EVALUATIONS OF PRESSURE DROP AND HEAT LOSS IN SOLAR THERMAL ENERGY STORAGE

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การประเมินความดันที่ลดลงและการสูญเสียความร้อนในชุดกักเก็บพลังงานความร้อนแสงอาทิตย์

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Title	Evaluations of pressure drop and heat loss in solar thermal energy storage
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Abstract

At present, solar thermal energy storage is becoming very popular for household heat production to reduce electricity use. One important problem for the solar thermal energy storage is heat loss which causes the performance of the solar thermal energy storage to decrease.

This research aims to develop a system to reduce heat loss and to study the effects of solar intensity on thermal energy accumulation in the system and the occurrence of pressure drop. The solar thermal energy storage used in this study consists of 20 evacuated tubes, experimented at flow rate of 100 l/hr and 20 kg of propylene glycol are used to exchange heat in the system. The experimental results showed that the maximum temperature of propylene glycol was 93.4 ^{o}C at the average solar intensity of 861.30 W/m^2 for system without insulation while the maximum temperature of propylene glycol was 113 ^{o}C at the average solar intensity of 824.25 W/m^2 for the system with insulation which means, the temperature of the working fluid in the storage tank increased by about 21% and heat loss was reduced from the original system by about 13%.

Keywords: Solar Collector, Solar Thermal Energy Storage System, Propylene Glycol

เรื่อง การประเมินความดันที่ลดลงและการสูญเสียความร้อนในชุดกักเก็บพลังงานความร้อนแสงอาทิตย์

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บทคัดย่อ

ในปัจจุบันชุดกักเก็บพลังงานความร้อนจากแสงอาทิตย์กำลังเป็นที่นิยมมากสำหรับการผลิตความร้อนภายในครัวเรือนเพื่อลดการใช้กระแสไฟฟ้า หนึ่งปัญหาที่สำคัญสำหรับชุดกักเก็บพลังงานความร้อนจากแสงอาทิตย์คือปัญหาการสูญเสียความร้อน ซึ่งสาเหตุนี้ส่งผลทำให้ชุดกักเก็บพลังงานความร้อนจากแสงอาทิตย์มีประสิทธิภาพที่ต่ำ เป้าหมายของงานวิจัยนี้คือ เพื่อลดการสูญเสียความร้อนและเพื่อศึกษาผลของความเข้มแสงต่อการเก็บสะสมพลังงานความร้อนในระบบและการลดลงของความดันที่เกิดขึ้นในระบบ ซึ่งชุดกักเก็บพลังงานความร้อนจากแสงอาทิตย์ที่ใช้เพื่อทำการศึกษาประกอบด้วยท่อกักเก็บพลังงานแสงอาทิตย์แบบสูญญากาศจำนวน 20 ท่อ ทดลองที่อัตราการไหล 100 ลิตรต่อชั่วโมง โดยมี 20 กิโลกรัมของโพรพิลีนไกลคอลเป็นสารสำหรับแลกเปลี่ยนความร้อนในระบบ จากผลการทดลองพบว่าสำหรับระบบที่ปราศจากฉนวนกันความร้อนอุณภูมิสูงสุดที่สามารถวัดได้คือ 93.4 องศาเซลเซียส ที่ความเข้มแสงเฉลี่ย 861.30 วัตต์ต่อตารางเมตร ขณะที่ระบบทีมีฉนวนกับความร้อนอุณภูมิสูงสุดที่สามารถวัดได้คือ 113 องศาเซลเซียส ที่ความเข้มแสงเฉลี่ย 824.25 วัตต์ต่อตารางเมตร ซึ่งหมายความว่าสามารถเพิ่มอุณภูมิของโพรพิลีนไกลคอลได้ประมาณ 21 เปอร์เซ็นต์ และยังสามารถลดการสูญเสียความร้อนจากระบบเดิมได้ถึง 13 เปอร์เซ็นต์

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Ratthasit Laothaiwanan

Table of Contents

List of Figures

List of Tables

CHAPTER I
INTRODUCTION

1.1 Background

Current energy demand is increasing which may cause future shortages, especially fossil energy. This causes renewable energies to be promoted. One of the renewable energies being developed for use in the future is solar thermal energy because it is clean energy, eco-friendly and can be applied in many ways such as drying processes, household heating and others. One of the major problems in using the solar thermal energy is instability of energy for use during the day. Because of this, the solar thermal energy storage (STESs) is a tool developed to collect the solar thermal energy and prevent instability of solar energy for use during the day. The STESs consists of two main parts which are the solar collector and the storage tank. The storage tank is made of stainless steel, covered by heat insulation and used to store solar thermal energy. The solar collectors are divided into several types such as compound parabolic collectors (CPCs), evacuated tube collectors (ETCs) and flat plate collectors (FPCs). The evacuated tube collectors are devices that collect solar energy. It has the high heat transfer rate and non-corrosion and easy to install and treatment [1]. The evacuated tube collectors were chosen in this system.

The principle of this STESs system is that the evacuated tube collectors absorbs solar thermal energy during the day and collects it in the storage tank for use at night. One of the problems encountering in the STESs is heat loss which results in insufficient heat production for usability.

Thermal insulators are materials that have the ability to prevent heat transfer from one side to the other. They are used to prevent heat loss in various equipment in the industries. Insulators are divided into several types as shown in Table 1. Good thermal insulator must have a minimum K value, heat resistance and safe.

Table 1. Types and thermal conductivity of insulators.[2]

Insulation material	Thermal conductivity(W/m•K)
Cork	0.045
Coco	0.045
Wood fiber boards	0.045
Cellulose	0.040
Foam glass	0.040-0.055
Rock wool	0.035-0.040
Fiber glass	0.035-0.040
Polystyrene	0.035-0.040
Polyurethane boards	0.025-0.035
Perlite	0.55-0.070

The aims of this work are to study principle of the solar thermal energy storage operation, the performance of the solar thermal energy storage and to develop the system to reduce heat loss.

1.2 Objectives

1.2.1 To develop the solar thermal energy storage system by reducing heat loss.

1.2.2 To measure pressure drop in the system during operation.

1.2.4 To study the effect of solar intensity on the system.

1.3 Scopes of Work

1.3.1 Design and develop the system to prevent or reduce heat loss.

1.3.2 Install equipment to measure the pressure drop in the system.

1.3.2 Compare results from system development.

1.4 Expected Outputs

1.4.1 Know the basics of the solar thermal energy storage system and be able to analyze the performance of the system.

1.4.2 Reduce heat loss in the system and increase efficiency in the STESs.

CHAPTER II
LITERATURE REVIEW

2.1 Solar thermal energy collector (STECs)

The solar collectors are the basic equipment for the STECs building, which is divided into three types

2.1.1 Evacuated tube collectors (ETCs)

Evacuated tube collectors consist of double-walled vacuum insulation pipe and the heat pipe made of copper metal pipe as shown in Figure 1.

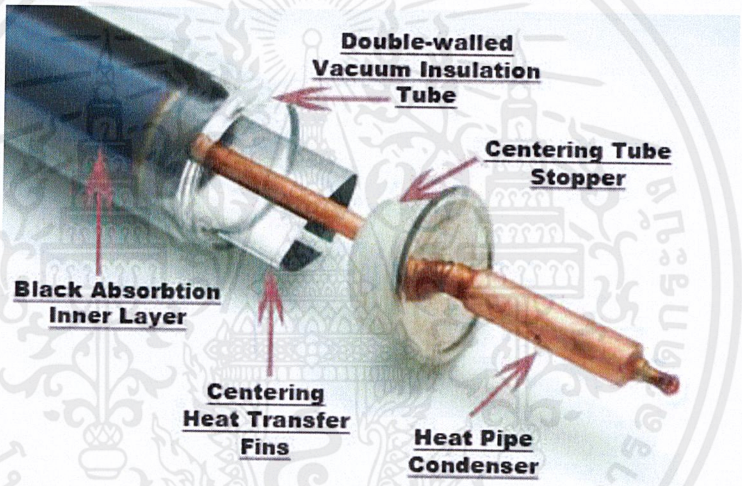

Figure 1: Components of the evacuated tube collector. [1]

Principle of this system, sun radiation is absorbed by the selective coating materials on a double-walled vacuum insulation pipe then heat is transferred to the copper metal pipe by radiation when copper metal pipe is heated, the propylene glycol in the copper metal pipe change phase into a vapor phase then the propylene glycol in vapor phase will exchange heat on pipe end and condensate into liquid phase as shown in Figure 2.

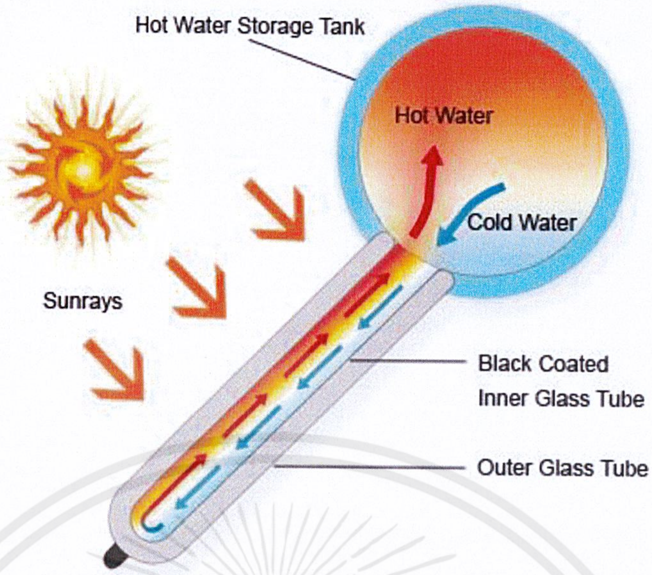

Figure 2: The principle of the collection tube evacuation. [2]

Advantages of the evacuated tube collectors are easy to install, long life, non-corrosion and easy to maintenance.

2.1.2 Compound parabolic collector (CPC)

Compound parabolic collector consists of a vacuum tube covered with black absorber film, parabolic glass reflector and solar field piping as shown in Figure 3.

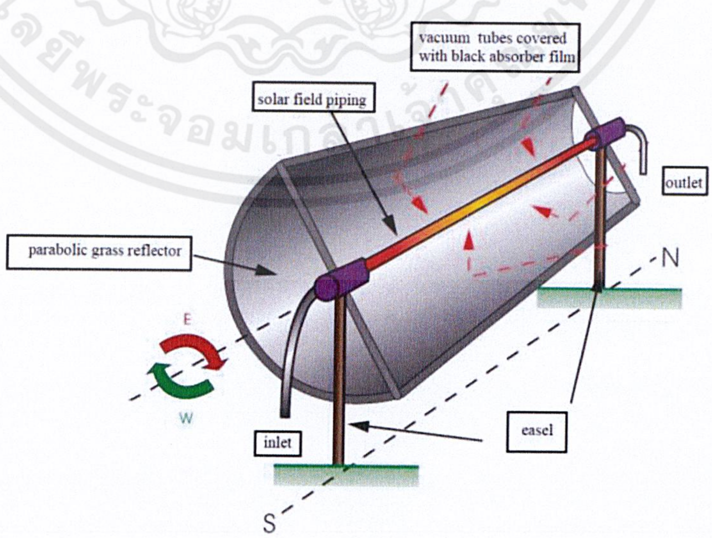

Figure 3: Components of Compound parabolic collector. [3]

For this system, cold fluid is fed into the vacuum tube to exchange heat from sun radiation. The obtained hot water from the heat exchanger is stored in a tank. The temperature of water is more than 100 °C. Application is such as electric generator.

2.1.3 Flat plate collectors (FPCs)

Figure 4 presents the components of the flat plate collectors. The flat plate collectors consist of glass gasket, universal mounting flame, laser welding, embossed aluminum backsheet, insulation sheathing, copper absorber tubes, full sheet aluminum absorber, corner brackets, lightweight aluminum frame and aluminum extruded batten.

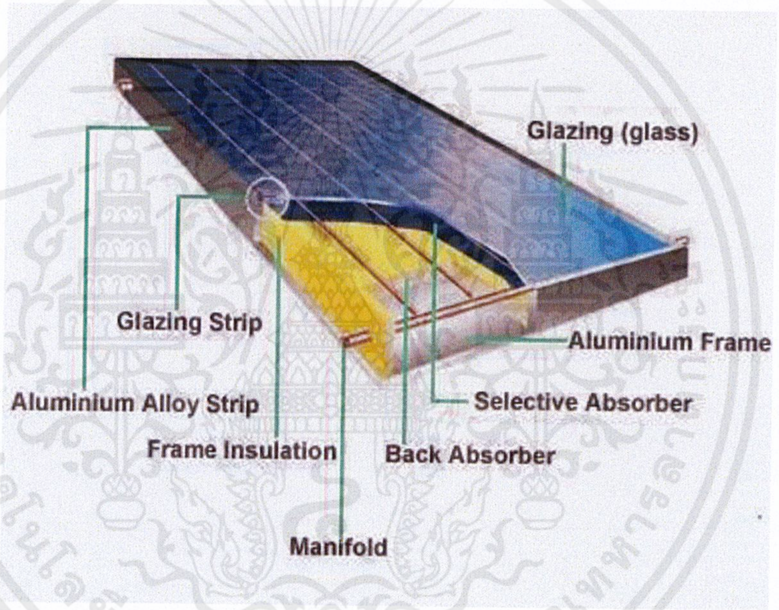

Figure 4: Components of flat plate collectors. [4]

In this system, flat plate collectors will absorb heat from the sun by heat radiation. After that cold fluid is fed into the bottom of the flat plate collectors to exchange heat and then the hot fluid is out on top of the flat plate collectors into storage tank as shown in Figure 5.

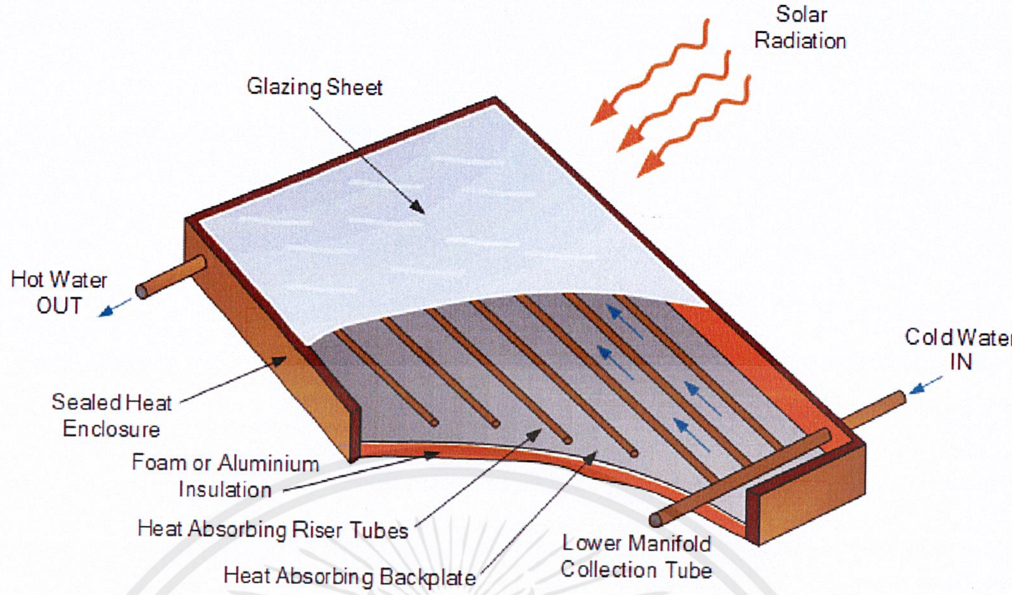

Figure 5: The principle of the flat plate collector. [5]

2.2 Thermal energy storage material

Thermal energy storage material is a material used for thermal energy storage to optimize and solve unstable power issues in the solar thermal energy collectors. Thermal energy storage material is divided into three types as follows.

2.2.1 Sensible heat storage material

For this the sensible heat storage material, thermal energy is stored by changing the temperature of the substance. Thermal energy is stored depending on the heat capacity and the temperature difference during the process charging and discharging of each substance, which can be explained by the following equation 1. [6]

$$Q = \int_{T_0}^{T} MCdT = MC\int_{T_0}^{T} dT = MC(T - T_0) = \rho CV(T - T_0) \quad (1)$$

where Q = Desired heat energy (J)

M = Mass of the substance (kg)

C = Heat capacity of the substance (J/kg•°C)

T_0 = Initial temperature of the substance (°C)

T = Final temperature of the substance (°C)

2.2.2 Phase change material (PCM)

In phase change material, charging and discharging of substance occur when a substance changes phase from solid to liquid or from liquid to gas. Thermal energy is accumulated by the latent heat of the substance. Substance having high-latent heat can accumulate more energy than low-latent heat, which can be explained by the following Equation 2 [6].

$$Q = ML \tag{2}$$

where Q = Desired heat energy (J)

M = Mass of the substance (Kg)

L = Latent heat of the substance (J/kg)

The properties of good PCMs consists of suitable phase transition temperature, cost effective, good heat transfer quality, favorable phase equilibrium, high density, low vapor pressure, no supercooling, sufficient crystallization rate, low thermal expansion, no fire hazard, no toxicity, available. [7][8]

2.2.3 Thermal chemical energy storage material

In thermal chemical energy storage material, charging and discharging of substance occur when the substance has breaking bonding and structural change of the molecule in a complete reversible chemical reaction. This heat stored depends upon the amount of storage material, the endothermic heat of reaction and fraction reacted, which can be explained by the following equation 3.[9]

$$Q = a_r M \Delta H_r \tag{3}$$

Where Q = Desired heat energy (J)

M = Mass of the substance (kg)

a_r = Fraction reacted

ΔH_r = Heat of reaction (J/kg)

2.3 Thermal insulators

Thermal insulators are materials that have the ability to block heat to pass easily from one side to the other. Thermal insulators are divided into several types as show Table 2.

Table 2. Types and properties of insulation.[10]

Type	Property	Advantages	Disadvantage
Aluminum foil	Emissivity of low aluminum surface.	High reflect heat, Good moisture resistance, Non-flammable and non-tear.	Can not protect the sound.
Foam insulation	Heat protection and keep good cool	Low conductivity and resistant to heavy compression.	Toxic gas when burned.
Fiberglass insulation	Made from glass or fiber glass.	Low conductivity and resistant to heavy compression	Irritant to user.
Mineral Wool	Made from natural fibers and compounds of Asbestos. Unsafe to health.	Resistant to fire and good sound absorption.	Not resistant to wet.
Ceramic Coating	Apply or spray to help reflect heat.	Easy installation.	Low lifespan.

For insulation selection, the thermal conductivity and temperature range of application and safety are considered. Each insulator has different properties. Therefore, choosing the right insulation can improve the high performance in operation.

2.4 Solar thermal energy storage system

This solar thermal energy storage system consists of 20 evacuated tubes, a storage tank and a pump as show in Figure 6. Each evacuated tube consists of two concentric tubes where vacuum was induced in between. The inner tube was coated with aluminum nitride to absorb solar radiation from the sun. A heat pipe is installed inside the evacuated tube. The diameter of heat pipe was 0.008 m. The outer diameter of evacuated tube is 0.058 m and the tube length is 1.8 m.

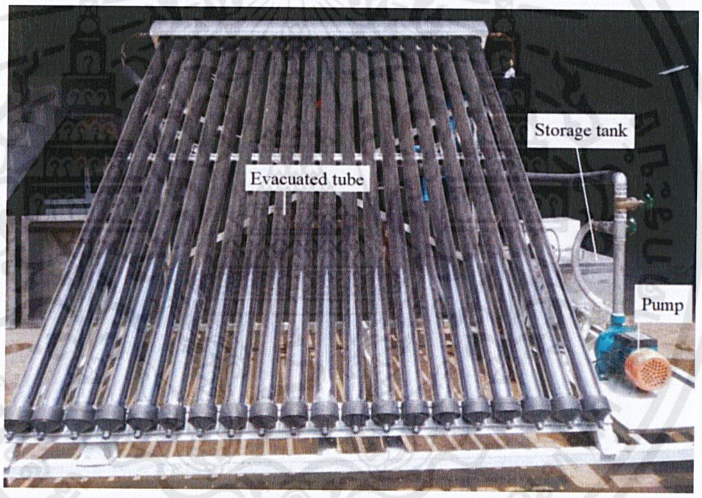

Figure 6: Components of the solar thermal energy storage system.

The principle of this solar thermal energy collector system is that the solar radiation ray is absorbed by evacuated tubes. After that, the heat in evacuated tube is transferred to the heat pipe equipped inside the evacuated tube. The working fluid inside the heat pipe is boiled, vaporizes and flow up to the heat pipe tip stored in the manifold. Meanwhile, the cold heat transfer medium such as propylene glycol is pumped from the tank bottom to the manifold to exchange heat with the heat pipe tips. The solar collector set and the mechanism of heat transfer are shown in Figures 7 and 8.

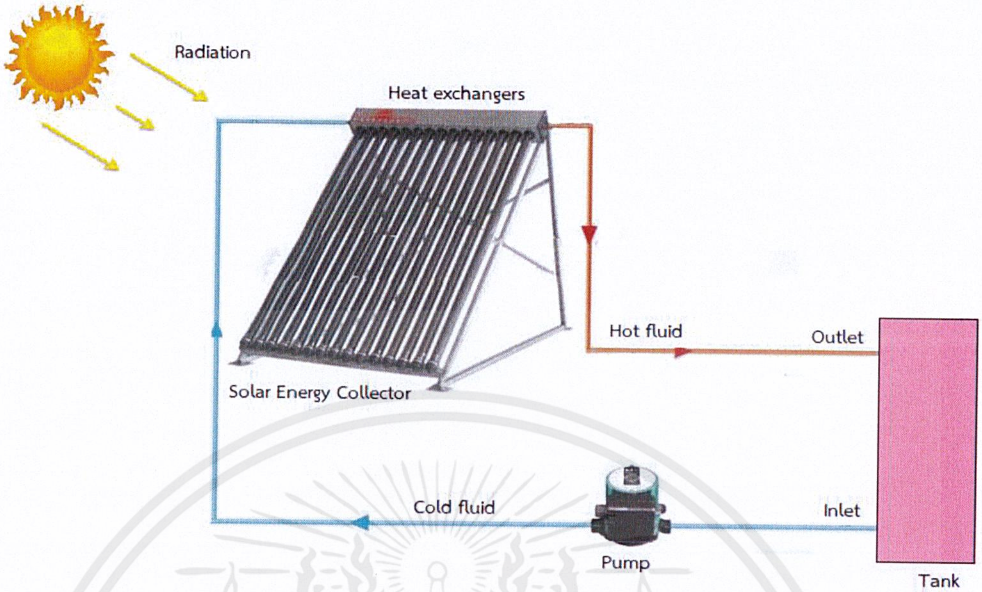

Figure 7: Principle of the solar thermal energy storage system.

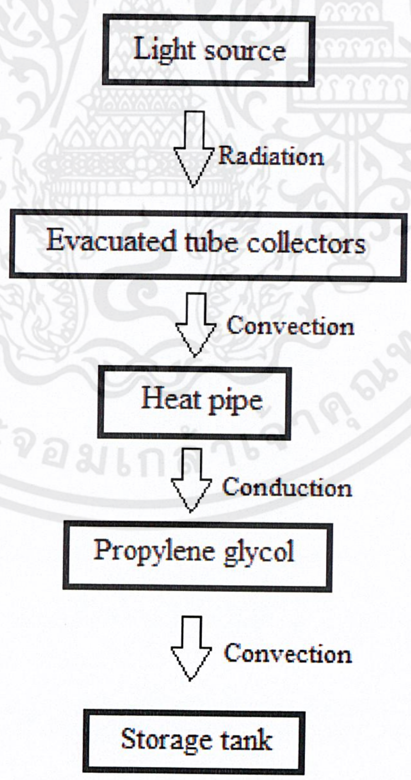

Figure 8: Mechanism of heat transfer in the STESs.

2.5 Equations for heat transfer analysis.

The amount of solar heat transferred to evacuated tube collectors. [11]

$$Q_{rad} = IAt \tag{4}$$

where

Q_{rad} = Heat of radiation (J)

I = Solar intensity (W/m^2)

A = Total surface area of the tube in the solar panel (m^2)

t = Time to absorb radiation (s)

Heat exchanging in pipes. [11]

$$Q_{pipe} = m_p C_p (T_{out} - T_{in}) \tag{5}$$

where

Q_{pipe} = Heat in pipes

m_p = Mass flow rate of propylene glycol

T_{out} = Output temperature

T_{in} = Input temperature

C_p = Specific heat of propylene glycol

Heat storage by PCM. [1]

$$Q_{pcm} = m_{pcm} C_{p,pcm} (T_{out} - T_{in}) + m_{pcm} L_{pcm} \tag{6}$$

where

Q_{pcm} = Heat storage by PCM (W)

m_{pcm} = Mass flow rate of PCM (kg/s)

C_{pcm} = Specific heat of PCM (J/kg•K)

L_{pcm} = Latent heat of PCM (J/kg)

Heat transfer efficiency in pipes. [11]

$$n_{pipe} = Q_{pipe} / Q_{radiation} \tag{7}$$

where

n_{pipe} = Heat transfer efficiency in pipes

Efficiency in heat storage . [11]

$$n_{pcm} = Q_{storage} / Q_{radiation} \quad (8)$$

where

n_{pcm} = Efficiency in heat storage by PCM

Equations for pressure drop analysis.[12]

$$Re = \frac{Du\rho}{\mu} \quad (9)$$

where

Re = Reynolds number

D = the diameter of the pipe (m)

U = the average velocity of the fluid (m/s)

ρ = the fluid density (kg/m^3)

μ = the fluid viscosity (Pa•s)

$$\frac{(u_2^2 - u_1^2)}{2\alpha} + g(z_2 - z_1) + \frac{\Delta P}{\rho} + \sum F + W_s = 0 \quad (10)$$

where

ΔP = Pressure drop (Pa)

u_1 = Inlet velocity of the fluid (m/s)

u_2 = Outlet velocity of the fluid (m/s)

α = Kinetic-energy velocity correction factor

g = Acceleration due to gravity (m/s^2)

z_1 = Initial height (m)

z_2 = Final height (m)

$\sum F$ = Frictional loss (J/kg)

W_s = System work (W)

$$\sum F = h_{fs} + h_{fe} + h_{fc} + h_{ff} \quad (11)$$

$$h_{fs} = 4f\frac{\Delta L u_1^2}{2D} \quad (12)$$

$$h_{fe} = K_e \frac{u_1^2}{2} ; K_e = (1 - \frac{A_1}{A_2}) \quad (13)$$

$$h_{fc} = K_c \frac{u_2^2}{2} ; K_c = 0.4(1 - \frac{A_2}{A_1}) \quad (14)$$

$$h_{ff} = K_f \frac{u_2^2}{2} \quad (15)$$

where

h_{fs} = Frictional loss in pipe (J/kg)

h_{fe}, h_{fc} = Frictional loss from changes in cross-section (J/kg)

h_{ff} = Frictional loss through fitting and valve (J/kg)

ΔL = Pipe length (m)

f = Fanning friction factor

A_1 = Inbound area (m^2)

A_2 = Outgoing area (m^2)

K_f = Number of velocity heads (J/kg)

2.6 Literature survey

Solar collector system is used for the first time at the end of the 1970s after the oil crisis in 1973, it has been continuously researched to use as a renewable energy. The system of Thewarat Triorarak [13] has studied the efficiency of a flat plate solar collector system. In this study, experiments were conducted using a flat plate solar collector, size 24 m^2, flow rate 69 l/min by using 150 liters of water for heat exchange in the system which found that this the system can generate a maximum heat of 68.2^oC and the system efficiency is 6%. The system of Jorawut Charin [14]. This system used a flat plate as a solar collector. The solar collector with area of 0.914 m^2 by using 3 liters of ethanol for heat exchange in the system. This system was tested at average intensity 858 W/m^2 and mass flow rate 0.11 kg/s. It found that the system can generate a maximum heat of 69 ^oC and the maximum system efficiency is 30%. In india, Jayant. V. Madan and Oshan. M. Sirse [15] have studied efficiency solar flat plate collector system for hot water production in winter. The solar flat plate collector area of 2 m^2 by 0.1 $m^3$of water for heat exchange in the system. The system is tested at average solar intensity of 480 W/m^2 and environmental temperature of 18 ^oC. It produces three hours of heat which found that this the system can generate a maximum heat of 73 ^oC and the system efficiency is 60%. In Macedonia, Marij a CHEKEROVSKA and Risto Vasil FILKOSKI [16] studied a flat-plate solar collector system by using 1.76 l of propylene glycol as working fluid. The solar collector with area of 0.98 cm^2, mineral wool insulator thick 50 mm. It found the system efficiency is 20%. In Poland, Sławomir Kurpaska, Hubert Latała and Jarosław Knga [17] studied flat and vacuum solar collector systems by using 2.25 $m^3$of water for heat exchange in both system. The solar collector area of 4.3 m^2, which is equal in both systems. It found that the efficiency of the vacuum collector was 46% and flat collectors was 40%. Therefore, vacuum collector were more effective than flat collectors. In Krakow, S Kurpaska, H Latała, M Malinowski and P Kiełbasa [18] research to compare the efficiency of solar conversion in flat plate and vacuum tube solar collectors, it found that the average efficiency of flat collectors was 42% and evacuum tube collector was 58%. Faizal, Saidur, Mekhilef, Hepbasli and Mahbubul [19] studied the results of the analysis of the relationship between the efficiency of flat-plate solar collector with volume flow rate by using SiO2–water nanofluid. Experiment, determined to compare the selection of water at different concentrations, consisting of water and 0.2 vol%SiO2-water and 0.4 vol%SiO2-water, it found that the increase efficiency of the flat-plate solar collector has the same direction as concentration and volume flow rate of SiO2–water nanofluid.

CHAPTER III
RESEARCH METHODOLOGY

3.1 Materials and equipment

1. Solar thermal energy storage
2. Anemometer
3. Propylene glycol
4. Aeroflex-standard insulator
5. Thermocouple
6. Solar power meter
7. Manometer

3.2 Method

In this work, the solar thermal energy storage consists of 20 evacuated tubes (diameter 0.058 m, length is 1.8 m),a storage tank and a pump (size 0.55 kW).

The solar thermal energy storage was installed as shown in Figure 9 and the system was tested in Ladkrabang Bangkok (13° 45′ 0″N, 100 ° 31′ 1.2″E). This experiment was conducted from 09:00 am to 16:00 pm for a total of 7 hours. The volumetric flow rate of propylene glycol was fixed at 100 liters per hour, with 20 kg propylene glycol being used as a heat transfer fluid. The parameters to be measured in the experiment were the temperature of the propylene glycol in the storage tank, the input temperature, the output temperature, solar intensity and wind speed. These data were recorded every 60 minutes for 7 hours. Heat collector, pressure drop and efficiency of the system were calculated by using sensible heat equation (1) and efficiency equation (8).

The experiment was divided into the following three parts. The first part was an experiment for the original system. The second part was a test after the system was covered by 1 inch thickness aeroflex-standard insulator as shown in Figure 10. The third part was to measure the pressure of the system by using a manometer to compare from the calculation results as shown in Figure 11.

Figure 9: The STESs installation

Figure 10: the system is covered by aeroflex-standard insulator

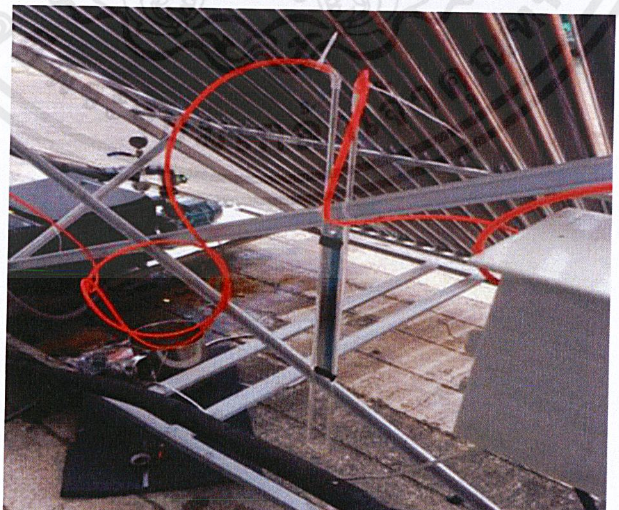

Figure 11: Pressure drop measurement

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Solar intensity analysis

Figure 12 showed the graph of the relationship between solar intensity with time. It showed that during 9:30 am, the solar intensity increases. After that, the solar intensity deviates within the range of 800 – 1,000 W/m^2 at around 10:30 am to 1:00 pm. At around 1:00 pm, the solar intensity begin to decrease gradually. the average solar intensities per day were in the range of 737.25-837.65 W / m^2.

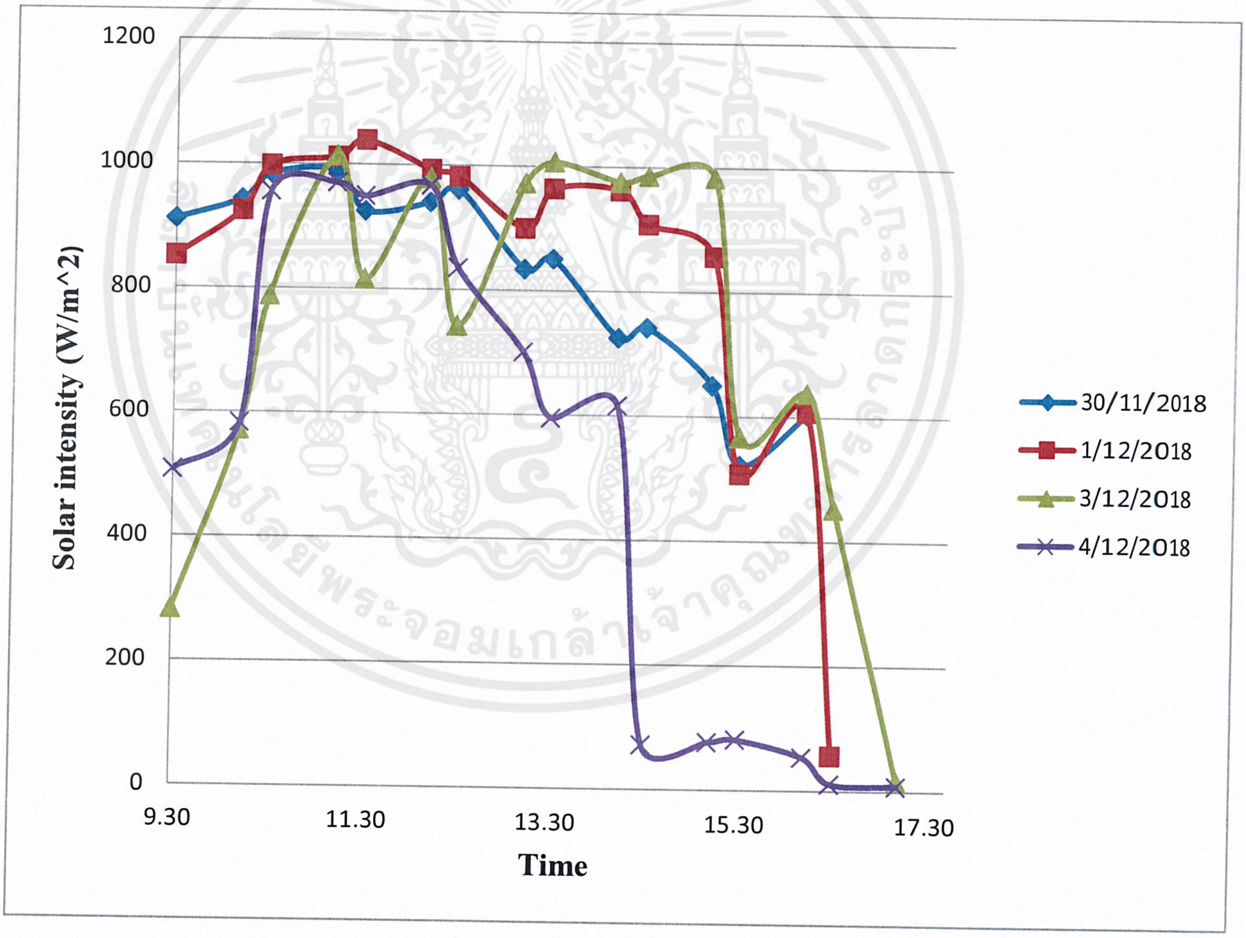

Figure 12: The graph of the relationship between solar intensity with time

4.2 Effect of solar intensity on solar thermal energy storage

Figure 13 shows the relationship between temperature of propylene glycol in the storage tank, time and average solar intensity per day which found that the temperature of propylene glycol in the storage tank depends on the solar intensity when the solar intensity increases, the temperature of propylene glycol in the storage tank will increase.

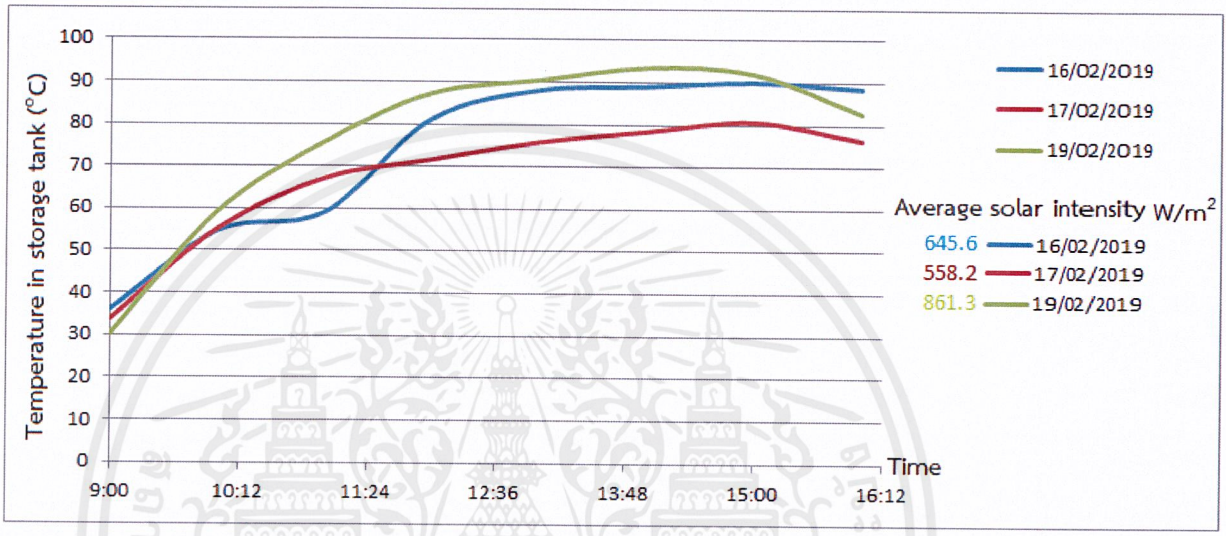

Figure 13: the relationship between the temperature of propylene glycol in the storage tank, time and solar intensity.

All the graphs in Figure 13 show the relationship between the temperatures of propylene glycol in the storage tank with time. It was found that at the beginning, the temperature of propylene glycol in the storage tank increased rapidly until about 12 pm the temperature of propylene glycol in the storage tank doesn't significantly change.

At this steady state found that the temperature change would be greatly reduced compared to the period before entering a steady state. This reason due to the decrease of driving force when the temperature in the storage tank is higher, the heat exchange will decrease due to the reduced driving force. The reduced driving force affect the heat exchange limit, causing the temperature in the tank to enter a steady state.

4.3 Effects of temperature changes of heat pipes on heat exchange of propylene glycol in storage tank

Table 3 shows the effect of the different temperature between inlet and outlet of the manifold ($T_{out} - T_{in}$) or driving force on the heat exchange of propylene glycol in the system. It was found that, at the starting time, the temperature difference was more than at any other time because it was the beginning of the system operation. After that, at 10 am, the difference between the temperatures would be constant as shown in Figure 14. Therefore found that when the temperature rises, the driving force will be reduced. Moreover, considering the difference between the temperatures of the heat pipe tip with the inlet temperature, it found that the temperature difference will be in the range of 20-39.8 ^{o}C. This information showed the limitations of heat exchange between working fluid with heat pipe tip in the system.

Table 3 and Figure 14 showed this system also has low heat exchange. For this reason, when considering at 9 am, the ideal maximum temperature difference that can be exchanged is 28.3^{o}C but in the actual system can be exchanged only 6 ^{o}C.

Table 3. The difference in temperature with time

Time	T_{in}	T_{out}	$T_{heat\ pipe\ tip}$	$T_{heat\ pipe\ tipe}$ -T_{in}	T_{out} -T_{in}
9:00	33.7	39.7	62	28.3	6
10:00	55.3	56.7	95	39.7	1.4
11:00	67.2	68.3	107	39.8	1.1
12:00	71.6	72.4	101	29.4	0.8
13:00	75.7	76.3	95.7	20	0.6
14:00	78.3	79.8	102	23.7	1.5
15:00	80.6	81.3	102	21.4	0.7
16:00	76.1	76	85	8.9	-0.1

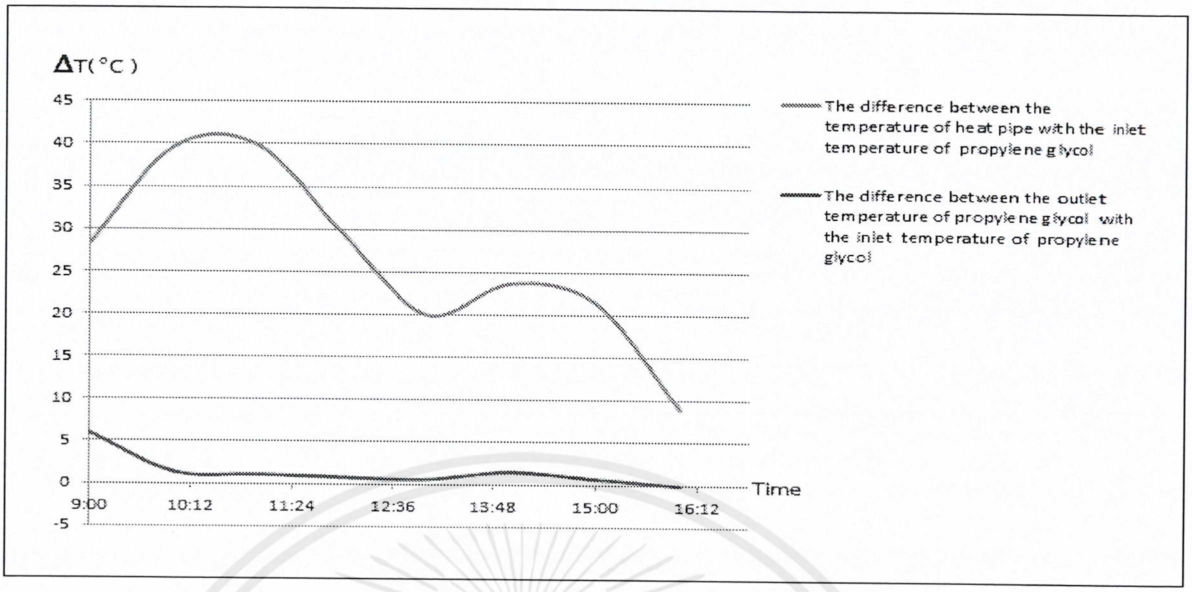

Figure 14: The effect of driving force on the heat change in the system with time.

4.4 System development results

The experimental results are shown in Tables 4 and 5. Table 4 shows the results of the original system and Table 5 shows the experimental results of the developed system. When comparing data, it was found that the original system could store heat at a maximum temperature of 93.4 °C at the average solar intensity is 861.30 W/m^2. For developed systems, the heat could be stored at the maximum temperature of 113°C at the average solar intensity is 824.25 W/m^2. As a result of both data sets, we know that the developed system can reduce the heat loss by about 13% and can increase the temperature of the propylene glycol in the storage tank by about 21% compared to the original system as shown in Figure 15.

Table 4. Experimental results from the original system.

Time	Solar intensity	T_{in}	T_{out}	T_{tank}	$T_{heat\ pipe\ tip}$
9:00	569	30.2	44.9	30.3	116
10:00	748	58.4	62.6	59.3	94
11:00	925	75.7	79	75.8	113
12:00	1007.4	87.1	89.2	87.2	120.4
13:00	1002	90.3	94.6	90.4	119
14:00	1070	93.4	94.7	93.4	113.1
15:00	880	91.8	94	91.9	126.3
16:00	689	82.6	87.7	82.6	122.5

Table 5. The results from the developed system.

Time	Solar intensity	T_{in}	T_{out}	T_{tank}	$T_{heat\ pipe\ tip}$
9:00	630	34.6	37	34.6	80
10:00	922	64.6	67.4	64.6	125
11:00	788	82.1	83.5	82.1	128
12:00	920	95.1	95.5	95.1	132
13:00	709	102.9	103.7	102.9	140
14:00	998	109.1	109.4	109.1	129
15:00	805	113	114	113	143
16:00	822	112.9	112.9	112.9	143

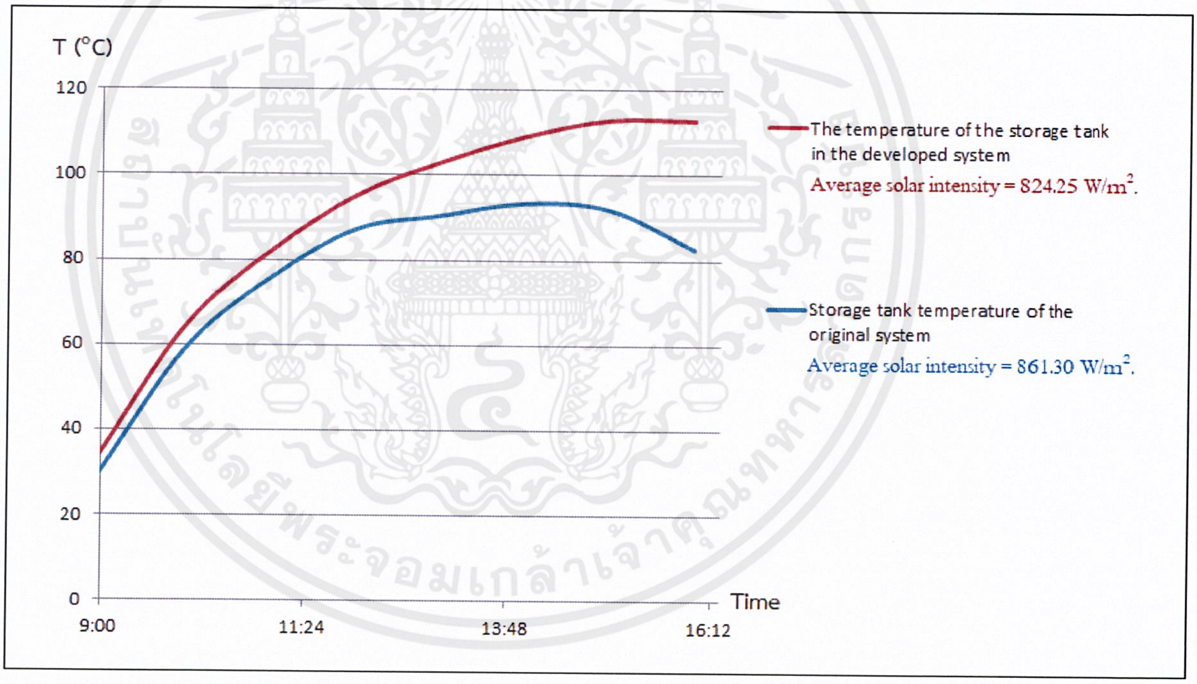

Figure 15: The comparison of the graph between the temperature in the storage tank of the original system and the temperature in the storage tank of the developed system.

4.5 Energy analysis

The comparison of the energy collection of the original system and the developed system are shown in Table 6. It was found that the efficiency of the original system is 5.14% while the efficiency of the insulated system is 6.58% when comparing the efficiency of both systems, it was found that insulator made the efficiency increase from the original system of 1.44 %.

From the analysis of the system, it was found that the current system still had low efficiency as a result of the following explanations.

1. The volume of propylene glycol was limited by the size of the storage tank. Therefore, if it was no load taken the energy from the propylene glycol in the tank, the stored thermal energy in the system would be limited by the storage capacity.
2. The heat exchange of the system was limited by the driving force. This caused the ability of the heat exchange of propylene glycol to be limited to a certain temperature which was in equilibrium with heat loss.
3. The insulator used in this system was too thin.

Table 6. The comparison of the energy collection of the original system and the developed system.

Date	Average solar intensity (W/m^2)	Thermal energy in storage tanks (MW)	Maximum temperature in storage tanks (°C)	Average efficiency of storage tank
16/02/2019	645.63	2.68	90.00	5.14%
17/02/2019	558.25	2.11	80.70	
19/02/2019	861.30	3.13	93.40	
Developed system				
24/02/2019	794.63	3.58	103.30	6.58%
26/02/2019	637.75	3.02	98.50	
12/03/2019	824.25	3.89	113.00	

4.6 Pressure drop analysis

The pressure drop in the part of heat exchange measured across the manifold by a U type manometer which was measured at a flow rate of 100 l/hr in a system consisting of 20 vacuum tubes was 1820 Pa. On the other hand, at the same position, it was found that the pressure drop was 23.7 Pa for the absence of vacuum tubes. The vacuum tubes were added in the system has effect a 77-fold increase of a pressure drop when comparing the absence of vacuum tubes. The total pressure drop in this the solar thermal energy storage system estimate 6815.85 Pa. This pressure drop value is used to select the pump specification for the system.

CHAPTER V

COCLUSION

5.1 Conclusion

The experimental results showed that the maximum temperature of propylene glycol is 93.40 °C at the average solar intensity of 861.30 W/m^2 for the systems that is not insulated. On the other hand, the maximum temperature of propylene glycol in the insulated systems is 113 °C at the average solar intensity of 824.25 W/m^2. In addition, it was found that after insulating the system, increase in the temperature of the working fluid in the storage tank is 21% approximately and the heat loss from the original system is reduced around 13%. Moreover, the pressure drop in the part of heat exchange at flow rate 100 l/hr is 1.82 kPa.

5.2 The suggestions

The suggestions for studies of solar thermal energy storage system are as follows:

1. Presently, the solar thermal energy storage system can generate the maximum temperature of 113 °C. In order to increase the efficiency of system, it is required to increase the thickness of insulator.

2. In order to calculate the capacity of heat generation, it is necessary to install other unit to transfer heat to specified fluid.

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APPENDIX A

EXPERIMENTAL RESULTS AND CALCULATION

Appendix A-1: Data list of experimental results of solar thermal energy storage

Appendix A-2: Data list of calculation of solar thermal energy storage

Appendix A-1: Data list of experimental results of solar thermal energy storage.

Table A-1.1 Experimental data for original systems.

16/02/2019

Time	Solar intensity	Tin	Tout	Ttank	$T_{heat\ pipe}$	Maximum heat exchang	Real heat exchang	Heat accumulated in the tank
9:00	119	36	37.6	36.1	58	1572.085149	107.677065	
10:00	754	54.7	57.3	54.7	89	2462.215553	186.640246	
11:00	853	59.2	64.6	59.2	126	4795.218628	387.637434	
12:00	952	81.1	84.9	81.1	120	2792.425219	272.781898	
13:00	886	88	90.1	88	103	1076.77065	150.747891	
14:00	600	89	89.5	89	101	861.41652	35.892355	
15:00	598	90	91.1	90	120	2153.5413	78.963181	
16:00	403	88.5	90.2	88.5	109.7	1521.835852	122.034007	
average	4235.3					2154.438609	167.7967596	
Total energy (MW)	45.74124					46.53587395	3.624410008	2.6776442
EFF						101.7372375	7.923724866	5.853895085

17/02/2019

Time	Solar intensity	Tin	Tout	Ttank	$T_{heat\ pipe}$	Maximum heat exchang	Real heat exchang	Heat accumulated in the tank
9:00	215	33.7	39.7	33.8	62	2024.328822	423.529789	
10:00	230	55.3	56.7	55.2	95	2857.031458	107.677065	
11:00	622	67.2	68.3	67.2	107	2857.031458	78.963181	
12:00	785	71.6	72.4	71.6	101	2110.470474	57.427768	
13:00	712	75.7	76.3	75.8	95.7	1428.515729	35.892355	
14:00	970	78.3	79.8	78.4	102	1694.119156	100.498594	
15:00	722	80.6	81.3	80.7	102	1529.014323	43.070826	
16:00	210	76.1	76	76.3	85	624.526977	-21.535413	
average	3662.12					1890.6298	103.1905206	
Total energy (MW)	39.550896					40.83760367	2.228915246	2.111315
EFF						103.2532959	5.635561949	5.338222932

19/02/2019

Time	Solar intensity	Tin	Tout	Ttank	$T_{heat\ pipe}$	Maximum heat exchang	Real heat exchang	Heat accumulated in the tank
9:00	569	30.2	44.9	30.3	116	6151.949647	1048.056766	
10:00	748	58.4	62.6	59.3	94	2490.929437	236.889543	
11:00	925	75.7	79	75.8	113	2670.391212	229.711072	
12:00	1007.4	87.1	89.2	87.2	120.4	2383.252372	143.56942	
13:00	1002	90.3	94.6	90.4	119	2053.042706	301.495782	
14:00	1070	93.4	94.7	93.4	113.1	1414.158787	93.320123	
15:00	880	91.8	94	91.9	126.3	2469.394024	150.747891	
16:00	689	82.6	87.7	82.6	122.5	2864.209929	366.102021	
average	5650.128					2812.166014	321.2365773	
Total energy (MW)	61.0213824					60.74278591	6.938710069	2.5981594
EFF						99.54344448	11.37094867	4.257785219

Table A-1.2 Experimental data for developed systems.

24/02/2019

Time	Solar intensity	Tin	Tout	Ttank	Theat pipe	Maximum heat exchang	Real heat exchang	Heat accumulated in the tank
9:00	686	31.2	33.4	31.2	73	3000.600878	157.926362	
10:00	888	39.9	42	40	104	4594.22144	143.56942	
11:00	816	61.2	62.9	61.2	120	4220.940948	122.034007	
12:00	703	76.8	77.2	76.8	112	2526.821792	28.713884	
13:00	749	87.7	90.4	87.7	102	1026.521353	193.818717	
14:00	949	93.5	94.1	93.5	124	2189.433655	43.070826	
15:00	789	98	99.2	98	113	1076.77065	86.141652	
16:00	777	103.3	103.3	103.3	142	2778.068277	0	
average	5212.74					2676.672374	96.9093585	
Total energy (MW)	56.297592					57.81612328	2.093242144	3.5817838
EFF						102.697329	3.718173494	6.362232687

26/02/2019

Time	Solar intensity	Tin	Tout	Ttank	Theat pipe	Maximum heat exchang	Real heat exchang	Heat accumulated in the tank
9:00	507	32.8	37.9	33.4	73	2842.674516	366.102021	
10:00	750	53.1	56	53.1	104	3653.841739	208.175659	
11:00	567	76.1	78.5	76.2	118	3000.600878	172.283304	
12:00	852	88.3	90.5	88.4	109	1478.765026	157.926362	
13:00	612	92.4	94.3	92.5	101	610.170035	136.390949	
14:00	873	98.1	98.5	98.1	119.3	1521.835852	28.713884	
15:00	313	98.5	99.3	98.5	130	2261.218365	57.427768	
16:00	628	94.3	93.7	94.3	120	1844.867047	-43.070826	
average	4183.64					2151.746682	135.4936401	
Total energy (MW)	45.183312					46.47772834	2.926662627	3.0253902
EFF						102.8648107	6.477308761	6.695813268

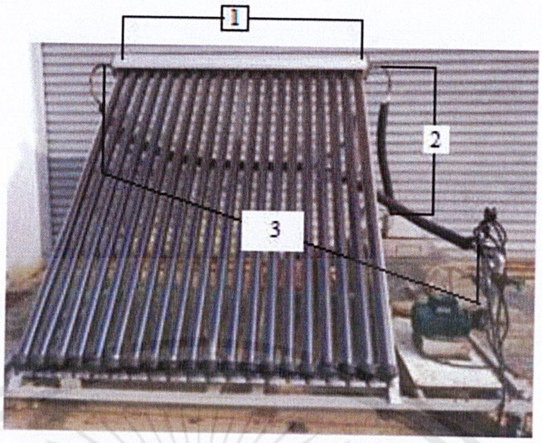
17/03/2019

Time	Solar intensity	Tin	Tout	Ttank	Theat pipe	Maximum heat exchang	Real heat exchang	Heat accumulated in the tank
9:00	630	34.6	37	34.6	80	3259.025834	172.283304	
10:00	922	64.6	67.4	64.6	125	4335.796484	200.997188	
11:00	788	82.1	83.5	82.1	128	3294.918189	100.498594	
12:00	920	95.1	95.5	95.1	132	2648.855799	28.713884	
13:00	709	102.9	103.7	102.9	140	2663.212741	57.427768	
14:00	998	109.1	109.4	109.1	129	1428.515729	21.535413	
15:00	805	113	114	113	143	2153.5413	71.78471	
16:00	822	112.9	112.9	112.9	143	2160.719771	0	
average	5407.08					2743.073231	81.65510763	
Total energy (MW)	58.396464					59.25038179	1.763750325	3.8947552
EFF						101.4622765	3.020303292	6.669505195

Table A-1.3 Data of solar thermal energy storage for heat production.

Lists	Values
Evacuated solar thermal energy collector 1.An angle of system 2.The number of evacuated tubes 3.Flow rate of propylene glycol in system	 45^{o} 20 100 l/hr
Propylene glycol 1.Density 2.Heat capacity 3.Mass of propylene glycol	 1.04 g/cm^3 2483.9 J/kg•K 20 kg
Storage tank 1.Wide 2.Hight 3. EPDM RUBBER	 56.50 cm 22.50 cm 1 in
EPDM RUBBER 1.K- Value 2.Usage range	 0.038 W/m•K -57 to +125 ^{o}C
Circular tube 1.Material 2.Diameter 3.Length	 Copper 0.0011 m 1.50 m

Appendix A-2: Data list of calculation of solar thermal energy storage



Calculating pressure drop at position 1

<u>Assumption</u>

1. Steady operation condition and the temperature at 25 °C and the pipe is a smooth surface and it has no effect from the heat pipe tip.

2. No system work and the frictional loss from changes in cross-section and the frictional loss through fitting and valve in the system.

3. Potential energy and kinetic energy in the system are very low.

<u>Reynolds number</u>

D_h = 0.042 m, u =0.02 m/s, ρ = 1040 Kg/m^3, μ = 0.042 Pa•s

$$\text{Re} = \frac{D_h u\rho}{\mu} = \frac{(0.042)(0.02)(1040)}{0.042} = 20.8$$

<u>Pressure drop</u>

f =0.7692; ΔL=1.555 m; D=0.042 m

$$\Delta P = \rho h_{fs} = \frac{4\rho f \Delta L u^2}{2D} = \frac{(4)(1040)(0.7692)(1.555)(0.02)^2}{2(0.042)} = 23.70\text{Pa}$$

Calculating pressure drop at position 2+3

Reynolds number

D_h = 0.0112 m, u =0.2820 m/s, ρ = 1040 Kg/m^3, μ = 0.0420 Pa•s

$$\mathrm{Re} = \frac{D_h \mathrm{u}\rho}{\mu} = \frac{(0.0112)(0.2820)(1040)}{0.0420} = 78.208$$

Pressure drop

f =0.2046; ΔL=6.2000 m; D=0.0112 m

$$\Delta P = \rho h_{fs} = \frac{4\rho f \Delta L u^2}{2D} = \frac{(4)(1040)(0.2046)(6.2)(0.2820)^2}{2(0.042)} = 4995.85 \text{ Pa}$$

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