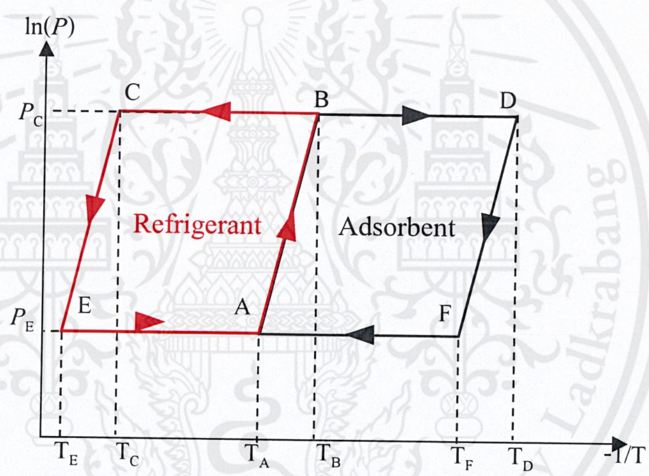

Figure 1: Clapeyron diagram [3]

The Figure 1 shows the condition of refrigerant and adsorbent in the system. The operation begins at the point A. At this point, the refrigerant will adsorb on the surface of adsorbent in adsorbent bed at the condition of T_A and P_E. Then, the system will be heated by heat source, thus the temperature and pressure will be increased to T_B and P_C at the point B, respectively. During the change of system from point A to point B, the refrigerant will vaporize from the adsorbent surface in the adsorbent bed. The operation from A to B is called "Isosteric Heating". After that, the bed will be heated continuously which affects to increasing temperature of the bed to T_D. Meanwhile, the pressure of system is still constant due to the vapor refrigerant will be driven to a condenser by the difference between temperatures in adsorbent bed and condenser. Due

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to the temperature of condenser (T_C) is lower than adsorbent bed, so the refrigerant will be condensed to liquid phase. The operation from point B to C of refrigerant and from point B to D of adsorbent bed are called “Isobaric Heating”.

After the adsorbent has been heated already, it will be cooled down which results to decreasing temperature of the bed from T_D to T_F. In addition, pressure of the system will decrease from P_C to P_E. At the same time, the liquid refrigerant in condenser will be fed to evaporator through expansion device for reducing the temperature and pressure of refrigerant. In the evaporator, the temperature and pressure will be T_E and P_E. This process is called “Isosteric Cooling”. At the temperature of T_E, the refrigerant can absorb heat from evaporator and vaporize to vapor phase. It effects to decreasing the temperature in evaporator but the refrigerant temperature increases from T_E to T_A. At this moment, the temperature of adsorbent bed require to reduce until it equals the temperature at point A or T_A. Otherwise, the vapor refrigerant from evaporator cannot adsorb on the surface of adsorbent and the cooling effect will not occur. Finally, the last process is called “Isobaric cooling”.

Due to the adsorption refrigeration system consumes only heat for operation. In addition, enormous heat source is solar energy. Therefore, the adsorption refrigeration system can be combined with a solar energy storage and become the solar adsorption refrigeration system.

2.1.2 Adsorbent and Refrigerant

The adsorbent and refrigerant are important coupled materials in the adsorption refrigeration system. The selection of them influence on the operating condition of the system. They can limit the lowest operating pressure and temperature of the system while the cooling effect is occurring in evaporator. Furthermore, they also affect to designed temperature for desorption of refrigerant from adsorbent in adsorbent bed. The selection of adsorbent and refrigerant can be analyzed by the criteria following [4];

- Refrigerant

1) The vapor pressure of refrigerant should be high enough. Therefore, the system does not require too low pressure to operate.

2) The latent heat of refrigerant should be high enough to be able to more remove heat in evaporator.

3) The refrigerant should be chemically stable during operating.

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4) The thermal conductivity of refrigerant should be high enough to be able to rapidly absorb heat.

5) The refrigerant should not corrode with system.

- Adsorbent

1) The adsorbent should adsorb more refrigerant at low temperature (room temperature) and mostly desorb at high temperature.

2) If the system is operated with physical adsorption, the adsorbent and refrigerant should not react together. Nevertheless, if the chemical adsorption is used, the chemical reaction of adsorption should be stable.

3) The thermal conductivity of adsorbent should be high enough to operate with shorten cycle.

4) The adsorbent should be stable and non-deterioration.

The widely adsorbent and refrigerant are activated carbon/methanol, silica gel/water and activated carbon/ammonia etc. The research of M. Li *et al*. [5] indicated that the coefficient of performance (COP) that is done by their system is between 0.12 – 0.13. Methanol and activated carbon are used in their system as refrigerant and adsorbent, respectively. Their system with 0.94 m^2 of plate solar collector can produce 4.0 – 4.5 kg of ice per day.

2.1.3 The construction of adsorption refrigeration system

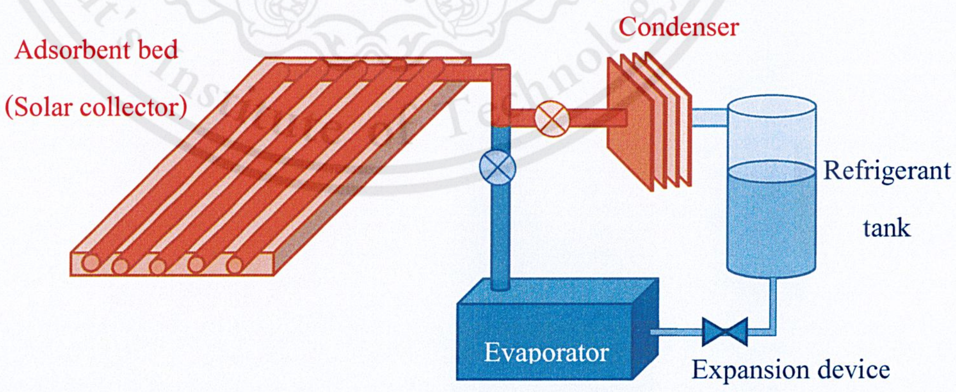

Figure 2: Schematic of solar adsorption refrigeration system

The system consists of 4 mains equipment containing 1) adsorbent bed, 2) condenser and refrigerant tank, 3) expansion device, and 4) evaporator. The absorbent bed is the main equipment of this refrigeration system as it is used in order to collect a

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heat from heat source for operation. Generally, a solar collector is used as an absorbent bed because it can collect heat from solar energy which is low cost energy. In the adsorbent bed, it will be loaded by refrigerant and solid adsorbent. The typical types of solar collector has 3 types consisting of 1) Plate collector, 2) Parabolic solar collector, and 3) Tube collector. The condenser are used in order to condense refrigerant vapor from adsorbent bed and decrease refrigerant temperature. Then, the refrigerant will be kept in the tank. The expansion device is a device that can reduce pressure and temperature of refrigerant before it will be fed to evaporator. In the evaporator, the refrigerant will absorb heat from cooling load and reduce temperature in evaporator.

2.1.4 The performance of adsorption refrigeration system

The coefficient of performance (COP) is a value used for measuring of the refrigeration efficiency. It is calculated by the ratio of the amount of removed heat from evaporator (Q_{evap}) to the amount of received heat from adsorbent bed (Q_{ads}).

$$COP = \frac{Q_{evap}}{Q_{ads}} \qquad (1)$$

The amount of received heat from adsorbent bed (Q_{ads}) is calculated from different methods depending on the type of heat sources. For example, if the solar energy is used as a heat source, it will be estimated by the equation following;

$$Q_{bed} = \int_{t_1}^{t_2} A \cdot \dot{q}(t)dt \qquad (2)$$

where: A = the exposure area, (m^2)

$\dot{q}(t)$ = the flux of solar energy, ($W/m^2.s$)

t = time, (s) mxyzptlk

The amount of removed heat from evaporator (Q_{evap}) is estimated by the decrease of temperature and heat of fusion of cooling load in evaporator by the equation following[6],[7];

$$Q_{evap} = m_c C_{p,l}(\Delta T) + m_c(H)_{fusion} + m_c C_{p,s}(\Delta T) \qquad (3)$$

where: m_c = the mass of cooling load, (kg)

$C_{P,l}$ = the heat capacity of cooling load in liquid phase, (kJ/kg.K)

ΔT = the change in temperature, (K or ^{o}C)

if the cooling load change from liquid to solid phase

$C_{P,s}$ = the heat capacity of cooling load in solid phase, (kJ/kg.K)

$(H)_{fusion}$= the heat of fusion of cooling load, (kJ/kg)

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2.2 Literature Review

The solar adsorption refrigeration system has been developed by many researchers for 60 years. The researchers use the basic of adsorption refrigeration principle to design the solar adsorption refrigeration system but it is designed in various forms. In Indonesia, Himsar Ambarita [2] designed the system by using methanol and mix of activated carbon/activated alumina as refrigerant and adsorbent, respectively. Their system with 0.25 m^2 of plate collector as an adsorbent bed can produce cold water at the temperature of 6 – 10 °C. The 0.054 – 0.074 of COP can be produced by their system. The system of K. Sumathy *et al* [8] collector was constructed by loading activated carbon and methanol as adsorbent and refrigerant, respectively. They reported that their system with 0.94 m^2 of solar collector could produce 4 - 5 kg of ice per day and COP of 0.1. M. Li *et al* [5] constructed the system as same as the system of K. Sumathy. Nevertheless, their system was tested 2 times. In the first times, was tested with Quartz lamp (17.3 – 19.24 MJ) as a heat source in laboratory room. The result indicated that 6 – 7 kg of ice and COP of 0.137 - 0.146 could be produced by their system. Furthermore, their system was tested with real solar radiation (16.28 – 17.10 MJ) in the second part. The results indicated that 4.0 - 4.5 kg of ice per day and 0.12 - 0.13 of COP were produced by their system. The system that used activated carbon and methanol as adsorbent and refrigerant also designed by N.M. Khattab *et al* [9]. Activated carbon and methanol were loaded into adsorbent bed that characterized capsule. The capsule was heated by solar reflector. The designed reflector is adjustable to receive maximum solar energy at any interval of time. Their system was tested under climatic condition of Cairo (18 – 20 MJ/m^2.day). The results showed that 6.9 – 9.4 kg of ice per day and 0.136 – 0.159 of COP were obtained from their system. M. Pons and J.J. Guilleminot [10] developed new solar ice maker by using 130 kg of activated and 18 kg of methanol as adsorbent and refrigerant, respectively. Their system with 6 m^2 of solar collector was tested in Orsay (August 29th, 1984). The result of this system showed that it could produce 30 – 35 kg of ice per day and 0.12 of COP was produced by their system. Furthermore, activated carbon and methanol were also used as adsorbent and refrigerant, respectively in the system of E.E. Anyanwu a and C.I. Ezekwe [11]. This system used a flat plate as a solar collector. The solar collector with area of 1.2 m^2 contained 6 tubes which each tube was loaded with 1.4 kg of activated carbon and 0.3 kg of methanol. This system could reduce the temperature of 3 kg of water from room

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temperature to be 1°C. It meant that this system could approximately remove 260 kJ of heat from cooling load. In addition, 0.22 of COP was obtained from this system.

Other adsorbent and refrigerant that was widely used are salts and Ammonia (NH_3), respectively. S. A. Anjorin & E. I. Bello [12] developed the system by using a mixed adsorbent consisting of 1) 70% of $CaCl_2$, 2) 10% of activated carbon and 3) 20% of $CaSO_4$ and using NH_3 as refrigerant. The experiment was tested in Akure, Nigeria. During the experiment, the range of ambient temperature and solar radiation were 23 °C – 28 °C and 319 W/m^2 – 471 W/m^2, respectively. The result showed that their system could produce 0.49 – 0.63 kg of ice per day. The COP of this system was between 0.021 – 0.033. Anadi Mondal [13] developed the system by using NH_3 and $CaCl_2$ as a refrigerant and adsorbent, respectively. The adsorbent and refrigerant were contained into the solar collector while 8 kg of water was loaded into evaporator as a cooling load. The type of this collector is parabolic solar collector. The experiment was carried out in Khulna, Bangladesh which the ambient temperature and solar intensity were 25°C - 35 °C and 700 – 760 W/m^2, respectively. The results showed that their system can produce chilled water at temperature of 4°C – 8.5°C. The COP of their system was between 0.104 – 0.126. C. Li *et al* [14] focused on production of 50 kg of ice per day with 36 m^2 of the parabolic trough collector (PTC). Their system was tested in Shanghai. In this system, the adsorbent consisted of 6 kg of AC and 24 kg of $CaCl_2$ and NH_3 was used as a refrigerant. The adsorption between adsorbent and refrigerant was chemical adsorption. The results showed that their system could produce 30 kg of ice per day and the value of system's COP was 0.21. Moreno-Quintanar *et al* [15] developed a solar intermittent refrigeration system at the Centro de Investigación en Energía of the Universidad Nacional Autónoma de México. Their system contained $NH_3/LiNO_3/H_2O$ which NH_3 was used as a refrigerant. The system used a Compound Parabolic Concentrator (CPC) with a cylindrical receiver acting as a solar collector. The results showed that the evaporator temperature was lower than -11°C for a period higher than 8 hours. In addition, the COP of their system was 0.06 - 0.098. Hildbrand *et al* [1] built a solar refrigerator in Yverdon-les-Bains. The experiment was started from July 25th 2001 to September 30th 2001. The system contained silica gel and water as adsorbent and refrigerant, respectively. The results showed that their system could produce 40 L of ice per day in the evaporator. Furthermore, the COP of their system was 0.13. The silica gel and water was used the system of Fatih Bouzeffou *et al*[16]. Their system with 0.63 m^2 of solar collector could produce chilled water at the

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temperature of 5 °C. In the solar collector, 4.5 kg of silica gel was loaded in the tubes. Their system was tested in the weather conditions of Bou-Ismail, Algeria (the average solar intensity was equal to 800 MJ/m^2). 0.09 of COP was received from this system.

2.3 Design of the Solar Ice Maker

2.3.1 Mass of refrigerant

The mass of refrigerant can be estimated from the equation following;

$$m_R = \frac{Q_{evap}}{H_{vap,R}} \quad \text{(4)}$$

where Q_{evap} = the removed heat in evaporator is estimated by equation (3), (kJ)

m_R = the mass of refrigerant, (kg)

$H_{vap,R}$ = the latent heat of refrigerant at the operating pressure, (kJ/kg)

2.3.2 Mass of adsorbent

The mass of adsorbent can be estimated from the equation following;

$$m_{ads} = \frac{m_R}{r_{ads}} \quad \text{(5)}$$

where m_{ads} = the mass of adsorbent, (kg)

r_{ads} = the mass ratio of refrigerant to adsorbent (depend on the surface area of adsorbent).

2.3.3 Design of operating condition

The operating condition is designed by the thermodynamics properties of refrigerant. It means that if the desired temperature is T_E, the pressure of system, when the refrigerant absorb on adsorbent, is the vapor pressure of refrigerant at the temperature of T_E. This pressure is operating pressure which it can be calculated by Antoine equation [17].

$$P = \exp\left(A - \frac{B}{T + C}\right) \quad \text{(6)}$$

where P = the operating pressure of the system, (kPa)

T = the desired temperature of the system, (K)

A, B, and C are the constant values depending on material.

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2.3.4 Design of solar collector

The solar collector will be designed based on the adsorption properties of adsorbent and refrigerant. Due to the temperature generated by solar collector at daytime has to be high enough for desorption of refrigerant from adsorbent. Nevertheless, this temperature must not affect to deterioration of refrigerant. Furthermore, the solar collector should rapidly remove heat at nighttime and its temperature should be low enough for adsorption of refrigerant on adsorbent. These condition leads to the design of material for solar collector. The thermal conductivity of material is important property for selection. It is estimated by the below equation.

Heat transfer calculation of solar collector

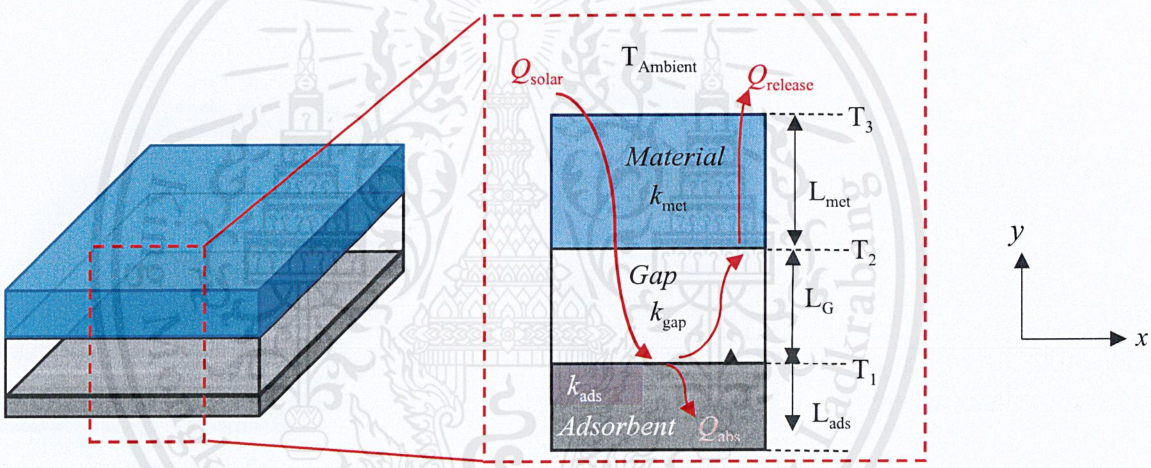

Figure 3: Schematic of Heating of solar collector by solar radiation at daytime

Assumption: 1) Heat transfers only *y*-direction.

2) This phenomena is calculated at steady state.

$$Q_{loss} = \frac{T_{AC} - T_{m,o}}{R_{total}} \quad \text{..........} (7)$$

$$R_{total} = R_{gap} + R_{Material} \quad \text{..........} (8)$$

$$R_{total} = \frac{L_G}{k_{gap}A} + \frac{L_{mat}}{k_{mat}A} \quad \text{..........} (9)$$

$$A = \frac{m_{ads}}{d_{ads}\rho_{ads}} \quad \text{..........} (10)$$

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$$Q_{release} = Q_{solar} - Q_{abs} \quad (11)$$

$$Q_{solar} = \varepsilon A \cdot \dot{q}(t) \quad (12)$$

where: A = the exposure area, (m^2)

$\dot{q}(t)$ = the flux of solar energy, (W/m^2)

Q_{solar} = Heat flux from solar energy, (W/m^2)

$Q_{release}$ = the heat transfer from solar collector to ambient, (W)

Q_{abs} = Heat flux absorbed by activated carbon, (W/m^2)

t = time, (s)

R_{gap} = the thermal resistance of gap, (K/W)

$R_{material}$ = the thermal resistance of material, (K/W)

L_G = thickness of gap, (m)

L_{mat} = thickness of cover material, (m)

L_{ads} = thickness of adsorbent, (m)

k_{gap} = the thermal conductivity of gap, (W/m.K)

k_{mat} = the thermal conductivity of material, (W/m.K)

m_{ads} = the mass of adsorbent, (kg)

ρ_{ads} = the density of adsorbent, (kg/m^3)

T_1 = Surface temperature of activated carbon, (K)

T_2 = Surface temperature of inner acrylic plate, (K)

T_3 = Surface temperature of outer acrylic plate, (K)

2.3.5 Design of refrigerant tank

The volume of refrigerant tank can be estimated by the ratio of mass of refrigerant to its density which can be expressed as the equation following;

$$V_{TANK} = \frac{m_R}{\rho_R} \quad (14)$$

where V_{TANK} = the volume of refrigerant tank, (m^3)

ρ_R = the density of refrigerant, (kg/m^3)

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2.3.6 Design of evaporator and expansion device

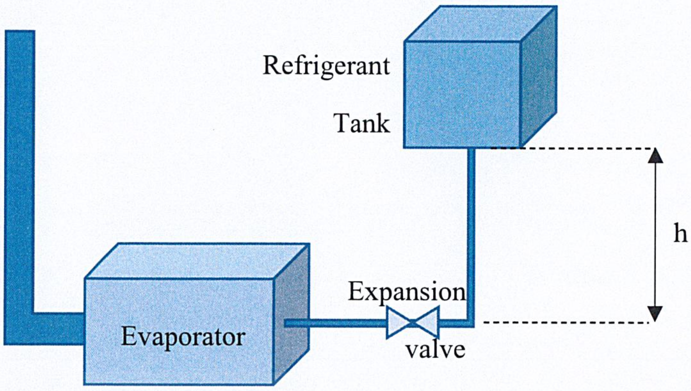

Figure 4: Schematic of refrigerant tank, expansion valve, and evaporator

The volume of evaporator can be estimated from the ratio of mass to specific volume in gas phase of refrigerant at the operating pressure. The specific volume in gas phase is necessary to design because the refrigerant has to vaporize as soon as possible in evaporator. In addition, the rapid vaporization will affect to the reduction of heat in evaporator. However, if the vaporization is too slow, the partial liquid of refrigerant will remain in the evaporator and then the cooling effect will do not occur. The specific volume can be obtained from the P-v diagrams or equation of state.

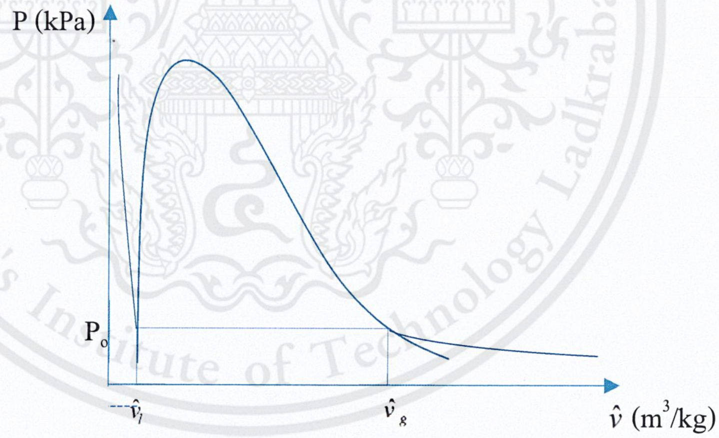

Figure 5: P-*v* diagrams

The Peng-Robinson equation of state is used for estimation and it can be expressed following [17];

$$P = \frac{RT}{\hat{v}-b} - \frac{a(T)}{(\hat{v}+\varepsilon b)(\hat{v}+\sigma b)} \quad (15)$$

$$a(T) = \psi \frac{\alpha(T_r) R^2 T_c^{\,2}}{P_c} \quad (16)$$

$$b = \Omega \frac{RT_c}{P_c} \quad (17)$$

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$$T_r = \frac{T}{T_c} \quad \text{...(18)}$$

$$\alpha(T_r) = [1 + (0.3764 + 1.54226\omega - 0.26992\omega^2)(1 - T_r^{1/2})]^2 \quad \text{...(19)}$$

where P = the operating pressure of the system, (kPa)

T = the desired temperature of the system, (K)

$\hat{v}$ = the specific volume of refrigerant, (m^3/kg)

T_c = the critical temperature of refrigerant, (K)

P_c = the critical pressure of refrigerant, (kPa)

R = gas constant, (8.314 kJ/kg.K)

$\varepsilon = 1 - (2)^{0.5}$, $\sigma = 1 + (2)^{0.5}$, $\Omega = 0.07780$, $\omega = 0.564$, $\psi = 0.45724$

After the specific volume of refrigerant has been calculated, the volume of evaporator (V_{evap}) can be estimated by the equation following;

$$V_{evap} = r_{evap} \cdot \hat{v} \cdot \hat{m}_R - V_{solar} \quad \text{...(20)}$$

where $\hat{m}_R$ = the entrance mass of refrigerant in evaporator, (kg)

V_{solar} = the volume of solar collector, (cm^3)

r_{evap} = the time of refrigerant movement from evaporator to solar collector, (s)

The entrance mass of refrigerant in evaporator come from the refrigerant tank through expansion device. The entrance mass of refrigerant will be controlled by the expansion valve. The expansion valve will help to reduce the volume of evaporator.

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CHAPTER III
EXPERIMENTAL

3.1 Research Question

The first step of the project is selection of an interesting topic relating with the knowledge that is studied in the bachelor degree of petrochemical engineering. Furthermore, the topic should be benefit for humanity. The topic of this project is the construction of solar ice maker. The solar ice maker will be designed by using the basic principle of the adsorption refrigeration system and thermodynamics. It is expected that 300 g of ice per day will be produced from this system.

3.2 Study of the principle of adsorption refrigeration system

From the study, it indicates that this system can be explained by the Clapeyron diagram. In the diagram, it shows that the cycle of system contains 4 steps including 1) Isosteric Heating, 2) Isobaric Heating, 3) Isosteric Cooling and 4) Isobaric cooling. In the system, it contains adsorbent and refrigerant. The widely used adsorbent is activated carbon and salt while general refrigerant is methanol and ammonia.

3.3 Selection of adsorbent and refrigerant

In this project, activated carbon is used as an adsorbent. In addition, there are 2 suitable refrigerants for this adsorbent that are methanol and acetone. The latent heat of methanol is higher than acetone. However, acetone can be theoretically operated at higher pressure than methanol for ice making. Furthermore, methanol and acetone are reasonable for using with solar ice maker for human because they are non-toxic materials. The activated carbon is used because it can be adsorbed by both refrigerant at the temperature below 40 ^{o}C and desorbed at the temperature above 80 ^{o}C.

3.4 Selection of solar collector

The operating condition of adsorbent and refrigerant in this system requires temperature above 80 ^{o}C at daytime and requires temperature below 40 ^{o}C at nighttime. Therefore, the type of solar collector and its material should be appropriately chosen. The solar collector type will be analyzed from packing of adsorbent and refrigerant. The material will be selected from the thermal conductivity.

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3.5 Design of operating condition

The objective of this project is production of 300 g of ice per day. It means that the desired temperature of refrigerant should be -10 °C in order to absorb heat from water or cooling load in evaporator. The operating pressure can be estimated from the equation (6)

Calculation of the operating pressure of methanol

Parameter[17]*: T = -10 °C = 263.15 K, A = 16.5785, B = 3638.27, C = -33.650*

Solve:
$$P = \exp\left(16.5785 - \frac{3638.27}{263.15 - 33.650}\right)$$

Therefore: $P \approx 2\ kPa$

Calculation of the operating pressure of acetone

Parameter[17]*: T = -10 °C = 263.15 K, A = 14.3145, B = 2756.22, C = -45.090*

Solve:
$$P = \exp\left(14.3145 - \frac{2756.22}{263.15 - 45.09}\right)$$

Therefore: $P \approx 5\ kPa$

3.6 Investigation of operating condition and design parameter

After the operating condition has been calculated, it necessary to investigate in laboratory room to confirm that this condition can be used. Furthermore, the important design parameters is the mass ratio of adsorbed refrigerant to activated carbon. This parameter is used for design of adsorbent mass and size of solar collector.

3.6.1 Investigation of operating condition

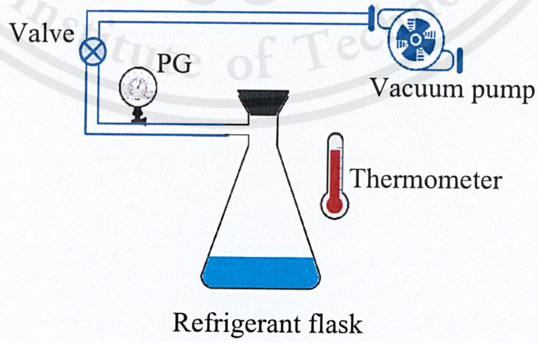

Figure 6: Experiment for investigation of operating condition

1) Measure the volume and mass of refrigerant and fill it into the flaks.

2) Assemble the equipment follow as shown in the Figure 6.

3) Reduce the pressure of system until it is equal to the operating pressure.

4) Measure the temperature of refrigerant at this pressure.

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3.6.2 The mass ratio of adsorbed refrigerant to activated carbon

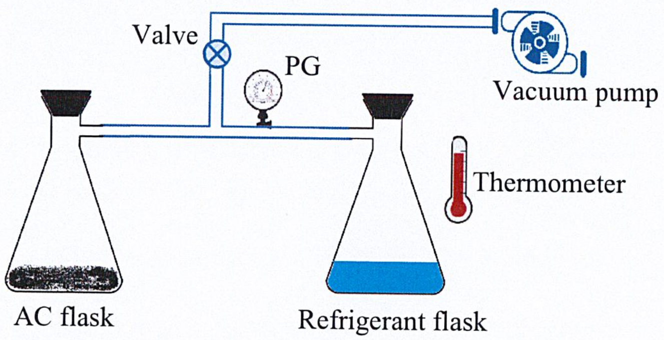

Figure 7: Experiment for investigation of design parameter

1) Weight a mass of activated carbon.

2) Fill the refrigerant and activated carbon into the each flasks and assemble the equipment as shown in the Figure 7.

3) Reduce the pressure of system until it is equal to the operating pressure and then close the valve.

4) Wait and observe the volume of refrigerant until it is constant.

5) Increase the pressure of the system and unstick the equipment.

6) Weight a mass of activated carbon again.

7) Calculate the mass of refrigerant adsorbed on the activated carbon.

8) Calculate the mass ratio of adsorbed refrigerant to activated carbon by using the equation (5).

3.7 Design of the solar ice maker

The parameter from laboratory test and properties of materials are used in order to design each part of solar ice maker. There are 3 main parts of the solar ice maker consisting of solar collector, refrigerant tank (condenser), and evaporator.

3.8 Construction of the solar ice maker

The solar ice maker will be constructed by technicians.

3.9 Testing and improvement of the solar ice maker

The solar ice maker will be tested in the 2nd semester. However, if the machine cannot produce 300 g of ice per day, it will be improved.

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CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Laboratory Part

4.1.1 Selection of adsorbent and refrigerant

Table 1: Physical properties of refrigerant

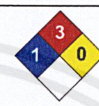
Physical properties	Refrigerant	
	Methanol	Acetone
Saturated pressure at -10°C (kPa)	2.5	5.0
Latent heat at -10°C (kJ/kg)	1211	564
Toxicity		
Thermal conductivity (W/m.K)	0.20	0.18
Density (kg/m^3)	792	784

Table 2: Compatibility between adsorbent and refrigerant

Adsorbent / Refrigerant	Activated Carbon (ID > 1000)	
	Adsorption capacity (%w/w)	Temperature of desorption (°C)
Methanol	19	75
Acetone	24	70
Adsorbent / Refrigerant	**Calcium chloride (purity = 75%)**	
	Adsorption capacity (%w/w)	**Temperature of desorption (°C)**
Methanol*	22	-
Acetone*	0	-

From the Table 1, it showed that methanol and acetone was able to be used as refrigerant in this experiment. In addition, the Table 2 showed that the reasonable adsorbent for the both refrigerants was activated carbon. The activated carbon could adsorb methanol and acetone at the mass percentage of 19% and 24%, respectively. Moreover, the both refrigerants could be desorbed when the temperature was higher than 75°C. This temperature could be generated from the typical solar collector. However, the calcium chloride could not be used as adsorbent due to the refrigerants reacted with the calcium chloride during adsorption. This reaction affected to the

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formation of calcium chloride crystal. It meant that the refrigerant could not desorb from calcium chloride and it was impossible that the cooling effect would occur.

The properties of refrigerant from Table 1, showed that acetone should be used as refrigerant more than methanol because acetone could vaporize into vapor phase faster than methanol at the same pressure. The rapid vaporization affected to the removal of heat from cooling load (water) in evaporator.

4.1.2 Condition test in laboratory room

(a) (b)

Figure 8: Condition test in laboratory room,

(a) Desorption of acetone from activated carbon by using hot plate

(b) Adsorption of acetone on activated carbon (Cooling effect)

Collector part

Mass of activated carbon	=	200	g
Mass of acetone	=	40	g
Temperature of desorption	=	70 – 98	°C
Pressure of desorption	=	60	kPa
Desorption heat of acetone[18]	=	793	J/g (acetone)
Total heat of desorption (Q_d)	=	31720	J

Evaporation part

Mass of water	=	10	g
Temperature of water	=	20.4	°C
Pressure of evaporation	=	5	kPa
Removed heat from water (Q_r)	=	418	J

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Coefficient of performance (COP)

$$COP = Q_r/Q_d$$
$$= 418/31720$$
$$= 0.0132$$

From the laboratory part, it showed that 40 g of acetone could produce 10 g of chilled water at the temperature of 20.4 °C from water at room temperature. It meant that the 418 J of energy in water was removed. However, the energy of water should be more removed than 418 J due to the result from theoretical calculation showed that 40 g of acetone could remove 22.56 kJ of energy (40 g ×564 J/g (latent heat)) from the system. The reason that the removal of energy was low might be a result from the rate of energy removal from the water was less than the rate of heat transfer from environment to the water. The rate of energy removal depended on the rate of evaporation of acetone because if the acetone could rapidly evaporate to vapor phase, the energy in water would be rapidly removed too. Besides, the rate of heat transfer could be decreased by installation of insulator at evaporation part.

4.1.3 Design of Solar Ice Maker

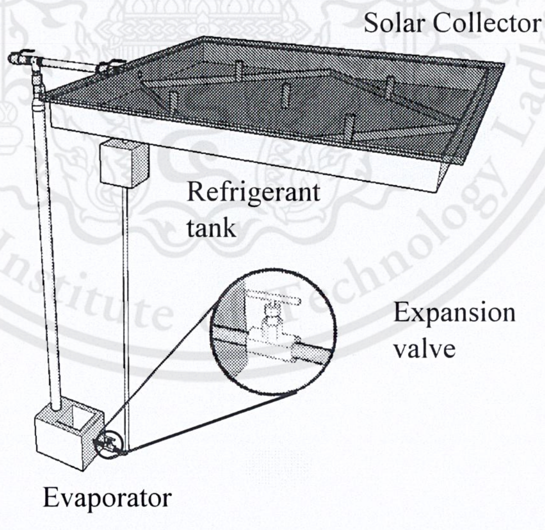

Figure 9: The Solar Ice Maker Design

In part of the solar ice maker design, it was divided into 3 main parts. The first part was design of solar collector while the last two parts were design of refrigerant tank and evaporator, respectively.

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4.1.3.1 Solar collector design

4.1.3.1.1 Estimation of acetone mass from the equation (3) and (4).

Target: Production of 0.3 kg of ice at 0°C

From the equation (3); $Q_{evap} = m_c C_{p,l}(\Delta T)_l + m_c(H)_{fusion} + m_c C_{p,s}(\Delta T)_s$

where; m_C = 0.3 kg

$C_{p,l}$ = 4.18 kJ/kg.°C

$(\Delta T)_l$ = 30 °C

$(H)_{fusion}$ = 334 kJ/kg

$m_c C_{p,s}(\Delta T)_s$ = 0 kJ (0.3 kg of ice at 0°C)

therefore; Q_{evap} = 137.82 kJ

From the equation (4); $m_{Acetone} = \frac{Q_{evap}}{H_{vap,Acetone}}$

where; $H_{vap,Acetone}$ = 564 kJ/kg

therefore; $m_{Acetone}$ = 0.244 kg

4.1.3.1.2 Estimation of activated carbon mass from the equation (5).

From the equation (5); $m_{AC} = \frac{m_{Acetone}}{r_{ads}}$

where; r_{ads} = 0.2 (From lab. r_{ads} = 0.24)

therefore; m_{AC} = 1.22 kg

4.1.3.1.3 Estimation of volume of activated carbon in solar collector (V_{AC}).

$$V_{AC} = \frac{m_{AC}}{\rho_{AC}} \quad ; \rho_{AC} = 420 \text{ kg/m}^3$$

$$V_{AC} = 0.0030 \text{ m}^3 = 3000 \text{ cm}^3$$

4.1.3.1.4 Design of the solar collector.

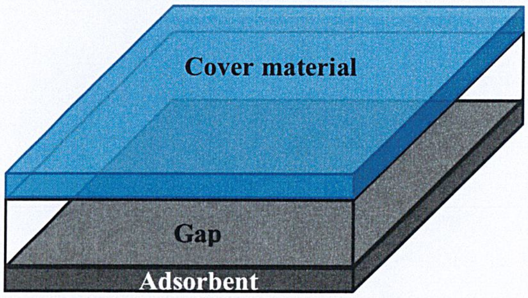

Figure 10: Plate Solar Collector

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In this experiment, the plate solar collector was selected because it was convenient to collect the activated carbon. Moreover, it could generate the temperature between 80 – 100°C which it was enough to desorb the refrigerant on the activated carbon. The component of solar collector was divided into 4 sections consisting of 1) Adsorbent section, 2) Cover material, 3) Gap between adsorbent and cover material, and 4) Structure.

1) Adsorbent section design

From the laboratory, the thickness of activated carbon should be 1 cm in order to adsorb refrigerant during cooling effect. Therefore, the solar collector requires 3000 cm^2 of area to collect the activated carbon.

The adsorbent plate was designed in a quadrat. The length of this plate was equal to the square root of the required area of activated carbon in the solar collector.

The length of this plate (Ls) $= (3000\ cm^2)^{1/2} = 54.77\ cm \approx 60\ cm$

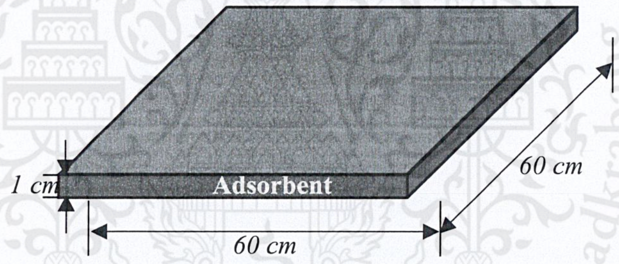

Figure 11: Adsorbent plate (Activated carbon)

2) Cover material design

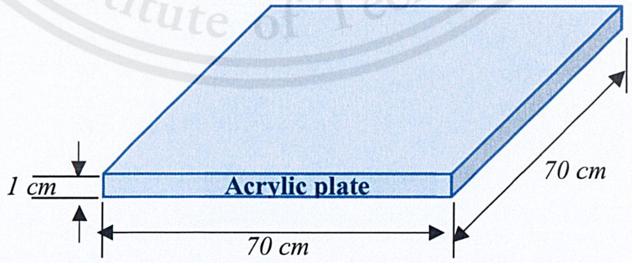

Figure 12: Cover material (Acrylic plate)

The acrylic plate was selected as cover material of the solar collector because it is a transparent material. Furthermore, the thermal conductivity of this material is low enough to maintain high temperature in the solar collector. The thickness of this plate was equal to 1 cm in order to prevent fracture from vacuum state during operation.

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3) Gap between adsorbent and cover material design

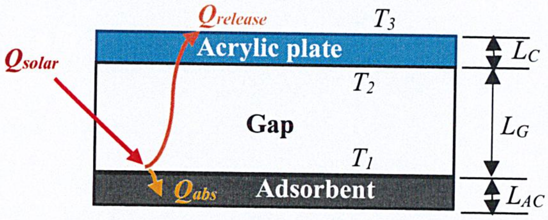

Figure 13: Gap between adsorbent and cover material

Definition of each parameter

1) L_C = Thickness of acrylic plate
2) L_G = Height of gap between adsorbent and cover material
3) L_{AC} = Thickness of activated carbon
4) Q_{solar} = Heat flux from solar energy
5) Q_{abs} = Heat flux absorbed by activated carbon
6) $Q_{release}$ = Heat flux released to environment
7) k_{AC} = Thermal conductivity of activated carbon
8) k_G = Thermal conductivity of gap (acetone is between gap)
9) k_C = Thermal conductivity of acrylic plate
10) T_1 = Surface temperature of activated carbon
11) T_2 = Surface temperature of inner acrylic plate
12) T_3 = Surface temperature of outer acrylic plate

Design equation of the gap

Assumptions: 1) The heat transfer of system is steady-state.
2) Heat transfers in one-direction.
3) Heat is generated from the solar energy.
4) Time of desorption = t_d =7 hr
5) Mass of acetone = $m_{Acetone}$ = 244 g
6) Mass of activated carbon = m_{AC} = 1220 g
7) The change in activated carbon temperature = $\Delta T = 70$ °C

Properties: 1) Heat capacity of activated carbon = $C_{PAC} = 0.92\ J/g.^{o}C$
2) The desorption heat of acetone = 793 kJ/kg
3) The solar intensity = I_{solar} = 700 W/m^2
4) The efficiency of typical plate solar collector[19] = $\varepsilon = 0.15$

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5) k_{AC} = 0.15 W/m.K, k_G = 0.0156 W/m.K, and k_C = 0.2 W/m.K

6) L_{AC} = 0.01 m, and L_C = 0.01 m

7) T_1 = 100 °C, and T_3 = 40 °C

8) Area of solar collector = A = 0.36 m^2

Calculation: 1) Calculation of Q_{abs}

$$Q_{abs} = \frac{m_{AC}C_{PAC}\Delta T + m_{Acetone}H_{des}}{t_d}$$

$$Q_{abs} = \frac{(1220\,g)(0.92\,J/g\cdot^{o}C)(70^{o}C) + (244\,g)(793\,J/g)}{25200\,s}$$

$$Q_{abs} = 10.796\ W$$

2) Calculation of Q_{solar}

$$Q_{solar} = \varepsilon A I_{solar}$$

$$Q_{solar} = 0.15\ (0.36\ m^2)(700\ W/m^2)$$

$$Q_{solar} = 37.80\ W$$

3) Calculation of L_C

$$Q_{release} = \frac{T_1 - T_3}{\left(\frac{L_G}{k_G} + \frac{L_C}{k_C}\right)\cdot\left(\frac{1}{A}\right)}$$

$$Q_{release} = Q_{solar} - Q_{abs} = \frac{T_1 - T_3}{\left(\frac{L_G}{k_G} + \frac{L_C}{k_C}\right)\cdot\left(\frac{1}{A}\right)}$$

$$L_G = \left(\frac{(T_1 - T_3)\cdot A}{(Q_{solar} - Q_{abs})} - \frac{L_C}{k_C}\right)k_G$$

$$L_C = \left(\frac{(100^{o}C - 40^{o}C)\cdot(0.36m^2)}{(37.80W - 10.80W)} - \frac{0.01m}{0.0156W/m^{o}C}\right)0.2W/m^{o}C$$

$$L_C = 0.032\ m \approx 0.035\ m$$

From the calculation, the results showed that the length of the gap was equal to 0.035 approximately in order to maintain the temperature of activated carbon at 100°C.

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4) Structure

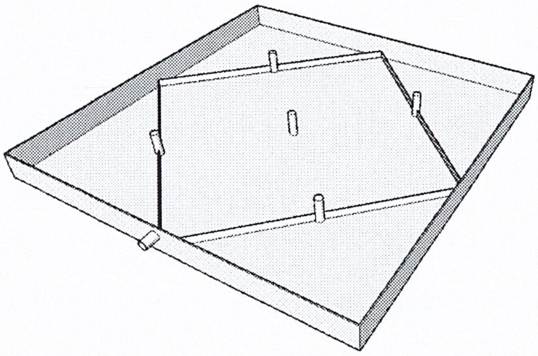

Figure 14: The structure of solar collector

The data shown in the Table 1, indicated that if acetone was selected as refrigerant, the system was necessary to be operated at the pressure of 5 kPa. Therefore, the suitable material for this system was stainless steel because it was resistant to distortion and rust during operation. Furthermore, the structure was necessary to install the beam to receive the force due to the difference in pressure between inside and outside of the solar collector. The specification of the solar collector would be showed in the Table 3.

Table 3: The specification of the solar collector

Specification	Value	Unit
Material	stainless steel	
Length×Width×Height	60×60×4.5	cm
Activated carbon	1.22	kg
Acetone	0.244	kg
Maximum temperature	100	°C
Operating pressure	5	kPa

4.1.3.2 Design of the refrigerant tank

4.1.3.2.1 Estimation of the refrigerant tank volume by the equation (14).

From the equation (14); $V_{TANK} = \frac{m_{Acetone}}{\rho_{Acetone}}$

where; $\rho_{Acetone}$ = 784 kg/m^3

therefore; V_{TANK} = 0.00031 m^3 = 0.31 L = 310 cm^3

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4.1.3.2.2 Design of refrigerant tank dimension

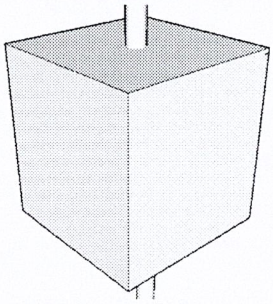

Figure 15: The refrigerant tank

Calculation of the refrigerant tank dimension

The refrigerant tank was designed as a cubic.

The length of each edge = $L_T = (310\ cm^3)^{1/3} = 6.77\ cm \approx 7\ cm$

4.1.3.3 Design of the evaporator

The evaporator was design by using the equation (15) – (21).

From the equation (15); $P = \frac{RT}{\hat{v} - b} - \frac{a(T)}{(\hat{v} + \varepsilon b)(\hat{v} + \sigma b)}$

From the equation (16); $a(T) = \psi \frac{\alpha(T_r) R^2 T_c^{\ 2}}{P_c}$

From the equation (17); $b = \Omega \frac{RT_c}{P_c}$

From the equation (18); $T_r = \frac{T}{T_c}$

From the equation (19); $\alpha(T_r) = [1 + (0.3764 + 1.54226\omega - 0.26992\omega^2)(1 - T_r^{1/2})]^2$

Where; $P \approx 5\ kPa$

P_C = 4701 kPa

T = 263.15 K

T_C = 508.2 K

R = 8.314 kJ/kg.K

$\varepsilon = 1 - (2)^{0.5}$, $\sigma = 1 + (2)^{0.5}$, $\Omega = 0.07780$, $\omega = 0.307$ and ψ = 0.45724

therefore; $\hat{v} = 7.41\ m^3/kg$

From the equation (20); $V_{evap} = r_{evap} \cdot \hat{v} \cdot \hat{m}_R - V_{solar}$

Assumptions: 1) In this system, it required to produce ice in 30 minutes.

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2) The refrigerant would vaporize and came back to solar collector in 13.55 seconds.

Calculation of evaporator

1) Mass flow rate of refrigerant ($\hat{m}_{Acetone}$)

$$\hat{m}_{Acetone} = m_{Acetone}/(operating\ time)$$

$$\hat{m}_{Acetone} = (244\ g)/(30\times 60\ \mathrm{s})$$

$$\hat{m}_{Acetone} = 0.136\ \mathrm{g/s}$$

2) Volume of solar collector (V_{solar})

$$V_{solar} = (60\ \mathrm{cm})(60\ \mathrm{cm})(3.5\ \mathrm{cm})$$

$$V_{solar} = 12600\ \mathrm{cm}^3$$

3) Volume of evaporator (V_{evap})

$$V_{evap} = (13.55\ \mathrm{s})(7410\ \mathrm{cm}^3/\mathrm{g})(0.136\ \mathrm{g/s}) - (12600\ \mathrm{cm}^3)$$

$$V_{evap} = 1057\ \mathrm{cm}^3$$

Design of evaporator

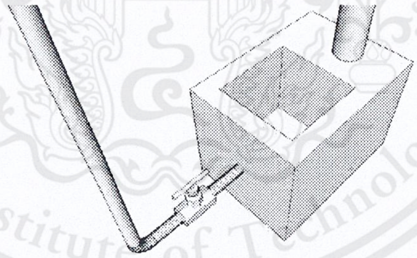

Figure 16: Evaporator and expansion valve

The feature of evaporator was designed as a box shown in the Figure 14. There was a hole on the top of the box for loading water. The hole was designed as a cubic that the length of each edge was equal to 7 cm. Moreover, the needle valve was used as an expansion valve installed in front of the evaporator. The flow rate of refrigerant was controlled by this valve. In order to reduce the heat transfer from environment, the evaporator was packed in Styrofoam (Insulator).

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Table 4: The specification of the evaporator

Specification	Value	Unit
Material	Stainless steel	
Insulator material	Styrofoam	
Expansion valve	Needle valve ½"	
Evaporator: Length×Width×Height	10×14×10	cm
Water hole: Length×Width×Height	7×7×7	cm
Expected minimum temperature	-10	°C
Operating pressure	5	kPa

4.2 Experiment with the Solar Ice Maker

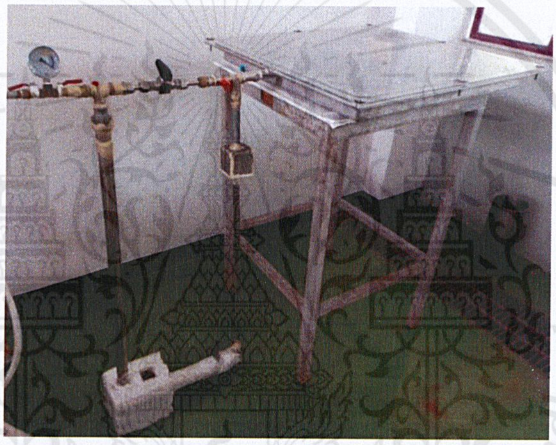

Figure 17: The Solar Ice Maker

The solar ice maker was constructed in February and was tested in March. It was experimented in department of chemical engineering building (CCA) of King Mongkut's Institute of Technology Ladkrabang. Before the experiment, 1.22 kg of activated carbon was loaded into the solar collector while 244 g of acetone was filled into refrigerant tank. Water was used as a cooling load and was filled in the evaporator. The mass of water was varied until all of it became ice. Then, the pressure of system would be decreased until it was equal to 5 kPa. After that, the needle valve would be slightly opened to allow the acetone to enter into evaporator. In the evaporator acetone would vaporize to vapor phase and absorb heat from the water. After acetone had absorbed heat, it would be adsorbed by activated carbon in solar collector. At the daytime, the solar collector would be heated by solar energy to release acetone on activated carbon and then acetone would be kept in the refrigerant tank again. The

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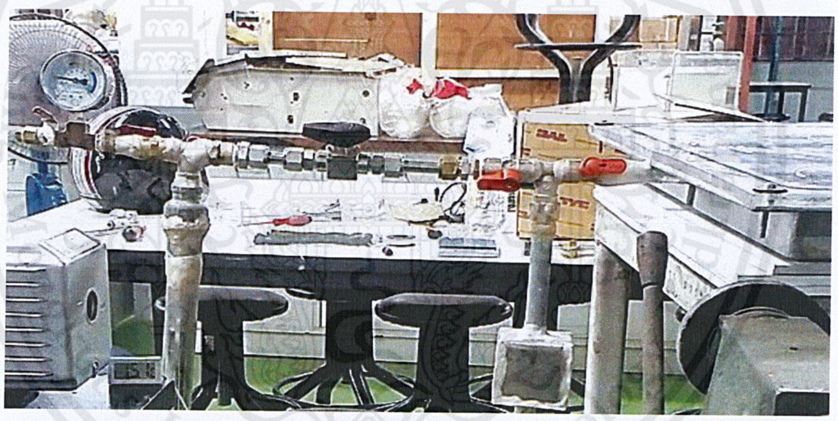
results of this experiment was divided into 2 parts. The first part was related to the cooling capacity of this system while another part was related to desorption of acetone from activated carbon by using solar energy.

4.2.1 The Cooling Capacity of the Solar Ice Maker

(a)



(b)

(c)

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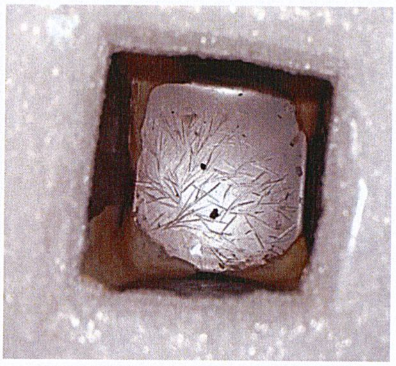
(d)



(e)

Figure 18: The Experimental Results of Cooling Capacity from the Solar Ice Maker

(a) The result when the mass of used water was equal to 300 g,

(b) The result when the mass of used water was equal to 100 g,

(c) The result when the mass of used water was equal to 50 g,

(d) The result when the mass of used water was equal to 15 g, and

(e) The form of ice that occurred

Table 5: The Experimental Results of Cooling Capacity from the Solar Ice Maker

Day	Pressure in Evaporator (kPa)	Minimum temperature of water (°C)	Mass of water (g)	Heat Removal (J)
1	15	24.0	300	7524
2	15	15.1	100	6228
3	10	4.7	50	5288
4	5	-2.8	15	6980
Average Heat Removal				**6438**

In this experiment, it was tested for 4 days which the mass of water was differently used as a cooling load in each day until the water became ice. In the first day, 300 g of water was used as a cooling load and the result indicated that acetone could reduce the temperature of water to 24.0 °C from room temperature. In addition, the result of calculation showed that 7524 J of heat in water was removed. In order to produce ice, the mass of water was successively reduced to 15 g in the fourth day. On that day, 6980 J of the energy was removed. However, the calculation from the part of design indicated that 244 g of acetone could produce 300 g of ice. Nevertheless, the experiment could produce only 15 g of ice. It might be a result from the design in part

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of evaporator was not suitable which it affected to the evaporation rate of acetone. To increase the rate of evaporation, it was necessary to increase the volume of evaporator. Furthermore, the decrease of the pipe length from evaporator to solar collector also caused increase of the evaporation rate as the vapor phase of acetone would be rapidly adsorbed by activated carbon resulting to the liquid acetone could rapidly vaporized too.

To increase the efficiency of evaporator, the installation of well insulator around evaporator was very important because it could reduce the rate of heat transfer from environment. The rate of heat transfer affected to the temperature reduction of water in evaporator. It meant that if the rate of heat transfer was high, the temperature would be decreased slightly that meant the heat removal and the efficiency of evaporator were low.

4.2.2 Desorption of acetone from activated carbon by using solar energy

Figure 19: Desorption of acetone from activated carbon by using solar energy

Table 6: The Experimental Results of acetone desorption from activated carbon

Day	Mass of acetone in refrigerant tank (g)	Average solar intensity (W/m^2)	Desorption time (h)	Total received energy (MJ)
1	0.0	682.29	7	6.19
2	0.0	727.43	7	6.60
3	0.0	615.14	7	5.58
4	0.0	691.21	7	6.27
Average		**679.08**	**7**	**6.16**

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Calculation of COP

From the equation (1): $$COP = \frac{Q_{evap}}{Q_{ads}}$$

Where, Q_{evap} = 6.438 kJ and Q_{ads} = 6.16 MJ

Therefore, $$\boldsymbol{COP} = \frac{6.438}{6160} = \mathbf{0.001}$$

In order to recovery the activated carbon after it had been adsorbed by the acetone during the cooling effect, it was necessary to heat the activated carbon for desorption of acetone. The heat source for this system was the solar energy. From the Figure 19, it showed that the acetone would be condensed on the surface of acrylic plate after the activated carbon had been heated by the solar energy. It meant that this system could release the acetone from the activated carbon. However, it could not drive the acetone from the solar collector to the refrigerant tank. Therefore, the acetone in this system could not be completely operated as a cycle. To operate this system, it was necessary to fill the acetone into the refrigerant tank.

The result from the experiment shown in the Table 6, indicated that if the system could operate completely, it would consume 6.16 MJ of the solar energy to release the acetone from the activated carbon. In addition, the coefficient of performance (COP) of this system could be calculated from the ratio of heat that remove from the water in evaporator to the solar energy that this system consumed. From the calculation, the value of COP was equal to 0.001.

4.3 Improvement of the Solar Ice Maker

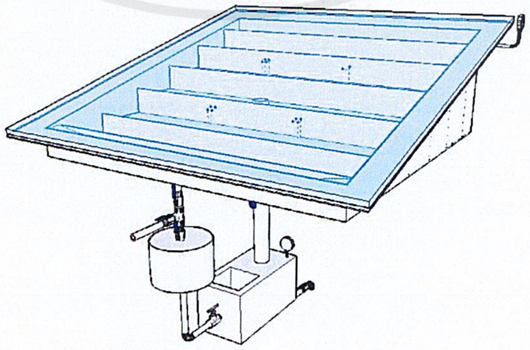

Figure 20: The New Solar Ice Maker

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During the experiment with the solar ice maker, there were 2 problems that occurred. The first problem was the low evaporation rate of acetone from evaporator to solar collector during the cooling effect. In addition, another problem was removal of acetone from the solar collector to the refrigerant tank. Both problems could be fixed by designing the new solar collector and evaporator. However, the result of the experiment with the new solar ice maker might not be complete in this semester since it is constructed in the end of this semester and the construction will spend more time.

4.3.1 Design of the new solar collector

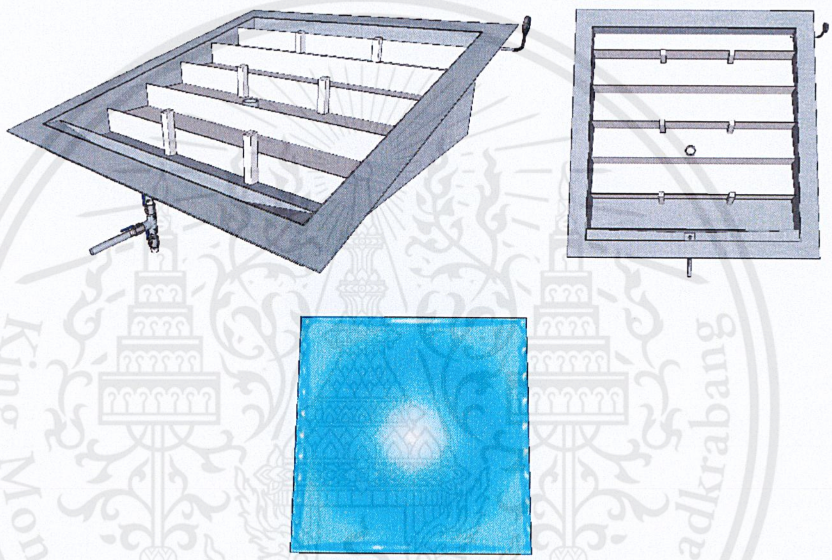

Figure 21: The New Solar Collector

Due to the acetone would be condensed on the surface of acrylic plate, therefore the acrylic plate should be slant in order to slip the condensed acetone to the refrigerant tank. The angle of acrylic plate was equal to 15°. The new solar collector was designed from the solar water distillation[20].

In the new solar collector, it was designed as a layer to collect the activated carbon and to equally maintain the temperature of the activated carbon at each position. Furthermore, the design in this feature could still prevent the collapse during the operation at vacuum state because each layer was able to be a beam in the structure.

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4.3.2 Design of the new evaporator

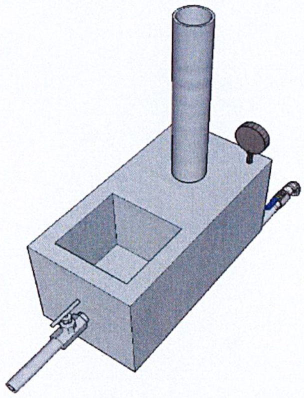

Figure 22: The New Evaporator

The result from the experiment showed that the removal of heat from water in evaporator was very low because of low evaporation rate of acetone. To increase the rate of evaporation, it was necessary to increase the volume of evaporator. The volume of new evaporator was increase 1.6 times of the previous evaporator.

Furthermore, the decrease of the pipe length from evaporator to solar collector also caused increase of the evaporation rate due to the vapor phase of acetone would be rapidly adsorbed by activated carbon resulting to the liquid acetone could rapidly vaporized too.

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CHAPTER V
CONCLUSIONS

5.1 CONCLUSIONS

In this research, it is expected to study and develop the solar adsorption refrigeration system for construction of the solar ice maker. The experiment of this research begins with the seeking for the suitable refrigerant and adsorbent. The result indicates that the suitable refrigerant and adsorbent are acetone and activated carbon, respectively. In addition, the adsorption capacity of acetone on activated carbon is 20%w/w approximately. After that, it is carried on with the test of appropriate condition in the solar adsorption refrigeration system for ice making. The condition used in this system is operated at the pressure of 5 kPa. The adsorption capacity and the appropriate condition is used in order to design the solar ice maker. The design of solar ice maker is divided into 3 main parts consisting of 1) Solar collector, 2) Refrigerant tank (condenser), and 3) Evaporator. The size of solar collector (60 cm x 60 cm x 4.5 cm) is designed to be able to collect 1.22 kg of activated carbon and maintain the temperature during desorption time. Besides, 244 g of acetone is necessary to be collected in the volume of refrigerant tank with a size of 343 cm^3. In the part of evaporator design, its size is designed to be 1057 cm^3 for evaporation of acetone. Furthermore, the evaporator can load 300 g of water for ice maker. However, the result shows that the solar ice maker can produce only 15 g of ice. In addition, the average removal of heat from water of this system is equal to 6980 J while it approximately requires 6.16 MJ for desorption of acetone from activated carbon. Therefore, the coefficient of performance (COP) of this system is equal to 0.001. However, this system cannot be completely operated as a cycle because it cannot drive the acetone from solar collector to the refrigerant tank during desorption.

5.2 SUGGESTIONS

1) The new solar collector is necessary to be designed in order to be able to move the acetone from solar collector to the refrigerant tank during desorption.

2) In order to increase the evaporation rate of acetone from evaporator to solar collector during the cooling effect, it is necessary to design the new evaporation part.

3) The new adsorbent and refrigerant should be researched for improving the efficiency of the solar adsorption refrigeration system.

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APPENDIX

King Mongkut's Institute of Technology Ladkrabang

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A: Properties of materials

1A Activated carbon used in this experiment

Figure A1: Activated carbon used in this experiment

Table A1: Properties of activated carbon

Properties	Value	Unit
Natural Material	Coconut shell	
Color	Black	
Shape	Sphere	
Thermal conductivity	0.15	W/m.K
Heat capacity	0.92	J/g.K
Iodine Number	>1000	
Particle size (Diameter)	1.19 - 2.38	mm
Density	420	kg/m^3

2A Calcium chloride used in this experiment

Figure A2: Calcium chloride used in this experiment

Table A2: Properties of Calcium chloride

Properties	Value	Unit
Purity	75%	
Color	White	
Shape	Sphere	

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Table A2: Properties of Calcium chloride (Cont.)

Properties	Value	Unit
Particle size (Diameter)	3 - 5	mm
Chemical structure	$CaCl_2 \cdot 2H_2O$	
Molar mass	129	g/mol
Density	1850	kg/m^3
Solubility in 100 g of water (at 25°C)	81.10	g

3A Methanol

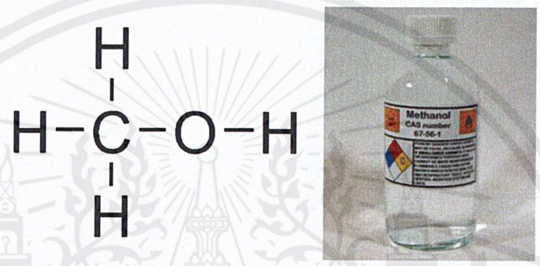


Figure A3: Methanol and its chemical structure

Table A3.1: Properties of methanol

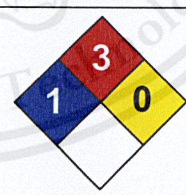
Properties	Value	Unit
Purity	95%	
Color	Colorless	
Hazardous		
Molar mass	32.04	g/mol
Critical temperature	239.35	°C
Critical pressure	8084	kPa
Critical specific volume	0.003656	m^3/kg
Ω	0.07780	
ω	0.56400	
ψ	0.45724	

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Table A3.2: Saturated properties of methanol

Temperature (°C)	Pressure (kPa)	Density (kg/m³)		Latent heat (kJ/kg)	Entropy change (kJ/kg.K)
		Liquid	Vapor		
-10	2.02	833.3110	0.0296	1210.95	4.6017
-9	2.17	832.1890	0.0316	1209.99	4.5807
-8	2.32	831.0640	0.0337	1209.02	4.5598
-7	2.48	829.9380	0.0360	1208.03	4.5389
-6	2.66	828.8110	0.0384	1207.04	4.5182
-5	2.84	827.6810	0.0409	1206.03	4.4976
-4	3.04	826.5500	0.0435	1205.00	4.4771
-3	3.25	825.4170	0.0463	1203.96	4.4566
-2	3.47	824.2820	0.0493	1202.91	4.4363
-1	3.70	823.1460	0.0524	1201.83	4.4161
0	3.95	822.0070	0.0557	1200.75	4.3960
1	4.21	820.8670	0.0591	1199.66	4.3759
2	4.48	819.7250	0.0628	1198.55	4.3560
3	4.77	818.5810	0.0666	1197.42	4.3361
4	5.08	817.4350	0.0706	1196.28	4.3164
5	5.40	816.2880	0.0749	1195.13	4.2967
6	5.75	815.1380	0.0793	1193.96	4.2771
7	6.11	813.9870	0.0840	1192.78	4.2576
8	6.48	812.8330	0.0889	1191.58	4.2382
9	6.88	811.6780	0.0940	1190.37	4.2189
10	7.30	810.5210	0.0994	1189.15	4.1997
11	7.75	809.3620	0.1051	1187.91	4.1806
12	8.21	808.2010	0.1110	1186.66	4.1615
13	8.70	807.0380	0.1172	1185.39	4.1425
14	9.22	805.8730	0.1237	1184.11	4.1237
15	9.76	804.7050	0.1305	1182.81	4.1049
16	10.32	803.5360	0.1376	1181.50	4.0861
17	10.92	802.3650	0.1450	1180.17	4.0675
18	11.54	801.1920	0.1528	1178.84	4.0489
19	12.20	800.0170	0.1609	1177.49	4.0304
20	12.88	798.8390	0.1693	1176.13	4.0120
21	13.60	797.6600	0.1782	1174.74	3.9937
22	14.35	796.4780	0.1874	1173.35	3.9754
23	15.14	795.2950	0.1970	1171.93	3.9572
24	15.96	794.1090	0.2070	1170.51	3.9391
25	16.83	792.9210	0.2175	1169.08	3.9211
26	17.73	791.7310	0.2284	1167.63	3.9032
27	18.67	790.5380	0.2397	1166.16	3.8853
28	19.65	789.3440	0.2515	1164.69	3.8674
29	20.68	788.1470	0.2638	1163.19	3.8497
30	21.76	786.9480	0.2766	1161.68	3.8320
31	22.88	785.7460	0.2899	1160.15	3.8144
32	24.05	784.5430	0.3037	1158.62	3.7969
33	25.27	783.3370	0.3181	1157.07	3.7794

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Table A3.2: Saturated properties of methanol (Cont.)

Temperature (°C)	Pressure (kPa)	Density (kg/m³)		Latent heat (kJ/kg)	Entropy change (kJ/kg.K)
		Liquid	Vapor		
34	26.54	782.1290	0.3330	1155.51	3.7620
35	27.86	780.9180	0.3485	1153.92	3.7447
36	29.24	779.7050	0.3646	1152.33	3.7274
37	30.68	778.4900	0.3813	1150.73	3.7102
38	32.18	777.2720	0.3986	1149.11	3.6931
39	33.74	776.0520	0.4166	1147.47	3.6760
40	35.36	774.8290	0.4352	1145.82	3.6590
41	37.05	773.6050	0.4545	1144.16	3.6421
42	38.80	772.3770	0.4745	1142.47	3.6252
43	40.63	771.1470	0.4953	1140.78	3.6084
44	42.52	769.9150	0.5167	1139.08	3.5916
45	44.49	768.6800	0.5390	1137.35	3.5749
46	46.54	767.4420	0.5620	1135.62	3.5583
47	48.66	766.2020	0.5858	1133.87	3.5417
48	50.87	764.9590	0.6104	1132.10	3.5252
49	53.15	763.7140	0.6359	1130.32	3.5087
50	55.53	762.4660	0.6622	1128.53	3.4923
51	57.99	761.2150	0.6894	1126.72	3.4759
52	60.54	759.9620	0.7175	1124.90	3.4596
53	63.18	758.7060	0.7466	1123.07	3.4434
54	65.92	757.4470	0.7766	1121.21	3.4272
55	68.76	756.1850	0.8076	1119.35	3.4111
56	71.70	754.9210	0.8395	1117.47	3.3950
57	74.75	753.6540	0.8725	1115.58	3.3790
58	77.90	752.3840	0.9066	1113.67	3.3630
59	81.16	751.1110	0.9417	1111.75	3.3471
60	84.53	749.8350	0.9779	1109.82	3.3313
61	88.02	748.5570	1.0152	1107.86	3.3155
62	91.63	747.2750	1.0536	1105.90	3.2997
63	95.36	745.9910	1.0932	1103.92	3.2840
64	99.21	744.7030	1.1341	1101.92	3.2683
65	103.19	743.4120	1.1761	1099.91	3.2527
66	107.31	742.1190	1.2194	1097.89	3.2372
67	111.56	740.8220	1.2639	1095.85	3.2217
68	115.94	739.5220	1.3098	1093.80	3.2062
69	120.47	738.2190	1.3570	1091.74	3.1908
70	125.15	736.9130	1.4055	1089.65	3.1754
71	129.97	735.6040	1.4554	1087.55	3.1601
72	134.94	734.2920	1.5067	1085.45	3.1449
73	140.07	732.9760	1.5595	1083.32	3.1296
74	145.36	731.6570	1.6137	1081.18	3.1145
75	150.82	730.3340	1.6694	1079.02	3.0993
76	156.44	729.0090	1.7267	1076.86	3.0842
77	162.23	727.6800	1.7855	1074.67	3.0692
78	168.19	726.3470	1.8459	1072.48	3.0542

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Table A3.2: Saturated properties of methanol (Cont.)

Temperature (°C)	Pressure (kPa)	Density (kg/m³)		Latent heat (kJ/kg)	Entropy change (kJ/kg.K)
		Liquid	Vapor		
79	174.34	725.0110	1.9079	1070.26	3.0392
80	180.67	723.6720	1.9716	1068.03	3.0243
81	187.18	722.3290	2.0369	1065.79	3.0094
82	193.89	720.9820	2.1040	1063.54	2.9946
83	200.79	719.6320	2.1727	1061.26	2.9798
84	207.89	718.2780	2.2433	1058.98	2.9651
85	215.20	716.9200	2.3156	1056.67	2.9504
86	222.71	715.5590	2.3898	1054.35	2.9357
87	230.44	714.1940	2.4659	1052.02	2.9211
88	238.39	712.8260	2.5438	1049.67	2.9065
89	246.55	711.4530	2.6237	1047.31	2.8919
90	254.95	710.0770	2.7056	1044.93	2.8774
91	263.57	708.6960	2.7894	1042.54	2.8630
92	272.43	707.3120	2.8753	1040.14	2.8485
93	281.54	705.9240	2.9633	1037.72	2.8341
94	290.88	704.5310	3.0533	1035.28	2.8198
95	300.48	703.1350	3.1455	1032.82	2.8054
96	310.34	701.7340	3.2399	1030.35	2.7912
97	320.45	700.3290	3.3364	1027.87	2.7769
98	330.84	698.9200	3.4352	1025.37	2.7627
99	341.49	697.5070	3.5363	1022.85	2.7485
100	352.42	696.0890	3.6397	1020.33	2.7344

4A Acetone

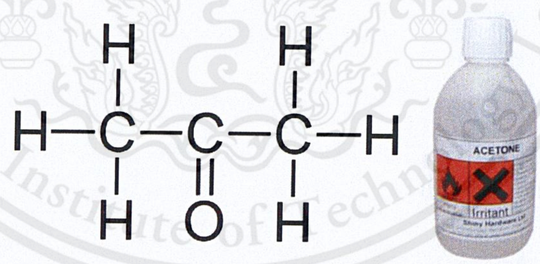

Figure A4: Acetone and its chemical structure

Table A4.1: Properties of acetone

Properties	Value	Unit
Purity	97%	
Color	Colorless	
Hazardous		

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Table A4.1: Properties of acetone (Cont.)

Properties	Value	Unit
Molar mass	58.08	g/mol
Critical temperature	235.05	^oC
Critical pressure	4701	kPa
Critical specific volume	0.00360	m^3/kg
Ω	0.07780	
ω	0.30700	
ψ	0.45724	

Table A4.2: Saturated properties of acetone

Temperature (^oC)	Pressure (kPa)	Density (kg/m^3)		Latent heat (kJ/kg)	Entropy change (kJ/kg.K)
		Liquid	Vapor		
-10	5.43	828.2110	0.1442	564.01	2.1433
-9	5.75	827.1060	0.1520	563.24	2.1323
-8	6.08	826.0000	0.1603	562.47	2.1213
-7	6.43	824.8920	0.1688	561.71	2.1105
-6	6.80	823.7820	0.1778	560.94	2.0997
-5	7.18	822.6700	0.1871	560.18	2.0890
-4	7.59	821.5570	0.1969	559.41	2.0784
-3	8.01	820.4420	0.2071	558.64	2.0679
-2	8.45	819.3240	0.2176	557.87	2.0574
-1	8.91	818.2050	0.2287	557.10	2.0470
0	9.39	817.0850	0.2402	556.32	2.0367
1	9.89	815.9620	0.2521	555.55	2.0265
2	10.42	814.8370	0.2646	554.79	2.0163
3	10.97	813.7110	0.2775	554.01	2.0062
4	11.54	812.5820	0.2910	553.23	1.9962
5	12.14	811.4520	0.3049	552.45	1.9862
6	12.77	810.3200	0.3195	551.68	1.9763
7	13.42	809.1860	0.3345	550.90	1.9664
8	14.09	808.0500	0.3502	550.11	1.9567
9	14.80	806.9110	0.3664	549.34	1.9470
10	15.54	805.7710	0.3833	548.55	1.9373
11	16.30	804.6290	0.4008	547.77	1.9278
12	17.10	803.4850	0.4189	546.98	1.9182
13	17.93	802.3390	0.4376	546.20	1.9088
14	18.79	801.1910	0.4571	545.40	1.8994
15	19.68	800.0400	0.4772	544.61	1.8900
16	20.62	798.8880	0.4981	543.83	1.8808
17	21.58	797.7330	0.5196	543.03	1.8716
18	22.59	796.5770	0.5419	542.23	1.8624
19	23.63	795.4180	0.5650	541.44	1.8533

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Table A4.2: Saturated properties of acetone (Cont.)

Temperature (^oC)	Pressure (kPa)	Density (kg/m^3)		Latent heat (kJ/kg)	Entropy change (kJ/kg.K)
		Liquid	Vapor		
20	24.71	794.2570	0.5889	540.64	1.8442
21	25.83	793.0940	0.6135	539.84	1.8352
22	27.00	791.9290	0.6390	539.03	1.8263
23	28.20	790.7620	0.6653	538.23	1.8174
24	29.46	789.5920	0.6925	537.42	1.8086
25	30.75	788.4200	0.7205	536.61	1.7998
26	32.09	787.2460	0.7494	535.80	1.7911
27	33.48	786.0700	0.7793	534.99	1.7824
28	34.92	784.8910	0.8101	534.17	1.7738
29	36.41	783.7100	0.8418	533.36	1.7652
30	37.95	782.5270	0.8746	532.53	1.7567
31	39.55	781.3420	0.9083	531.71	1.7482
32	41.20	780.1540	0.9431	530.88	1.7398
33	42.90	778.9630	0.9788	530.06	1.7314
34	44.66	777.7710	1.0157	529.23	1.7230
35	46.48	776.5760	1.0536	528.39	1.7148
36	48.36	775.3780	1.0927	527.57	1.7065
37	50.30	774.1780	1.1328	526.72	1.6983
38	52.30	772.9760	1.1742	525.88	1.6901
39	54.37	771.7710	1.2166	525.04	1.6820
40	56.50	770.5630	1.2603	524.20	1.6740
41	58.70	769.3530	1.3052	523.34	1.6659
42	60.97	768.1410	1.3514	522.50	1.6579
43	63.30	766.9260	1.3988	521.64	1.6500
44	65.72	765.7080	1.4474	520.79	1.6421
45	68.20	764.4880	1.4974	519.92	1.6342
46	70.76	763.2650	1.5488	519.06	1.6264
47	73.39	762.0390	1.6014	518.19	1.6186
48	76.11	760.8110	1.6555	517.32	1.6108
49	78.90	759.5800	1.7109	516.45	1.6031
50	81.78	758.3460	1.7678	515.57	1.5955
51	84.74	757.1100	1.8262	514.69	1.5878
52	87.78	755.8710	1.8860	513.80	1.5802
53	90.92	754.6290	1.9473	512.92	1.5726
54	94.14	753.3840	2.0101	512.02	1.5651
55	97.45	752.1360	2.0745	511.13	1.5576
56	100.85	750.8850	2.1404	510.23	1.5502
57	104.35	749.6320	2.2079	509.33	1.5427
58	107.95	748.3760	2.2771	508.43	1.5353
59	111.64	747.1160	2.3479	507.51	1.5280
60	115.43	745.8540	2.4204	506.59	1.5206
61	119.32	744.5880	2.4945	505.67	1.5133
62	123.32	743.3200	2.5704	504.75	1.5061
63	127.43	742.0480	2.6480	503.83	1.4988
64	131.64	740.7740	2.7274	502.90	1.4916

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Table A4.2: Saturated properties of acetone (Cont.)

Temperature (^oC)	Pressure (kPa)	Density (kg/m^3)		Latent heat (kJ/kg)	Entropy change (kJ/kg.K)
		Liquid	Vapor		
65	135.96	739.4960	2.8086	501.96	1.4844
66	140.39	738.2150	2.8916	501.02	1.4773
67	144.94	736.9310	2.9765	500.08	1.4702
68	149.60	735.6430	3.0632	499.13	1.4631
69	154.38	734.3530	3.1518	498.17	1.4560
70	159.28	733.0590	3.2424	497.22	1.4490
71	164.30	731.7620	3.3349	496.25	1.4420
72	169.44	730.4610	3.4294	495.28	1.4350
73	174.71	729.1570	3.5258	494.31	1.4280
74	180.11	727.8500	3.6243	493.33	1.4211
75	185.64	726.5390	3.7249	492.35	1.4142
76	191.30	725.2250	3.8275	491.36	1.4073
77	197.10	723.9070	3.9322	490.37	1.4005
78	203.04	722.5860	4.0391	489.37	1.3936
79	209.11	721.2610	4.1481	488.36	1.3868
80	215.32	719.9320	4.2592	487.36	1.3800
81	221.68	718.6000	4.3726	486.34	1.3733
82	228.19	717.2640	4.4883	485.32	1.3665
83	234.84	715.9240	4.6061	484.30	1.3598
84	241.64	714.5810	4.7263	483.27	1.3531
85	248.60	713.2330	4.8488	482.23	1.3464
86	255.71	711.8820	4.9736	481.18	1.3398
87	262.98	710.5270	5.1008	480.13	1.3331
88	270.41	709.1680	5.2304	479.07	1.3265
89	278.00	707.8050	5.3624	478.02	1.3199
90	285.76	706.4380	5.4968	476.94	1.3134
91	293.68	705.0660	5.6337	475.87	1.3068
92	301.77	703.6910	5.7731	474.79	1.3003
93	310.04	702.3120	5.9150	473.70	1.2937
94	318.48	700.9280	6.0595	472.60	1.2872
95	327.09	699.5400	6.2065	471.50	1.2807
96	335.89	698.1470	6.3561	470.40	1.2743
97	344.87	696.7510	6.5084	469.28	1.2678
98	354.03	695.3500	6.6633	468.16	1.2614
99	363.38	693.9440	6.8209	467.03	1.2549
100	372.92	692.5340	6.9812	465.89	1.2485

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B: The Solar Ice Maker Assembly

1B Assembly of the Solar Collector

Figure B1: The Assembly of the Solar Collector

2B Assembly of Refrigerant tank

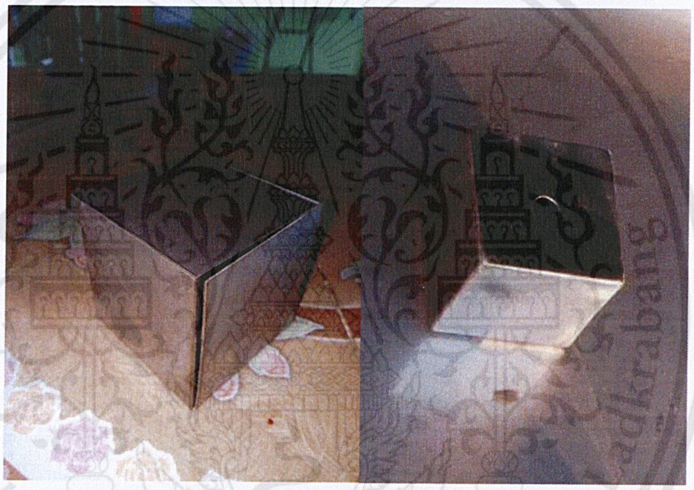

Figure B2: The Assembly of Refrigerant tank

3B Assembly of Evaporator part

Figure B3: The Assembly of Evaporator part

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4B Assembly of the Solar Ice Maker

Figure B4: The Assembly the Solar Ice Maker

C: The Heat from Solar Intensity

Table C1: The solar intensity on each day

Time	Solar Intensity (W/m^2)			
	1st Day	2nd Day	3rd Day	4th Day
10:00	888	922	750	888
11:00	816	788	567	816
12:00	703	920	852	703
13:00	749	709	612	749
14:00	949	998	873	949
15:00	789	805	713	789
16:00	652	822	628	777

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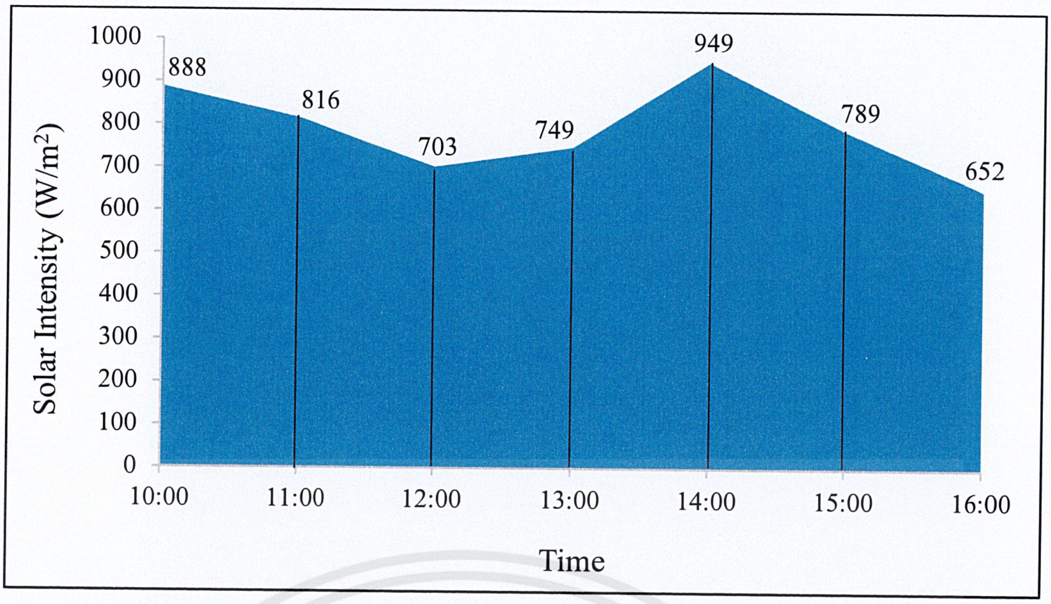

Figure C1: The Solar Intensity of the 1st day of experiment with the Solar Ice Maker

The total of solar energy in the 1st day of experiment can be calculated from the area under the graph shown in the Figure C1.

Area under the graph = [888 + 2(816 + 703 + 749 +949 +789) +652](3600)(0.5)

Area under the graph = The total of solar energy = 17193600 J/m^2

Average of the solar intensity = (17193600 J/m^2)/(3600 x 7 s) = 682.28 W/m^2

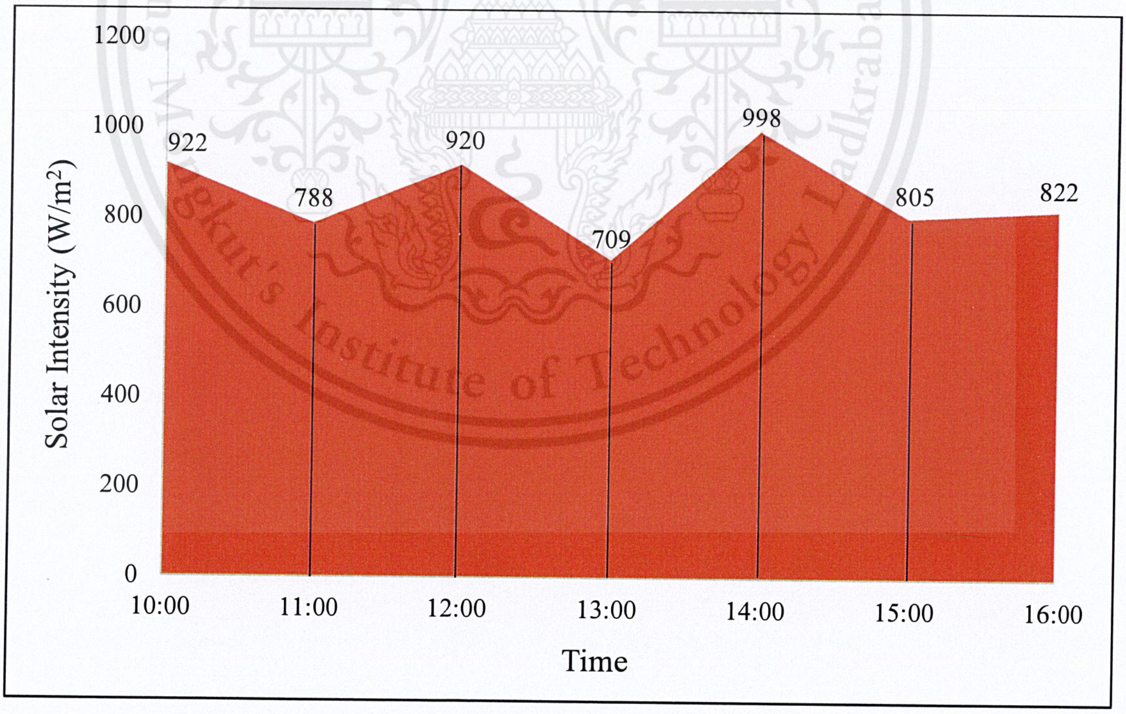

Figure C2: The Solar Intensity of the 2nd day of experiment with the Solar Ice Maker

The total of solar energy in the 2nd day of experiment can be calculated from the area under the graph shown in the Figure C2.

Area under the graph = [922 + 2(788 + 920 + 709 +998 +805) +822](3600)(0.5)

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Area under the graph = The total of solar energy = 18331200 J/m^2

Average of the solar intensity = (18331200 J/m^2)/(3600 x 7 s) = 727.43 W/m^2

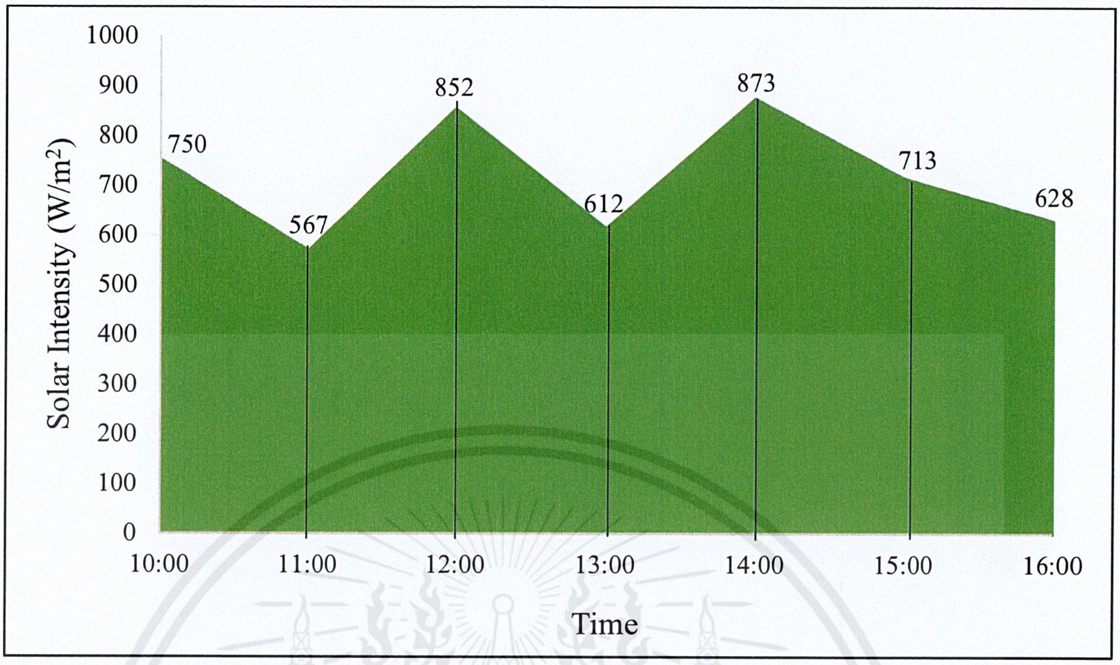

Figure C3: The Solar Intensity of the 3rd day of experiment with the Solar Ice Maker

The total of solar energy in the 3rd day of experiment can be calculated from the area under the graph shown in the Figure C3.

Area under the graph = [750 + 2(567 + 852 + 612 +873 +713) +628](3600)(0.5)

Area under the graph = The total of solar energy = 15501600 J/m^2

Average of the solar intensity = (15501600 J/m^2)/(3600 x 7 s) = 615.14 W/m^2

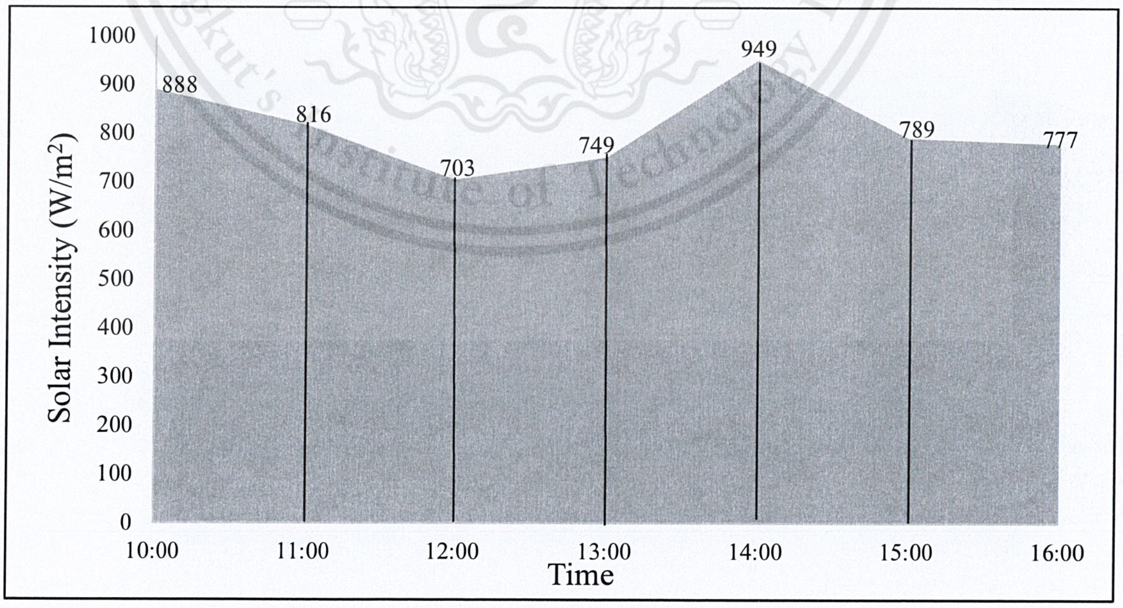

Figure C4: The Solar Intensity of the 4th day of experiment with the Solar Ice Maker

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The total of solar energy in the 4th day of experiment can be calculated from the area under the graph shown in the Figure C4.

Area under the graph = [888 + 2(816 + 703 + 749 +949 +789) +777](3600)(0.5)

Area under the graph = The total of solar energy = 17418600 J/m^2

Average of the solar intensity = (17418600 J/m^2)/(3600 x 7 s) = 691.21 W/m^2

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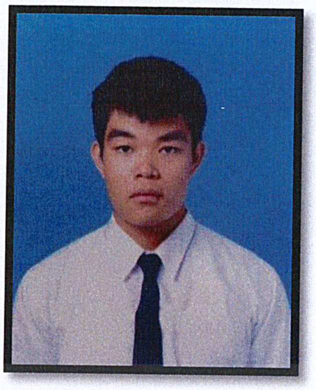
BIBLIOGRAPHY



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