Solar Thermal Energy Collector System Design for Extending Serviceable Time Using Organic PCM as an Energy Storage Material

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A Report Submitted in Partial Fulfillment of the Requirements
for the Degree of Bachelor of Engineering (Petrochemical Engineering)
Department of Chemical Engineering, Faculty of Engineering,
King Mongkut's Institute of Technology Ladkrabang
Academic Year 2017

การออกแบบระบบเก็บพลังงานความร้อนจากแสงอาทิตย์ เพื่อยืดระยะเวลาการใช้งานให้นานขึ้น โดยใช้วัสดุเปลี่ยนสถานะอินทรีย์เป็นวัสดุกักเก็บพลังงาน

บุญยภา เบญจมาลัย

ปริญญานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตร

วิศวกรรมศาสตร์บัณฑิต สาขาวิชาวิศวกรรมปิโตรเคมี

ภาควิชาวิศวกรรมเคมี คณะวิศวกรรมศาสตร์

สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง

ปีการศึกษา **2560**

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Abstract

At the present the evacuated solar collector is widely used to produce hot water in domesticity but the main problem of using this system is the solar thermal energy can produce hot water only day time.

This research focuses on improving the system to extend serviceable time when without the solar radiation from the sun. Hot water heating system design was created by using phase change material (PCM) and propylene glycol to be heat storage and heating medium fluid respectively. The experimental results show the highest temperature of heating medium fluid at 93.20 °C during 12.00-13.00 PM at flow rate of 4.13 liter per hour. Based on this condition, to produce hot water at 40 °C, the calculated results show that the system using PCM as a heat storage should extend the serviceable time by 3 hours in comparison with the one without PCM.

เรื่อง	การออกแบบระบบเก็บพลังงานความร้อนจากแสงอาทิตย์ เพื่อยืดระยะเวลาการใช้งานให้นานขึ้น โดยใช้วัสดุเปลี่ยนสถานะอินทรีย์เป็นวัสดุกักเก็บพลังงาน
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บทคัดย่อ

ระบบจัดเก็บพลังงานความร้อนจากแสงอาทิตย์ชนิดหลอดแก้วสุญญากาศกำลังเป็นที่นิยมอย่างมากในการผลิตน้ำร้อนภายในครัวเรือน เพื่อลดปริมาณการใช้ไฟฟ้า แต่เนื่องจากปัญหาที่พบอย่างหนึ่งจากการใช้ระบบทำความร้อนจากพลังงานแสงอาทิตย์โดยใช้หลอดแก้วสุญญากาศคือ พลังงานความร้อนจากแสงอาทิตย์สามารถผลิตน้ำร้อนได้แค่ช่วงกลางวันเท่านั้น งานวิจัยนี้จึงมีความมุ่งหมายที่จะพัฒนาความสามารถของระบบเพื่อลดอัตราการลดลงของอุณหภูมิเมื่อปราศจากแสงอาทิตย์โดยออกแบบระบบผลิตน้ำร้อนร่วมกับวัสดุเปลี่ยนวัฏภาค และใช้ propylene glycol เป็นของเหลวตัวกลางในการแลกเปลี่ยนความร้อน จากผลการทดลองระบบที่ใช้ propylene glycol เป็นของเหลวตัวกลางแลกเปลี่ยนความร้อนกับท่อน้ำ พบว่าอุณหภูมิสูงสุดของของเหลวตัวกลางในการแลกเปลี่ยนความร้อนในแท้งเท่ากับ 93.20 $^{\circ}C$ ในช่วงเวลา 12.00-13.00 น .เมื่ออัตราการไหลของสารภายในระบบเท่ากับ 200 ลิตรต่อชั่วโมง จากข้อมูลดังกล่าว นำมาออกแบบระบบผลิตน้ำร้อน โดยหุ้มท่อผลิตน้ำร้อนด้วยวัสดุเปลี่ยนวัฏภาค และผ่านท่อผลิตน้ำร้อนเข้าไปในถัง propylene glycol จากผลการคำนวณระยะเวลาการผลิตน้ำร้อนอุณหภูมิ 40 $^{\circ}C$ เปรียบระบบที่ใช้วัสดุเปลี่ยนเฟสเป็นตัวกลางแลกเปลี่ยนความร้อน ที่อัตราการไหลเท่ากับ 4.13 ลิตรต่อชั่วโมง พบว่า ระบบที่ท่อผลิตน้ำร้อนหุ้มด้วยวัสดุเปลี่ยนเฟสสามารถผลิตน้ำอุณหภูมิ 40 $^{\circ}C$ ได้นาน 25 ชั่วโมง ซึ่งมากกว่าระบบที่ไม่หุ้มวัสดุเปลี่ยนเฟสประมาณ 12 ชั่วโมง

Acknowledgements

The research work was made possible through from Department of Chemical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang (Petrochemical Engineering). I am very much thankful to Assist.Prof.Dr. Walairat Chandra-ambhorn, my advisor who gives me in knowledge, direction and support me.

I also wish to thank Assoc. Prof. Dr Prakob Kitchaiya and Mr. Boonchai Chotiyiriyavanich to giving suggestion, and inspirations in my work.

For evacuated solar collector tube system author must thankful Mr Pison Polpoh and Mr. Somsak Veeraphan to support and helped to perform equipment and to resolve a problem from equipment.

In addition, author really thankful for Nutcha Phumsrisawat, my best friend and my laboratory member for advice and give morale to me. And I would like to thank my friends at Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang who give the best relationship for 4 years.

Lastly, I grateful to my family for loves, power, inspiration, cares for hard work to me, thank you everything you done to me.

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CHAPTER I
INTRODUCTION

1.1 Background

Nowadays, solar thermal energy collectors (STECs) have got attention for water heating in both domesticity and industry because thermal energy from the sun is renewable energy. The STECs are divided into several types such as flat plate collectors (FPCs), evacuated tube collector (ETCs) and compound parabolic collectors (CPCs). However STECs have a major problem to be concerned about design of system i.e. the energy can be stored only within limited time because they can collect thermal energy through solar radiation which presents only during daytime. Although FPCs and ETCs are widely used to heat water in domesticity but it has been proven that performance of ETCs is better than that of FPCs [1]. ETCs are wickless and operated in vacuum state so working fluid can release heat at temperatures below 100℃ [2] and the heat pipe is enveloped by a vacuum tube to reduce heat loss due to conduction and convection, thus they can be operated even in cold weather. Therefore, smart design is needed to extend service time of solar thermal energy storage system.

Phase change materials (PCMs) are used to store heat in the form of latent heat. Heat is stored and released during the cycle of phase change.

The PCMs can be classified into 3 groups.

1. Organic compounds such as sugar alcohol, paraffin and glycols.
2. Inorganic compounds such as salt hydrates metals and metal alloys.
3. Eutectic compounds.

The organic PCMs are attractive to application of low-medium temperature because high thermal conductivity, abundantly available and low price. In the present work, an organic compound is chosen as a latent heat thermal energy storage material in this system.

The aims of this work are to study operating principle of evacuated tube solar thermal energy collector and to design the system to reduce heat loss and be serviceable even at night time by using a paraffin for PCM as a heat storage material.

1.2 Objectives

1.2.1 To develop the solar thermal energy collecting system to serviceable at night and produce hot water more than 40℃.

1.2.2 To study the distribution of thermal energy into phase change material.

1.2.3 To study and improve the efficiency of system.

1.3 Scopes of work

1.3.1 Design the solar thermal energy collecting system.

1.3.2 Study the properties of phase change material i.e. melting temperature, latent heat and thermal conductivity.

1.3.3 Design tank of phase change material and loading of phase change material.

1.3.4 Determine overall energy of system.

1.4 Expected Outputs

1.4.1 Enhancement of solar thermal energy storage system and prolongation of water heating production even without heat source.

1.4.2 Apply system for collector thermal energy from another heat source.

CHAPTER II
LITERATURE REVIEW

2.1 Solar Thermal Energy Storage; STEC

The solar collectors are basic equipment of any STEC systems. The common of solar collectors used at the present time can be divided into 3 types.

2.1.1 Flat Plate Collectors (FPCs)

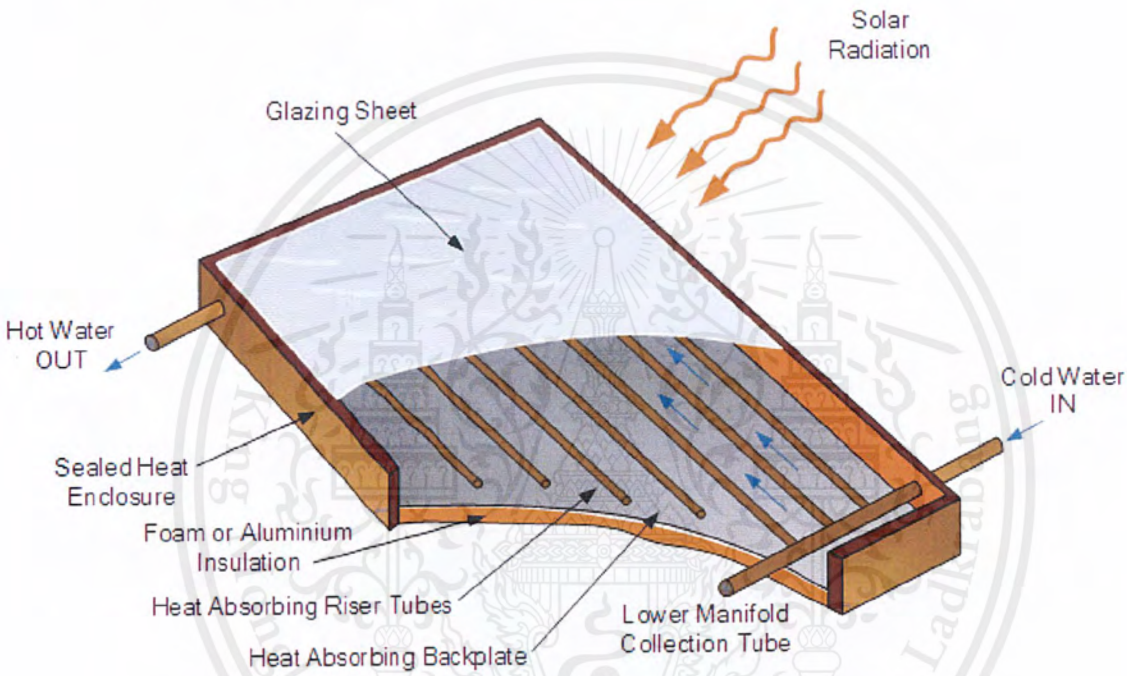

Figure 1: Flat plate solar collector [3].

Figure 1 represents component of flat plate solar collector. The flat plate solar collector has been developed since the 1950's. The features of FPCs are heat absorbing backplate made by a sheet of copper or aluminum and covered by black color, transparent glazing sheet, heat absorbing riser tubes and thermosyphon where fluid is fed to be heated.

For this system, cold fluid is fed into the bottom of FPCs. Solar radiation is absorbed and transferred to fluid and then the hot fluid is flowed out at top of panel to water tank storage. The temperature of water is around 30-70℃.

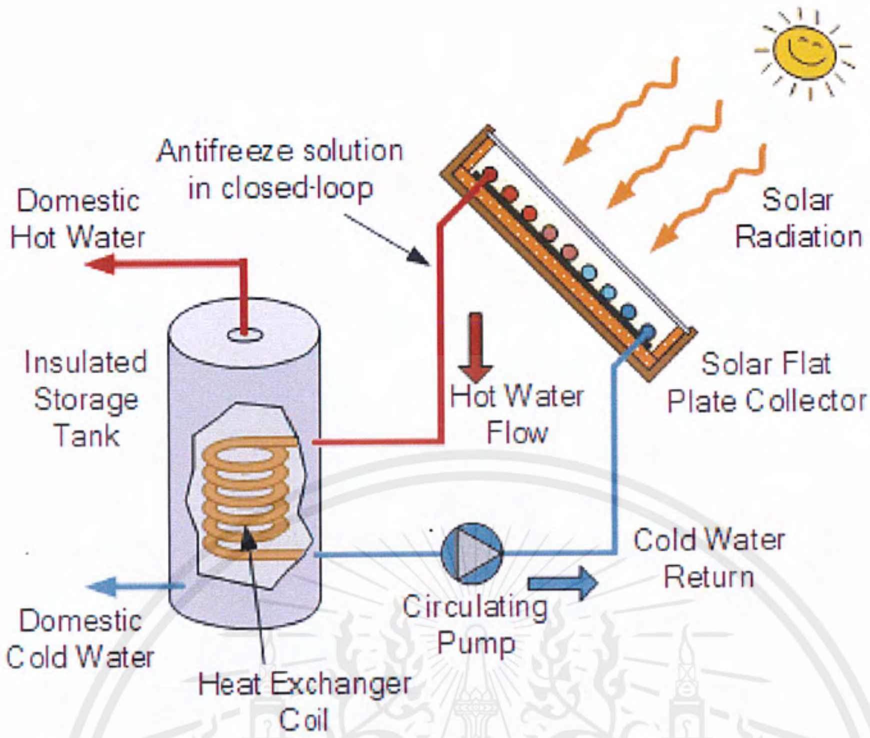

Figure 2: The solar water tank with heat exchange coil system. [4]

Figure 2 represents solar water tank with heat exchange coil system. Antifreeze solution used as a working fluid is fed into bottom of solar flat plate collector to absorb heat of solar radiation and transfer to water tank with copper coil inside storage tank. The advantages of using antifreeze solution are being able to protect the system from corrosion by untreated tap water and produce hot water at temperature higher than using water as a working fluid.

2.1.2 Compound Parabolic Collectors (CPCs)

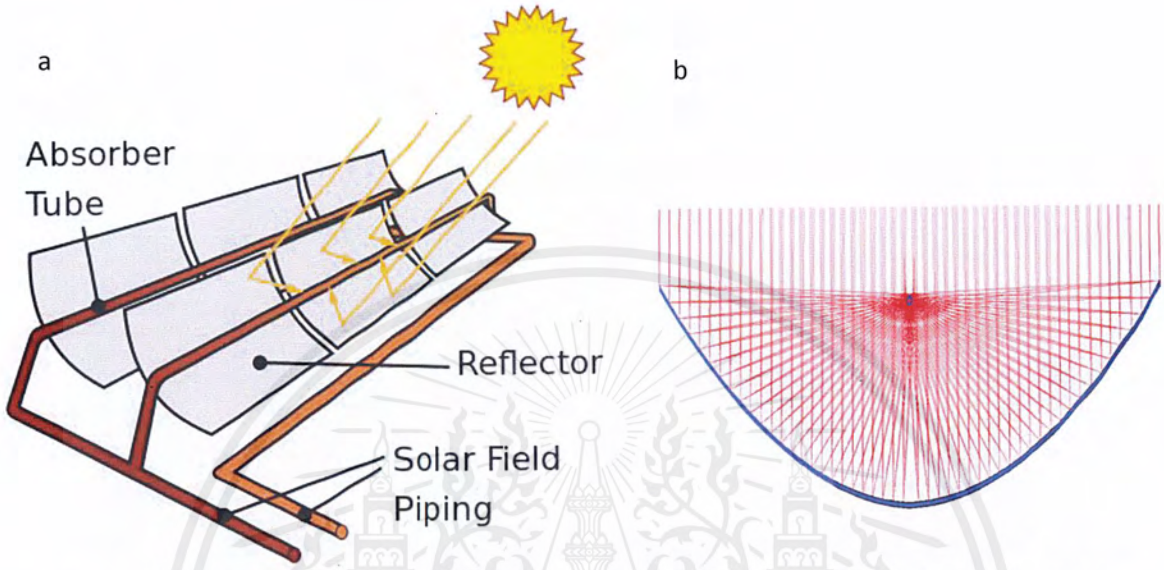

Figure 3: a) The compound parabolic collector system [5]. b) Optical analysis [6].

Figure 3 represents the features of compound parabolic collectors system. The CPCs consist of vacuum tubes covered with black absorber film, parabolic glass reflector and solar field piping. Some CPC systems have tracking mechanism for following the sun.

In this system, cold fluid flows through vacuum tube to absorb heat and hot fluid transfers heat to water in water tank. Figure 3b represents the ray reflected to absorber so this system can provide hot water at 100 ℃ – 180 ℃.

2.1.3 Evacuated Solar Collectors (ESCs) [7]

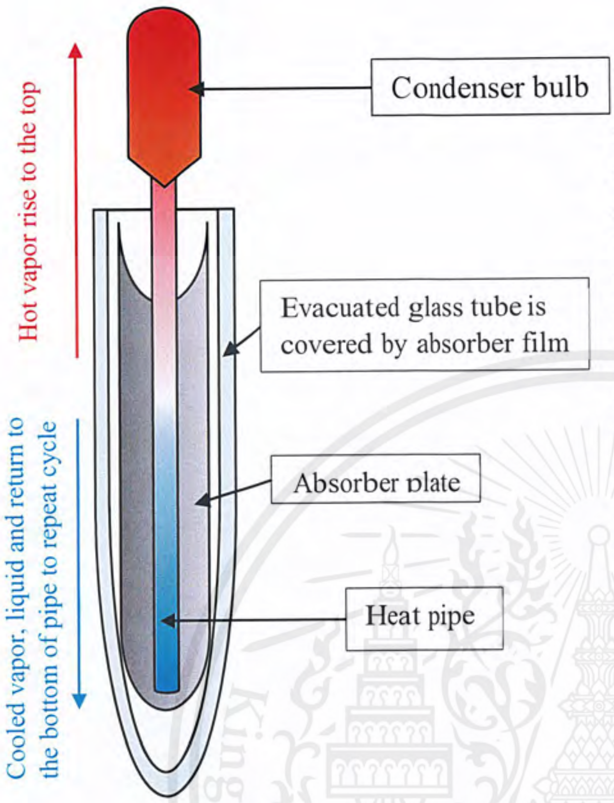

Figure 4: Evacuated solar

In 1991, the Thermomax Mazdon developed an evacuated solar collector (Figure 4) that could solve the problem about performance of flat plate solar collector system. The efficiency of this system was up to 80% that was better than that of flat plate solar collector because of their thermophysical properties such as reduction of heat loss from heat pipe by covering with evacuated glass tube and their heat transfer rate better than that of solid storage collector by thousands times at the same size. The advantages of these STECs are as follows.

High efficiency of system.

- High heat transfer rate.
- Provide medium- high temperature.
- Non corrosion and easy to maintenance.
- Can operate in cold weather.
- Easy to install.

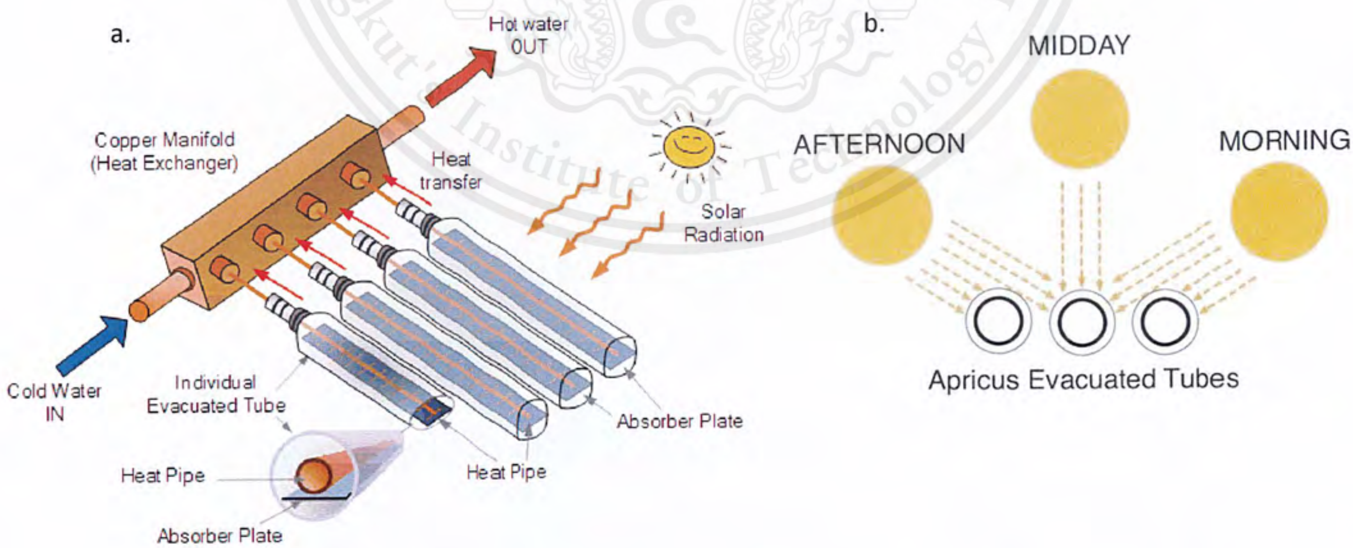

Figure 5: a) evacuated solar collector system, b) solar collector tube tracking passively [8].

Figure 5a represents the evacuated solar collector system. In this system, the inside of evacuated tubes consists of glass tubes covered with absorber coating, heat pipe connected with copper manifold and absorber plate. The heat pipes are filled with working fluid to absorb heat from solar radiation and volatilize to condenser bulb for heat transferring to water that are flowed throughout the copper manifold. Finally, working fluid condenses to heat pipe to absorb heat again. The main advantage of ESCs is being able to be operated even in cold weather or cloudy because the round absorber surface of ESCs tubes can track the sun every time of the day (Figure 5b).

In this work, ETC will be used as a part of solar thermal energy storage system and the performance of system when this system is developed with phase change materials will be investigated.

- Analysis energy of STEC
  - Energy collected by the ETC.

The energy is collected by ETC (E_{coll}) and transferred to the medium fluid. In addition, the energy is calculated by Equation (1).

$$E_{coll} = mc_p(T_2 - T_1) = \rho c_p V(T_2 - T_1) \tag{1}$$

where c_p specific heat of fluid

ρ density of fluid

V volumetric of fluid

- Energy collected by the PCM.

The energy is collected by the PCM (E_{PCM}) and that transferred by medium. Indeed, the E_{PCM} determine as follow.

$$E_{PCM} = (m_{PCM} L) + m_{PCM} c_{p,PCM} (T_{2,PCM} - T_{1,PCM}) \tag{2}$$

where m_{PCM} mass of PCM.

L latent heat of PCM,

$c_{p,\,PCM}$ specific heat of PCM.

$T_{1,\,PCM}$, $T_{2,\,PCM}$ Initial temperature and final temperature of PCM.

- Heat loss of STEC system

Thus, heat loss of STEC system is determined as the different between energy collected by the ETC and PCM as:

$$E_{loss} = E_{coll} - E_{PCM} \quad (3)$$

- o ETC system efficiency

The ETC system efficiency is calculate as:

$$\eta_{coll} = E_{coll} / E_{rad} \quad (4)$$

Where E_{rad} thermal energy of radiation (W) is $E_{rad} = \alpha_s G_{solar} A$

α_s absorptivity of a surface area.

A absorption surface area of collector (m^2).

G_{solar} direct solar radiation (W/m^2) [9].

$$G_{solar} = I_0 \bullet \exp(-T_{Linke} \bullet D_{Ro} \bullet m \bullet p / p_0) \quad (5)$$

Where I_0 solar constant is 1,373 W/m^2

T_{Linke} the number of pure dry air masses

D_{Ro} verticle optical density of the pure and dry standard atmosphere

m relative optical air mass or air mass (AM) is $AM = \frac{1}{\cos z}$, z is the zenith angle in degrees.

p/p_0 pressure correction for the reduction of the standard atmosphere's relative air-mass.

2.2 Energy storage materials

The STECs from heat sources can be operated by several ways depending on the form of heat stored in energy storage materials. Energy storage can be performed by 3 forms that are sensible heat, latent heat and chemical heat. Figures 6 and 7 represent the types of thermal energy storage materials.

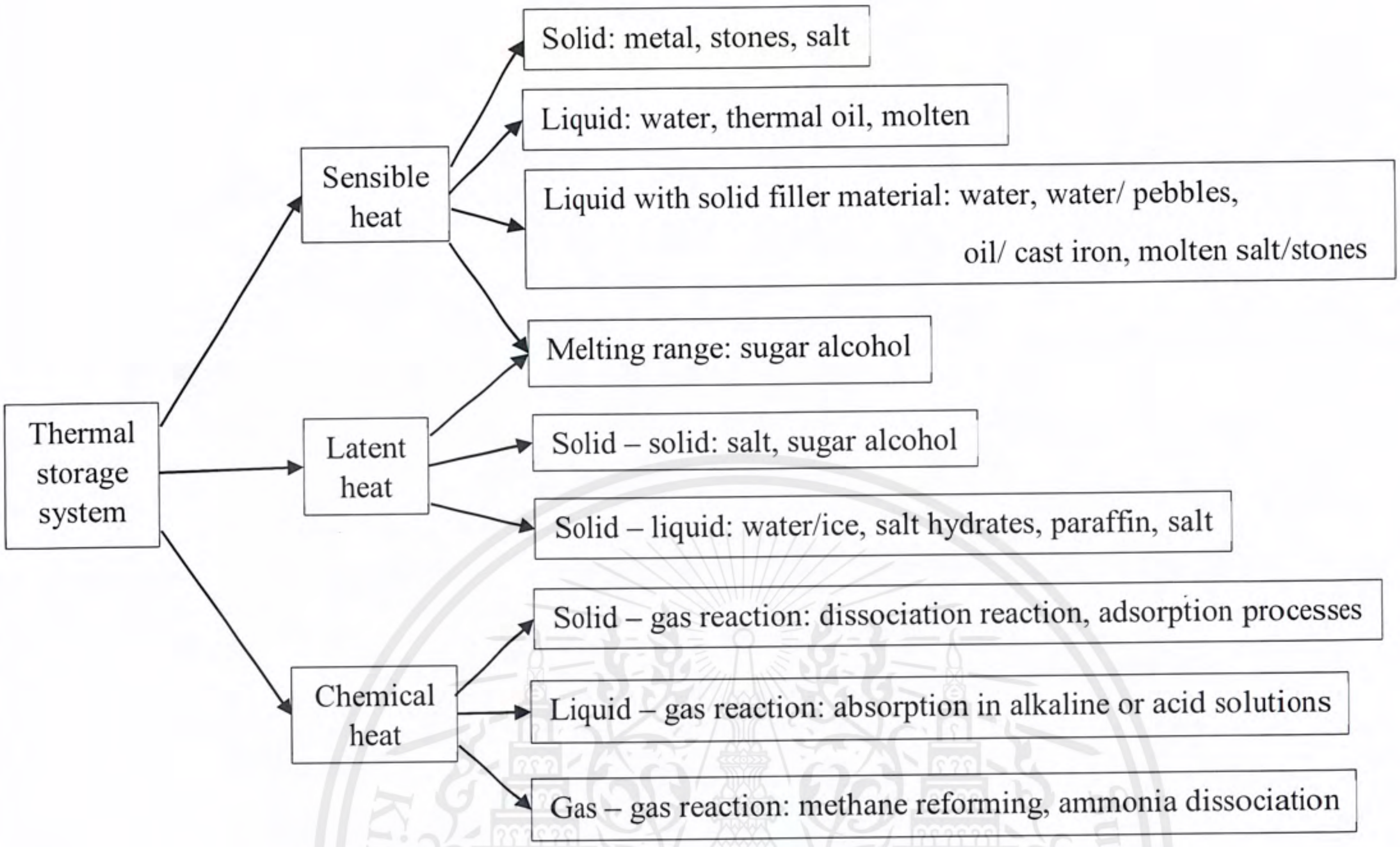

Figure 6: Types of thermal energy [9]

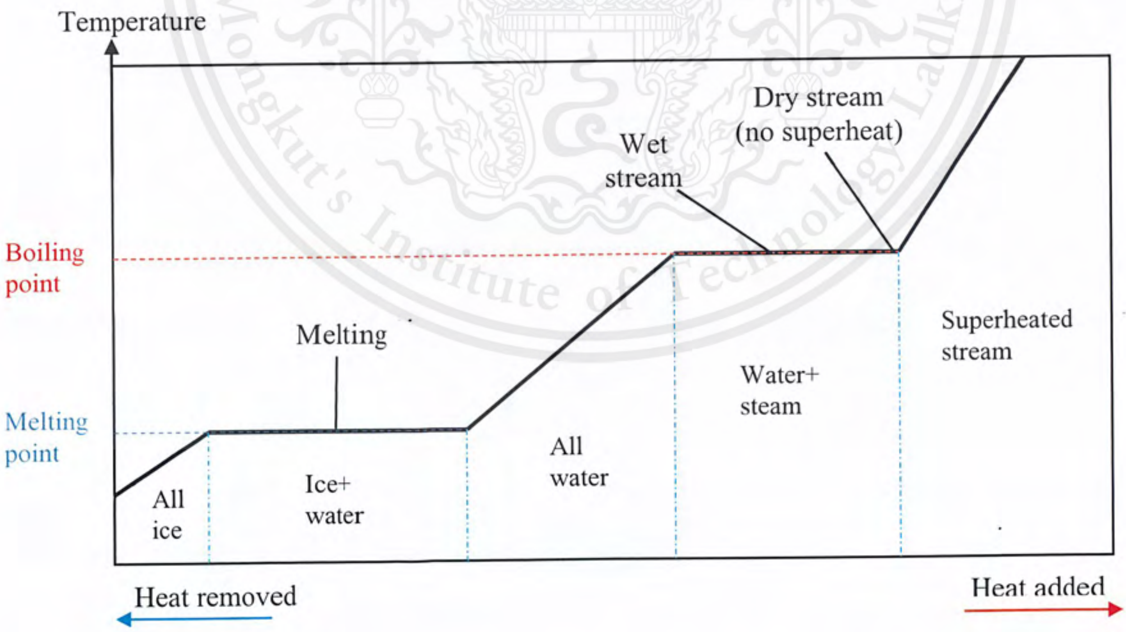

Figure 7: The state-change diagram of water [7]

2.2.1 Sensible TES

Sensible TES stores energy of heat by changing temperature of storage medium. Therefore the temperature of substance increases when energy is stored. The energy required E to heat substance volume V from temperature T_1 to temperature T_2 can be expressed as Equation (1).

$$E = mc_p(T_2 - T_1) = \rho c_p V(T_2 - T_1) \quad (1)$$

where c_p The specific heat of substance.

m Mass of substance.

T_1, T_2 Initial temperature and final temperature of substance.

ρ Density of substance.

2.2.2 Latent TES

Latent heat storage energy by phase change process when phase of material change, temperature still constant Latent heat of fusion is the amount of energy absorbed during melting and also the amount energy released during condensation at constant pressure. The energy required E to heat substance by latent heat can be determined as the Equation (2).

$$E = mL \quad (6)$$

where L latent heat of substance

2.2.3 Chemical heat

The chemical heat is the internal energy between atomic bonds by chemical reaction. The chemical reactions can be divided into 2 types,

1. Exothermic reaction: The energy of reaction is used to bond that release energy by heat or light.
2. Endothermic reaction: The energy of reaction is used to break bond that absorb energy or heat from surrounding.

2.3 Phase change material (PCM) [10]

Phase change materials are also called latent heat thermal energy storage material. PCMs use the properties of latent heat to store thermal energy. PCM can be divided into 3 types as follows.

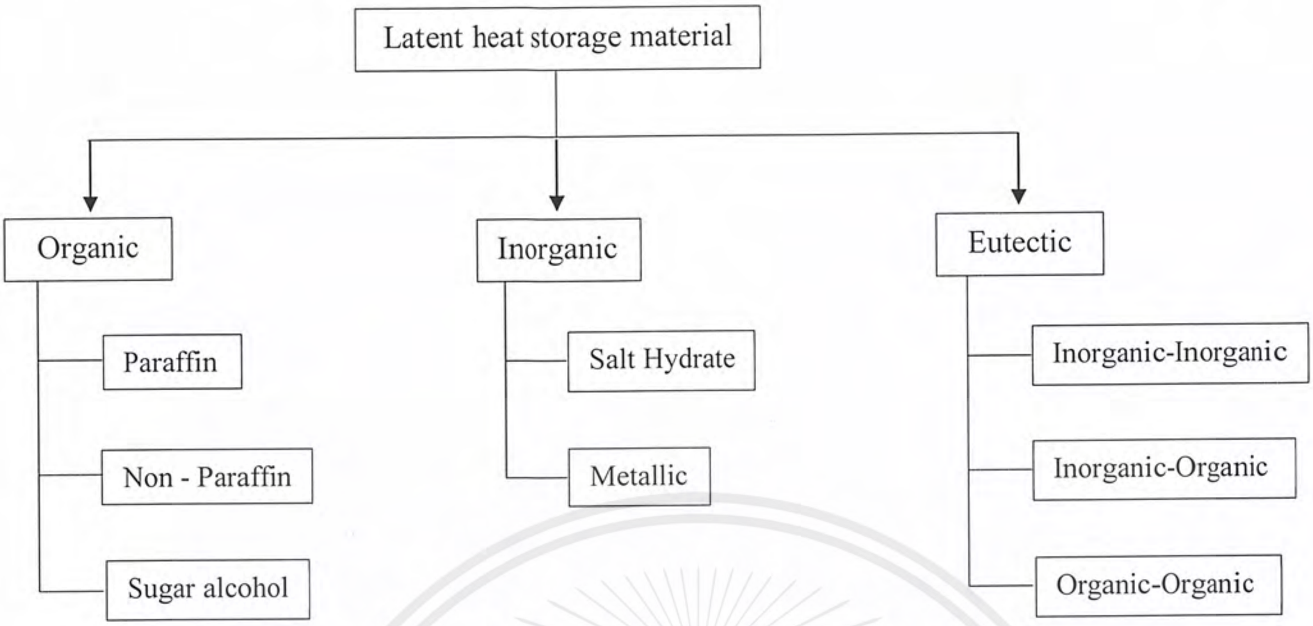

Figure 8: Types of latent heat storage material.

The properties of PCM for STECs as follow.

- Melting point: The melting point gradient of PCM is in line for operating.
- Density: High density effect to reduce volume of the TES system that can decrease PCM for use in process.
- Latent heat: PCM should have high latent heat due to improve energy storage density
- Specific heat (C_p): high specific heat of sensible heat storage materials improves energy storage density of material.
- Volume change: PCM should have low volume change for save cost of STEC tank.

2.3.1. Paraffin

The paraffin waxes are hydrocarbon compound and molecular formulas is C_nH_{2n+2} that produced from petroleum. They are attractive phase change materials for thermal energy storage application because non corrosion and cheap that suitable for low to medium temperature.

Table 1

Properties of paraffin. [11]

Paraffin	Compound	Melting temperature (℃)	Heat of fusion (kJ/kg)	c_p (kJ/(kgK))	k (W/(mK))	ρ (kg/m^3)
Cooling	Paraffin C14	4.5	165	-	-	-
	Paraffin C15-C16	8	153	2.2 (s)	-	-
	Polyglycol E400	8	99.6	-	0.187 (liq,38.6℃) 0.185 (liq, 69.9℃)	1125 (liq, 25℃) 1228 (s, 3℃)
	Dimethyl-sulfoxide (DMS)	16.5	85.7	-	-	1009 (s/liq)
	Paraffin C17-C18	20-22	152	2.2 (s)	-	-
	Polyglycol E600	22	127.2	-	0.189 (liq, 38.6℃) 0.187 (liq, 67.0℃)	1126 (liq, 25℃) 1232 (s, 4℃)
	Paraffin C13-C24	22-24	189	2.1 (s)	0.21 (s)	760 (liq, 70℃) 900 (s, 20℃)
	1-dodecanol	26	200	-	-	-
	Paraffin C18	28 27.5	244 243.5	2.2 (s)	0.148 (liq, 40℃) 0.15 (s)	774 (liq, 70℃) 814 (s, 20℃)
Heating	Paraffin C20-C33	48-50	189	-	0.21 (s)	769 (liq, 70℃) 912 (s, 20℃)
	Paraffin C22-C45	58-60	189	2.4 (s)	0.21 (s)	795 (liq, 70℃) 920 (s, 20℃)
	Paraffin wax	64	173.6 266	-	0.167 (liq, 63.5℃) 0.346 (s, 33.6℃) 0.339 (s, 45.7℃)	790 (liq, 65℃) 916 (s, 24℃)
	Polyglycol E6000	66	190.0	-	-	1085 (liq, 70℃) 1212 (s, 25℃)
	Paraffin C21-C50	66-68	189	-	0.21 (s)	830 (liq, 70℃) 930 (s, 20℃)
	1-Tetradecanol	38	205	-	-	-
	Paraffin C16-C28	48-50	189	-	0.21 (s)	795 (liq, 70℃) 910 (s, 20℃)
	Biphenyl	71	119.2	-	-	991 (liq, 73℃) 1166 (s, 24℃)
	Propionamide	79	168.2	-	-	-
	Naphthalene	80	147.7	2.8	0.132 (liq, 83.8℃) 0.341 (s, 49.9℃) 0.310 (s, 66.6℃)	976 (liq, 84℃) 1145 (s, 20℃)

2.4. Literature review

2.4.1 The design of solar thermal energy collector for water heating

Alva et al. [10] summarized the information of STECs system and the optimal properties for STECs materials as the following.

1. Two tanks direct active system

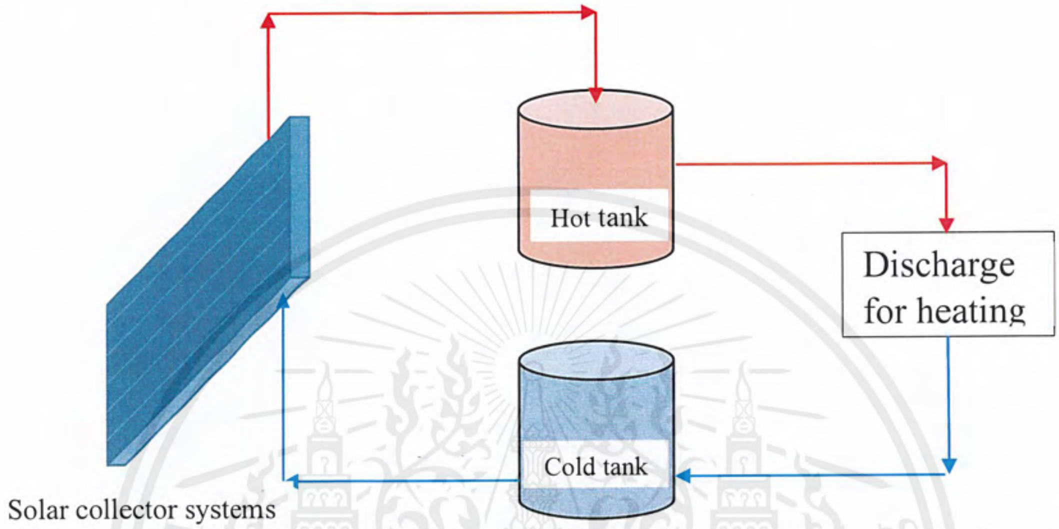

Figure 9: Two tanks direct system.

In this system, a heat transfer fluid was separated into two tanks. One was called hot tank and the other was called cold tank. The heat transfer fluid in their work, also used as a medium storage, was flowed from hot tank to discharge for water heating and then flowed back to cold tank. During daytime, the heat transfer fluid form cold tank flowed through the solar collector systems and got heated for being stored in hot tank again.

2. Two tanks indirect active system

The procedure of the two tanks indirect active system was also separated into hot tank and cold tank. Steam or mineral oil in this system represents heat transfer fluid in order to transfer heat to thermal storage medium such as molten salt, paraffin, sugar alcohol. In this case, heat was converted into electricity.

3. Single tank thermocline system

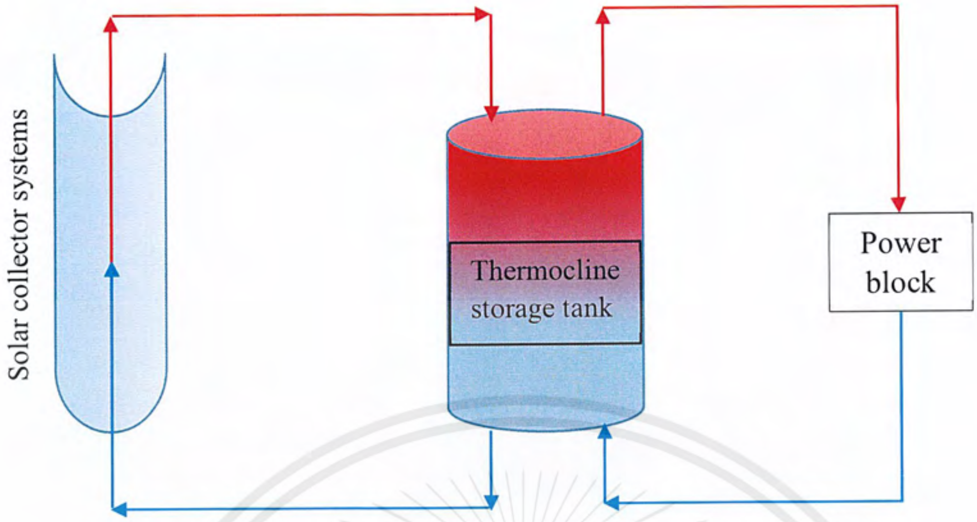

Figure 10: Single tank thermocline system.

The single tank thermocline system has one tank for loading thermal storage medium. The principle of thermocline storage tank is buoyancy effect lead to separate hot fluid at top and cold fluid at bottom. Thus, hot fluid was pumped at top thermocline tank in order to transfer thermal energy to power block and was flowed cold fluid back at bottom thermocline tank.

Sanitthai [13] designed water heating system by solar energy. PCM was used as a latent heat storage material as follows.

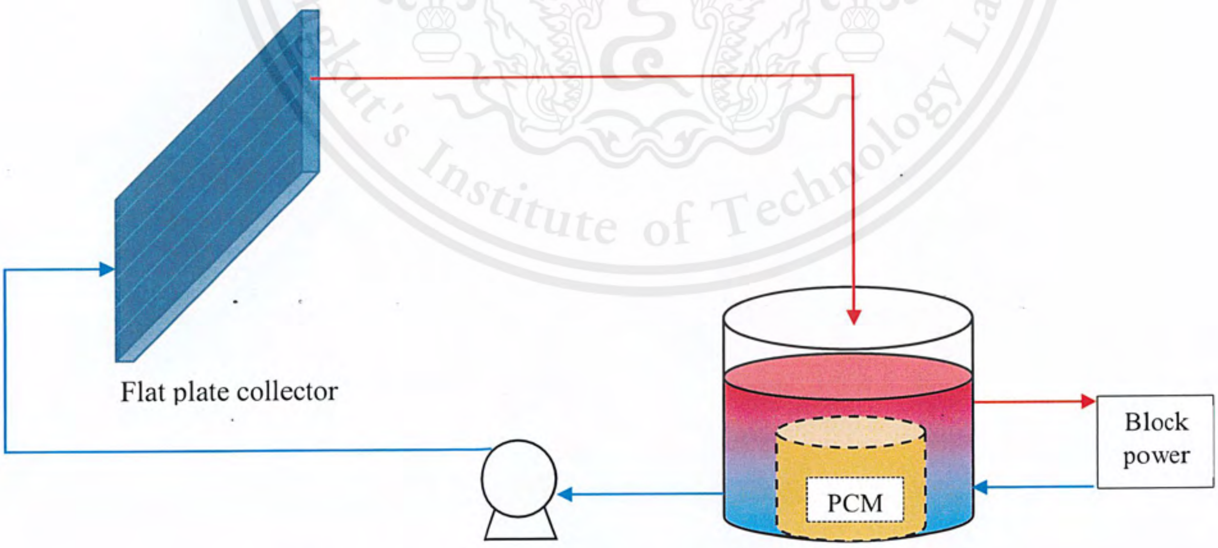

Figure 11: Design water heating system by solar energy.

Figure 11 shows the system of water heating that consists of flat plate collector, pump, and single tank thermocline. This research applied PCM in STEC system which consisted of a paraffin tank in water tank and compared cooling rate between water tanks with and without paraffin tank inside. The result showed that the cooling rate during a day of water in the tank with the paraffin tank inside was lower than that without the paraffin tank inside.

Daghigh and Shafieian [14] set up the mathematic model of evacuated heat pipe collector for investigating optimal number of heat pipes collector and compared performance with the experimental result in order to apply for a real system design. The experimental system of ETC is shown in Figure 12.

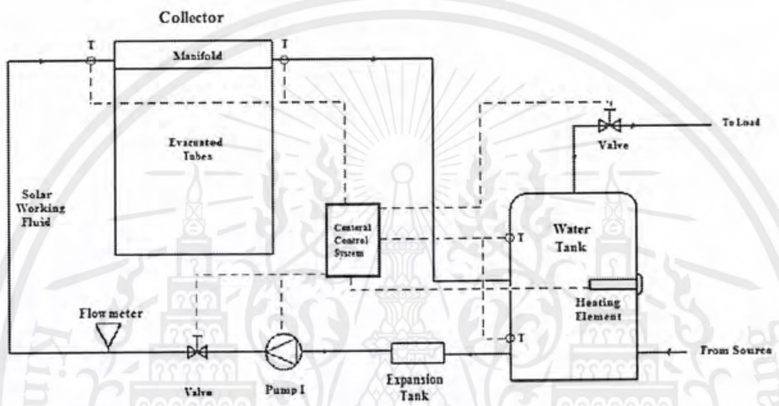

Figure 12. System schematic.

The result of this experiment showed the optimum numbers of solar collector pipes was 15. From report the trend of numbers of solar collector pipes have significant slope until that was reach to 15 and then increases slightly. The maximum water temperature outlet was 64℃ that occurred between 15:00 – 16:00 pm. The comparison water temperature outlet of this system between theoretical and experimental have similar in trend of slope. The maximum error was 8.4% due to heat loss of working fluid, which transfer thermal energy from manifold to heat pipes.

Carlos Javier Porras-Prieto et al. [15] designed the solar water heating with ETC and investigate the effect of required tank water heating system (rTWT) on energy operating system. The SWH consists of solar energy capture, energy distribution and accumulation, control and monitoring that was commercial design of SWH in household. The 24 pipes of ETC was installed on roof of a building. The optimize angle of ETC in this paper was 41° when this condition was examined between 25° - 65° and wind resistance was 30 m/s. The efficiency of ETC system was 61.7% so the location and angle of ETCs was installed effect with efficiency of system. Indeed, the efficiency of ETC also depend on rTWT. An increase rTWT influence on increase the heat loss from tubes and reduce overall energy of ETC system. In this work, when increase rTWT from 40° to 80°, the efficiency of ETC system fallen from 73% to 56% at a day with the energy of solar radiation input close to 8000W h m^{-2} d^{-1}. Since, more than 1800W h m^{-2} d^{-1} used for 80 ° of rTWT on a day.

CHAPTER III

RESEARCH METHODOLOGY

3.1. Materials and equipment

1. Paraffin wax
2. Hot plate
3. Analytical balance
4. Thermometer
5. Anemometer
6. Stainless tank
7. Stainless cylinder 2,000 ml and 5,000 ml
8. Copper pipe
9. Pump
10. Fittings
11. The evacuated thermal collector

3.2 Methods

3.2.1 Solar thermal collector system

An experimental solar thermal collector setup following the Figure_ that was test at Bangkok (longitude 100° 31' 23.4696" E; latitude 13° 44' 12.1812" N; elevation above sea level 12 m) Thailand

As for detail of system consists 20 evacuated tube solar thermal collector. The diameter of heat pipe was 0.008 m that was inside of evacuated tube. The outer diameter evacuated tube was 0.058 m, the tube length was 1.8 m and storage tank was insulated by polyethylene foam insulation 0.02 m. In the experiment, 25 kg propylene glycols was used to heat transfer fluid (HTF).

To study the energy of evacuated solar thermal energy collector system, inlet, outlet temperature, liquid temperature in storage tank every 30 minute and solar intensity every 3 hours that were measured by thermocouples type K and Solar Power Meter TM-206 respectively in the course of 7 hours for inlet and outlet temperature and 24 hours for the propylene glycols temperature in storage tank.

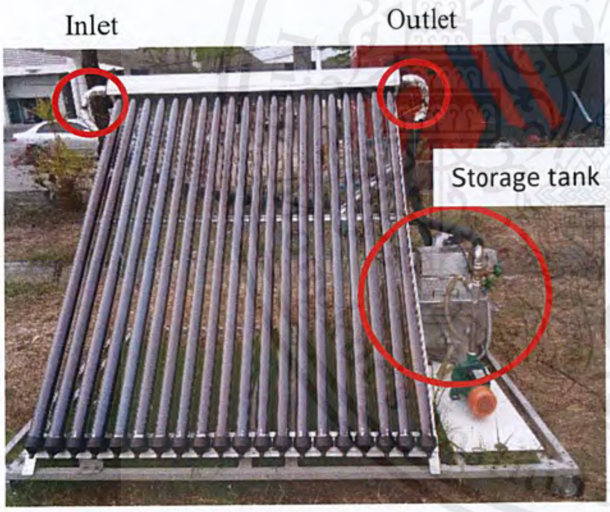

Figure 13. Solar thermal energy collector system.

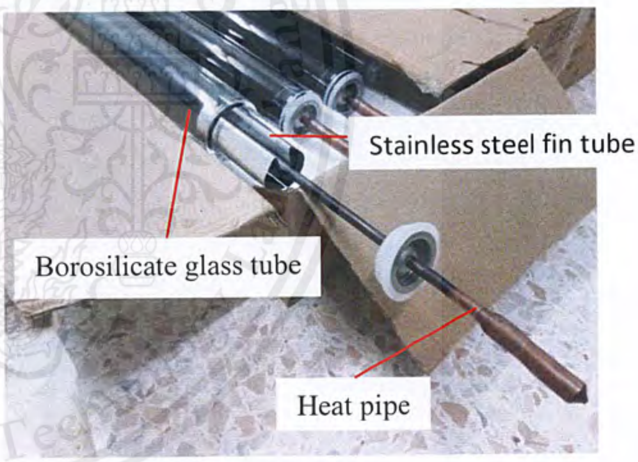

Figure 14. Heat pipe structure.

3.2.2 Solar thermal collector system using paraffin as a PCM

An experiment apparatus is shown in Figure. 15. The paraffin C22-C45 1.272 kg was stored in aluminum cylinder and put the circulated tube of water in paraffin cylinder following in Figure. 16. Both of water and paraffin cylinders was insulated by polyethylene foam insulation.

To study the temperature behavior of paraffin and water when paraffin was heated up to melting point until the paraffin melted completely by IKA C-MAG HS7 hot plate. After that, stop heating and start to circulate water 2 liter per hour (l/h) by chemical dosing pump. The thermocouples type K were measured the temperature in both of water and paraffin cylinders every 10 minute after stopped heating until temperatures of water and paraffin constant.

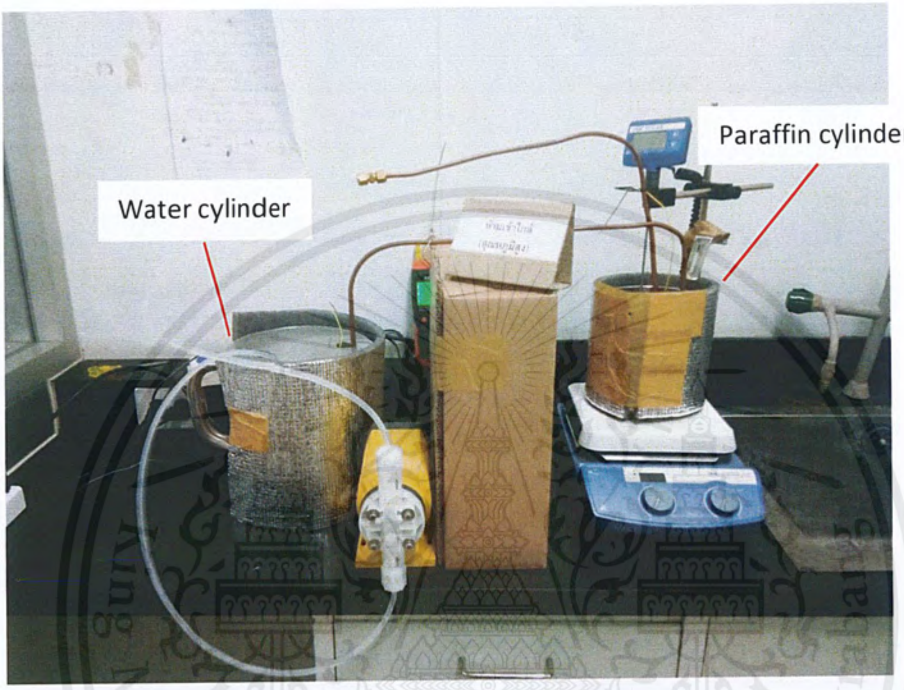

Figure. 15. The heating system with phase change materials.

Figure. 16. The paraffin cylinder and water tube.

Figure. 17. The water cylinder.

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Production of warm water by paraffin wax

Figure 18 shows the change of temperature versus time of 2 l/h of water that was heated by melt paraffin. As seen in Figure18, during heating up water, initially the temperature of paraffin rapidly decreases from the starting temperature of 85℃ to 58℃ which is the melting point of paraffin. After that, the temperature of paraffin remains constant at its melting point for about 40 minutes during the phase change of paraffin. After paraffin completely changed the phase from liquid to solid, the temperature of paraffin slightly decreased into room temperature. Meanwhile, at first, temperature of water increased from room temperature (about 30℃) into the highest temperature of water at 43.1℃ occurred when paraffin changed the phase from liquid to solid and ultimately decreased to room temperature.

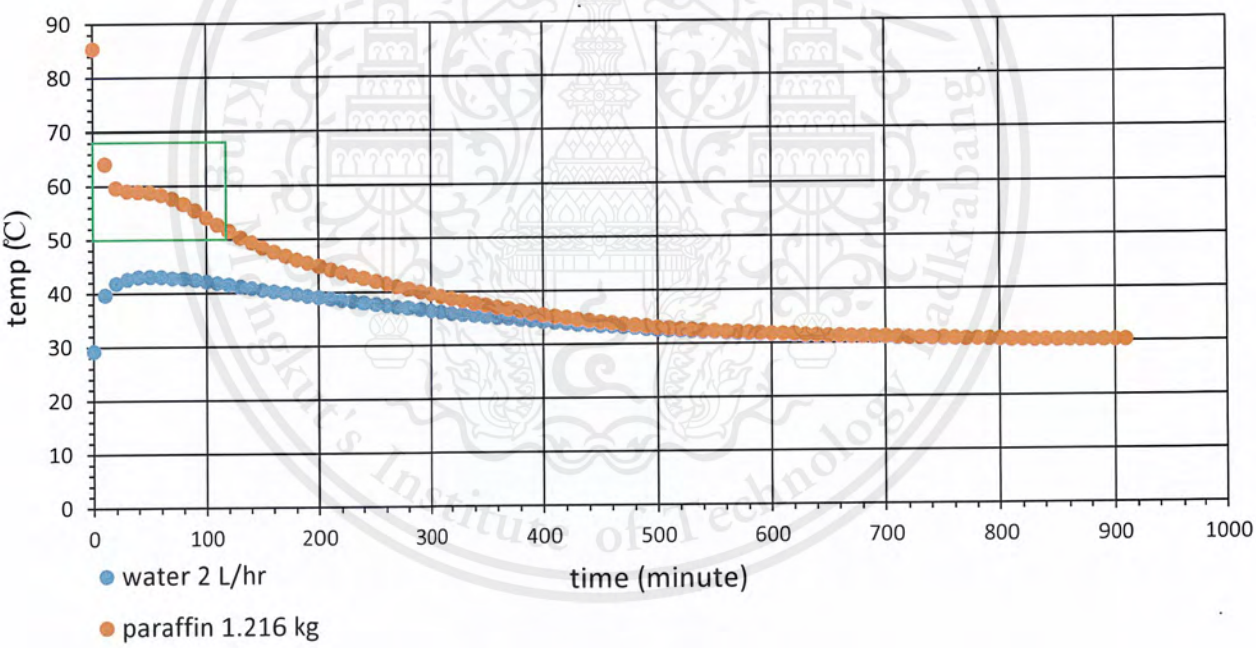

Figure 18. Temperature of warm water system form solar thermal energy collector.

4.2. Comparison between energy consumption from solar collector using paraffin and propylene glycol as energy storage materials.

4.2.1 Solar thermal collector system

A schematic diagram of the warm water heating is shown in Figure 19 and 20 that consist of evacuated tubes collector, centrifugal pump and 20 kg paraffin wax was stored in storage tank. In the storage tank was contained 25 liter and put circular water tube diameter 0.011 m and 1.5 m of length. This systems were calculated by hypothesis of common heating water system that was pumped cold water 25℃ and flow rate 100 l/h in heating system so the outlet temperature increases and flow to use in daily life [16].

Hypothesis for calculation

1). Calculated on steady state.

2). Water inlet was constancy temperature and flow.

3). Constant surface temperature of circulate water tube.

4). The conduction resistance of copper tube was negligible.

5). The inner surfaces of the pipeline were smooth.

6). Heat loss of pipe was negligible.

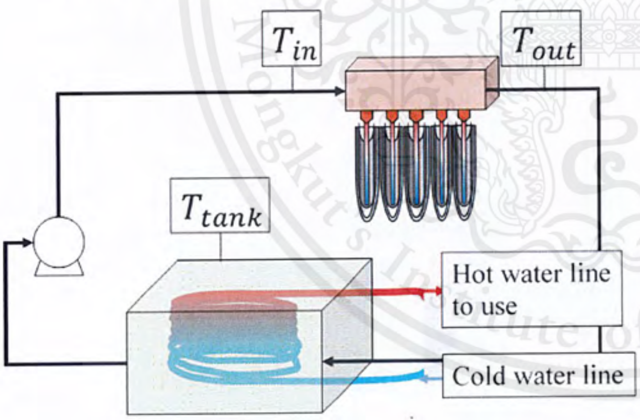

Figure 19. Water heating system without paraffin.

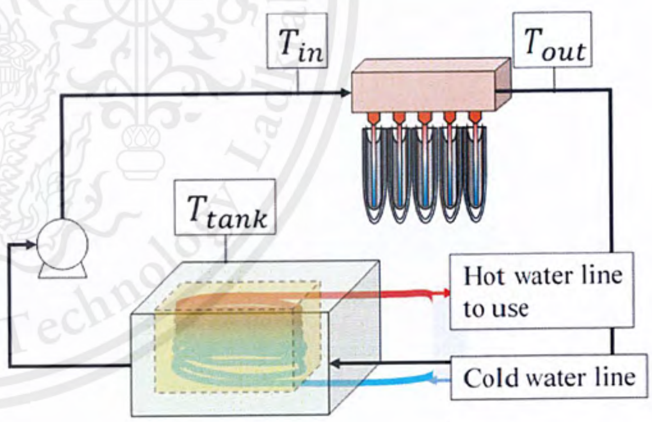

Figure 20. Water heating system with paraffin.

4.2.2 Calculation of water outlet temperature in each time for one day.

Table 2 shows the experimental temperature of warm water outlet that compared between propylene glycol and paraffin for using to heating media. The thermal energy were calculated from Equation (1). As a seen in Table 2, at first, the temperature heating up from 50.05℃ to 93.20℃ that was highest temperature of propylene glycol in tank on 1.00 p.m. The temperature of propylene glycol in storage tank depend on solar intensity so, the highest temperature occurred when highest solar intensity was 875 W/m^2. After that, the temperature of storage tank decreased into temperature ambient.

Table 2
Measured values of temperature of warm water by different heating media between propylene glycol versus paraffin.

Time	Intensity (W/m^2)	T_{tank} (℃)	$Q_{PG,tank}$ (kJ/hr)	T_i (℃)	$T_{o,PG}$ (℃)	$T_{o,P}$ (℃)
9.00	227	50.05	1478.88	25.00	45.80	49.62
10.00	-	65.30	923.52	25.00	58.47	52.41
11.00	-	76.40	368.16	25.00	67.69	52.41
12.00	-	88.35	667.68	25.00	77.61	61.65
13.00	875	93.20	31.20	25.00	81.64	52.41
14.00	-	91.30	-43.68	25.00	80.06	70.03
15.00	-	92.80	218.40	25.00	81.31	66.74
16.00	187 (16.30 a.m.)	88.60	-124.80	25.00	77.82	69.33
17.00		83.10	-430.56	25.00	73.25	62.08
18.00	-	64.50	-1060.80	25.00	57.80	52.58
19.00	-	54.80	-474.24	25.00	49.75	52.58
20.00	-	49.90	-249.60	25.00	45.68	52.58
21.00	-	47.20	-137.28	25.00	43.44	52.58
22.00	-	44.60	-149.76	25.00	41.28	52.58
23.00	-	42.40	-149.76	25.00	39.45	52.58
24.00	-	41.30	-62.40	25.00	38.54	52.58
1.00	-	40.60	-87.36	25.00	37.96	52.58
2.00	-	39.40	-99.84	25.00	36.96	52.58
3.00	-	38.10	-87.36	25.00	35.88	52.58
4.00	-	36.90	-74.88	25.00	34.88	52.58
5.00	-	36.20	-37.44	25.00	34.30	52.58
6.00	-	35.50	-49.92	25.00	33.72	52.58
7.00	-	35.20	-37.44	25.00	33.47	52.58
8.00	-	34.30	-112.32	25.00	32.72	47.02
9.00	-	35.50	137.28	25.00	33.72	42.58

Figure 21 shows the comparison of the predicted temperature of water outlet versus time from solar thermal energy collector system without paraffin to heating media and temperature of propylene glycol in storage tank. The water outlet temperature of water heating system without paraffin tank depended on propylene glycol temperature in storage tank. The temperature of water outlet increases from 45.80℃ on 9.00 a.m. to 81.64℃ on 1.00 p.m. After that, the temperature of water outlet were slowly decrease to 73.25℃ on 5.00 p.m. because of effect from solar intensity. After 6.00 p.m., the solar intensity was equal to 0 W/m^2 so water temperature outlet rapidly decreased into temperature ambient (33.72℃). The temperature of water outlet were defined as follows:

$$T_o = T_s - (T_s - T_i) \times \exp(-hA_s / \dot{m}c_p) \qquad (7)$$

where T_o is outlet temperature, T_s is surface temperature, h is the heat transfer coefficient, A_s heat transfer surface area (it is equal to πDL for circular pipe of length L) and c_p is the specific heat of the heating media.

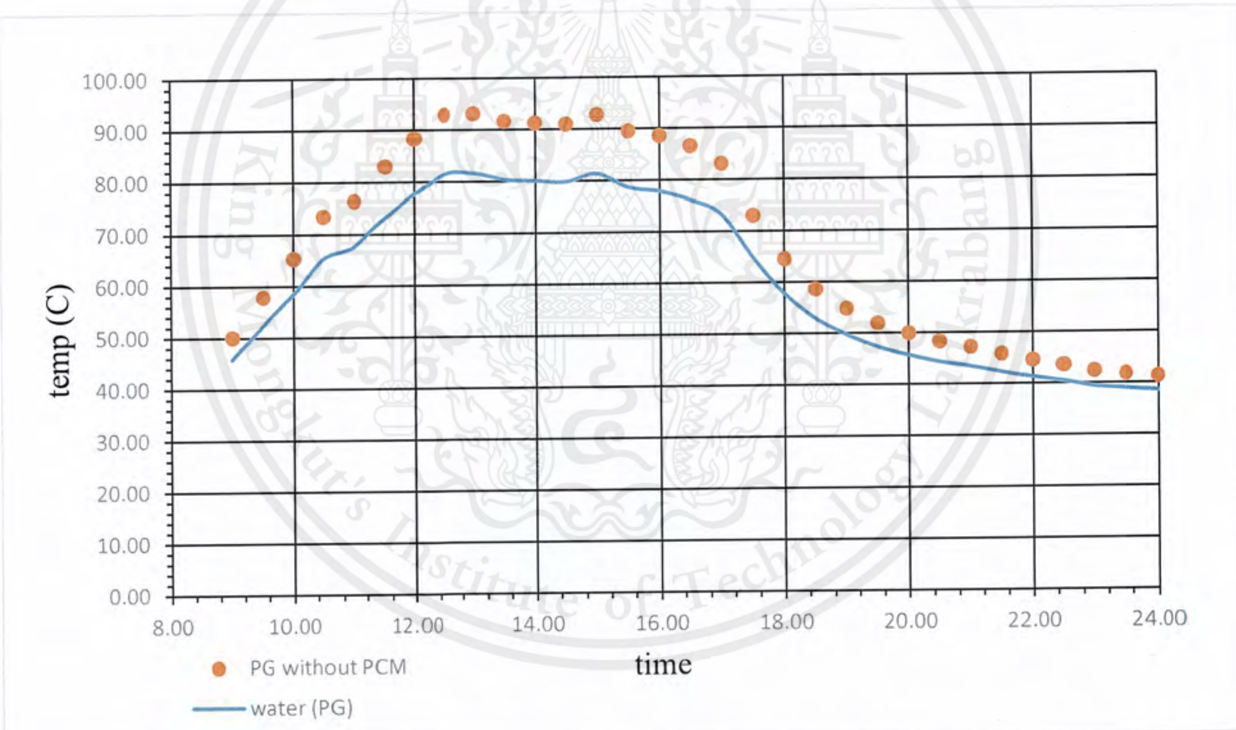

Figure 21. Temperature of water outlet and propylene glycol without paraffin tank on 30/03/18.

Figure 22 shows the comparison of the water outlet temperature from solar thermal energy collector with and without paraffin tank. At the initial, the tendency of water outlets temperature were corresponding in both cases because of solar intensity effect so the temperature of water heating without paraffin tank decreases after 5.00 p.m. but the temperature of water heating with paraffin tank stable at 52.28℃ from 6.00 p.m. to 7.00 a.m. for 13 hours. The stable temperature from water heating with paraffin system occurred when paraffin change phase from liquid to solid because of latent heat of fusion effect to thermal energy that defined by Equation (6) so the temperature constant at melting point (58℃). After that, the temperature of water outlet rapidly decrease into 42.58℃ when the paraffin change phase completely.

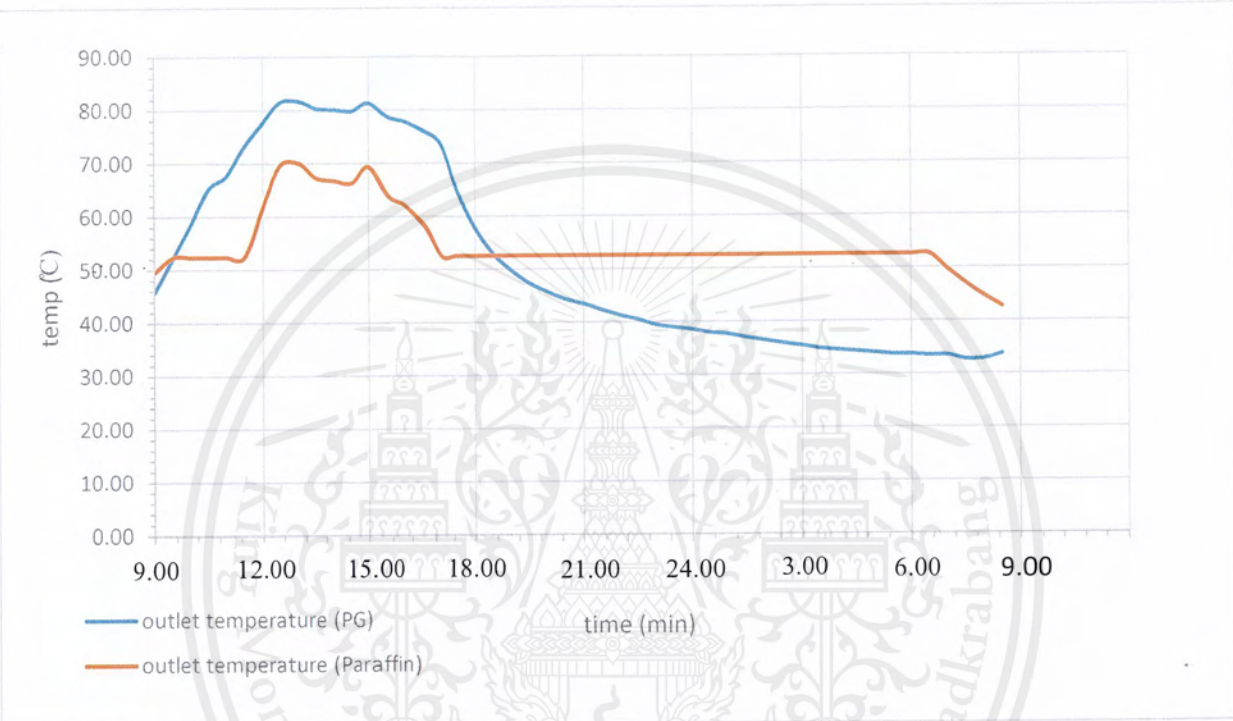

Figure 22. Temperature of water heating system with and without paraffin tank on 30/03/18.

Figure 23 shows melting fraction of 25 kg paraffin. The melting fraction increase from 0 to 1 on 12.00 a.m. because of sensible heat of paraffin at solid phase. After that, the temperature of paraffin equal to melting point and decrease to 0 again on 7.30 a.m. when solar intensity equal to 0. The melting fraction were defined on Equation (6).

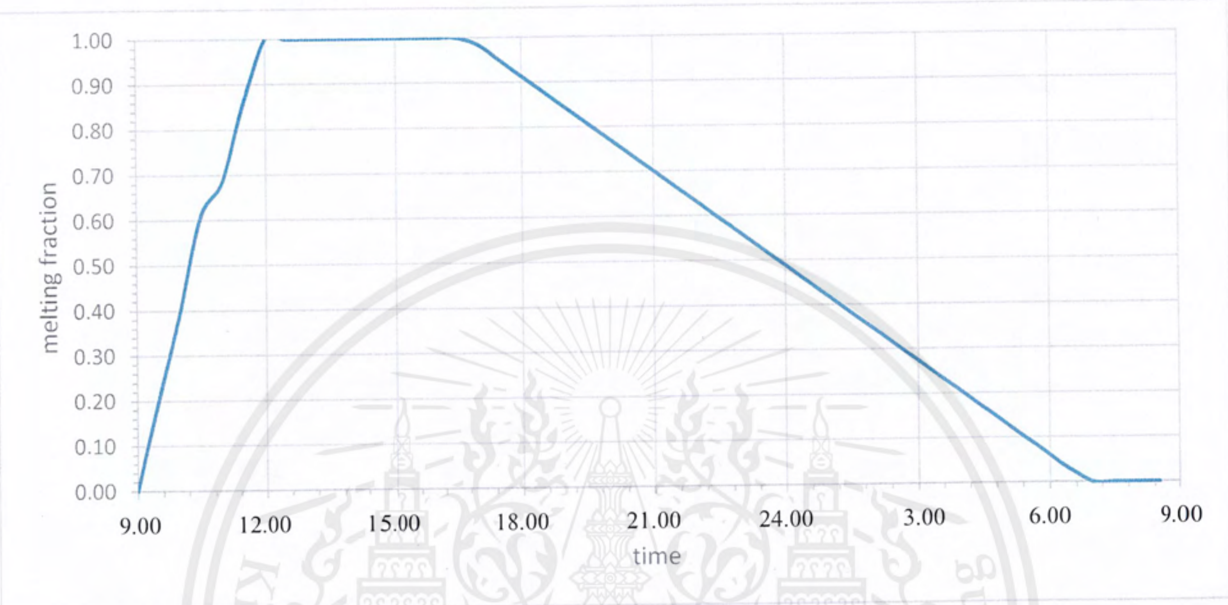

Figure 23. The melting fraction of paraffin in water heating system on 30/03/18.

CHAPTER V

CONCLUSION

5.1 Conclusion

The experiment study enhancement system of solar thermal energy collector by add paraffin tank. The serviceable time of water heating to produce hot water over 40 ℃ for one day were calculated to compare system with and without paraffin. The serviceable time of the system with paraffin equal to 25 hours that higher than the system without paraffin tank 12 hours. So the system of water heating system with paraffin 25 kg for 4.167 L/h of water flow rate can produce hot water all day that was calculated based on hotel 1 room which use hot water for take a shower and cooking [16]. The results of distribution of thermal energy into phase change material investigate by melting fraction of paraffin that completely change phase from solid to liquid in 3 hours.

5.2 Suggestions

The suggestions for further study of solar thermal energy collector system for produce hot water are as following:

1. In this water heating system from this research just estimation from evacuated solar thermal energy storage for water heating in domesticity so the highest temperature from measurement was higher than real system because of heat loss from this system were negligible.
2. Paraffin is phase change material for low to medium temperature so the temperature of hot water did not high when compare with another phase change materials.
3. The configuration of phase change material effect to thermal distribution.

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APPENDIX A
EXPERIMENTAL CONDITION AND CALCULATION

Appendix A-1: Data lists of warm water system with solar thermal energy collector.

Appendix A-2: Calculation for temperature of water heating system.

Appendix A-1: Data lists of warm water system with solar thermal energy collector.

Table A-1.1

Experimental temperature and measurement temperature of warm water.

Time	Intensity (W/m2)	T_{tank} (℃)	$Q_{PG,tank}$ (kJ/h)	T_i (℃)	$T_{o,PG}$ (℃)	$T_{o,P}$ (℃)	Melting fraction
9.00	227	50.05	1478.88	25.00	45.80	49.62	0.00
9.30	-	57.90	979.68	25.00	52.32	52.41	0.20
10.00	-	65.30	923.52	25.00	58.47	52.41	0.40
10.30	-	73.45	1017.12	25.00	65.24	52.41	0.61
11.00	-	76.40	368.16	25.00	67.69	52.41	0.69
11.30	-	83.00	823.68	25.00	73.17	52.41	0.86
12.00	-	50.05	667.68	25.00	77.61	61.65	1.00
12.30	-	57.90	574.08	25.00	81.43	69.59	1.00
13.00	875	65.30	31.20	25.00	81.64	70.03	1.00
13.30	-	73.45	-193.44	25.00	80.35	67.35	1.00
14.00	-	76.40	-43.68	25.00	80.06	66.74	1.00
14.30	-	83.00	-31.20	25.00	79.85	66.31	1.00
15.00	-	88.35	218.40	25.00	81.31	69.33	1.00
15.30	-	92.95	-399.36	25.00	78.65	63.81	1.00
16.00	-	93.20	-124.80	25.00	77.82	62.08	1.00
16.30	187	91.65	-255.84	25.00	76.12	58.54	1.00
17.00	-	91.30	-430.56	25.00	73.25	52.58	0.98
17.30	-	91.05	-1260.48	25.00	64.86	52.58	0.95
18.00	-	92.80	-1060.80	25.00	57.80	52.58	0.91
18.30	-	89.60	-736.32	25.00	52.90	52.58	0.88
19.00	-	88.60	-474.24	25.00	49.75	52.58	0.84
19.30	-	86.55	-361.92	25.00	47.34	52.58	0.81
20.00	-	83.10	-249.60	25.00	45.68	52.58	0.77
20.30	-	73.00	-199.68	25.00	44.35	52.58	0.74
21.00	-	64.50	-137.28	25.00	43.44	52.58	0.70
21.30	-	58.60	-174.72	25.00	42.27	52.58	0.67
22.00	-	54.80	-149.76	25.00	41.28	52.58	0.63
22.30	-	51.90	-124.80	25.00	40.45	52.58	0.59
23.00	-	49.90	-149.76	25.00	39.45	52.58	0.56
23.30	-	48.30	-74.88	25.00	38.95	52.58	0.52
24.00	-	47.20	-62.40	25.00	38.54	52.58	0.49
0.50	-	45.80	-87.36	25.00	37.96	52.58	0.45
1.00	-	44.60	-49.92	25.00	37.62	52.58	0.42
1.50	-	43.60	-99.84	25.00	36.96	52.58	0.38
2.00	-	42.40	-74.88	25.00	36.46	52.58	0.35

2.50	-	41.80	-87.36	25.00	35.88	52.58	0.31
3.00	-	41.30	-74.88	25.00	35.38	52.58	0.27
3.50	-	40.60	-74.88	25.00	34.88	52.58	0.24
4.00	-	40.20	-49.92	25.00	34.55	52.58	0.20
4.50	-	39.40	-37.44	25.00	34.30	52.58	0.17
5.00	-	38.80	-37.44	25.00	34.05	52.58	0.13
5.50	-	38.10	-49.92	25.00	33.72	52.58	0.10
6.00	-	37.50	0.00	25.00	33.72	52.58	0.06
6.50	-	36.90	-37.44	25.00	33.47	52.58	0.03
7.00	-	36.50	0.00	25.00	33.47	49.64	0.00
7.50	-	36.20	-112.32	25.00	32.72	47.02	0.00
8.00	-	35.90	12.48	25.00	32.81	44.68	0.00
8.50	-	35.50	137.28	25.00	33.72	42.58	0.00

Note: 1) This data for calculated on 30-31 March 2018

Table A-1.2

Data of solar thermal energy collector for water heating.

Lists	Values	
Evacuated solar thermal energy collector		
1. An angle of system	45 °	
2. The number of evacuated tubes	20	
3. Flow rate of propylene glycol in system	200	l/h
Paraffin		
1. Type of paraffin	Paraffin C22-C45	
2. Mass of paraffin	25	kg
3. Melting point	58.00	°C
4. Latent heat (L_p)	189	kJ/kg
5. Heat capacity ($c_{pp,s}$)	2.4	kJ/kg ℃
6. Density (ρ_p)	795 (liq, 70 ℃)	kg/m^3
	920 (s, 20 ℃)	kg/m^3
7. Initial temperature	30	℃
Water		
1. Mass flow rate	4.13	kg/h
2. Heat capacity (c_{pw})	4.18	kJ/kg ℃ (at 40 ℃)
3. Density (ρ_w)	992.1	kg/m^3 (at 40 ℃)
4. Initial temperature	25	℃
5. Nussle number (Nu)	3.66	
6. Thermal conductivity (k)	0.631	W/m ℃ (at 40 ℃)
Storage tank		
1. Wide	56.50	cm
2. High	22.50	cm
3. Insulator	polyethylene foam	
Circular tube		
1. Material	Copper	
1. Diameter (D)	0.0011	m
2. Length (L)	1.50	m

Appendix A-2: Calculation for temperature of water heating system.

A-2.1 Calculation mass of paraffin

For 100 L water heating system of temperature from 25℃ to 40℃ by using paraffin to heating media. The mass of paraffin for used as:

Energy balance

$$Q_{heat,w} = m_w c_p (T_o - T_i) = m_p c_{pp,s} (T_{melt} - T_i) + m_p L$$

$$100 \times 4.179 \times (40 - 25) = m_p \times 2.4 \times (58 - 30) + m_p \times 189$$

$$\therefore m_p = 24.47 \ kg$$

In this experiment mass of paraffin equal to 25.00 kg

A-2.2 Calculation temperature of outlet temperature

1. Calculated heat transfer coefficient

$$h = \frac{Nu \times k}{D}$$

$$h = \frac{3.66 \times 0.631}{0011} = 209.95 \ W/m^2 \ ℃$$

2. Calculated surface area of circular tube

$$A_s = \pi \times D \times L$$

$$A_s = \pi \times 0.011 \times 1.5$$

$$A_s = 0.052 \ m^2$$

3. Temperature of outlet water in water heating system without paraffin.

$$T_{o,PG} = T_s - (T_s - T_i) \times \exp(-hA_s / \dot{m}c_p)$$

$$T_{o,PG} = 50.05 - (50.05 - 25) \times \exp(-209.95 \times 0.052 / 0.001472 \times 4179)$$

$$T_{o,PG} = 45.80 \ ^\circ C$$

4. Temperature of outlet water in water heating system with paraffin.

$$Q_{coll} = \Delta t m_{PG} c_{p,PG} (T_{\Delta s,f} - T_i)$$

$$Q_{coll} = 2 \times 25 \times 2.496 \times (50.05 - 38.2)$$

$$Q_{coll} = 1478.88 \ \ kJ/kg$$

$$T_{s,PCM} = \frac{Q_{coll}}{m_p c_{pp,s}} + T_{i,PCM}$$

$$T_{s,PCM} = \frac{1478.88}{25 \times 2.4} + 30$$

$$T_{s,PCM} = 54.65 \ ^{\circ}C$$

$$\therefore T_{o,P} = T_s - (T_s - T_i) \times \exp(-hA_s / \dot{m} c_p)$$

$$T_{o,P} = 54.65 - (54.56 - 25) \times \exp(-209.95 \times 0.052 / 0.001472 \times 4179)$$

$$T_{o.p} = 49.62 \ ^{\circ}C$$

5. Melting fraction of paraffin.

5.1 Melting fraction of paraffin for charging (9.00-12.00 a.m.)

$$Q_{coll} = m_{p,melt} L_p$$

$$\therefore m_{p,melt} = \frac{Q_{coll}}{L_p} = \frac{979.68}{189} = 5.18 \ \ kg$$

So, melting fraction equal to 5.18/25 = 0.20

5.2 Melting fraction of paraffin for discharging (5.00 p.m.-8.30 a.m.)

$$Q_{p,\text{tank}} = hA_s \Delta T_{lm}$$

$$\Delta T_{lm} = \frac{T_i - T_{o,p}}{\ln[(T_{s,p} - T_{o,p})/(T_{s,p} - T_i)]} = \frac{25 - 52.58}{\ln[(58.21 - 52.58)/(58.21 - 25)]} = 15.54 \ ^{\circ}C$$

$$\therefore Q_{p,\text{tank}} = 209.95 \times 0.052 \times 15.54 = 169.65 \ \ kJ/h$$

$$\therefore m_{p,melt} = \frac{169.65}{189} = 0.89 \ \ kg$$

So, mass fraction of paraffin equal to (25-0.89)/25 = 0.96

6. Time of serviceable to heating water from 25℃ to 40℃

$$Q_{heat,w} = \dot{m}c_{p,w}(T_o - T_i) = 4.13 \times 4.179 \times (40 - 25) = 258.89\ kJ/h$$

$$Q_{PCM} = m \times [c_{pp,s}(T_{melt} - T_i) + L_p + c_{pp,l}(T_f - T_{melt})] = 25 \times [2.4 \times (58 - 30) + 189 + 2.4 \times (58.21 - 58)]$$
$$= 6417.6 kJ$$

So, serviceable time was equal to 6417.6/258.89 = 24.79 h

BIBLIOGRAPHY

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