Design & Development of Lab Scale Latent Heat Energy Storage Equipment using Paraffin Wax

by

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Universiti Teknologi PETRONAS
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CERTIFICATION OF APPROVAL

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TRONOH, PERAK

November

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUNIRAH BINTI MOHD ALI

ABSTRACT

Latent heat storage is a new and developing technology, which has found considerable interest in recent times due to its operational advantages of smaller temperature fluctuation, smaller size and lower weight per unit of storage capacity. For the development of a latent heat thermal energy storage system, the choice of the phase change material (PCM) plays an important role in addition to heat transfer mechanisms in the PCM. In the application of solar thermal energy storage, it is very important to provide the storage of solar energy during the day and then to use this stored energy for water-heating during the evening and night after the sunset. By choosing a suitable phase change material for the latent heat absorbed during the phase change of the material from solid to liquid, large part of solar thermal energy can be stored during daytime and this energy can be used for water-heating at a later time. PCMs can be used to provide this advantage in various heat energy applications.

Heat energy storage systems by phase changing materials (PCM) need to identify the performance limits and optimize processes and cycles with heat energy analysis. A literature review is presented to explain more deeply on latent heat energy storage, types of PCM and the application of PCM as space heating. The latent heat thermal energy storage system is analyzed experimentally. A design for the storage unit whose geometry is consistent with the melting/solidification characteristics of PCMs is introduced. Four kinds of paraffin waxes with different melting temperatures are used as PCMs. At first, the thermophysical properties of the paraffin waxes used are determined through the differential scanning calorimeter (DSC) analysis. Water is used as the heat transfer fluid (HTF). An experimental set-up is also presented to show the basic concepts on the experiments to be done. The next chapter on results and discussion is completed to show the thermal analysis of paraffin waxes, the thermal storage experimental results and heat energy analysis. A conclusion is done to wrap all the information stated in this report.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Thermal storage can either take the form of sensible heat storage (SHS) or latent heat storage (LHS). Latent heat is the large quantity of energy which needs to be absorbed or released when a material changes phase from solid state to liquid state or vice versa [1]. Latent heat storage is accomplished by changing a material's physical state whereas SHS is accomplished by increasing a material's temperature. SHS processes start at an elevated temperature while LHS processes start at a lower temperature. Thus the heat loss by the SHS is higher than the LHS. This affecting the period of heat storage where SHH store heat for a shorter period of time and LHS store heat for a longer period of time. To store the same amount of energy smaller quantities of material are required for LHS than for SHS. A further advantage of LHS is that heat storage and delivery occurs at a constant temperature, which makes it ideal for reducing temperature fluctuation in space heating applications.

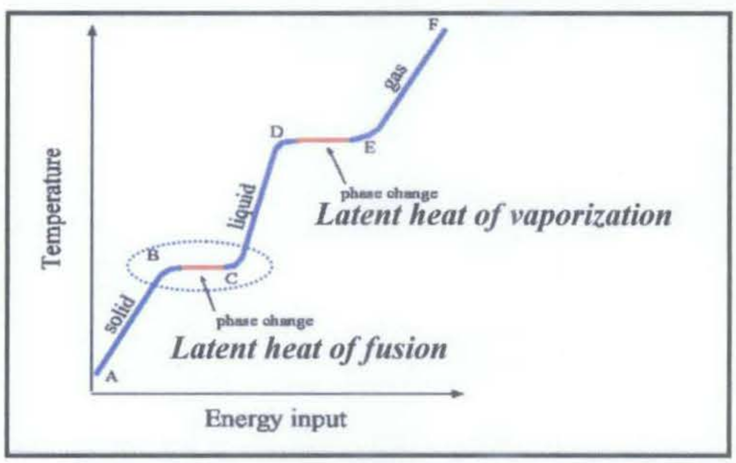


Figure 1 Temperature change with energy input

1.2 Problem Statement

The world energy demand has increased day by day. In UK for example, 27% of UK's energy consumption is used in residential buildings [2]. In Malaysia, the energy consumption in the form of electricity demand is increased by years, as illustrated in Table 1.

Table 1 Electricity demand, Malaysia

Year	Electricity Demand
2000	12,801 MW
2005	18,215 MW
2010	20,087 MW

Source: Ninth Malaysia Plan 2006-2010, Table 19.5

Table 2 Fuel mix (percent) in total electricity generation, Malaysia

Year	Oil	Coal	Gas	Hydro	Other	Total (GWh)
2000	4.2	8.8	77.0	10.0	0.0	69 280
2005	2.2	21.8	70.2	5.5	0.3	94 299
2010	0.2	36.5	55.9	5.6	1.8	137 909

Source: Ninth Malaysia Plan 2006-2010, Table 19.5

The electricity generation in Malaysia also increasing by years, as illustrated in Table 2. But the percentage of fossil fuels (oil and gas) used to generate the electric are decreasing. In an attempt to conserve energy and reduce dependency on fossil fuels, it has become necessary to seek effective ways of reducing peaks in power consumption and to shift portions of the load from periods of maximum demand. One way is by having thermal energy storage, to store the energy and lessen the usage of electricity. This study is to design and develop the thermal energy storage system using paraffin wax as PCM.

1.3 Significance of Study

Study on designing latent heat storage applies different principles of knowledge and background. A strong fundamental in heat transfer, thermodynamics, fluid mechanics and mechanical engineering design is highly needed. This study involves a lot of calculations and also design skills during the designing and development phase. The thermal performance of latent heat storage will be experimented and analyzed.

1.4 Objectives

1. To study on paraffin wax characteristics and the mechanism of latent heat energy storage
2. To design a laboratory scale, phase change energy storage equipment
3. To develop the thermal energy storage system using available sources
4. To test and confirm the energy storing capabilities of various PCM

The 1st and 2nd objectives are to be achieved in the Semester 1 while the 3rd and 4th objectives are to be achieved in the Semester 2.

1.5 Scope of Work

For Semester 1, the whole project would start with knowledge gathering and theoretical studies on PCM characteristics for PCM with melting temperature below 100°C. Experiments on several waxes obtain from market will be done to know their thermal properties and choose the best wax for the project. Lab scale phase change energy storage equipment will be designed using Auto-CAD and CATIA based on the best design criteria which are limited by size of storage and volume of paraffin wax.

For Semester 2, the whole project would start with completing the system design by adding all the components for the system and also for the measurement. Procurement of the components will be done in parallel with the development of the heat storage. After the completion of the development of design system, experiments will be carried out to test for the thermal performance of the system. Data analysis received from the experiments will be analyzed.

CHAPTER 2
LITERATURE REVIEW

2.1 Latent Heat Energy Storage

Latent heat is the heat that is transferred at constant temperature and the process of transferring either absorbing or releasing heat involves changing the phase of the materials. A latent heat storage use phase change material (PCM) as the mechanism of storing the latent heat. There are three different options when using a PCM as the storage materials which are evaporation of the storage material, solid-liquid phase changes (melting) and solid-solid phase changes [3]. Relatively few solid-solid PCMs have been identified that have heats of fusion and transition temperatures suitable for thermal storage application. Liquid-gas PCMs usually have high heats of transformations, however, due to the large volume change during transformation, they are not usually considered for practical applications. Solid-liquid PCMs are useful because they store a relatively large quantity of heat over a narrow temperature range, without corresponding large volume change [4].

In this case, a solid-liquid phase changes is used as the latent heat storage. Upon melting heat is transferred to the storage material while the material keeps its temperature constant at the melting temperature. If the melting enthalpy has been transferred to the storage material the melting is completed and further transfer of heat results in sensible heat storage. The storage of the heat of melting cannot be detected from the temperature and the heat stored (melting enthalpy) is called latent heat [5]. Materials with solid-liquid phase change, which are suitable for heat storage, are commonly referred to as "latent heat storage material" or simply "phase change material" (PCM).

Any latent heat thermal energy storage must possess at least the three following basic components [6]:

a. A heat storage substance that undergoes a solid-to-liquid phase transition in the required operating temperature range and where the bulk of heat added is stored as latent heat fusion
b. A container for holding the storage substance
c. A heat exchanging surface for transferring heat from the source to the PCM and from the PCM to the receiver of heat sink.

The development of a latent heat thermal energy storage system, therefore, involves an understanding of two essentially diverse subjects: heat storage materials (or PCMs) and thermal storage of heat exchanger.

2.2 Phase Change Material

Organic and inorganic compounds are the two most common groups of PCMs. Inorganic compounds have a high latent heat per unit mass and volume, are low in cost in comparison to organic compounds and are non-flammable. However they can suffer from decomposition and supercooling which can affect their phase change properties.

Most organic PCMs are non-corrosive, chemically stable, and compatible with most building materials and have a high latent heat per unit weight.

Table 3 The properties of some of PCM studied

Commercial Name	Chemical Name	Molecular Formula	Melting Temp. (°C)	Heat of Fusion (kJ/kg)	Thermal Conductivity (W/m.K)	Density (kg/m^3)
Paraffin wax	Paraffin wax	Not available	64	266	0.167 (*l*, 63.5°C) 0.346 (*s*, 33.6°C)	790 (*l*, 65°C) 916 (*s*, 24°C)
High density polyethylene wax (HDPE)	High density polyethylene wax (HDPE)	Not available	(100 – 150)	200	Not available	Not available
Not available	Paraffin C-18	$C_{18}H_{38}$	28	244	0.148 (*l*, 40°C) 0.358 (*s*, 25°C)	774 (*l*, 70°C) 814 (*s*, 20°C)
Rock salt	Calcium chloride hexahydrate	$CaCl_2.6H_2O$	29 29.2 29.6	190.8 171 174.4	0.540 (*l*, 39°C) 0.561 (*l*, 61.2°C) 1.088 (*s*, 23°C)	1562 (*l*, 32°C) 1496 (*l*) 1802 (*s*,24°C) 1710 (*s*,25°C)
Glauber's salt	Sodium sulphate decahydrate	$Na_2SO_4.10H_2O$	32	254 251.1	0.544	1485 (*s*) 1458

Source: Halime O. Paksoy, 2007 [3], Belén Zalba, José M Marín, Luisa F. Cabeza and Harald Mehling, 2003 [7], Mohammed M. Farid, Amar M. Khudhair, Siddique Ali K. Razack and Said Al-Hallaj, 2004 [8].

A suitable phase change temperature and a large melting enthalpy are the requirements that have always to be met by a PCM. However, there are more requirements that have to be met in term of physical, technical and environmental issues. These requirements are explained next.

2.2.1 Physical Requirements [1]

- *Suitable phase change temperature*: To assure storage and extraction of heat in this project is with a fixed temperature range
- *Large phase change enthalpy ΔH*: To achieve high storage density compared to sensible storage
- *Large thermal conductivity*: To be able to extract the stored heat with sufficiently large heat flux
- *Reproducible phase change*: To use the storage material many times (also called cycling stability)
- *Little subcooling*: To assure that melting and solidification proceed at the same temperature

2.2.2 Technical Requirements [1]

- *Low vapour pressure*: To reduce requirements of mechanical stability on a vessel containing the PCM
- *Small volume change*: To reduce requirements of mechanical stability on a vessel containing the PCM
- *Chemical and physical stability*: To assure long lifetime of the PCM
- *Compatibility with other materials*: To assure long lifetime of the vessel containing the PCM and surrounding materials in case of leakage

2.2.3 Economic Requirements [1]

- *Low price*: To be competitive with other options for heat storage
- *Non-toxicity*: For environmental and safety reasons
- *Recyclability*: For environmental and economic reasons

From Table 3, paraffin wax is chosen to be the main latent heat storage material because it is offering large thermal storage densities and have melting temperatures lying in practical ranges suitable for thermal storage. Conversely, the crystallization of C_nH_{2n+2} chain releases a large amount of latent heat while cooling. Both the melting point and the heat of fusion increase with increasing chain length. Paraffin wax is chemically stable, showing no phase segregation with minimum sub-cooling during repetitive phase transitions, non-toxic, non-corrosive, odorless and easily available. On the other hand, a study is going to be done to enhance paraffin wax performance in term of heat storage capacity and heat transfer.

2.3 PCM as Space Heating

A key advantage with the use of a PCM is that heat storage and recovery occurs isothermally which makes them ideal for space heating applications, where improved occupancy comfort can be obtained as a result of a reduction in temperature swings. Phase change materials have been used successfully for thermal storage.

Six potential implementations of thermal energy storage using PCM have been identified for energy conservation in buildings. A number of modes of implementation PCM technology are given in Table 4. All potential implementations of PCM technology are not equally advanced where experimental prototypes of PCM wall boards have been produced, but most other technologies are still at conceptual stage [6].Table below summarizes the potential implementation of thermal storage by the phase change materials.

Table 4 The potential implementation of thermal storage by the phase change materials

Mode of implementation PCMs technology	Load target	Objective	Sector
Distributed PCM storage in gypsum boards	Space heating and air-conditioning	Load shifting and conservation	All
Electrical heating units with PCM storage	Space heating	Load shifting and conservation	Residential, commercial and institutional
Heat and cold PCM storage in air-ducts	Space heating and air-conditioning	Load shifting	Commercial, institutional and industrial
PCM air pre-heaters for heat pumps	Space heating	Load shifting and conservation	Residential, commercial and industrial
Curtain walls with PCM system	Space heating	Conservation	Commercial, institutional and industrial
Water heater with PCM storage	Water heating	Load shifting	Residential, commercial and institutional

Source: S. M. Hasnain, 1997 [6]

A study on some research done by the previous researchers had been done to further increase in understanding the concept design needed. The study focus on the mechanism and design of the thermal storage proposed depending on the function and application of thermal storage.

2.3.1 Electrical underfloor heating system

An electrical underfloor heating system that uses a paraffin wax with a melting point of 40° C has been proposed by Farid, M.M. and Chen, X.D., 1999. The paraffins are mostly used as PCMs, due to their easy availability and due to their suitable thermal characteristics, in low temperature applications where the working fluid temperature range is 0–100 °C. A 30 mm layer of PCM was placed between the heating surface and the floor tiles. Using computer simulation it was found that the heat output of the floor could be raised significantly from 30 W/m^2 to 75 W/m^2 if PCM storage is used.

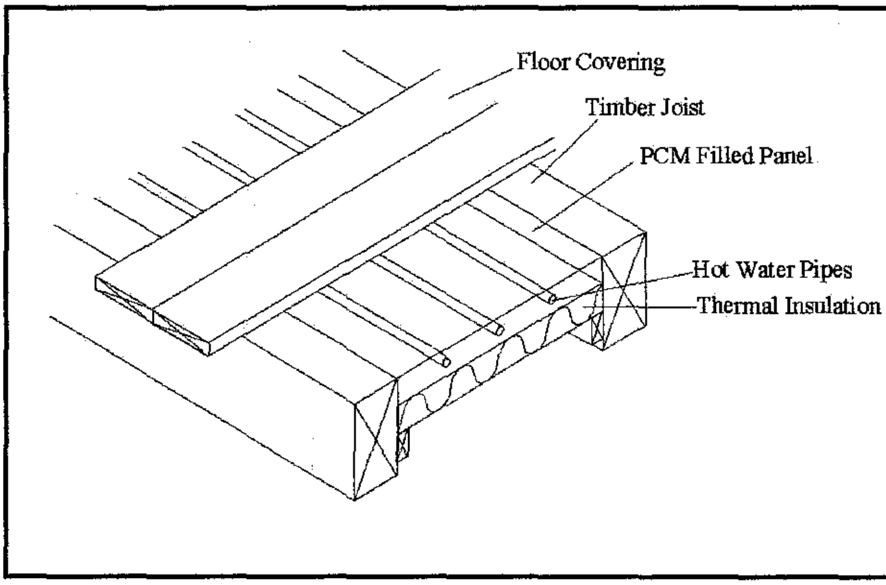


Figure 2 PCM panels installed in the floor

The mentioned research programs highlight the potential of using PCMs for space heating. However, a criticism of some of the systems previously proposed is that they can only be used with suspended timber floors or they are cemented into the floor slab and so are difficult to remove if the building is decommissioned. Therefore Farid, M.M. and Chen, X.D., 1999 studies aim to evaluate the thermal performance of a PCM storage system, and to improve the system features in term of the portability. To make it suitable for both new build and retrofit applications and it can also be taken out of a building and re-used if the building is decommissioned.

2.3.2 Vertical tube thermal storage system

K. A. R. Ismail and M. M. Abugderah, 2000, has studied on the performance of a thermal storage system of the vertical tube type where a phase change thermal energy storage system of the shell and tube type is numerically modeled. The heat transfer fluid is flowing by forced convection. The PCM is in the shell around the HTF carrying tubes, Figure 3. From the numerical analysis done, it shows that the accumulated heat increases significantly with the increase of the outer radius of the system and the phase change temperature interval does not have much effect on the system performance.

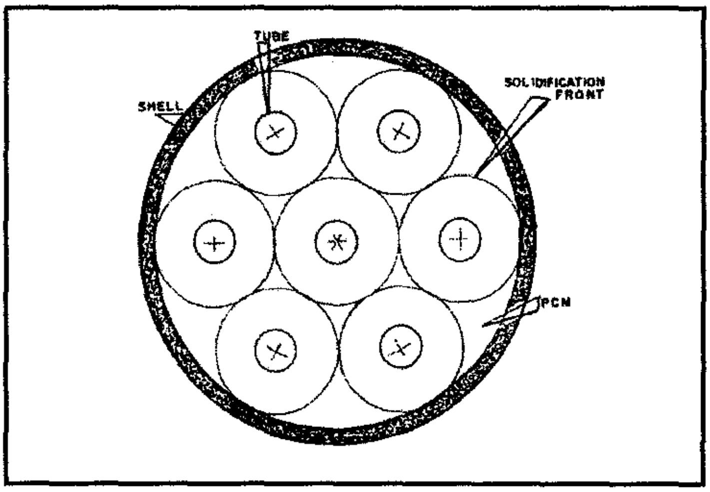


Figure 3 Cross section of the heat transfer storage system

2.3.3 Shell and tube latent heat thermal energy storage system

Anica Trp, 2005, has analyzed the transient heat transfer phenomenon during technical grade paraffin melting and solidification, in the shell-and-tube latent thermal energy storage system with water as HTF with moderate Prandtl number, numerically and experimentally, Figure 4. Experimental investigations underline that melting of used PCM occurs non-isothermally but within the melting zone, on the other hand solidification occurs isothermally. The results of numerical analysis show that the HTF velocity field reaches the fully developed condition quickly, while the temperature field never reaches a steady state condition due to the moving melting and solidification fronts. Due to the relatively large Prandtl number of the water as a HTF, the heat transfer from the HTF to the PCM is slow. Therefore, a large amount of heat is carried downstream with the HTF, while a small amount of heat is transferred directly to the PCM upstream.

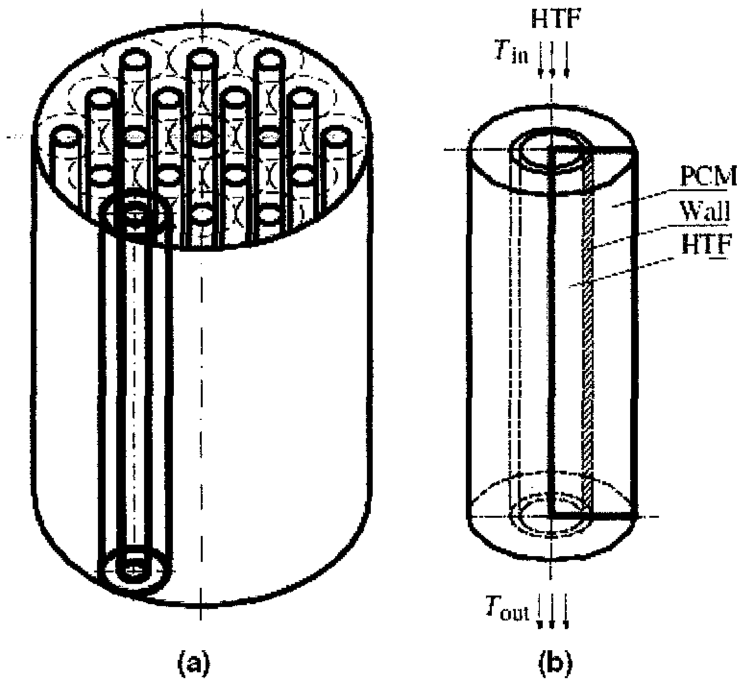


Figure 4 (a) Latent thermal energy storage system; (b) thermal energy storage unit

2.3.4 Spiral thermal energy storage system

J. Banaszek, R. DomanÄ ski, M. Rebow and F. El-Sagier, 2000 has studied on two-dimensional computer simulation is presented for conjugate heat transfer and solid-liquid phase change, concurrently occurring within a domain of the paraffin wax-air spiral thermal energy storage unit during its charging and discharging. Energy conservation principle is set up within each (small but finite) control-volume from a set of non-overlapping balance sub-domains of the domain discretization. Finite difference approximation is used to calculate the temperature gradient. Heat transfer in a spiral channel is higher than that in a straight channel. This is due to centrifugal forces and a secondary motion (cross-flow) appearing in a fluid flow in a curved conduit.

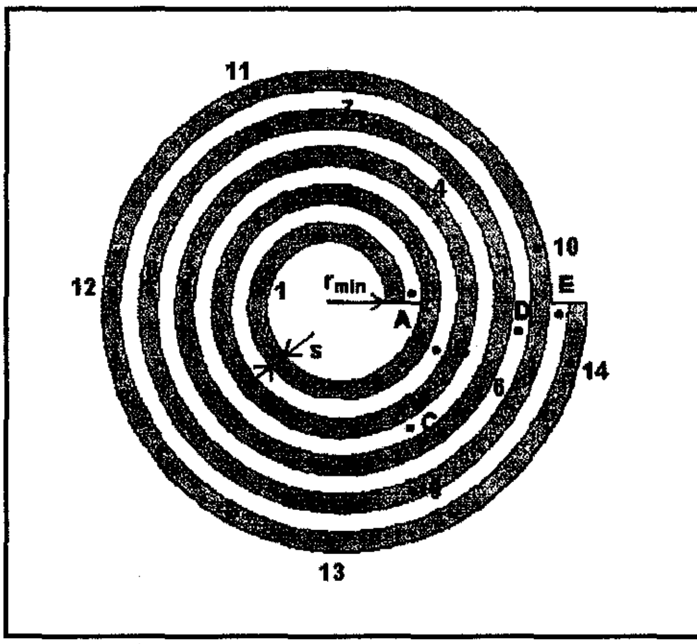


Figure 5 Geometry of mid-height cross-section and thermocouples positions in air (letters) and PCM (numbers) passages of spiral TES unit

CHAPTER 3

METHODOLOGY

3.1 Procedures/ Methods Identification

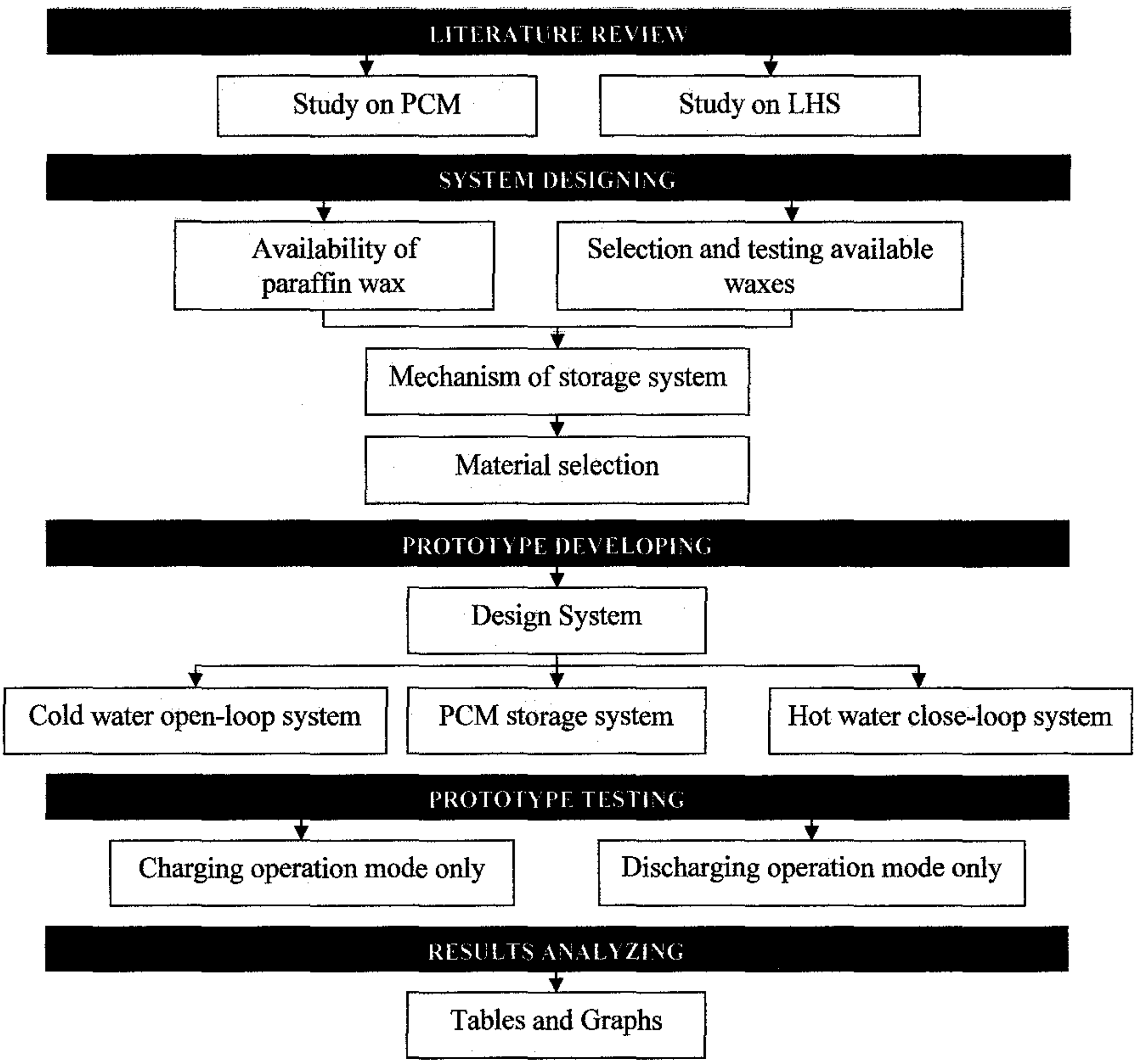


Figure 6 Combined of Semester 1 and Semester 2 project work flow

3.1.1 Semester 1 flow chart

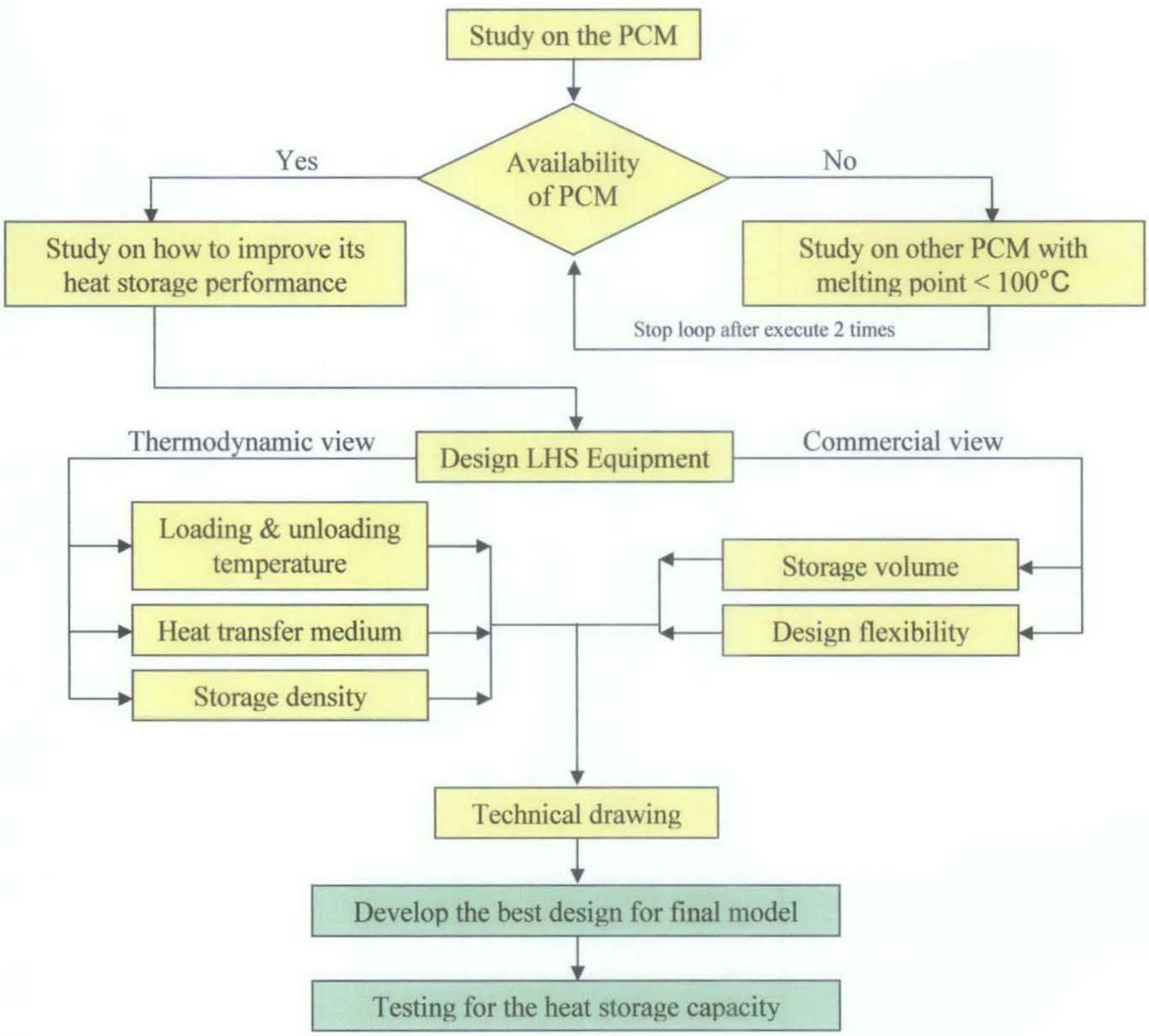
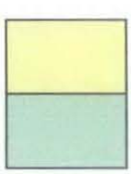


Figure 7 Specific semester 1 project work flow

Legend:



3.1.2 Semester 2 flow chart

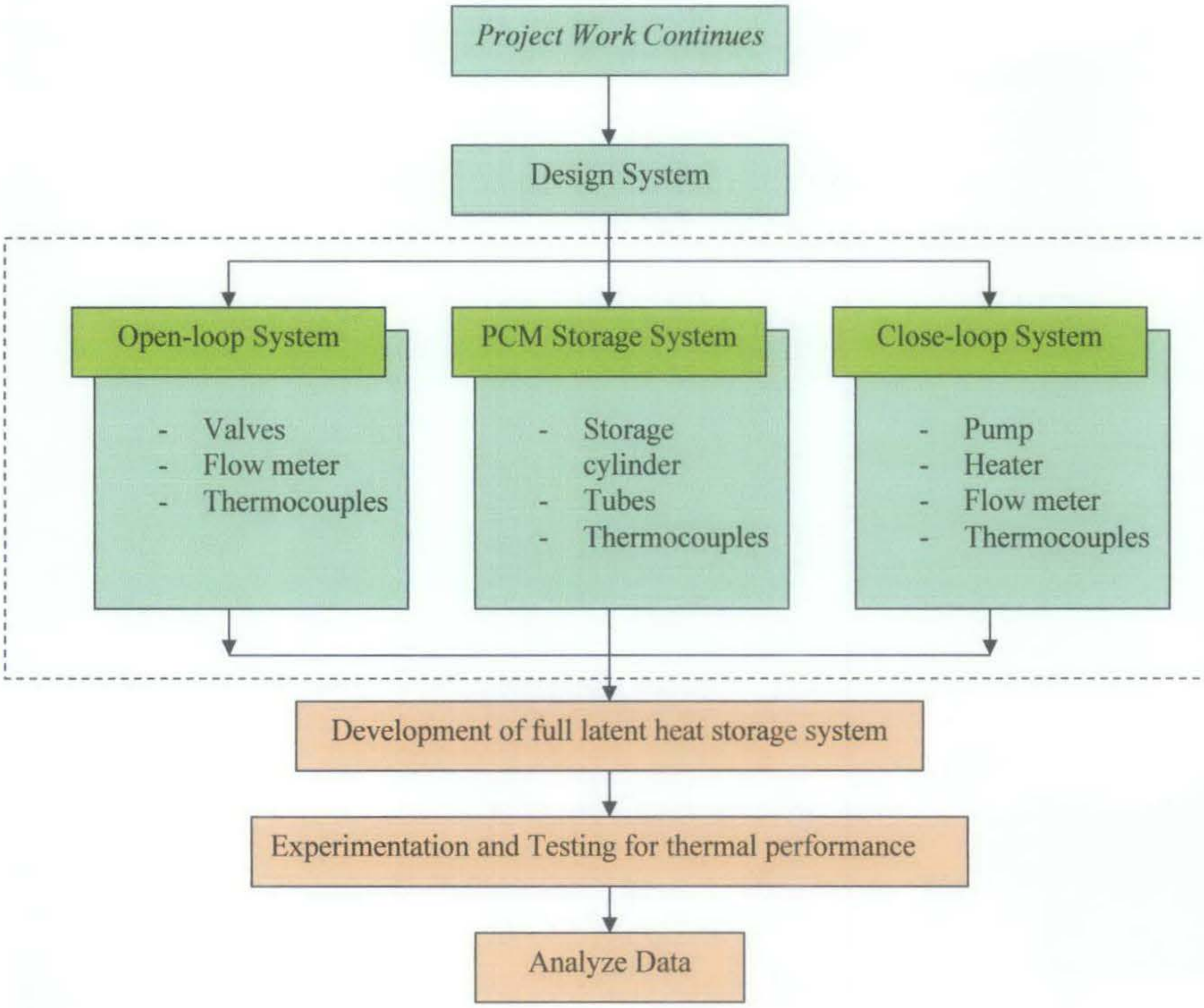


Figure 8 Specific semester 2 project work flow

Legend:

Designing the system stage

Developing and experimentation of design stage

3.2 Tools/ Equipments Required

The tools and equipments required for this project are listed as below:

1. Mechanical designing software (Auto-CAD)
2. Experiment apparatus, Differential Scanning Calorimetry (DSC) to measure thermal properties
3. Mechanical laboratory facilities like machining and welding for prototype design and development

3.3 Mechanism of the Design Equipment

The equipment is designed based on the concept that hot water will transfer heat to the wax (that is initially in the solid phase) and the heat transferred cause the wax to melt. The wax will store sufficiently high latent heat in the PCM storage where 1kg of wax can store heat up to 266 kJ. This heat will then be used for heating the cold water. Cold water will absorbed the heat from the wax and cause the wax to resolidify. The temperature of hot water flows in and out and the temperature of cold water flows in and out will be monitored using the thermocouples and temperature gauges. There are also activities of monitoring the temperature at the inside of storage container to detect the temperature of wax, surface temperature of coils with hot and cold water flows inside the coils. The flow rate of hot and cold water flows in will also be observed using the flow meter.

Based on Figure 9, basically there are 3 sub-systems made up the operation system which is the open-loop system, the PCM storage system and the close-loop system. Open-loop system is for the cold water flows in and out and this flow is controlled manually using ball valves. The PCM storage system is the main component in this project. It is used to store the wax and the heat transfer from either hot to cold water or cold to hot water will take place in this storage compartment called the PCM storage. Close-loop system is for the hot water flows in and out in a close-loop cycle.

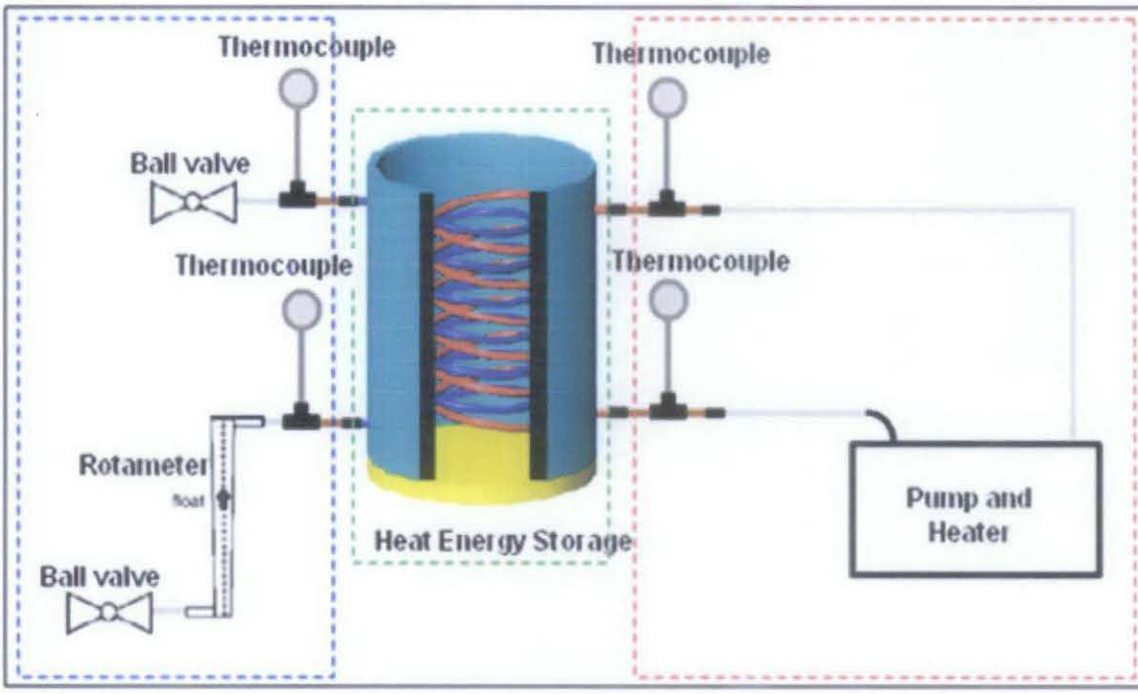


Figure 9 The schematic diagram of the design system

i. Open-loop system
ii. PCM Storage system
iii. Close-loop system

3.4 Design and Fabrication

For this stage the first step is to identify the components that are needed for the development of the project. The components identification is divided into two categories which are the components for the system and the components for the measurement (for the experimentation stage).

3.4.1 Components for the system

Table 5 Components specification for the system

No	Components	Description	Unit
1	PCM Storage cylinder	Well insulated	1
2	Tubes	Material: Copper	2
3	Valves	Heavy duty type of ball valve	2
4	Pump	Constant flow rate: 8L/min	1
5	Heater	Minimum temperature: 30°C Maximum temperature: 100°C	1

3.4.2 Components for the measurement

Table 6 Components specification for the measurement

No	Components	Types	Description	Unit
1	Thermocouples	Probe Thermocouple type	Maximum temperature: 635°C	8
2	Flow meter	Rotameter	Maximum flow rate: 120L/hr	1

3.5 Experimentation Construction Stage

There are two different types of experiment that had been done. One is done in Semester 1 and another 1 is done in Semester 2. During Semester 1, the experiment focuses on the paraffin wax to know the thermal properties of the waxes and for Semester 2, the experiment focuses on the developed thermal storage system to test the system performance.

3.5.1 Experimentation on four (4) different waxes

An experiment was set up to test on four samples of waxes; one pure paraffin wax and three ordinary waxes, available from the market. The objectives of this experiment are:

1. To determine the melting temperature of all waxes.
2. To determine the latent heat of fusion of all waxes.
3. To find one ordinary wax that has properties almost similar with pure paraffin wax.

Basically this experiment is done to know the thermal properties of each waxes and to choose one suitable wax to be used in the project. The equipment used for these experiments is Differential Scanning Calorimetry (DSC) machine.

3.5.1.1 Differential Scanning Calorimetry (DSC)

DSC is a technique in which the difference in energy inputs into a substance and a reference material is measured as a function of temperature, while the substance and a reference material are subjected to a controlled temperature program. The record is the DSC curve [12]. DSC operates in power compensation mode, is capable of heating at 10 ± 1°C/min from 15°C to 150°C. The calorimeter is able to record automatically the different signals versus temperature with a temperature repeatability of ± 0.5°C. It is also able to make a simultaneous record of temperature versus time.

3.5.1.2 Procedures

1. 10 ± 1 mg of wax pieces is weighed using weight balance.
2. The weigh wax is placed into a sample pan and a metal cover is crimped against the pan with the sample sandwiched in between to ensure maximum sample-to-pan thermal contact.
3. The pan is inserted in the calorimeter sample compartment.
4. The sample compartment of the test cell is flushed with inert gas throughout the test with a flow of 10 to 50 mL/min.
5. The thermal scan of record is performed and recorded. The DSC curve is recorded using a heating rate of 20°C/min from 25°C to 150°C.

3.5.2 Experimentation on PCM storage system

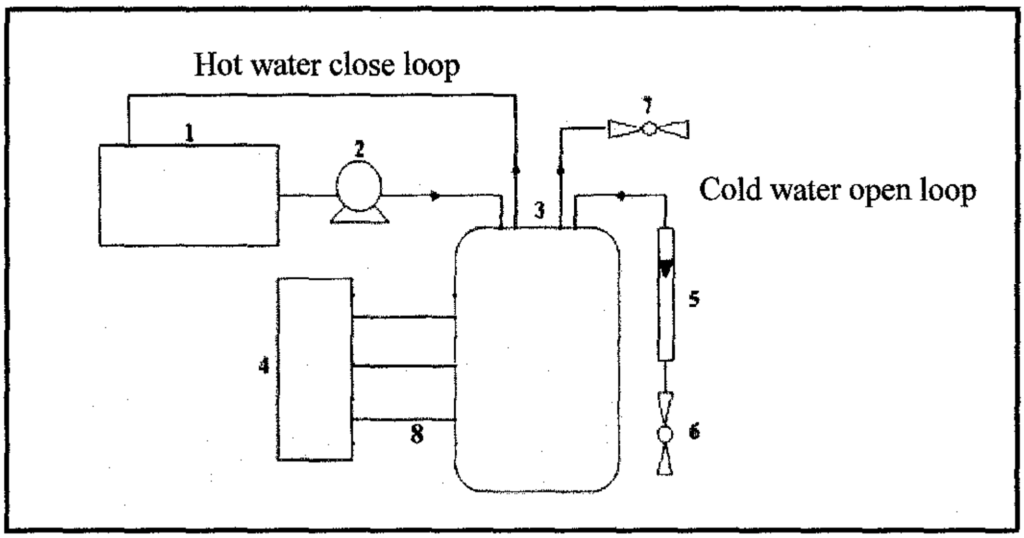


Figure 10 Schematic diagram of the experimental system. (1) High temperature bath; (2) circulation pump; (3) thermal energy storage (TES); (4) data logger; (5) flow meter; (7) valve and (8) thermocouples

The purpose of the testing is to evaluate the thermal performance of the PCM storage system during charging and discharging process. This experiment is focusing on the effect of heat transfer fluid (in this project, water) temperature on the system performance.

A heater installed inside the high temperature bath to provide the hot water that will be cycled through the heat storage equipment. Water heated by the heater is pumped via a circulation pump through the tubes inside the storage cylinder. The temperature of the water entering and exiting the heater is measured using thermocouples and their outputs are displayed on data logger.

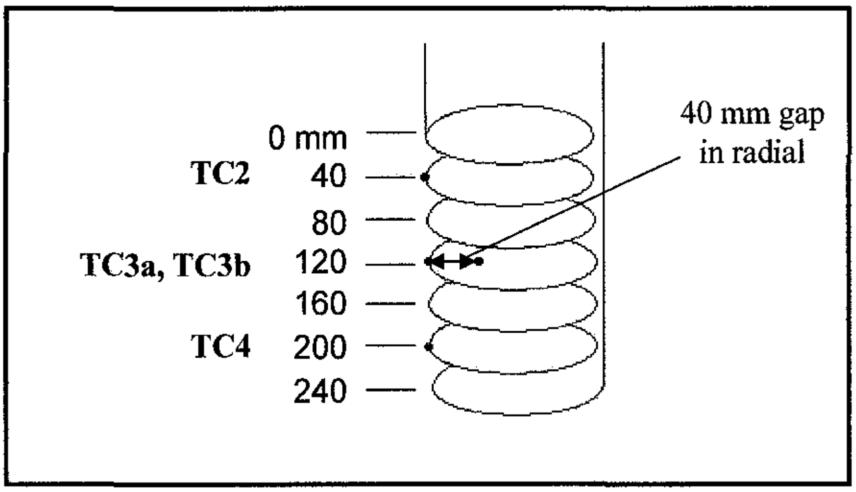


Figure 11 Location of thermocouples inside TES

The flow rate of water entering the heat storage is constant, which is 8L/minute. While the flow rate of water exiting the heat storage is measured using a flow meter called rotameter. The temperature of the tubes at the hot water inlet and outlet and also cold water inlet and outlet in the storage cylinder is measured using probe thermocouples; sited in the copper tubes. This will allow charge and discharge times and thermal performance to be established.

CHAPTER 4
RESULTS AND DISCUSSION

The results and discussion is divided into three parts which are:

1. Results obtained from the wax experiment
2. Results obtained from the thermal storage system experiment
3. Heat transfer analysis based on the results obtained in part (2)

4.1 Differential Scanning Calorimetry (DSC) Results Analysis

Separate samples of wax and a reference material or blank (empty sample container) are heated at a controlled rate in an inert atmosphere. A sensor continuously monitors the difference in heat flow to the two samples. The DSC curve is a record of this difference versus temperature. A transition in the wax involves the absorption of energy relative to the reference, resulting in a peak in the DSC curve. Several transitions may present. The highest temperature transition is a solid-liquid transition associated with complete melting. The lowest transition is the solid-solid transition related to the properties of the solid, which is the hardness and blocking temperature.

One graph is obtained from the experiment for each of the paraffin wax tested. Thus there will be four graphs in total presented representing four waxes tested.

4.1.2 Ordinary wax 1 (P2)

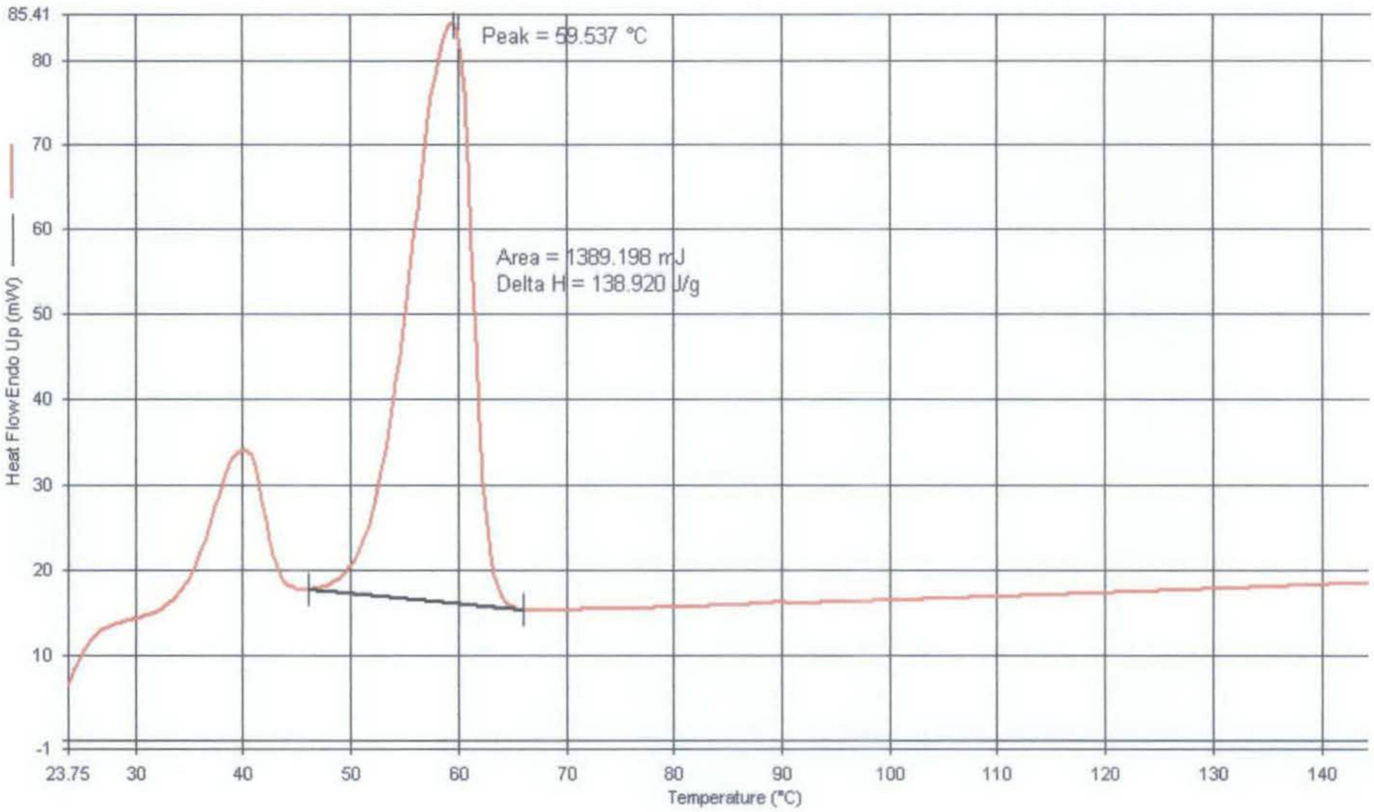


Figure 13 The result of DSC analysis for P2

The above graph shows the solid-liquid transition peak for the ordinary wax 1, sample P2. From the graph, the latent heat of fusion read 138.92 J/g. This reading is also being taken three times to reduce the percentage of human error and the average value is calculated. From the calculation, the average latent heat of fusion for P1 is 138.737 J/g. The recorded melting temperature is 59.537 °C.

4.1.3 Ordinary wax 2 (P3)

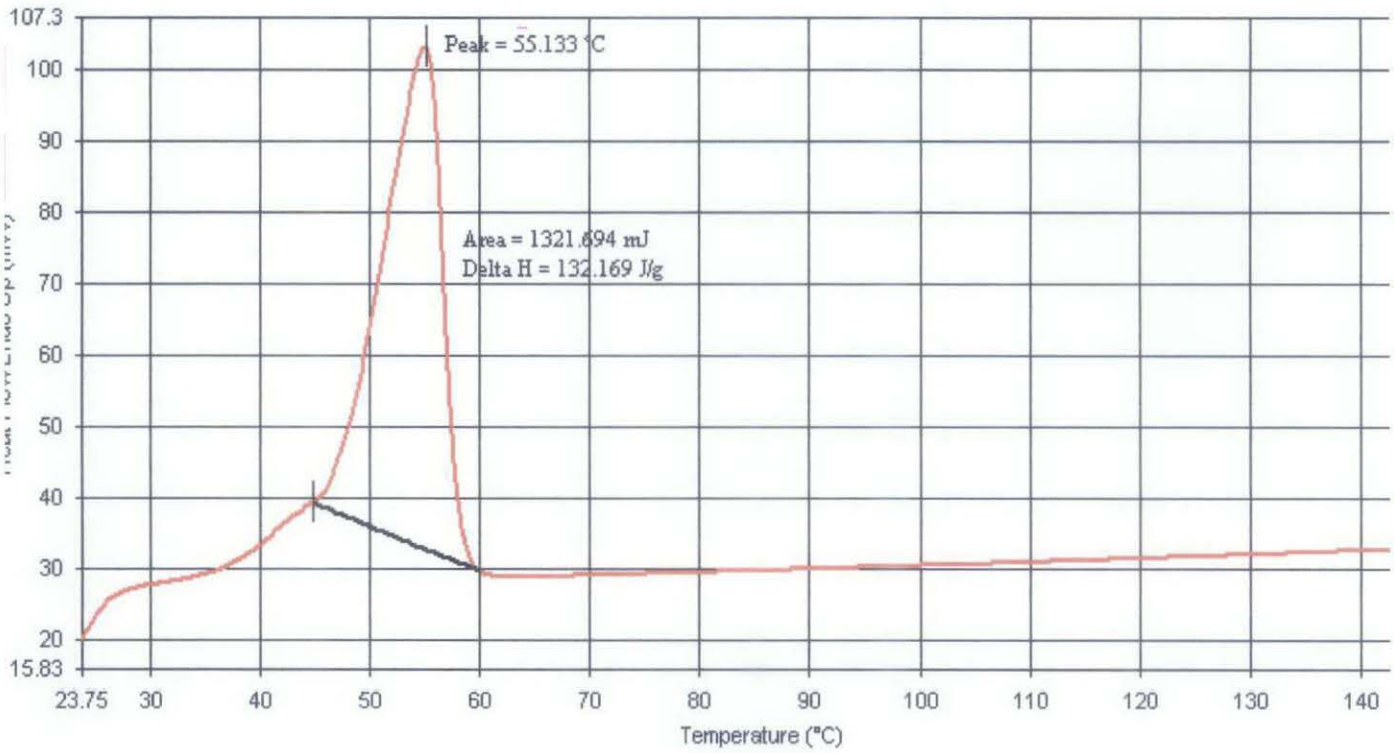


Figure 14 The result of DSC analysis for P3

The above graph shows the solid-liquid transition peak for the ordinary wax 2, sample P3. From the graph, the latent heat of fusion read 132.169 J/g. This reading is also being taken three times to reduce the percentage of human error and the average value is calculated. From the calculation, the average latent heat of fusion for P1 is 131.918 J/g. The recorded melting temperature is 55.133 °C.

4.1.4 Ordinary wax 3 (P4)

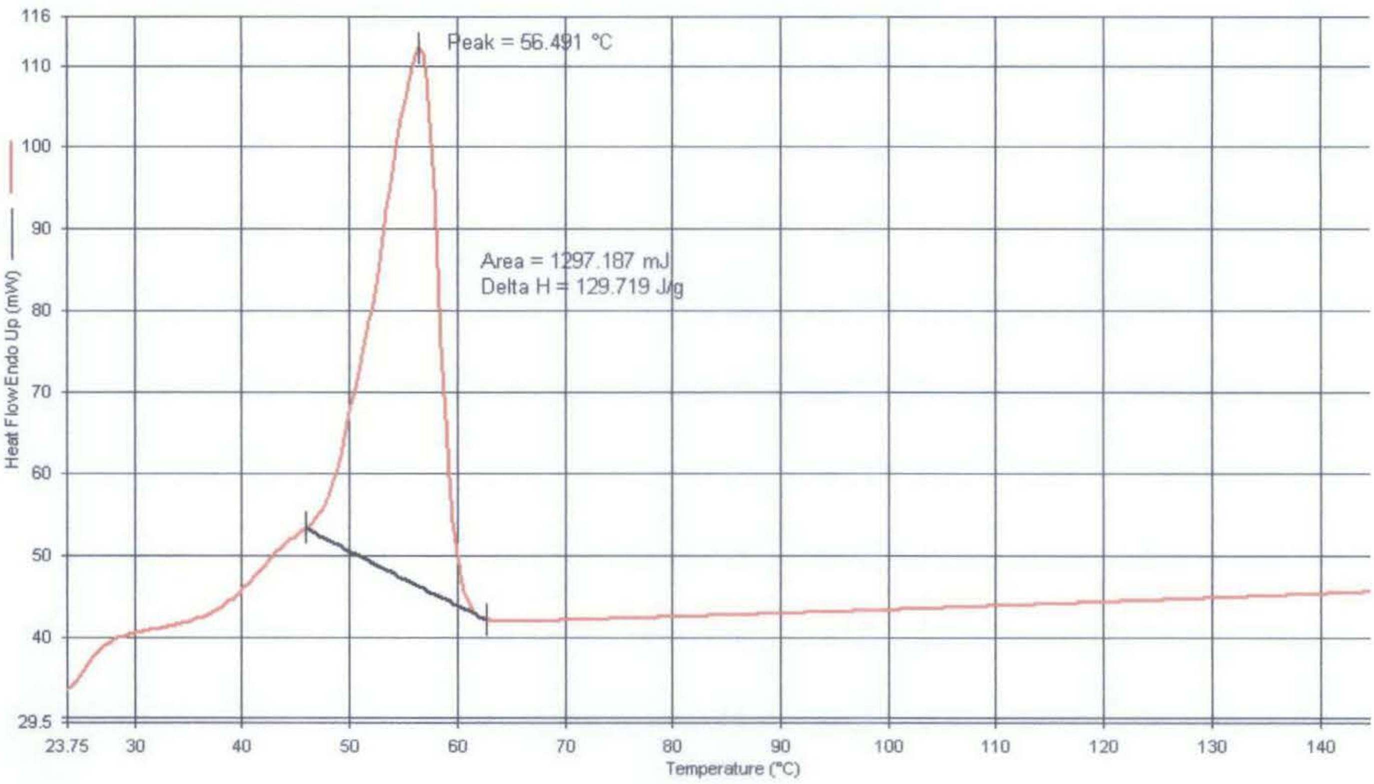


Figure 15 The result of DSC analysis for P4

The above graph shows the solid-liquid transition peak for the ordinary wax 3, sample P4. From the graph, the latent heat of fusion read 129.719 J/g. This reading is also being taken three times to reduce the percentage of human error and the average value is calculated. From the calculation, the average latent heat of fusion for P1 is 130.003 J/g. The recorded melting temperature is 56.491 °C.

4.1.4 Ordinary wax 3 (P4)

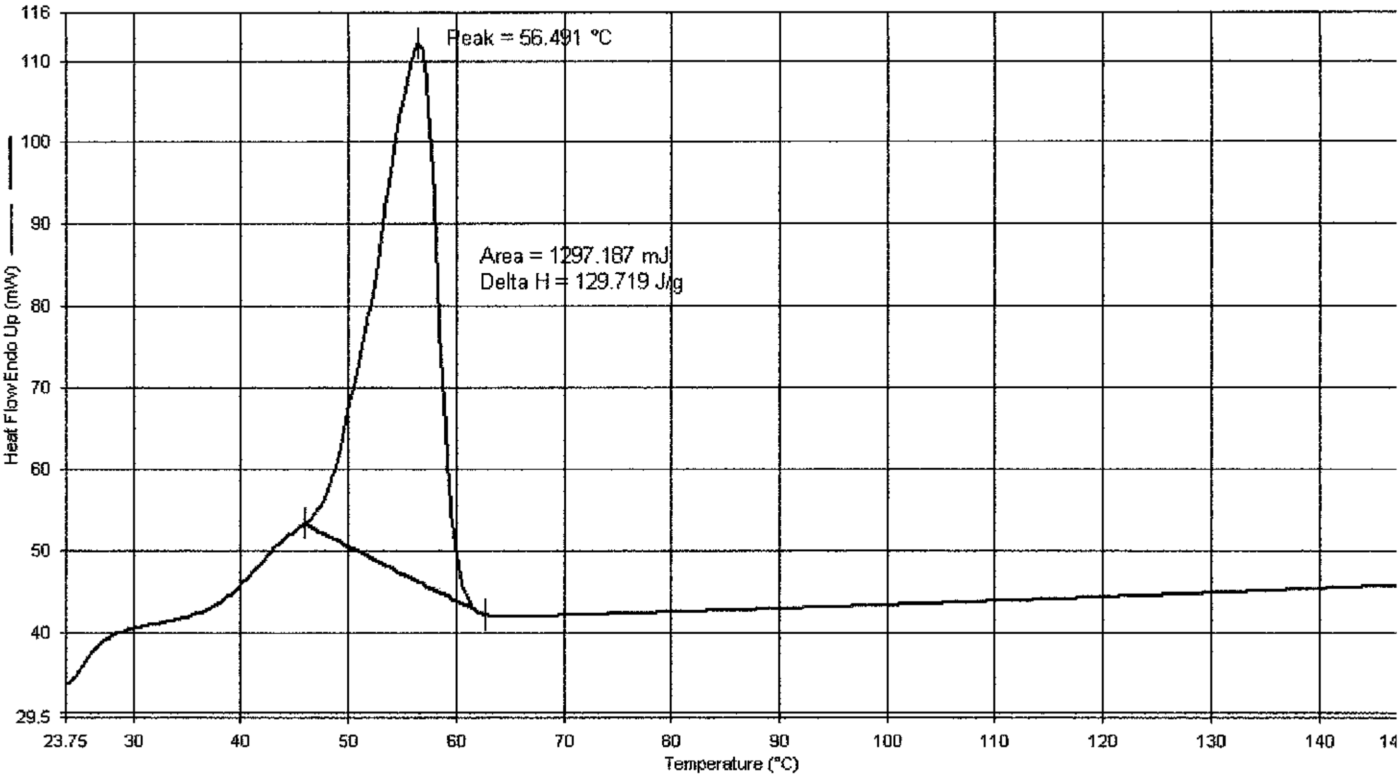


Figure 15 The result of DSC analysis for P4

The above graph shows the solid-liquid transition peak for the ordinary wax 3, sample P4. From the graph, the latent heat of fusion read 129.719 J/g. This reading is also being taken three times to reduce the percentage of human error and the average value is calculated. From the calculation, the average latent heat of fusion for P1 is 130.003 J/g. The recorded melting temperature is 56.491 °C.

4.1.5 Summarize the data

The latent heat of the sample was determined as total of latent heat of solid–solid phase change and latent heat of solid–liquid phase change. The total latent heat was determined by numerical integration of the area under the peaks which represent solid–solid phase change and solid–liquid phase change.

Table 7 Thermophysical properties of paraffin types considered in the study

Type of paraffin	Melting temperature range (°C)	Total latent heat (J/g)
P1	53.562	118.288
P2	59.537	138.737
P3	55.133	131.918
P4	56.491	130.003

4.1.6 Discussion

a) Thermal properties of PCMs

In the present study, the paraffin waxes with different melting temperature were used as PCM. Thermophysical properties of the PCMs such as the melting temperature range (°C) and total latent heat (kJ/kg) for solid and liquid phases of the PCMs were measured using DSC thermal analysis technique. The DSC heating curves of the PCMs are shown in the results section. As seen from DSC thermograms, the heating curves consist of two peaks.

The most important peaks represent the solid–liquid phase transitions of the paraffins as the small peaks show the solid–solid phase transitions of the paraffins. The reason of having the solid-solid phase transition is explained next. As the temperature increases, an amorphous solid will become less viscous. At some point the molecules may obtain enough freedom of motion to spontaneously arrange themselves into a crystalline form. This is known as the crystallization temperature (T_c). This transition from amorphous solid to crystalline solid is an exothermic process, and results in a peak in the DSC signal. As the temperature increases the sample eventually reaches its melting temperature (T_m). The melting process results in an endothermic peak in the DSC curve.

Thermal properties evaluated from the DSC curves are given in Table 7. Taking into account of these DSC results, it can be noted that the paraffins (P1, P2, P3 and P4) are promising PCMs for thermal energy storage applications in terms of their suitable melting temperatures and high latent heat capacities.

b) Melting temperature

The melting temperature obtained from the peak of the solid-liquid phase change curve. As can be seen from the graphs obtained and from the summarize data in the Table 7, the highest melting temperature is P2 at 59.537°C. The pure paraffin wax, P1 has the lowest melting temperature at 53.562°C. From the literature study done, for pure paraffin wax the melting temperature is 64°C. There is a large difference on the temperature between the study done and experiment's result. This might be due to the unconformity of the exact type of paraffin wax used. 64°C is for paraffin wax with chemical formula $C_{25}H_{52}$. The chemical formula of paraffin wax used in this experiment is unknown.

c) Total latent heat of fusion

The total latent heat of fusion is known by calculating the area covered under the curve of solid-liquid transition phase. Area obtained is divided with the sample's weight which is 10mg to have the amount of latent heat of fusion.

The highest total latent heat of fusion is P2 which is 138.737 J/g. Meaning at every 1 kg of P2 wax; it can store about 138.737 kJ of heat. While for the pure paraffin, P1; it can store 118.288 J/g heat only. Comparing to the literature study done, the paraffin wax's total latent heat of fusion is 266 J/g. A big amount of heat difference must be because the paraffin used in the experiment is not the same with the paraffin studied. But from the experiment, all the paraffins show that they can store an amount of heat that can be considered high. Therefore, the capabilities for these paraffins storing heat are high. Total latent heat of fusion is correlating with the melting temperature where with higher melting temperature; it has higher total latent heat of fusion.

4.1.7 The selection of suitable wax to be used in the project

The best paraffin that can give the best result of storing higher heat must have high melting temperature so that it can store larger energy and store the energy for a longer period of time. As indicated by the graph, the best paraffin chosen is P2 which has melting temperature of 59.537 °C and latent heat of fusion 138.737 J/g or equivalent to 138.737 kJ heat can be stored using 1 kg of this wax.

4.2 Experimental Analysis on Developed System

This experiment aims to investigate the effect of flow temperature on charge and discharge times. It is done by analyzing the thermocouple readings. Charge times will be determined by monitoring inlet and outlet temperatures of heat storage, when inlet temperature is close to the outlet temperature the PCM is considered to be fully charged. Discharge times will be determined by analyzing the inlet and outlet temperature of the cold water. During discharge heat output should be isothermal for a period of time, when this begins to fall steadily this is a sign that the PCM has solidified and all that is being released is stored sensible energy. The heat transfer analysis will be analyzed numerically.

4.2.1 Charging only operation performance

a) Influences of the hot water inlet temperature

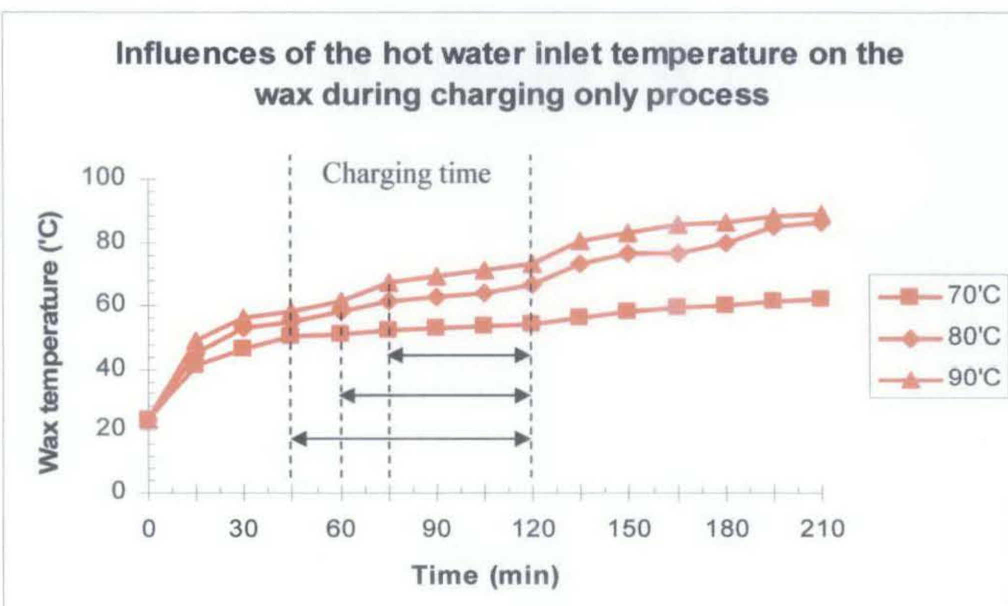


Figure 16 Influences of the hot water inlet temperature on the wax during charging only process: wax temperature at T3 ($T_{pcm,0}$ = 23.7 °C, $\dot{m}_h$ = 8 L/min)

Figure 16 summarizes the results and depicts the influences of hot water inlet temperature on the PCM temperature variation. It is shown from this figure that the inlet temperature of hot water has a very strong and direct influence. This is because, under the same initial temperature and flow rate conditions (both 23.7 °C and 8 L/min respectively), the overall heat transfer coefficient from the hot water to the PCM is basically a constant, and therefore, the heat flow from the hot water to the PCM (via copper tubes) is directly proportional to the temperature difference between the hot water and the PCM. From the figure, it is clearly seen that as the water inlet temperature increasing, the charging time decreasing. The charging time for the inlet temperature of 70 °C is 1.5 hours, for 80 °C, this value is reduced to 1 hour and for 90 °C, it is only 45 minutes.

b) Melting curves at different vertical positions

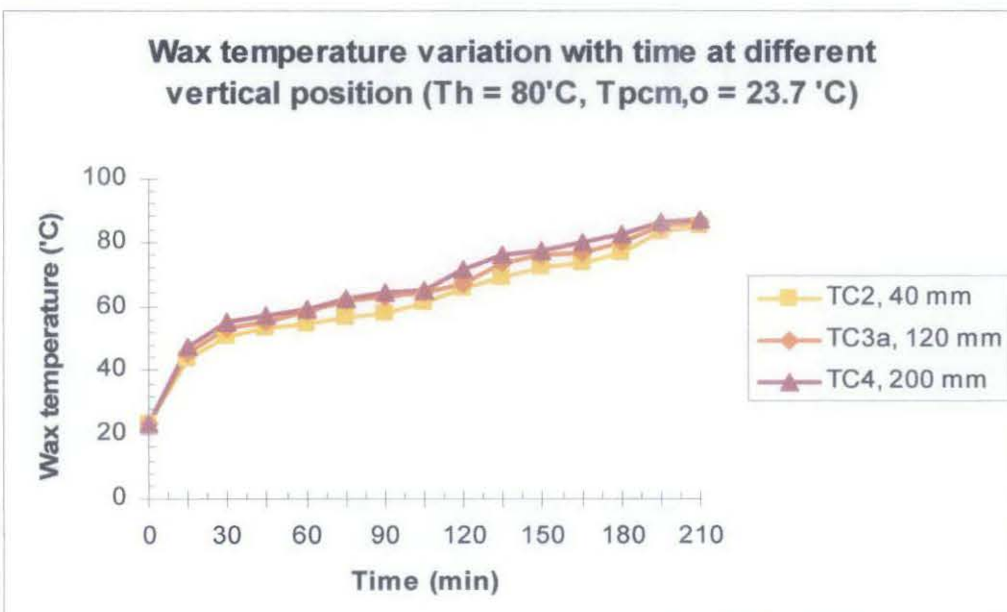


Figure 17 Wax temperature variation with time at different vertical positions $z = 40$, 120 and 200 mm from the top axis of copper tube. Charging only mode: $T_h = 80$ °C, $T_{pcm,0} = 23.7$ °C, $\dot{m}_h = 8$ L/min

Figure 17 depicts the measured PCM temperature variation with time with a hot water flow rate of 8 L/min and hot water inlet temperature 80 °C. From this figure, it can be seen that during the early stage of the charging process, the heat transferred from the hot water to the copper tube is mainly used to heat the walls of the tube and, thus, to raise the temperature of the tube, which explains the rapid raise of PCM temperature during this period. It can also be seen that the heat transfer performance is consistent along the vertical position from the axis of copper tube.

c) Melting curves at different radial positions

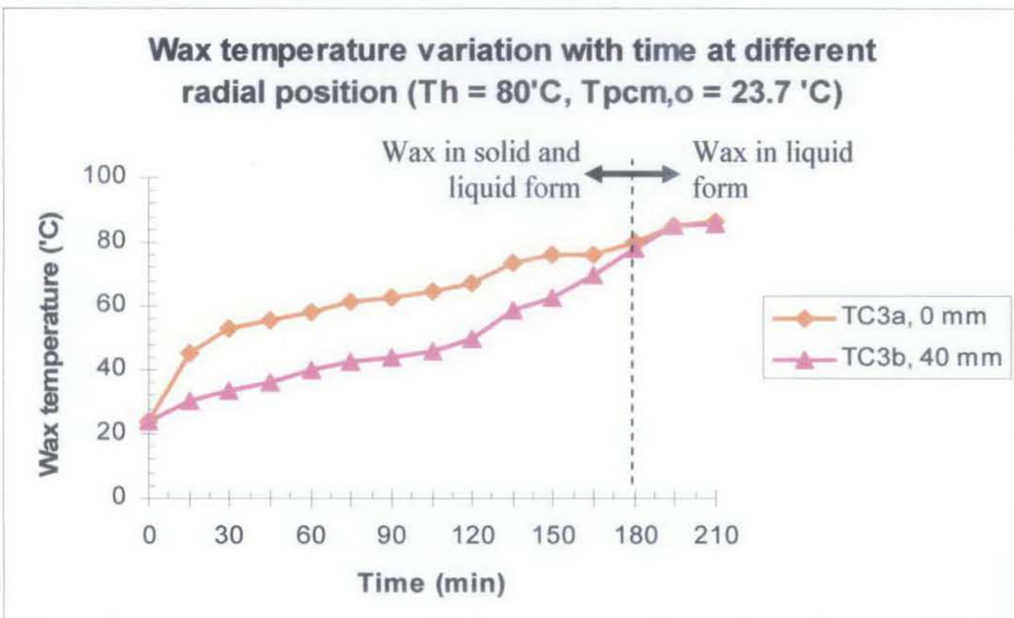


Figure 18 Wax temperature variation with time at different radial positions $r = 0$ and 40 mm from top axis of copper tubes $z = 120$ mm. Charging only mode: $T_h = 80$ °C, $T_{pcm,0} = 23.7$ °C, $\dot{m}_h = 8$ L/min

Figure 18 is melting curves at two different radial positions at the same elevation position T3 from top axis, z = 120mm. During the initial period of heating, the PCM absorbs and stores heat in the form of sensible heat and the heat transfer through the PCM is pure conduction. This heat is used to raise the temperature to its melting point.

From Figure 18, it can be concluded that it takes 3 hours to reach 40 mm distance in radial during charging. See Figure 19 for illustration.

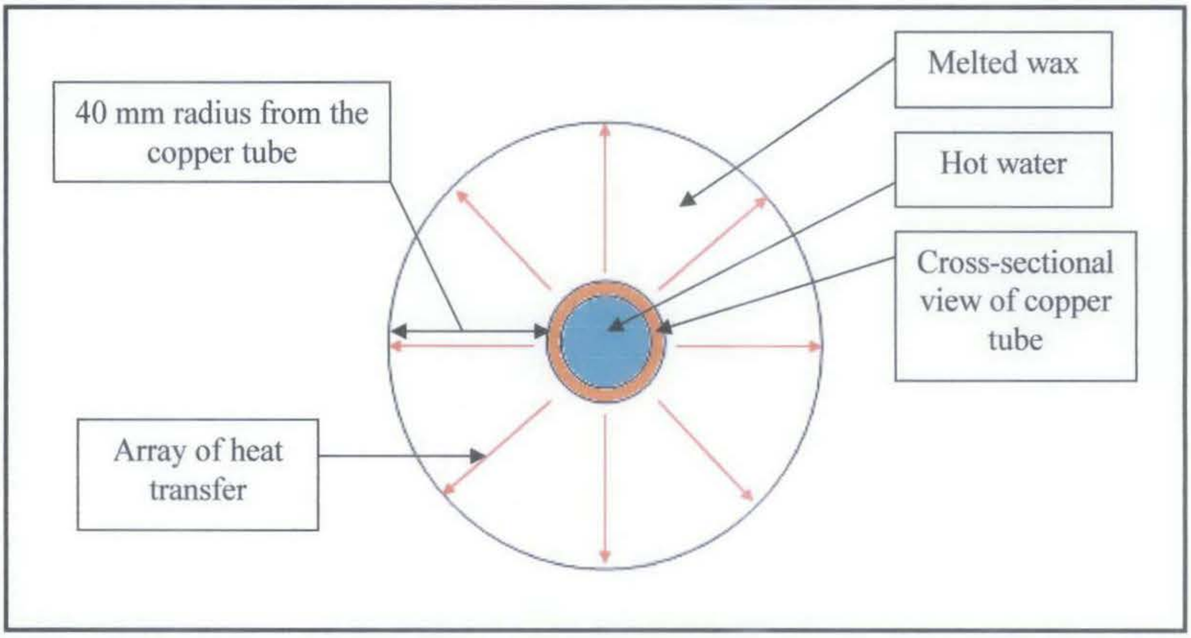


Figure 19 The cross-sectional view of copper tube during charging; showing the heat is transfer to the wax homogeneously 40 mm in radial

4.2.2 Discharging only operation performance

The discharging only operation experiments were conducted at cold water inlet temperature 23.5 °, and at constant water flow rate of 8 L/min. In order to perform the discharging only operation experiments, the PCM was first heated to a temperature higher than the melting temperature of PCM (in this case 86.1 °C) by circulating the hot water for 3.5 hours. Then, after PCM reached the temperature, the hot water circulation is stopped. As soon as the hot water was evacuated from the hot water tube, the cold water is started to flows in the cold water tube and the experiment starts.

a) Influences of the cold water inlet temperature

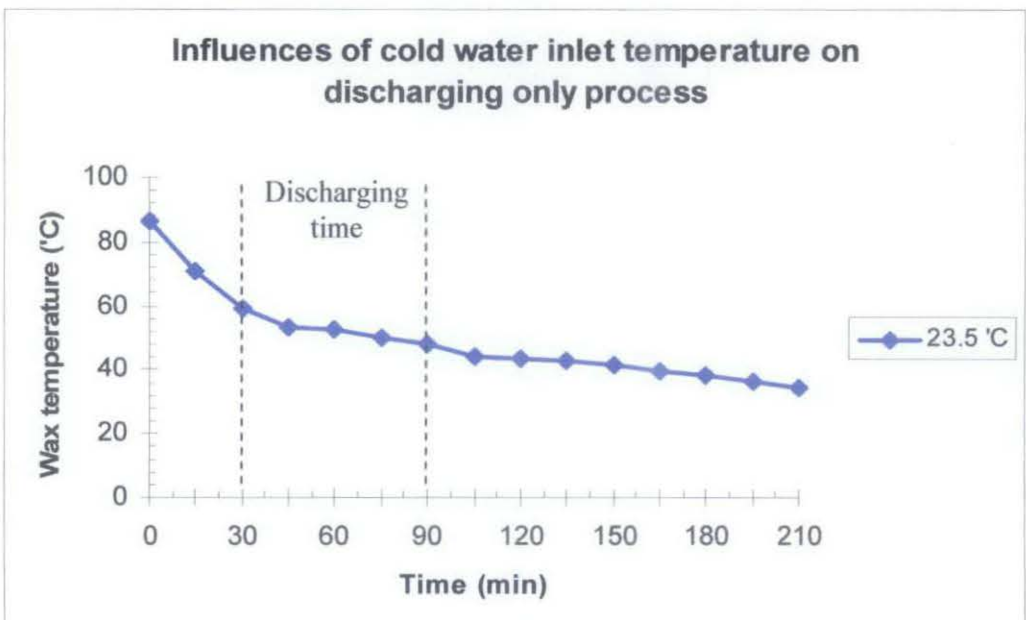


Figure 20 Influences of the cold water inlet temperature on the wax during discharging only process: wax temperature at T3 ($T_{pcm,0}$ = 86.1 °C, $\dot{m}_c$ = 8 L/min.)

Figure 20 depicts the influences of the cold water inlet temperature on the discharging process. It can be seen from this figure that the inlet temperature of cold water has an important influence. The reason is, the overall heat transfer coefficient from the cold water to the PCM is basically a constant, and therefore, the heat flow from the PCM to the cold water (via copper tube) is directly proportional to the temperature difference between PCM and cold water temperature. The discharging time for this system is from minute 30 to minute 90.

b) Solidification curves at different vertical positions

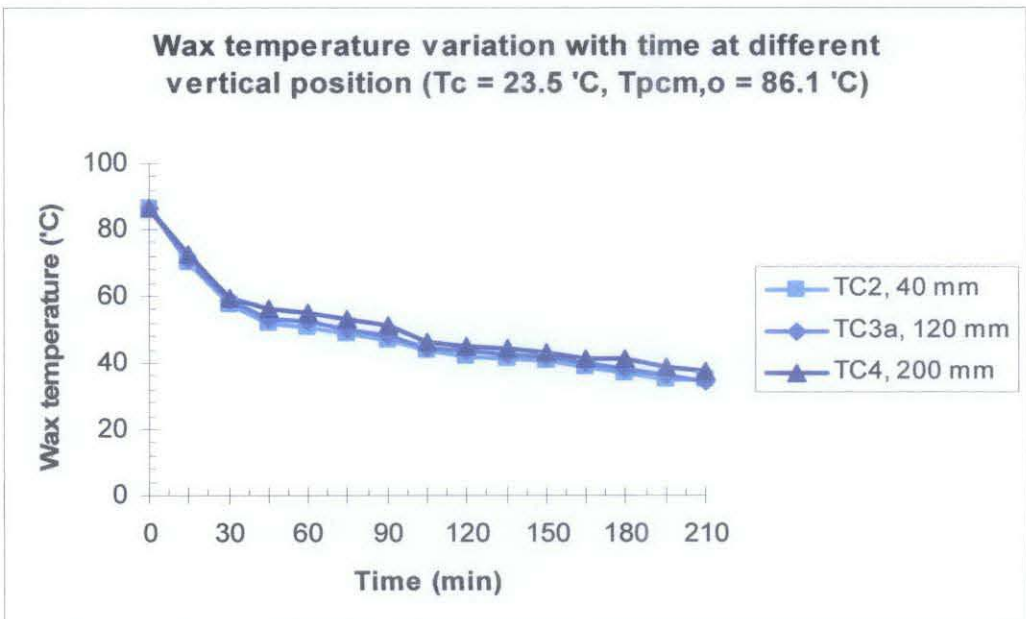


Figure 21 Wax temperature variation with time at different vertical positions $z = 40$, 120 and 200 mm from the top axis of copper tube. Discharging only mode: T_c = 23.5 °C, $T_{pcm,0}$ = 86.1 °C, $\dot{m}_c$ = 8 L/min

Figure 21 depicts the measured PCM temperature variation with time with a hot water flow rate of 8 L/min and cold water inlet temperature 23.5 °C. From this figure, it can be seen that the heat transfer performance is consistent along the vertical position from the axis of copper tube.

c) Solidification curves at different radial positions

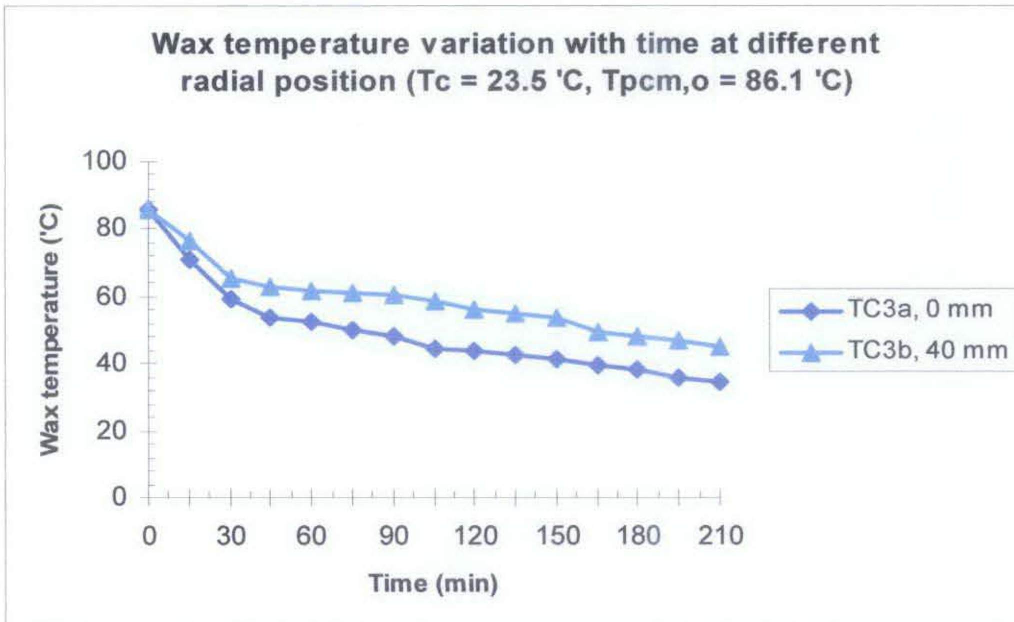


Figure 22 Wax temperature variation with time at different radial positions $r = 0$ and 40 mm from top axis of copper tubes $z = 120$ mm. Discharging only mode: $T_c =$ 23.5 °C, $T_{pcm,0} = 86.1$ °C, $\dot{m}_c = 8$ L/min

Figure 22 presents the solidification curves of PCM that were obtained from various radial positions in discharging only mode operation. From this figure, it can be seen that the PCM was cooled very quickly from liquid to solid state. Until 210 minutes of discharging the system, the curves are still not intersecting each other. To know the time taken to reach 40 mm distance in radial during discharging, the curves must be intersecting each other. Therefore, this experiment should be continued until the curves meet an intersecting point.

4.3 Heat Energy Analysis

To analyze the storage system, the following assumptions have been made:

i. The thermophysical properties of the PCM are independent of temperature. However, they are different for the solid and liquid phases of PCM.
ii. The PCM is initially in solid phase
iii. The PCM is homogeneous and isotropic
iv. There is no convection, only heat conduction

Figure 23 shows the charging and discharging operations of the system and temperature profile for countercurrent latent heat storage with subcooling and sensible heating.

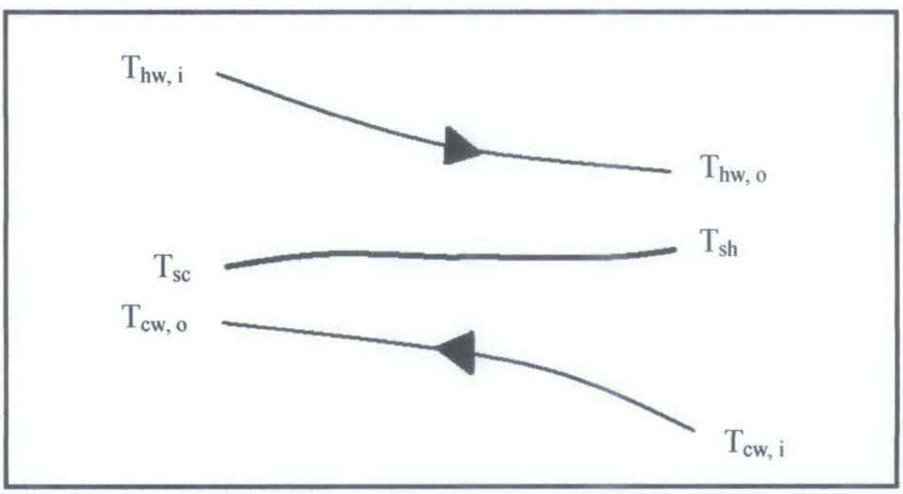
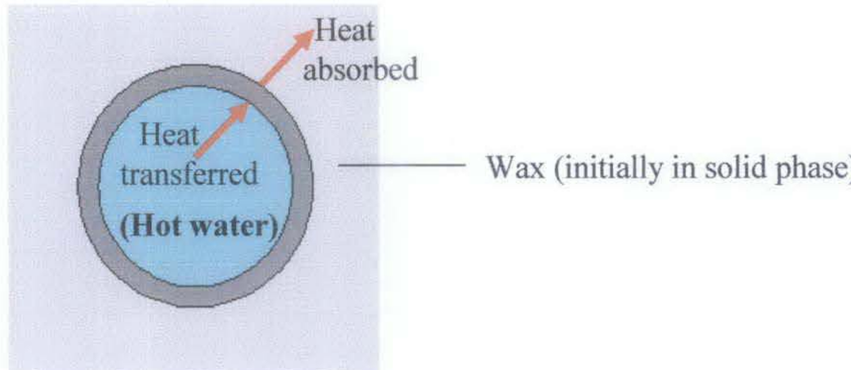


Figure 23 Typical temperature profile of a LHS system for charging and discharging operation [13]

$T_{hw,i}$	Temperature of hot water at the inlet,
$T_{hw,o}$	Temperature of hot water at the outlet
$T_{cw,i}$	Temperature of cold water at the inlet
$T_{cw,o}$	Temperature of cold water at the outlet
T_{sc}	Temperature of sub-cooled PCM
T_{sh}	Temperature of sensible heat PCM

4.3.1 During Charging of PCM



A charging fluid (hot water supply) heats PCM, which may initially be at a subcooled temperature T_{sc}, and may eventually reach to a temperature T_{sh} after sensible heating. Therefore, LHS undergoes a temperature difference of $T_{sh} - T_{sc}$, as shown in Figure 23 at page 39. Heat lost by the charging fluid would be:

$$\dot{Q}_c = \dot{m}_c C_{pc}(T_{hw,i} - T_{hw,o})$$

where $\dot{m}_c$ is the charging fluid flow rate, C_{pc} is the specific heat of charging fluid, in this case, water. ($\dot{m}_c$ = 8 L/min = 8 kg/min, C_{pc} = 4.186 kJ/kg.°C).

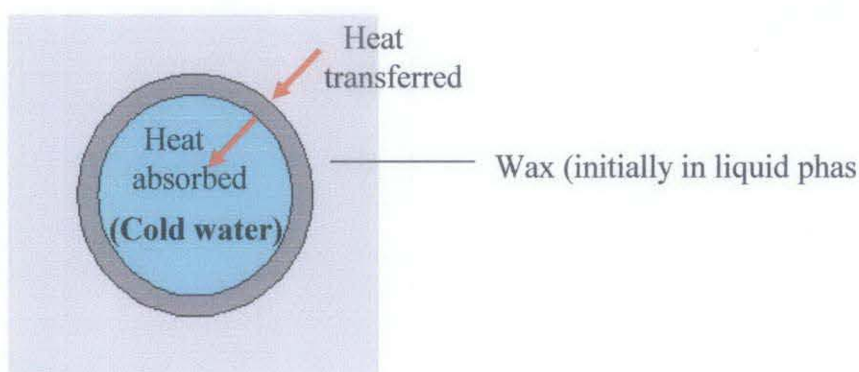
The heat lost by the charging fluid will be gained by the PCM [3]. From Figure 16 at page 32, the charging time with hot water inlet temperature, $T_{hw,i}$ = 80 °C is from minute 60 to 120. Thus the rate of heat removed from the hot water will be the average rate of heat removed at minute 60, 75, 90, 105 and 120.

Table 8 The calculated rate of heat transfer removed from the hot water to the wax

Time (min)	$T_{hw,i}$ (°C)	$T_{hw,o}$ (°C)	Q'_c (kJ/hr)
60	80.0	74.4	11251.97
75	80.0	73.7	12658.46
90	80.0	73.3	13462.18
105	80.0	73.0	14064.96
120	80.0	72.8	14466.82
Average Q'_c (kJ/hr)			**13180.88**

Therefore average heat transfer rate from the hot water to the wax during the charging period is 13180.88 kJ/hr.

4.3.2 During Discharging of PCM



It is assumed that the PCM is totally melted and heated to a temperature T_{sh} when discharging fluid (cold water supply) starts recovering heat estimated by:

$$\dot{Q}_d = \dot{m}_d C_{pd} (T_{cw,i} - T_{cw,o})$$

where $\dot{m}_d$ is the discharging fluid flow rate, C_{pd} is the specific heat of discharging fluid, in this case, water. ($\dot{m}_d$ = 8 L/min = 8 kg/min, C_{pd}= 4.186 kJ/kg.°C).

The heat gained by the discharging fluid will be lost by the PCM [3]. From Figure 20 at page 36, the discharging time with cold water inlet temperature, $T_{cw,i}$ = 23.5 °C is from minute 30 to 90. Thus the rate of heat removed from the hot water will be the average rate of heat removed at minute 30, 45, 60, 75 and 90.

Table 9 The calculated rate of heat transfer absorbed by the cold water from the wax

Time (min)	$T_{cw,i}$ (°C)	$T_{cw,o}$ (°C)	Q'_d (kJ/hr)
30	23.5	28.6	-10247.33
45	23.5	28.6	-10247.33
60	23.5	28.5	-10046.40
75	23.5	28.4	-9845.47
90	23.5	28.3	-9644.54
Average Q'_d (kJ/hr)			-10006.21

Therefore average heat transfer rate absorbed by the cold water from the wax during the discharging period is 10006.21 kJ/hr.

4.4 Prototype of the Latent Heat Storage

The prototype main components in separate form:

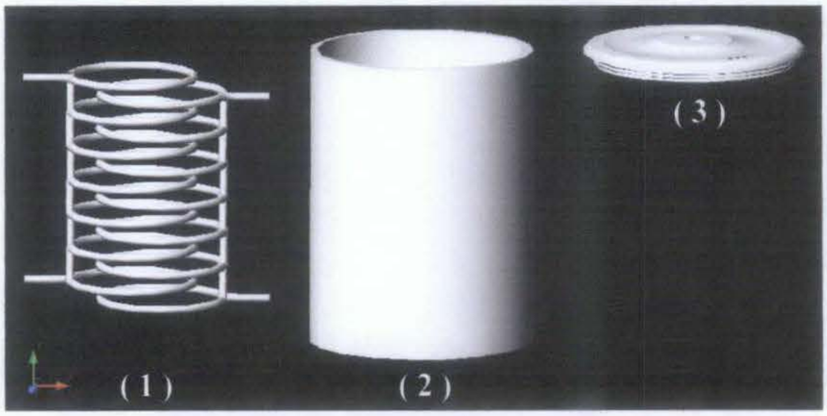


Figure 24 The main components of the prototype

Notation:

(1) The coils

(2) Thermal storage

(3) Removable cover

There are 2 main components in developing the prototype which are the coils and the thermal storage for paraffin wax.

Refer to APPENDIX C and D for the technical drawing of the coils and thermal storage.

4.4.1 The coils

The material chosen for tubes that are going to be used for the thermal storage design is copper. This is because the copper is soft, thus it can be shaped into any curves easily without broken, fractured or experience any fatigue defects. It is also a good conductor with thermal conductivity, k = 401 W/m.K. The size of copper tube is 9.5mm O.D and 7.5mm I.D.

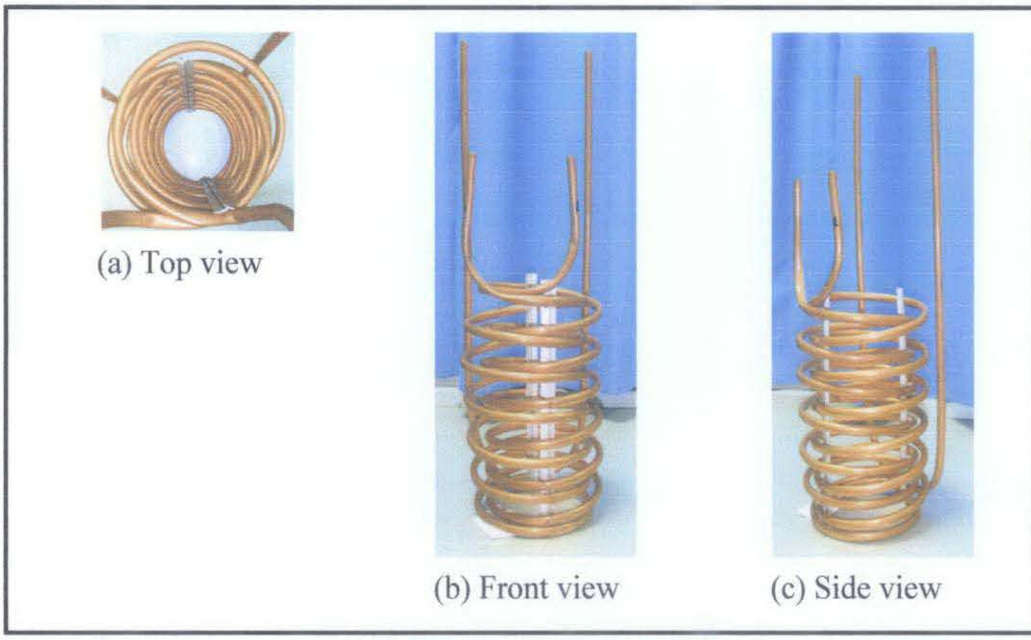


Figure 25 The (a) top, (b) front, and (c) side views for two copper tubes that placed in between each other

4.4.2 The thermal energy storage

The thermal energy storage used in this project is chosen from the conventional storage available from the market. This storage chosen has an installed good insulator, thus it is able to store large heat for a long period of time without releasing the heat to the surrounding. The size of this storage must be an adequate size; therefore it is possible to study the efficiency of wax storing heat. It is 13.5 inches in height and 10.6 inches in diameter.

Figure 26 Copper tubes are installed inside the thermal energy storage

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As a conclusion, the heat storage system is mainly made up of three systems which are the open-loop system, close-loop system and PCM storage system. Each of the system has their own task and components. The design for each system has been finalized. During the designing stage several aspects are taken into account which are the parameters, shape and size of the storage equipment, materials selection, and feasibility and availability of materials and equipment that will be used for the construction of the prototype. In working on developing the whole system, some surveys and procurements of the components from the local market had been done. During the completion stage of the prototype, the prototype is assembled with the piping system (open-loop and close-loop systems). The system is then undergone some experimentations in order to test and analyze the thermal performance of the system. The experimental results on the charging only mode and discharging only mode of the system show that the device performs the designed functions very well. It can both store and release the thermal energy efficiently. The system takes 2 hours to charge the whole system and 1.5 hours to discharge at the same flow rate of 8 L/min. After calculated the heat transfer rate during charging only operation mode is 13180.88 kJ/hr and the heat transfer rate during discharging only operation mode is 10006.21 kJ/hr. Therefore, this lab scale latent heat energy storage device can be used as a conventional system in which the charging and discharging are operated independently.

5.2 Recommendation

The performance of the designed system can be further increased by adding fins to the copper tubes and installing highly conductive filaments inside the storage. The fins will increase the contact areas of heat transfer thus improve the heat transfer rate between the charging/ discharging fluid and the wax. The filaments will form myriad network of interconnected conductive paths, thus will also improve the heat transfer rate of wax inside the storage.

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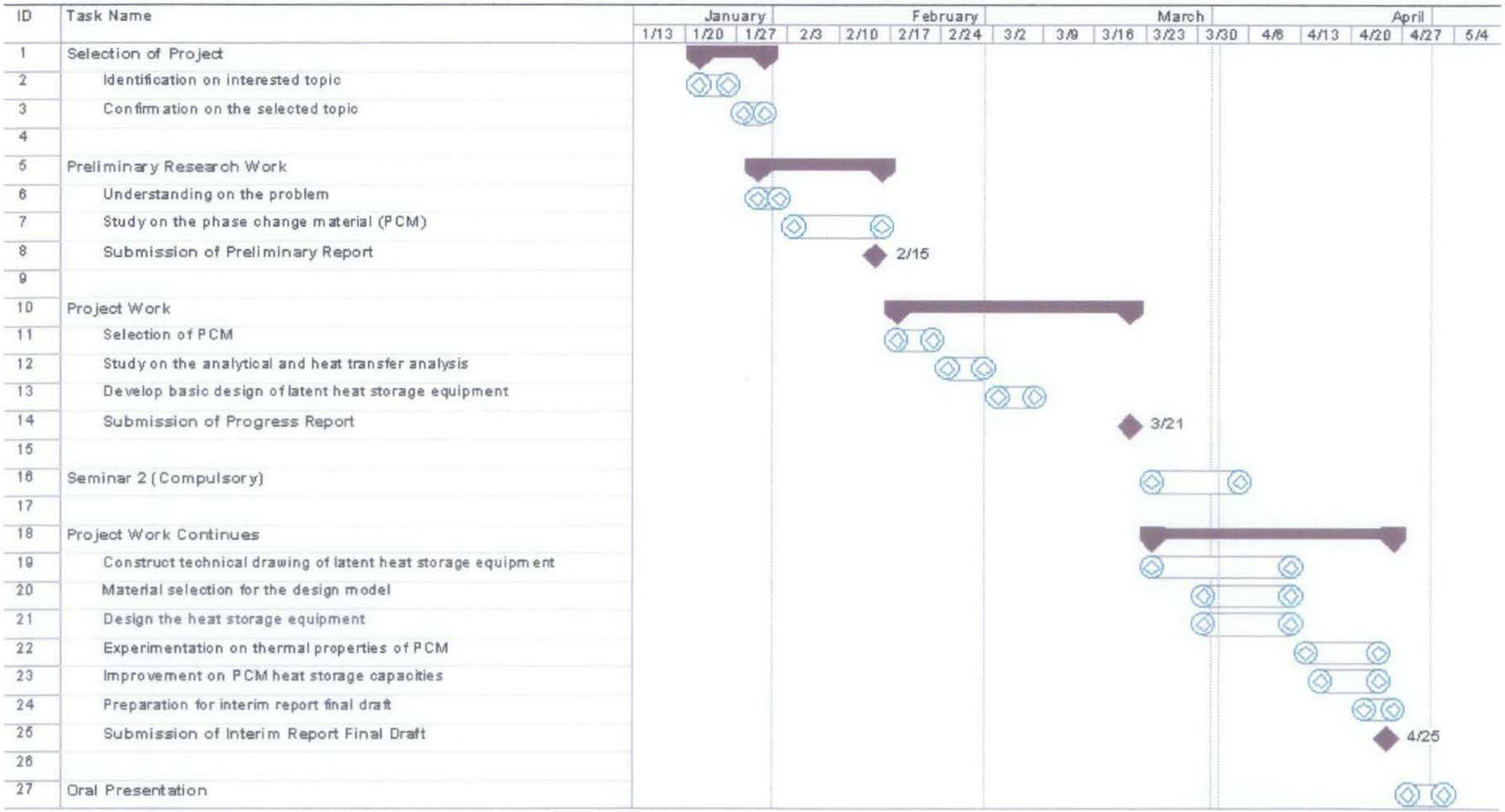
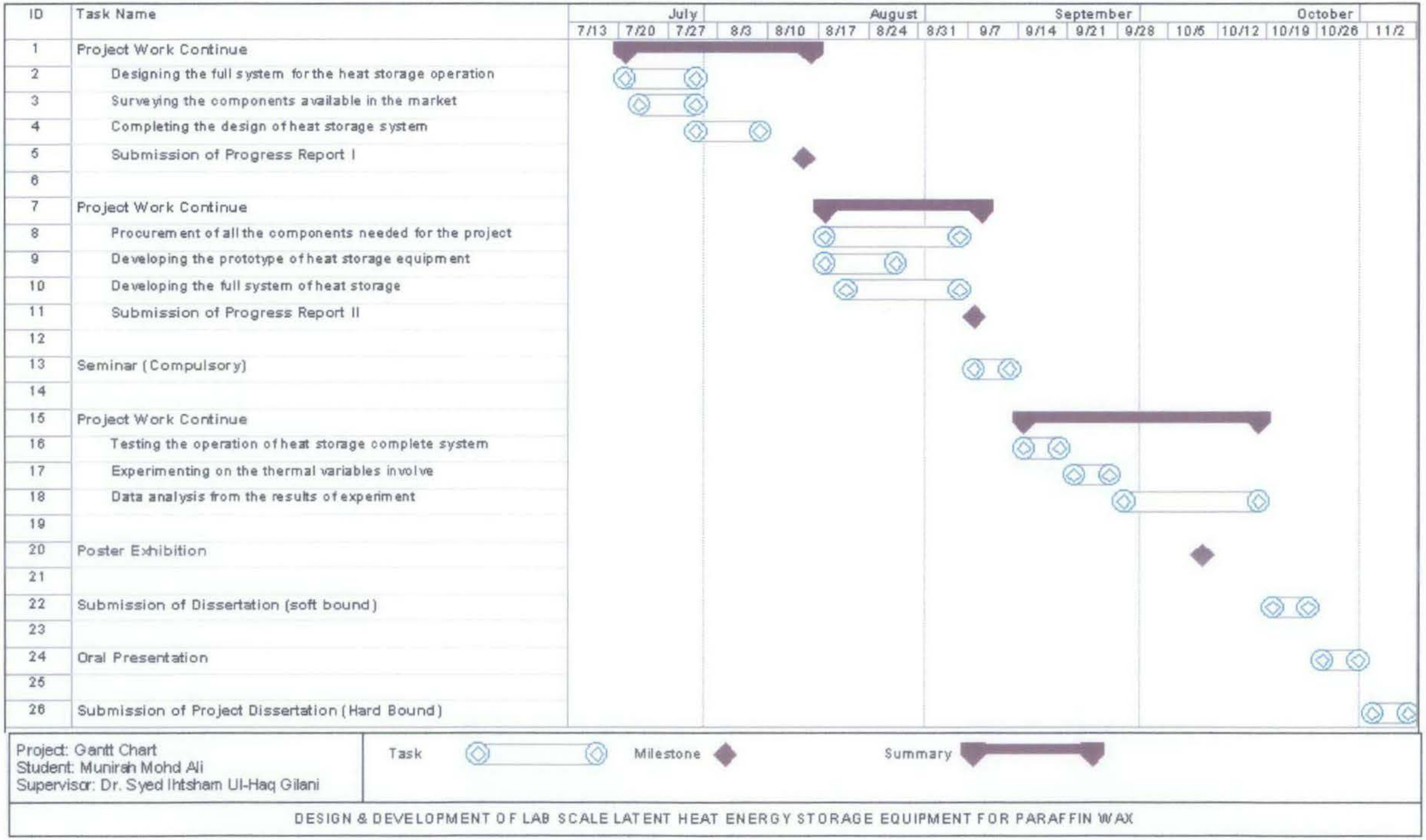
APPENDIX A

The Gantt Chart for Semester 1



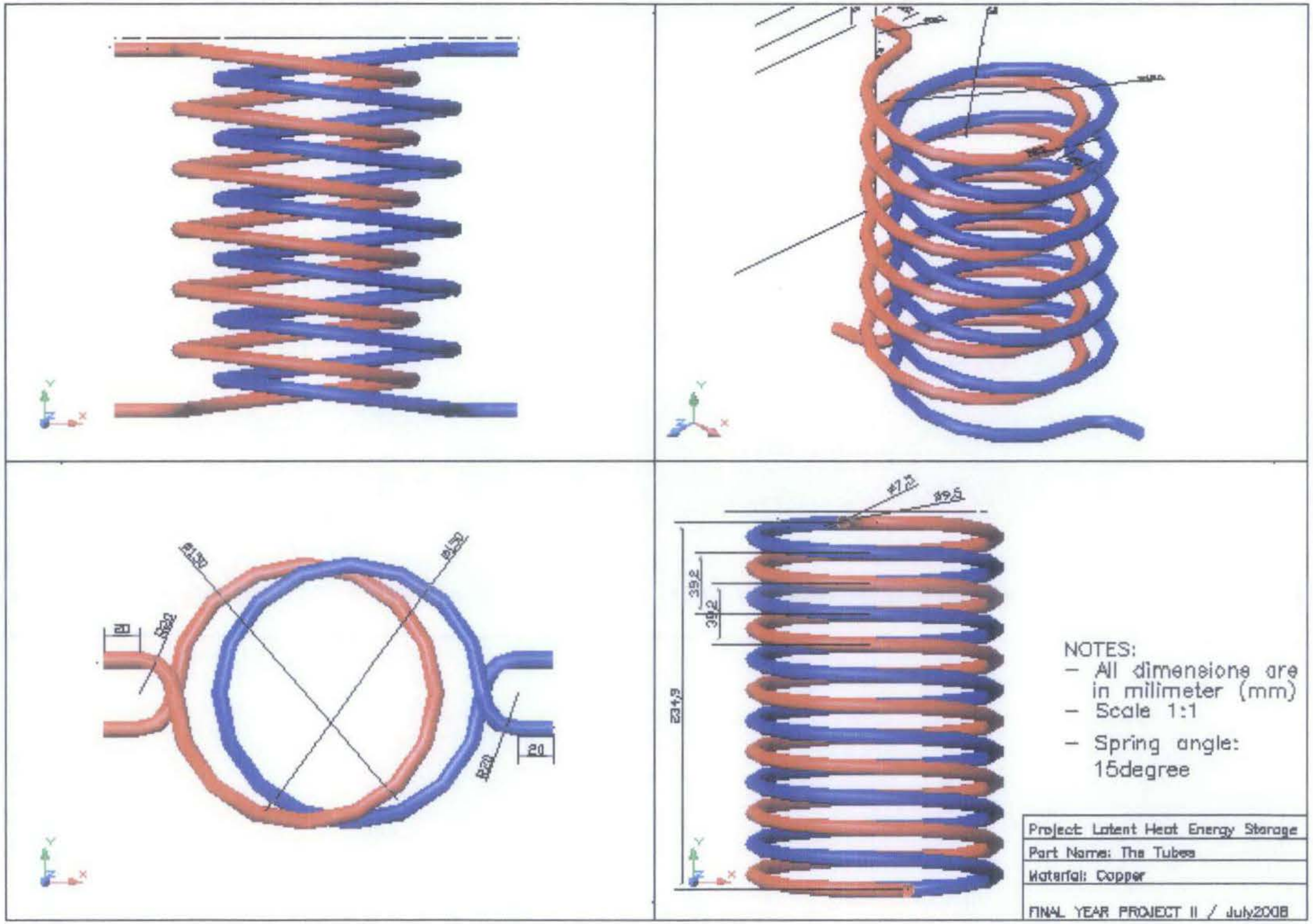
APPENDIX B

The Gantt Chart for Semester 2



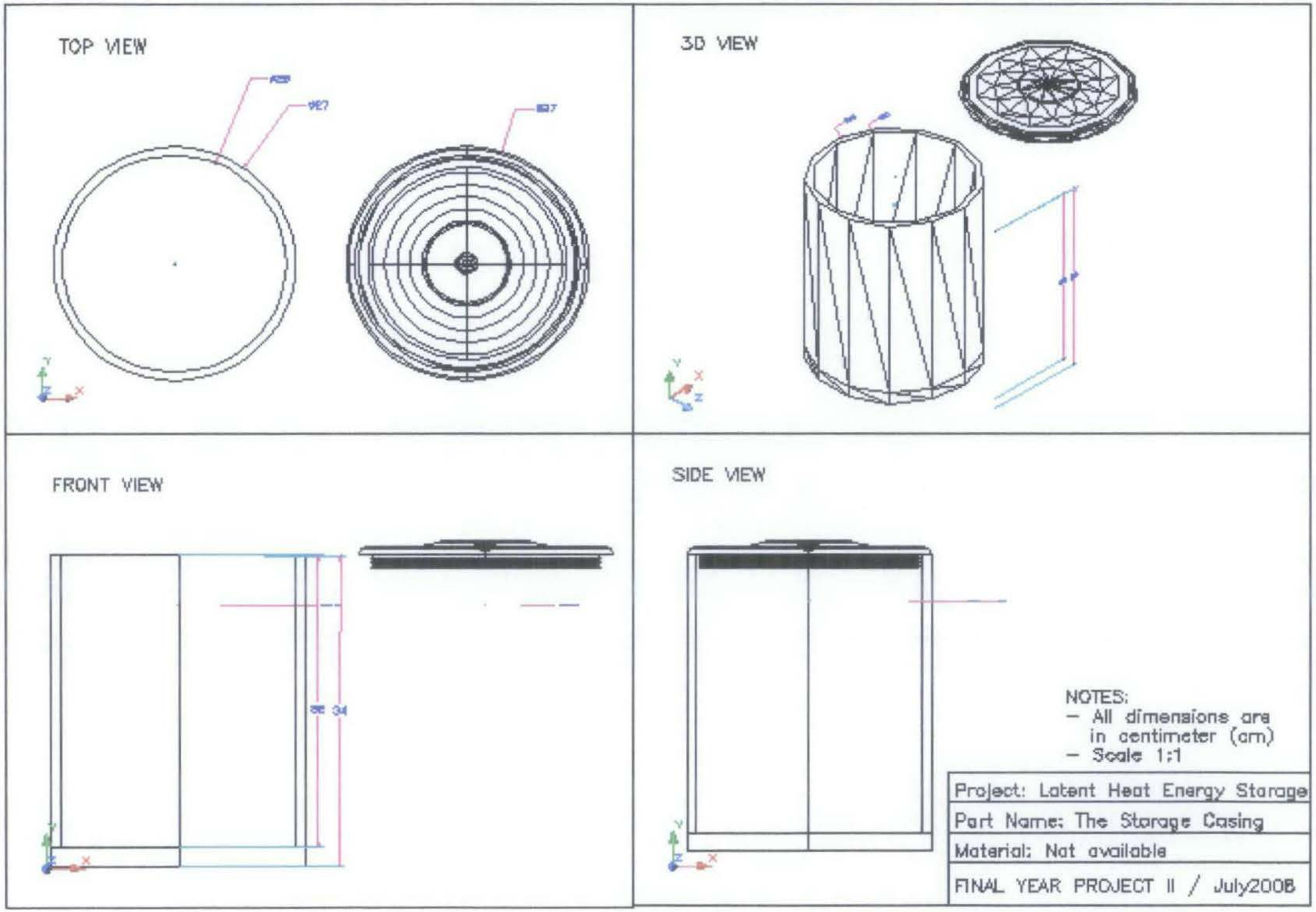
APPENDIX C

The technical drawing of the coils



APPENDIX D

The technical drawing of the thermal storage



APPENDIX E

Tables summarizing the values obtained from DSC curve for each waxes

Pure paraffin wax, sample P1

Trial	Melting temperature, T_m (°C)	Latent heat of fusion, ΔH (J/g)	Area under curve, A (mJ)
1	53.562	118.185	1181.854
2	53.562	118.244	1182.438
3	53.562	118.435	1184.345
Average	**53.562**	**118.288**	1182.879

Ordinary wax 1, sample P2

Trial	Melting temperature, T_m (°C)	Latent heat of fusion, ΔH (J/g)	Area under curve, A (mJ)
1	59.537	138.920	1389.198
2	59.537	138.516	1385.161
3	59.537	138.774	1387.737
Average	**59.537**	**138.737**	1387.365

Ordinary wax 2, sample P3

Trial	Melting temperature, T_m (°C)	Latent heat of fusion, ΔH (J/g)	Area under curve, A (mJ)
1	55.133	132.169	1321.964
2	55.133	131.956	1319.560
3	55.133	131.630	1316.299
Average	**55.133**	**131.918**	1319.274

Ordinary wax 3, sample P4

Trial	Melting temperature, T_m (°C)	Latent heat of fusion, ΔH (J/g)	Area under curve, A (mJ)
1	56.491	129.719	1297.187
2	56.491	129.242	1292.418
3	56.491	131.048	1310.477
Average	**56.491**	**130.003**	1300.027

APPENDIX F

Data obtained from the experiment on the designed system

1) Influences of hot water inlet temperature on the charging only process

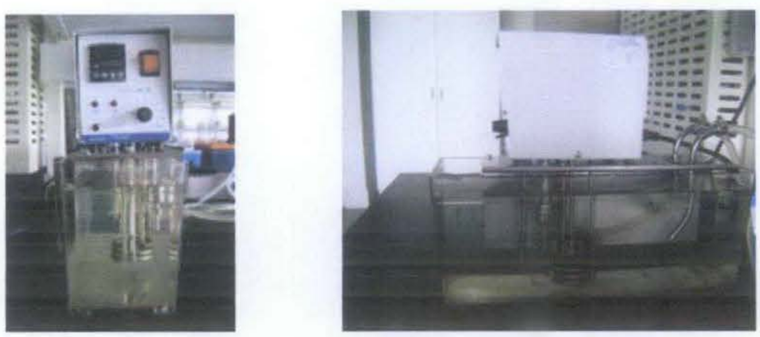
	80 'C					70 'C	90 'C	
t(min)	TC2	TC3a	TC3b	TC4	Tout	TC3a	TC3a	Q'
0	23.7	23.7	23.7	23.7	74.8	23.7	23.7	10448.26
15	43.8	45.3	30.5	47.4	75.0	41.3	48.7	10046.40
30	50.9	53.1	33.5	55.3	73.3	46.2	55.9	13462.18
45	53.2	55.2	36.1	57.0	76.0	50.1	58.1	8037.12
60	54.8	58.3	39.8	58.9	74.4	51.2	61.3	11251.97
75	56.7	61.5	42.3	62.3	73.7	52.5	67.5	12658.46
90	58.1	62.7	44.0	64.1	73.3	52.9	69.2	13462.18
105	60.8	64.2	45.8	65.2	73.0	53.4	71.1	14064.96
120	65.7	66.9	49.8	71.2	72.8	54.2	73.5	14466.82
135	68.9	73.5	58.4	75.7	73.1	56.5	80.5	13864.03
150	72.1	76.2	62.5	77.1	73.1	58.1	82.9	13864.03
165	73.5	76.4	69.5	79.8	73.2	59.4	85.3	13663.10
180	76.3	79.8	78.2	82.7	73.0	60.1	86.1	14064.96
195	83.4	85.2	85.1	86.4	73.1	61.3	88.2	13864.03
210	85.1	86.4	86.1	87.2	72.9	62.1	88.6	14265.89

2) Influences of cold water inlet temperature on the discharging only process

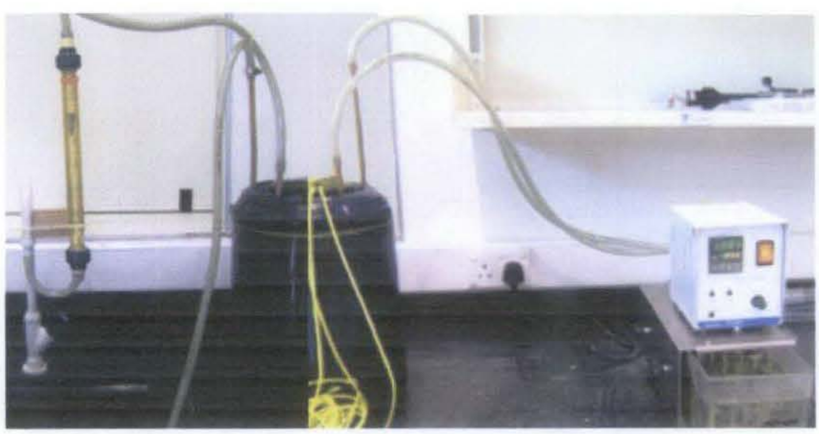
	23.5 'C					
t(min)	TC2	TC3a	TC3b	TC4	Tout	Q'
0	86.1	86.1	86.1	86.1	24.5	2009.28
15	70.1	70.8	76.5	72.5	28.5	10046.40
30	57.8	59.0	65.4	59.3	28.6	10247.33
45	52.0	53.4	62.7	56.5	28.6	10247.33
60	50.9	52.3	61.8	55.1	28.5	10046.40
75	49.0	50.3	61.4	53.2	28.4	9845.47
90	47.1	48.0	60.8	51.2	28.3	9644.54
105	43.5	44.2	58.6	46.5	28.4	9845.47
120	41.6	43.6	56.3	45.1	28.3	9644.54
135	41.1	42.8	54.9	44.1	28.4	9845.47
150	40.5	41.6	53.6	43.1	28.5	10046.40
165	38.5	39.8	49.5	41.5	28.4	9845.47
180	37.1	38.4	48.1	41.1	28.5	10046.40
195	35.2	36.1	46.8	38.7	28.5	10046.40
210	35.0	34.5	45.2	37.2	28.4	9845.47

APPENDIX G

DSC machine



Falling ball heater and pump (240 V, 50 Hz)



Experimental setup: To test the performance of designed system