Design and Fabrication of a Lab Scale Thermal Energy Storage in Ice

by

Dee Boon Huei

Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

05/12/08

(Dr. Chalilullah Rangkuti)

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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.

DEE BOON HUEI

ABSTRACT

Thermal energy storage (TES) is a key technology for energy conservation of great practical importance. TES is the best method for correcting the mismatch between the supply and demand of energy. Universiti Teknologi PETRONAS did not have any lab equipment for study of cold thermal energy storage (CTES). Additional equipment can be added on to the current available water chiller unit in the lab to demonstrate the application of CTES. This project targeted to design and fabricated a lab scale CTES using phase change material (PCM), ice. This project studied the water chiller unit available in the lab and thermal properties of water and ice. CTES was designed according to the recommended capacity and fulfilled the design consideration requirement. Studies compared several types of thermal energy storage methods exist in the market and chosen encapsulated ice storage as the most suitable for lab demonstration which is also widely used in the world. Modifications were done on initial design to compromise and best suit with the current water chiller design and availability of material. Prototype fabrication was done by selecting the appropriate fabrication process, cost effective and ready market available material. Testing and analysis were carried out to evaluate the prototype performance. This project produced a 3700kJ insulated encapsulated ice storage type CTES with 88% efficiency for students as an additional lab equipment for study of CTES.

ACKNOWLEDGEMENT

I would like to thank my supervisor, Assoc. Prof. Dr Chalilullah Rangkuti who proposed this project title and guided me throughout the project. Whenever I having difficulty or got stuck in the progress, I would like to consult Dr. Chalil by having a discussion session and got the problem solved together. Dr. Chalil also recommended me some journals and books which are helpful in completing the study for this project.

I would also like to thank Mr. Zailan, lab technician for mechanical department, who had offered me every lab equipments and materials that I needed for this project. He also suggested me some ideas which will make this project simpler to fabricate but feasible. He also gave me the time flexibility to conduct my experiment in the lab. Without his assistance, I could not complete my project on schedule.

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Not to forget my parents who gave me a lot of support, financially and spiritually. I had my father's assistance in completing the fabrication of the prototype. His hand on experience suggested me the best way to complete the fabrication process.

Last but not least, thank you to everyone who had directly and indirectly assisted me in this project. I appreciate your kindness and assistance. Thank you.

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CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Cold thermal energy storage or CTES is advance energy storage for thermal applications such as air conditioning and room cooling. CTES is the best method for correcting the mismatch between the supply and demand of energy. CTES can be used to store cold energy via phase change material which can reduce the size of the storage compare to a single phase material. However, UTP is lack of CTES equipment for student study and experiment purpose. An appropriate CTES equipment will demonstrate to student how CTES been applied in the real life application.

1.2 Significance of Study

The study applies the knowledge and theory of thermodynamics, heat transfer, air conditioning and refrigeration. The properties and thermal energy of a phase change material, which is ice in this study, will be investigated. Study will find the most appropriate and cost effective design and materials for thermal energy storage in ice. It can be used in further chiller experiment and scale up for commercial used.

1.3 Objectives

- To design a lab scale phase change material (ice) thermal energy storage
- To develop and test the performance of thermal energy storage

1.4 Scope of Work

- Study on thermal properties of water and ice, water chiller available in lab
- Design the thermal energy storage

Choose the suitable storage method, design of storage, and calculate the possible capacity ice storage through the capacity output from lab water chiller equipment.

- Fabrication of the thermal energy storage equipment

Initial design can be modified to suit the water chiller, material availability and cost factor. The CTES will be fabricated by using combination of several processes, such as cutting and drilling. Insulation is required to reduce the energy loss from CTES and heat gain from surrounding into CTES.

Include sensors or probes into the system for monitoring if necessary.

- Thermal energy storage equipment testing

Data analysis must be carried out on the prototype to calculate its efficiency and performance. Costing analysis based on predefined situation will be evaluated.

CHAPTER 2
LITERATURE REVIEW

2.1 Heat and Thermal Properties of Water

This section studies the heat and thermal properties for water and ice. As this project is using water to form ice as phase change material, literature review is important to find out the theory and background for this project.

Heat (Q) is a thermal energy which is also the energy of a statistical system of particles randomly colliding with each other. It has dimensions of energy, but it is not a state variable. Temperature depends on the past history of the system. A system can be isothermally expanded by adding heat, or decrease its pressure slowly without addition of heat remaining the same final pressure, temperature and volume [1].

The heat energy of a system can be written as the product of two state variables which are the temperature and entropy (S) [1]. Entropy is a measure of the degeneracy of a system. Entropy is an intrinsic state variable. It never decreases in a completely isolated system. Since degeneracy is associated with randomness, it is true that entropy is also a measure of the disorder of a system [1].

Heat is most often measured in calories (cal). A calorie is 4.186 J which is the amount of heat required to raise one gram of water. The temperature of a substance changes as heat energy is added to it. The heat capacity (C) of an object is the ratio of change in heat to change in temperature, and the specific heat (c) of a substance is the heat capacity per unit mass [1].

$$Q = mc\Delta T$$

The specific heat of water is 1 cal / g K by definition. The specific heat of a substance is defined at the amount of heat that must be absorbed or lost for 1 g of that substance to change its temperature by 1° K [1]. The heat change per unit mass required for a phase transition is called the latent heat (L).

$$Q = mL$$

The heat added or lost during a phase change does not affect the temperature during the phase change.

Phase Change Diagram for Water

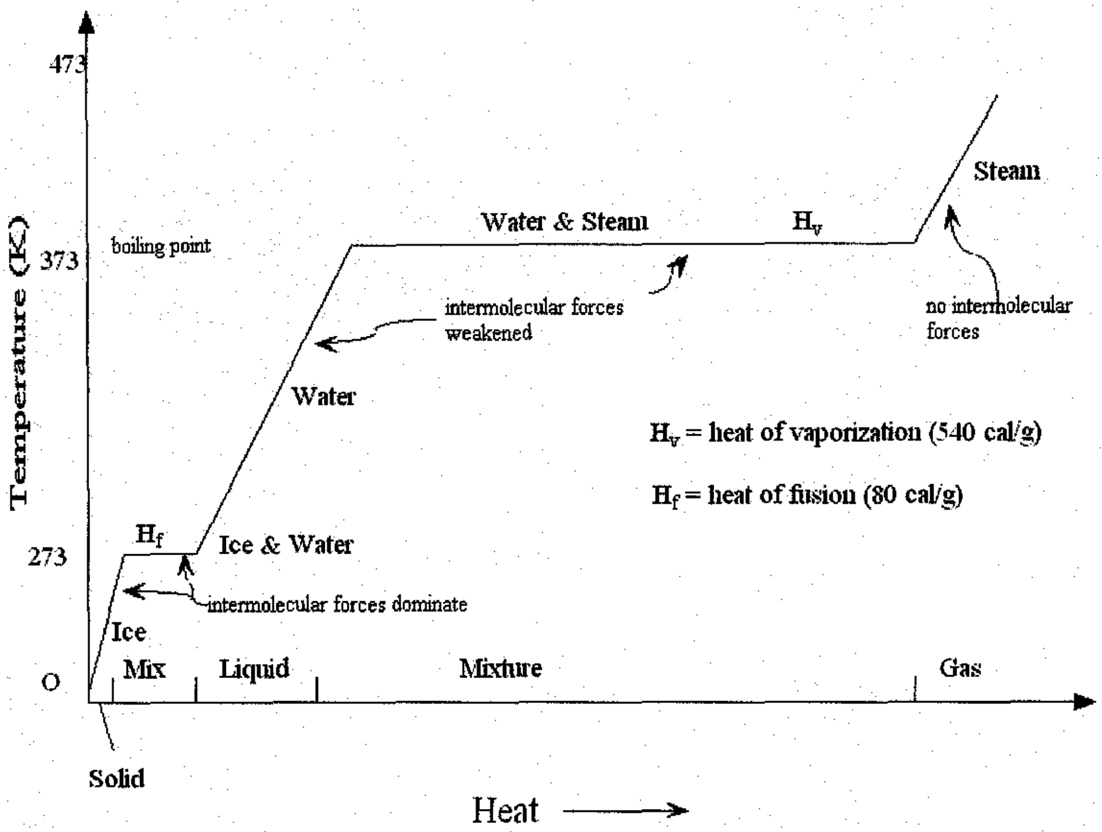

Figure 1: Phase change diagram for water [2]

Thermal energy quantities differ in temperature. Latent heat is associated with the changes of state or phase change of material. Many cooling TES systems use chilled-water systems to transfer the cooling capacity from the storage to the building air-distribution system. Ice systems use smaller tanks and offer the potential for the use of low temperature air systems, but require more complex chiller systems. Ice CTES systems use the latent heat of fusion of water which is around 335kJ/kg to store cooling capacity. To store energy at the temperature of ice requires refrigeration equipment that provides changing fluids at temperatures below the normal operating range of conventional air conditioning equipment. [3, pg. 166]

The ice produced through CTES can be used on cold air distribution in air conditioning system. Advantages of cold air distribution and CTES including reduce the peak electrical demand and lower capital cost as CTES require lesser volume to meet a cooling load relative to conventional systems, the mechanical system can be downsize and satisfy the same cooling load as conventional system [3, pg. 203]. Reduced mechanical system lowers the operating costs, and increased usable space. This would indirectly increase the product marketability.

2.2 Modular Ice Storage for Glycol System

This section studies the current available ice storage for glycol system. Study focuses on the two most popular and widely used storage system, modular and encapsulated ice storage.

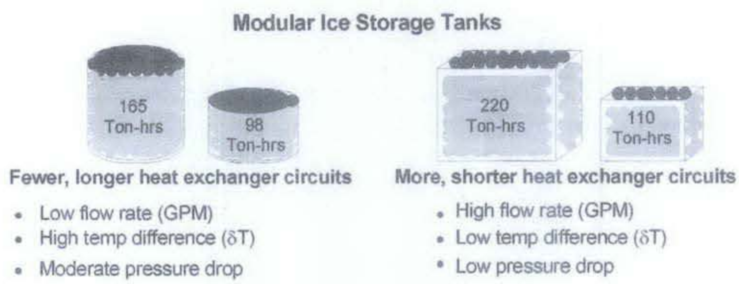

Figure 2: Modular ice storage tanks [3, pg. 186]

Modular ice storage tanks can be constructed in many sizes or shapes. Two common designs are cylindrical polyethylene tank with circular polyethylene heat exchangers and rectangular metal tank with polypropylene heat exchanges. In both modular ice storage designs, the heat exchanger separates the glycol solution from the water in the tank. The water is frozen by circulating -6C to -4C glycol through the heat exchanger.

The differences in tank geometry and heat exchanger design pose different problem. The shape of circular ice storage tanks allows heat exchangers with fewer circuits of longer length, and permits freezing or melting at lower flow rates and higher temperature differences. Low flow rate freeze cycles enable the designer to better match the capacities of the storage tanks and chiller. [4]

Rectangular tank incorporate high flow rate, low pressure drop heat exchangers that operate with a lower temperature difference during freezing [4]. These characteristics not only place additional design constraints on chiller selection, but require individual flow balancing for each storage tank.

2.3 Encapsulated Ice Storage for Glycol System

Encapsulated ice offers a wide degree of latitude in the design of the ice containment vessel. Encapsulated ice designs store the water to be frozen in a number of plastic containers. These containers may be thin and rectangular, spherical or annular. Number of containers or units required depends on their individual storage capacities.

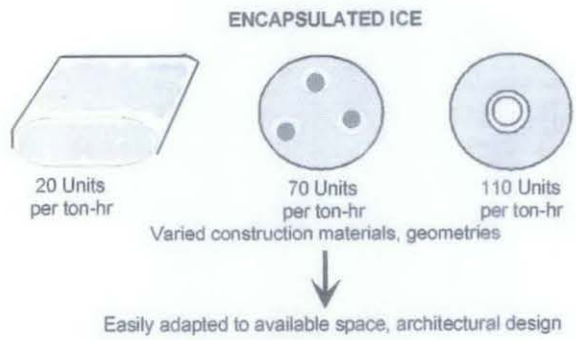

Figure 3: Encapsulated ice storage tanks [3, pg. 186]

The greatest advantage for encapsulated ice storage glycol system is the degree of application flexibility. Storage system can be customized to the application. Encapsulated ice units consists of plastic containers filled with ionized water an ice nucleating agent [3, pg. 185]. These primary containers are placed in storage tanks. In tanks with spherical containers, water usually flows vertically through the tank and in tanks with rectangular containers, water flows horizontally.

Glycol solution is cooled to -4 ° C to -3 ° C by a liquid chiller, and circulates through the tank and over the outside surface of the plastic containers, causing ice to form inside the containers. Plastic containers must be flexible to allow for change of shape during ice formation, the spherical type has preformed dimples in the surface, and the rectangular type is designed for direct flexure of the walls. During discharge, coolant flows either directly to the system load or through a heat exchanger, thereby removing heat from the load and melting the ice within the plastic container. As ice melts, the plastic containers return to their original shape.

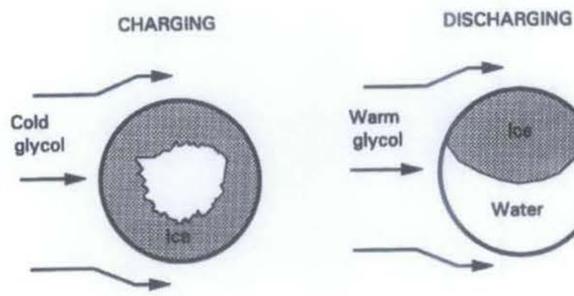

Figure 4: Encapsulated ice balls [6]

2.4 Ice Thermal Storage Control Strategies

This section studies the common control strategies in applying CTES for cold air distribution. Different management strategy produces different result thus different operating cost applied. Ice thermal storage systems can be operated in a variety of ways, with the major control strategies are full storage, partial storage and demand limited storage.

2.4.1 Full Storage

Under a full storage control strategy the total daytime cooling load is shift to the nighttime, with the chillers producing an ice store during the period when off-peak electricity charges apply. During the daytime the ice store is discharged to meet the building or process cooling load. While being the most effective of all the control strategies in terms of energy costs, full storage has the major drawback that the ice store and chiller plant required are much larger than for the other control strategies. Due to its prohibitively high capital cost full storage is rarely used. [5, pg.206]

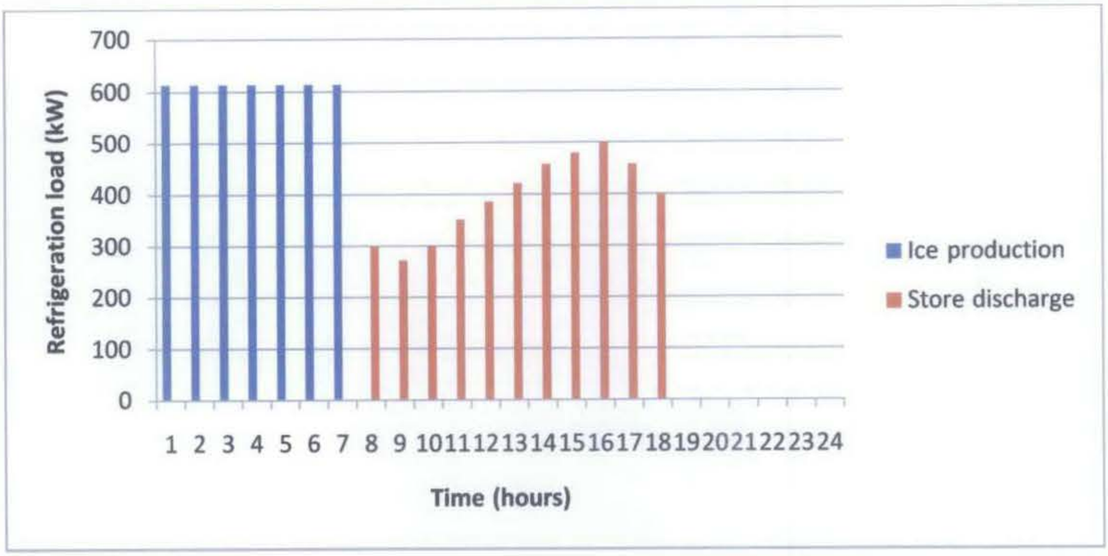

Figure 5: Full storage strategy [5, pg.206]

2.4.2 Partial Storage

Partial storage is the collective term given to those ice storage control strategies which require both the chiller plant and the ice store to operate together to satisfy the daytime cooling load. During periods in which the building or industrial process experiences a cooling load, the ice store and the chiller plant work simultaneously to satisfy the cooling load. The advantage of partial storage is that both the store and the chiller plant are substantially smaller than would be the case for a full storage installation and thus the capital cost is lower. This makes partial storage a very popular option. The umbrella term partial storage can be sub-divided into two separate and distinct sub-strategies, namely chiller priority and store priority [5, pg.206].

2.4.3 Chiller Priority Control Strategy

Under a chiller priority control strategy the refrigeration plant runs continuously through both the ice production and the store discharge periods. During the daytime the refrigeration plant carries out the base-load cooling and the ice store is used to top-up the refrigeration capacity of the chiller plant, which would otherwise be unable to cope with the peak demand. Under a chiller priority strategy it is possible to achieve reductions in the region of 50 % in chiller capacity when compared with a conventional refrigeration installation [5, pg.207]. The capital cost of installing an ice store can therefore be off-set against the capital cost saving arising from the reduction in chiller capacity.

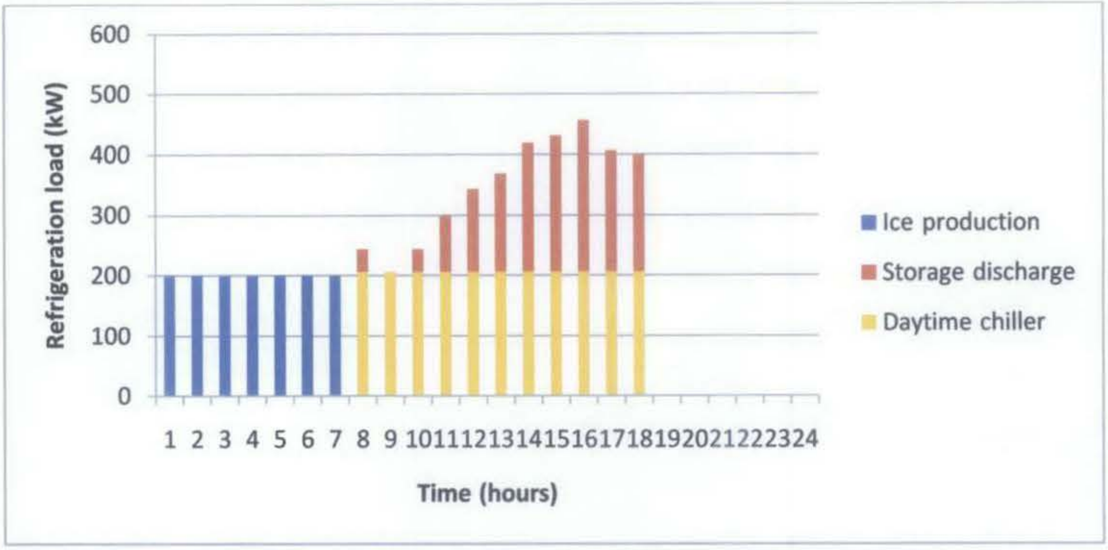

Figure 6: Chiller priority strategy [5, pg.207]

2.4.4 Store Priority Control Strategy

The philosophy behind the store priority control strategy is the opposite of the chiller priority strategy. Under a store priority strategy the ice store is given priority over the chiller during the daytime. The objective of this strategy is to minimize the operation of the refrigeration plant during periods when electricity prices are high [5, pg.207]. The refrigeration chiller is only used to top-up the refrigerating energy released by the ice store.

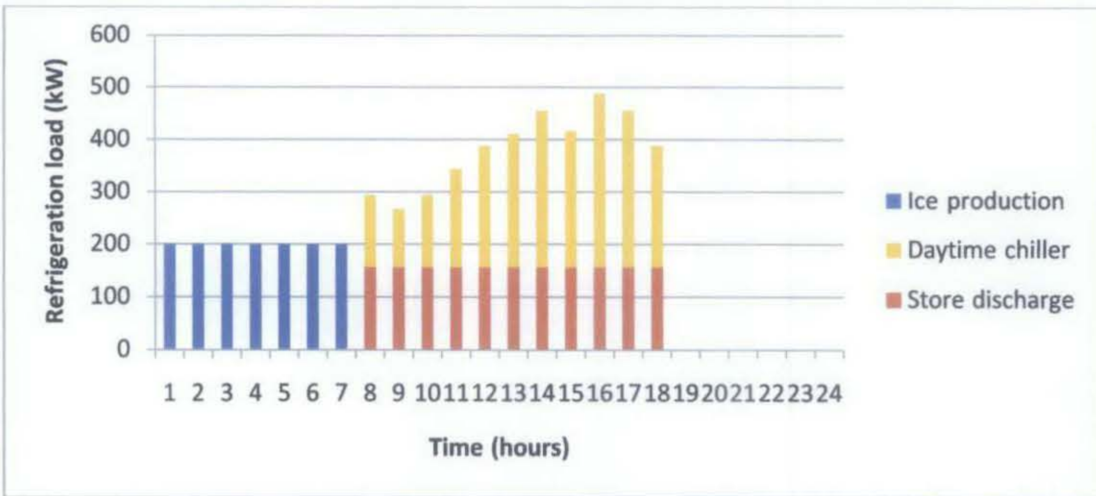

Figure 7: Store priority strategy [5, pg.207]

2.4.5 Demand Limited Storage

The object of a demand-limited control strategy is to limit peak electrical demand by shifting the cooling load out of periods in which the peak demand naturally occurs [5, pg.207]. This greatly reduces the overall maximum demand of the installation and improves the overall load factor of the building, putting the operators in a stronger position when it comes to negotiating electricity supply contracts with the utility companies.

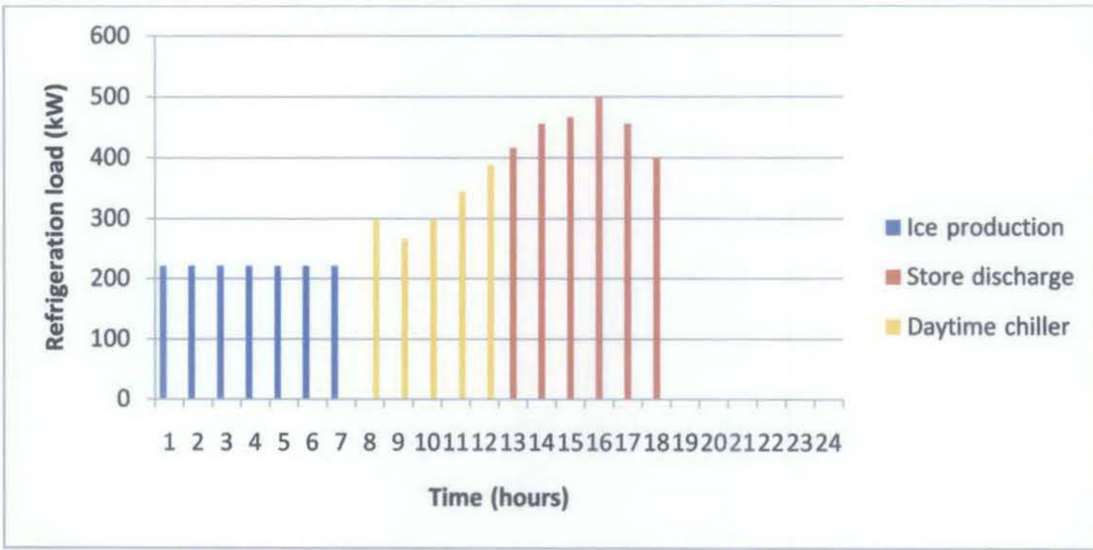

Figure 8: Demand limiting strategy [5, pg.207]

From the literature review, a draft design based on the ideas reviewed was created. Available ice storage system was evaluated by the weight percentage to determine the best method for this project. Design was based on mathematical calculation. The design will be discussed in the discussion chapter. Costing analysis was evaluated based on predefined control strategy.

CHAPTER 3
METHODOLOGY

In Final Year Project II, fabrication, testing and documentation were done. The difficulties in Final Year Project II are to obtain material from available market and fabricate it into a working prototype. Testing and cost analysing also were carried out upon completion of the project.

3.1 Designing

The design of the project was drafted on papers initially. Design was based on theoretical engineering calculation. Capacity of water chiller, time constraint for freezing determined the volume or size of the lab scale TES. Design then transferred into technical engineering drawings and got approved by supervisor prior proceed to the next step. Study on material selection was carried out to choose the most suitable and cost reasonable material.

3.2 Fabrication

Once materials were collected from supplier, fabrication was started in the lab. Prototype was fabricated according to the technical drawing. Sockets were installed to ensure convenience in connecting the prototype to the lab water chiller unit. Temperature probes, pumps, valves and piping were installed on the prototype.

3.3 Testing

Prototype was tested by connecting the prototype to the water chiller available in the lab. Data measured were recorded for analysis and discussion purpose. Testing procedures were documented for references. As this project tailored for student lab experiment used, series of recommended experiments, procedures and tables were prepared for this purpose.

3.4 Analysis and Discussion

Data recorded were analyzed for its efficiency. Costing analysis was carried out to determine the saving and cost effectiveness based on operation. Discussion was done to look for any possibilities which may improve the current prototype performance.

3.5 Documentation

Researches and results were documented for references. Reports are fully documented and hard bounded as requirement.

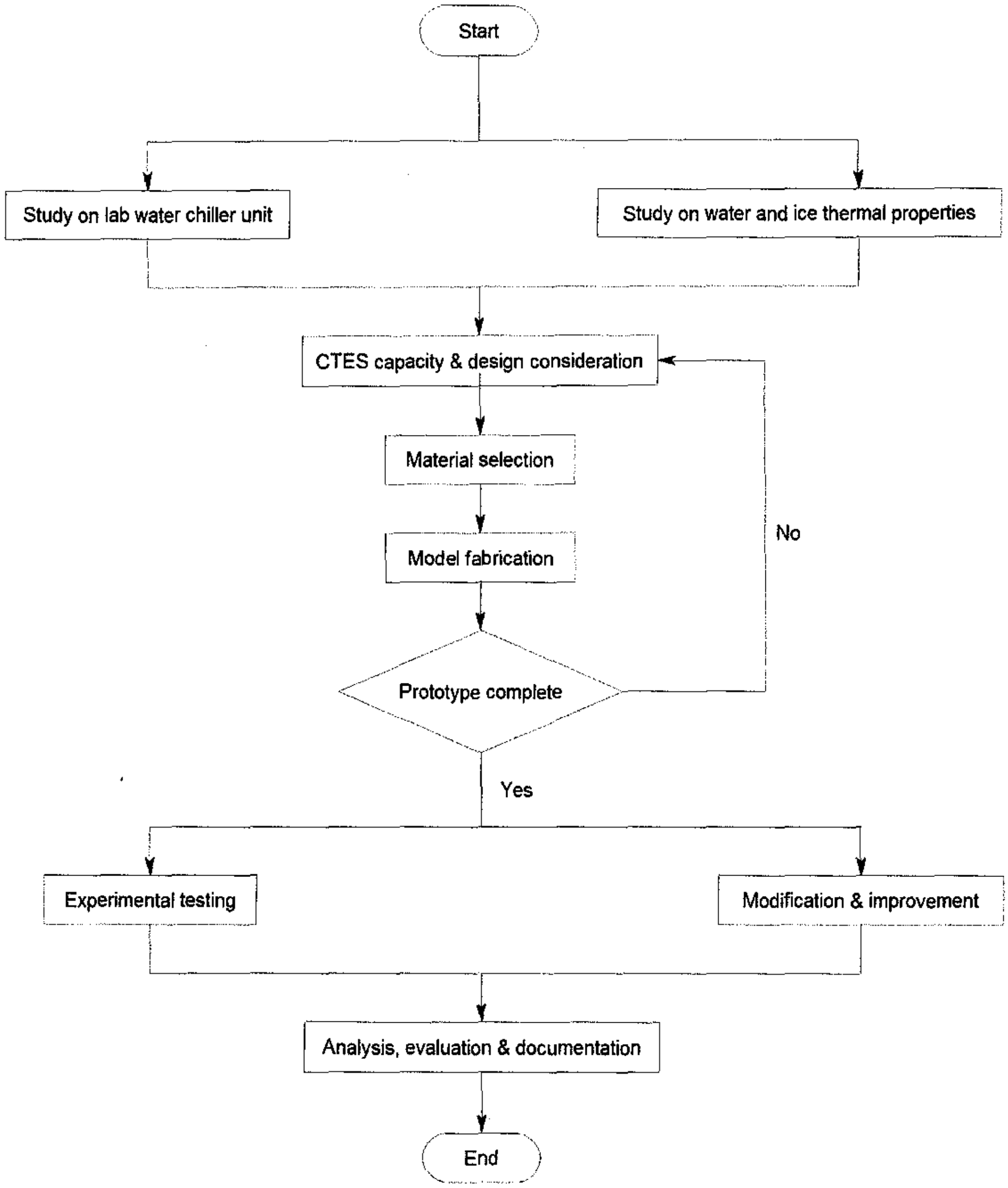

Figure 9: Flow chart for methodology

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Laboratory Water Chiller

The water chiller unit available in UTP laboratory is the Water Chiller Trainer 812 manufactured by P. A. Hilton Ltd. from England. The chiller is using R-134a as the refrigerant. The function of a water chiller is to remove heat from glycol solution to the refrigerant, then to the condensate water.

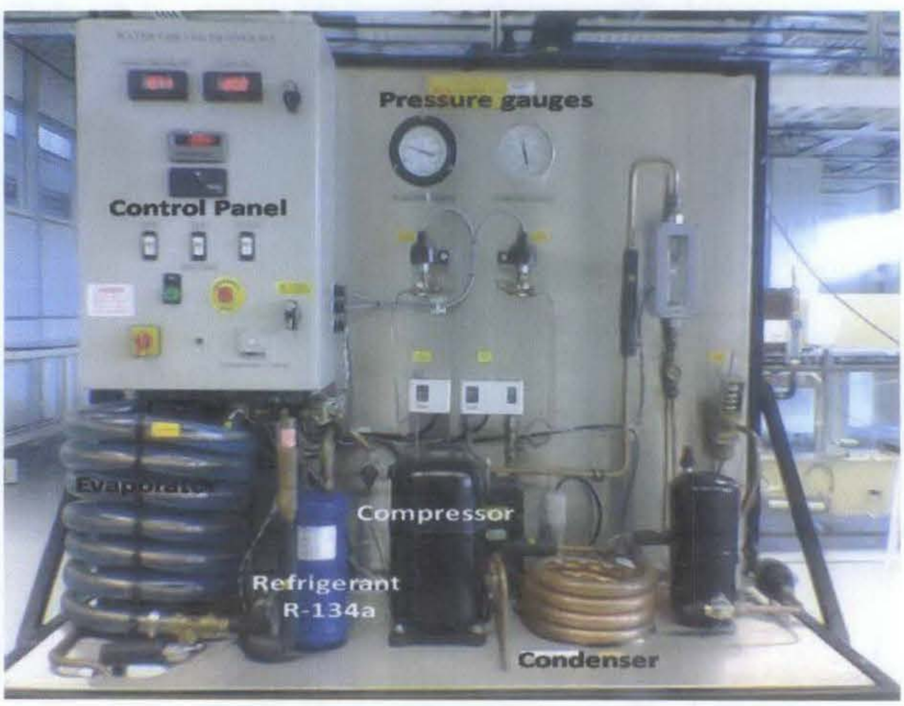

Figure 10: Laboratory water chiller

Specification

- Compressor: Hermetic - 732W
- Condenser: Coaxial type
- Evaporator: Coaxial type

- Refrigerant: R134a
- Safety devices: Thermostats, pressure control, emergency stop and earth leakage circuit breaker
- Measuring equipment: Flow meters, pressure gauges and thermo-couples
- Voltage: 380V 3-Phase 59Hz + Earth

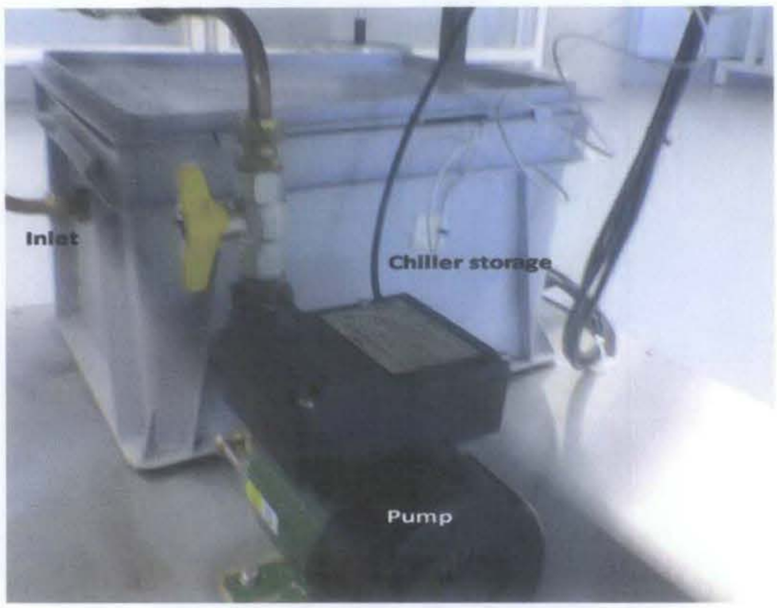

Figure 11: Chiller storage and pump

Figure 12: Evaporator system

The coolant storage contains water mix with anti freeze coolant which is ethylene glycol. Ethylene glycol prevents water from frozen which may cause the pump to malfunction. In this project, we are going to utilize the chilled glycol solution from the chiller storage to produce ice as thermal energy storage.

Initially, refrigerant (R-134a) will enter the compressor at superheated state. The refrigerant is being compressed by compressor to raise its temperature and pressure. Refrigerant then enter the condenser, where the condensing water (tap water) will also entering the condenser and remove heat from refrigerant. Refrigerant exits from the condenser as a compressed liquid. Refrigerant will enter the expansion valve to a lower temperature and become a mixture of liquid and gas. This mixture will enter the evaporator. Glycol solution from the chiller storage tank will be pumped into the evaporator. In evaporator, glycol solution lose heat to the refrigerant, in other words, the refrigerant absorb heat from the water and exit the evaporator as superheated state. Chill glycol solution exit the evaporator and return to the storage tank at lower temperature.

4.2 Water Chiller Experiment

4.2.1 Objectives

- Determine the cooling capacity and efficiency of water chiller
- Determine the lowest temperature of chill glycol solution produced and time required
- Record all parameters during the running of water chiller

4.2.2 Procedure

1. Water chiller was started according to the operating procedure
2. No additional equipment or application attached, heaters were switched off

Note that if no heat load as applied for a long period the water temperature can reach a low values and even with a 30% glycol mixture it is possible for the evaporator to freeze. If this occurs it will be necessary to turn off the unit and allow the evaporator to defrost.

3. Condenser water flow was set to 300g/s
4. Condenser pressure was set to 500kN/m^2
5. Calculate the refrigerating effect from the data collected

4.2.3 Results

Table 1: Water Chiller Refrigeration Data

Parameter	Units	
Compressor suction temperature	°C	8.4
Compressor discharge temperature	°C	59.0
Condensed liquid temperature	°C	20.3
Evaporator inlet (refrigerant)	°C	-5.0
Evaporator outlet (refrigerant)	°C	6.4
Evaporator pressure regulator outlet	°C	6.5
Condenser cooling water inlet	°C	15.9
Condenser cooling water outlet	°C	18.1
Evaporator water inlet	°C	7.6
Evaporator water outlet	°C	5.4
Condenser pressure	kN/m^2	460
Evaporator pressure	kN/m^2	120
Refrigerant flow rate	g/s	12
Condenser water flow	g/s	295
Evaporator water flow	g/s	199

Initial temperature of chill glycol solution: 21.0°C

Final temperature of chill glycol solution: -8.0°C

Lowest temperature of chill glycol solution achieved: -8.0°C

Time taken to achieve lowest temperature of chill glycol solution: 28mins

Volume of chill glycol solution: 0.37m x 0.27m x 0.18m = $0.018m^3$ = 18litres

4.2.4 Calculations

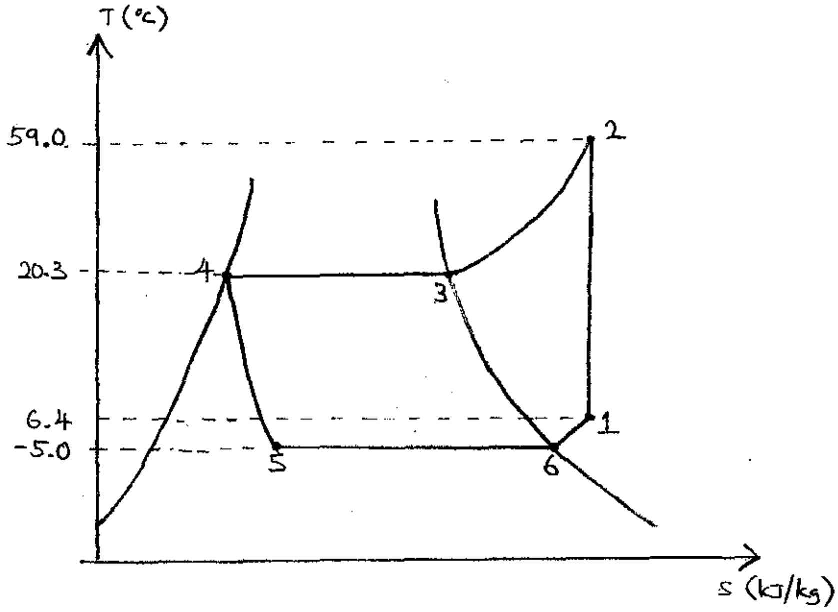

Figure 13: T-s diagram for water chiller

Assuming compression of the refrigerant is isentropic,

$h_6 = 244.31$kJ/kg $\quad$ $h_4 = h_5 = 77.26$kJ/kg $\quad$ $h_3 = 258.36$kJ/kg

$h_1 = h_6 + c_{pv}(T_1 - T_6) = 244.31 + 0.851(6.4 - (-5.0)) = 254$kJ/kg

$h_2 = h_3 + c_{pv}(T_2 - T_3) = 258.36 + 0.851(59.0 - 20.3) = 291.2937$kJ/kg

Refrigerating effect (R-134a)

The calculation below is the refrigerating effect done by the R-134a refrigerant

$\dot{Q}_{in} = \dot{m}(h_1 - h_5)$

$\dot{Q}_{in} = (0.012\text{kg/s})(60\text{s}/1\text{min})(254-77.26)\text{kJ/kg}(1\text{ton}/210\text{kJ/min})$

$\dot{Q}_{in} = 0.846\text{ton} = 177.6528\text{kJ/min}$

The above calculation is the refrigerating effect done by the R-134a refrigerant

Refrigerating effect (Glycol solution)

The calculation below is the actual refrigerating effect received by 18kg of glycol solution from 21.0°C to -8.0°C within 28 minutes.

m = 18kg of glycol solution

c = 0.902Btu/lb. °F (Taken Ethylene Glycol solution 30% at 26.7°C from table 5)

c = 0.902 x 4186.8 J/kg.K = 3776.49 J/kg.K (1 Btu/lb°F = 4,186.8 J/kg.K)

$\Delta T = 294K - 265K = 29K$

$Q = mc\Delta T$

$Q = 18kg \times 3.77649\ kJ/kg.K \times 29K$

$Q = 1971.328kJ$

$\dot{Q} = 1971.328kJ/28minutes = \underline{70.405kJ/min}$

Water chiller efficiency

$$\eta = \frac{output}{input} = \frac{Refrigerant\ effect\ (glycol)}{refrigerating\ effect\ (R-134a)}$$

Chiller efficiency, $\eta = 70.405/177.6528 = 0.396$ or <u>39.6%</u>

As water chiller is not insulated, only 39.6% of refrigerating effect was received by the glycol solution, the remaining was loss to the surrounding.

In this project, water is filled into encapsulated storage (bottle) and allows it to be frozen, storing the cold energy from the water chiller. Calculate the maximum mass and volume of water given an hour time frame.

Q_{in}= 70.405kJ/min

Q removed in an hour= 70.405kJ/min x 60min= 4224.30kJ

4224.30kJ= m(cΔT+latent heat)

m=4224.30kJ/ (4.184kJ/kg.K * 25K+334kJ/kg)

m= 9.631kg= <u>9.631litres</u>

Therefore, the total volume of water can be frozen in an hour by water chiller is 9.63litres. However, this calculation does not include losses in the piping, thermal conductivity, storage and efficiency.

4.3 CTES in Chill Glycol Solution

The water in the storage tank is re-circulated and mixed with 30% ethylene glycol. Ethylene glycol is an odourless, hygroscopic liquid. Ethylene glycol based water solutions are common in heat-transfer systems where the temperature in the heat transfer fluid can be below 0°C especially cooling systems where the fluid operates with temperatures below the water freezing point. Therefore, it is the most common anti freeze solution for standard cooling applications.

The low volatility and the high water solubility of ethylene glycol have led to its widespread use in antifreeze solutions, de-icing fluids, refrigerants and heat transfer agents. Ethylene glycol has low volatility and low molecular weight. It is therefore widely used in automobile antifreeze and coolants.

The viscosity, specific heat capacity, and specific weight of water and ethylene glycol mixture solution vary significantly with the percentage of ethylene glycol and the temperature of the fluid. The properties are different from clean water. Heat transfer systems with ethylene glycol should be calculated thoroughly for the actual temperatures and solutions.

In this project, the chill glycol solution is to be used as refrigerant in the designed cold thermal energy storage for ice. Chill glycol solution will be circulated into the thermal energy storage, cooling down water into ice. The cooling capacity can be stored in the ice. Ice act as a reservoir of cool material which is tapped when necessary to provide cooling capacity.

Table 2: Freezing point of ethylene glycol [7]

Freezing Point								
Ethylene Glycol Solution (% by volume)		0	10	20	30	40	50	60
Temperature	(°C)	0	-3	-8	-16	-25	-37	-55

Table 3: Boiling point of ethylene glycol solution [7]

Boiling Point								
Ethylene Glycol Solution (% by volume)		0	10	20	30	40	50	60
Temperature	(°C)	100	101.1	102.2	104.4	104.4	107.2	111.1

Table 4: Specific gravity of ethylene glycol [7]

Specific Gravity- SG -							
Temperature	Ethylene Glycol Solution (% by volume)						
(°C)	25	30	40	50	60	65	100
-40	1)	1)	1)	1)	1.12	1.13	1)
-17.8	1)	1)	1.08	1.1	1.11	1.12	1.16
4.4	1.048	1.057	1.07	1.088	1.1	1.11	1.145
26.7	1.04	1.048	1.06	1.077	1.09	1.095	1.13
48.9	1.03	1.038	1.05	1.064	1.077	1.082	1.115
71.1	1.018	1.025	1.038	1.05	1.062	1.068	1.049
93.3	1.005	1.013	1.026	1.038	1.049	1.054	1.084
115.6	2)	2)	2)	2)	2)	2)	1.067
137.8	2)	2)	2)	2)	2)	2)	1.05

1) Below freezing point 2) Above boiling point

Table 5: Specific heat capacity of ethylene glycol [7]

Specific Heat Capacity - cp - (Btu/lb. °F)							
Temperature	Ethylene Glycol Solution (% by volume)						
(°C)	25	30	40	50	60	65	100
-40	1)	1)	1)	1)	0,68	0.703	1)
-17.8	1)	1)	0.83	0.78	0.723	0.7	0.54
4.4	0.913	0.89	0.845	0.795	0.748	0.721	0.562
26.7	0.921	0.902	0.86	0.815	0.768	0.743	0.59
48.9	0.933	0.915	0.875	0.832	0.788	0.765	0.612
71.1	0.94	0.925	0.89	0.85	0.81	0.786	0.64
93.3	0.953	0.936	0.905	0.865	0.83	0.807	0.66
115.6	2)	2)	2)	2)	2)	0.828	0.689
137.8	2)	2)	2)	2)	2)	2)	0.71

1) Below freezing point 2) Above boiling point

1 Btu/ (lbm°F) = 4,186.8 J/ (kg K) = 1 kcal/ (kg°C)

4.4 Designs

4.4.1 Initial Design

In the initial design stage, the most suitable ice storage method was determined. Based on the selected method, a schematic diagram was drawn, as shown in appendix 1. Appendix 1 shows the schematic diagram of how the connection between the water chiller and thermal energy storage. Components in CTES such as storage tank size, piping connection and circulation flow rate were determined based on mathematical calculation.

Ice storage method

To determine the suitable storage method for lab scale CTES, comparison is made between modular ice storage and encapsulated ice storage. Each factor was evaluated based on its weight percentage. Factors evaluated are flexibility, simplicity, cost, and piping installation.

Table 6: Design decision weight table

Factor	Weight	Modular Ice Storage	Encapsulated Ice Storage
Application flexibility	0.3	2	4
Simplicity	0.25	3	5
Cost	0.25	2	3
Piping	0.2	1	4
Total Weight		2.05	**4**

The design decision weight table concluded the best design for this project, which is the encapsulated ice storage system. This system has advantages of flexibility and simplicity compare to the modular ice storage system.

Encapsulated ice storage size

Encapsulated ice storage or bottles determine the capacity of the CTES. As this project aims to produce a lab scale prototype for student experiment purpose, the capacity was fixed in such way it can be fully charged in an hour time. From section 4.2.4, it was calculated that the water chiller able to freeze 9.63kg of water in an hour time frame. For larger surface area, more bottles are recommended. Recommended volume for each bottle is 100ml, therefore required 90 bottles for a total of 9 litres water. If a sphere shape bottle is used, the cost can be minimized as sphere encloses the largest volume among all closed surfaces with a given surface area. 10% extra volume was added for ice expansion allowance during freezing.

Volume for sphere: $\frac{4}{3}\pi r^3$ = 110cm^3

R = $\sqrt[3]{110/\frac{4}{3}\pi}$ = 2.97cm = 29.7mm

D = 29.7mm x 2 = <u>59.4mm</u>

The sphere bottle diameter should be at least 60mm for ice expansion allowance.

Storage tanks size

The storage tank should be able to store all the bottles and provide allowance for gaps between bottles, as well as overflow protection.

Volume occupied for bottles: 9 litres or 9000cm^3

Additional 30% space for allowance: 9000 x 130/100 = 11700cm^3

Circulation flow rate

A pump is required for circulate the glycol solution from chiller storage tank to CTES tank. The recommended flow rate is 200g/s or equal to 12L/min. This flow rate is identical as the flow rate of glycol solution into the chiller evaporator. Glycol solution circulation is important to transfer heat load from CTES to water chiller during charging and heat load from chiller storage to CTES during discharging.

Current flow rate via chiller storage drain valve: 1.90 l/min or 3.17x10^{-5} m^3/s

Q = AV

Chiller storage drain valve inner diameter: 10mm or 0.01m

A = πd^2/4 = π x 0.01^2/4 = 7.85x10^{-5} m^2

V = Q/A = 3.17x10^{-5} m^3/s / 7.85x10^{-5} m^2 = 0.404m/s

Recommended flow rate = 200g/s or 2x10^{-4} m^3/s

A = Q/V = 2x10^{-4} m^3/s / 0.404m/s = 4.95x10^{-4} m^2

d = $\sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(4.95\times10^{-4})}{\pi}}$ = 0.025m = 25mm

The chiller storage outlet (drain valve) and the CTES inlet should have a diameter of 25mm.

4.4.2 Final Design

Installation schematic is shown in appendix 2. In appendix 1, CTES tank is connected to the chiller storage. Chiller unit will remove heat from glycol solution which stored in the chiller storage. Glycol from chiller storage will be delivered to the CTES tank, cooling and freezing bottles inside CTES tank then return to the chiller storage by the assistance of a circulation pump. The initial design was modified to compromise the equipments limitation, cost and market availability.

Figure 14: Connection from chiller storage to CTES

In appendix 2, the CTES tank inlet is located at the bottom of tank. Glycol solution is drawn out from the chiller storage tank via drain valve which is located at the bottom of the tank. There are 60mm height different between the drain valve of chiller storage tank and CTES tank inlet valve. The beauty of this design is to utilize the concept of gravity feed. Connecting both systems in this way will ensure the glycol level in both systems will remain the same. Therefore precise flow control is not necessary, thus reduce the project cost.

Circulation pump used is a submerged type pump. Pump was installed as closed as possible to the glycol water surface level, at the opposite side from the inlet to encourage better water circulation in the CTES tank. This configuration is proven the best after temperature was found mostly even in every corner. Venturi function from the pump is utilized to enhance the circulation of glycol solution inside the

CTES tank, especially at the surface area. The circulation flow rate however is throttled at 1.90L/min, due to the output diameter of drain valve at chiller storage tank.

4.5 Material Selection and Fabrication

4.5.1 Cold Thermal Energy Storage Tank

Polystyrene cooler box was selected as the CTES tank. The cooler box is available in very low cost, yet provides a basic insulation and storage for chilled glycol solution. In this project, two cooler boxes are used.

Cooler box A

- Outside dimension: 620mm (L) x 495mm (W) x 330mm (H)
- Inner dimension: 556mm (L) x 435mm (W) x 300mm (H)
- Cover: 35mm (T)

Cooler box B

- Outside dimension: 489mm (L) x 365mm (W) x 310mm (H)
- Inner dimension: 437mm (L) x 313mm (W) x 280mm (H)
- Cover: 30mm (T)

Figure 15: Polystyrene cooler box

The current setup utilizes both different in size polystyrene cooler box. The smaller box will be the main tank and placed inside the larger box. This can greatly increase insulation and prevent heat gain from surrounding into glycol solution and encapsulated ice storage. Rock wool insulation between the boxes will be introduced to further enhance insulation. Appendix 3 is the technical drawing for CTES tank.

4.5.2 Encapsulated Ice Storage Container

Encapsulated ice storage system has advantages of flexibility and simplicity compare to the modular ice storage system. Water as phase change material (PCM) is filled inside the plastic containers which can be placed in any shape tank to enable the chill glycol solution to pass around them in order to provide heat exchange capability.

The primary encapsulated ice storage is the PET ball type bottle manufactured in 200cm^3 volume. It can be stacked on the top of each other within the tank or randomly placed in order to provide centralized thermal energy storage concept.

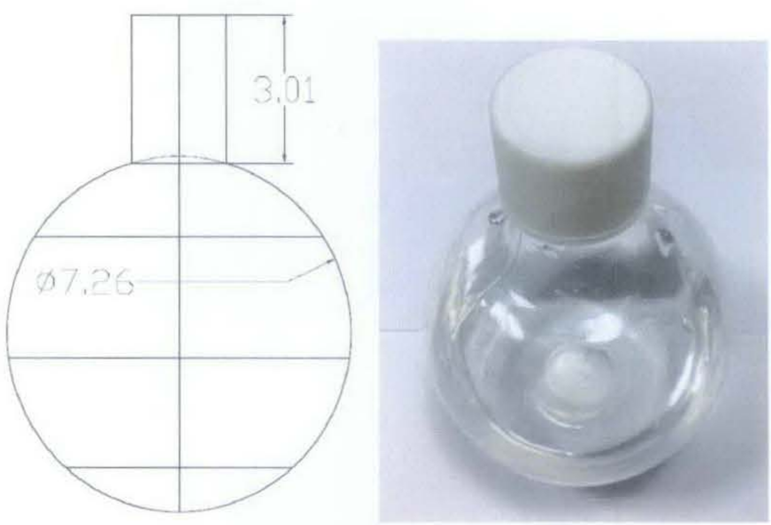

Figure 16: Encapsulated storage container in (cm)

The sphere has the smallest surface area among all surfaces enclosing a given volume and it encloses the largest volume among all closed surfaces with a given surface area. Sphere shape provides maximum linkage between the containers and maintains a uniform gap between the containers for an equal flow passages across the tank. The bottle is coming with a cap which able to store water or ice inside the bottle. PET material is suitable for slightly expansion during ice forming as it is flexible.

Each bottle is filled with 180ml of distilled water. Space allowance is given for expansion during formation of ice. A total number of 50 bottles will be filled and keeps 9 litres of water. Bottles will be placed inside the CTES tank surrounding with glycol solution.

Figure 17: TES filled with encapsulated ice storage

Table 7: Thermal properties of PET [9]

Coefficient of thermal expansion ($\times 10^{-6}$ K^{-1})	60
Heat-deflection temperature - 0.45MPa (°C)	115
Heat-deflection temperature - 1.8MPa (°C)	80
Lower working temperature (°C)	-40 to -60
Specific heat (J K^{-1} kg^{-1})	1200
Thermal conductivity (W m^{-1} K^{-1})	0.20 @ 23°C

4.5.3 Pump

Figure 18 is the pump installed on water chiller, functions as a circulation pump, circulating glycol solution from chiller storage to evaporator. Glycol solution from chiller storage reject heat to evaporator and back to the chiller storage again.

Figure 18: Lab water chiller pump

The specification for the current used pump in water chiller system is

- V: 230~ PH: 1 Hz: 50 ENCL: IP44
- W INPUT: 265 RPM: 2800 A: 1.1
- RTG: CONT (S1) INS. CL: F
- Motor to BS5000 part 11. AMB 40C MAX
- Motor fired with auto resetting thermo trip
- Duty Head: 15.5m @ 2l/min
- Duty Head: 2m @ 25l/min
- Head Max: 16.5m
- Maximum working pressure: 600kPa

In this project require a circulating pump which circulate glycol solution from chiller storage to cold thermal energy storage then back to chiller storage again. The flow rate was adjusted to 1.90L/min which is identical with the chilled glycol solution feed in rate to ensure constant volume of glycol solution in the both storage. Failure to do so may cause overflow or pump trip and stop the entire system.

Figure 19: Pump for new TES system

The recommended flow rate for the system is 200g/s or equal to 12L/min which is identical to the evaporator flow rate. The pump selected for this project is an aquarium pump which can provide flow rate up to 1200L/hour or 20L/min with maximum head of 100cm. Pump comes with venturi function or air feed function. This pump is suitable for pumping clean water without abrasive particles and liquids that are chemically non-aggressive to the materials from which the pump is made. Glycol solution is categorized as non-aggressive chemical.

4.5.4 Insulation

Insulation is placed in the gaps between the two different sizes of polystyrene cooler boxes. Insulation increases the thermal resistance between walls, thus reduces thermal conductivity and reduces heat gain from surrounding into CTES. CTES receives heat via conduction through wall, convection through inflation and radiation. An effective insulation maintains the low temperature in CTES, hence prevent ice inside encapsulated storage from melting.

Figure 20: Rock wool insulation at gaps

Insulation specification of insulation as below:

32mm and 26mm thickness of polystyrene cooler box

35mm thickness rock wool with thermal conductivity, λ : 0.034 W/mK

Thermal Resistance, R = Thickness (mm)/(1000 x λ (W/mK))

$= 35/1000 \times 0.034$

$= \underline{1.19 \times 10^{3}\ m^{2}K/W}$

4.5.5 Movable Tray

Figure 21: Movable tray

A movable tray is designed and fabricated to support the CTES tank. It gives storage tank the convenience of moving and easy for storage when not in used. The tray also jacks up CTES tank to a certain height to maintain the glycol level in both storage tanks. Movable tray is designed to support at least 40kg of weight. Two layers of 5.5mm plywood is placed on the movable tray, evenly distribute the CTES tank weight to the tray structure. Appendix 4 is the technical drawing for the movable tray.

4.6 CTES Experimental Results

Once fabrication of CTES prototype was completed, it was installed and connected to the water chiller for test run and evaluation.

Figure 22: CTES and water chiller

4.6.1 CTES Charging

<u>Procedure</u>

1. CTES tank was connected to the water chiller
2. 50 bottles with 180ml distill water each was placed into CTES tank
3. Inlet valve was closed and circulation pump was turned on to pump water from CTES tank to chiller storage until the maximum level
4. Pump was shut off once chiller storage reached the maximum level
5. Water chiller was started according to the operating procedure
6. Condenser water flow rate was set to 300g/s

7. Condenser pressure was set to $500kN/m^2$
8. Temperature for chiller storage was monitored
9. Once temperature for chiller storage reached approximately -5°C, inlet valve was opened and circulating pump was switched on
10. Glycol circulation flow was throttled until glycol level in both tanks remain constant (approximately 1.90L/min)
11. Continue monitoring of CTES inlet and outlet temperature

Table in appendix 5 is the measurable parameters available in the water chiller and the temperature inlet and outlet of CTES at 15 minutes interval. This experiment aims to evaluate the feasibility of the prototype and approximate time required for the CTES to be fully charged. Experiment was carried out for two hours.

Figure 24 shows that when CTES is charged to -5°C, only a portion encapsulated ice storages were frozen, mainly located at the bottom of CTES tank. Further study is required to look for the possibilities of frozen the entire encapsulated ice storage. Modification on the current CTES and chiller maybe is necessary.

Figure 23: Frozen encapsulated ice storage

Figure 24: CTES at -5°C

Experiment was repeated and simplified to focus on the temperature inlet, outlet and the difference. CTES is considered fully charged when water inside bottles was frozen, temperature difference is low and remains constant. Water chiller had achieved its maximum capacity or lowest achievable temperature, constant difference in temperature inlet and outlet indicating that the thermal equilibrium was achieved between both systems. In this experiment, data is collected in an interval of five minutes to present the temperature trend versus time.

Table 8: Chiller storage temperature during pre-cooling to -6°C

Charging – Pre-cooling	
Time (min)	Storage temperature (°C)
0	22
5	12.8
10	5.2
15	-0.2
20	-3.6
25	-6

Initial bottle temperature: 15.6°C

From table 8, it shows that pre-cooling of 18 litres of glycol solution from 22°C to -6°C required approximately 25 minutes. Circulation of glycol solution from CTES to chiller storage will begin after glycol solution in chiller storage achieved temperature of -5°C.

Table 9: Inlet and outlet temperature of CTES

Charging - Cooling			
Time (min)	T In (°C)	T Out (°C)	Diff (°C)
5	-3.0	13.5	16.5
10	-1.6	9.6	11.2
15	-2.0	6.8	8.8
20	-3.1	4.3	7.4
25	-3.7	3.1	6.8
30	-4.5	1.6	6.1
35	-5.3	0.1	5.4
40	-6.1	-1.2	4.9
45	-6.8	-2.4	4.4
50	-7.5	-3.2	4.3
55	-7.9	-4.1	3.8
60	-8.0	-4.6	3.4
65	-7.8	-4.7	3.1
70	-7.9	-5.0	2.9

Final bottle temperature: -3.2°C

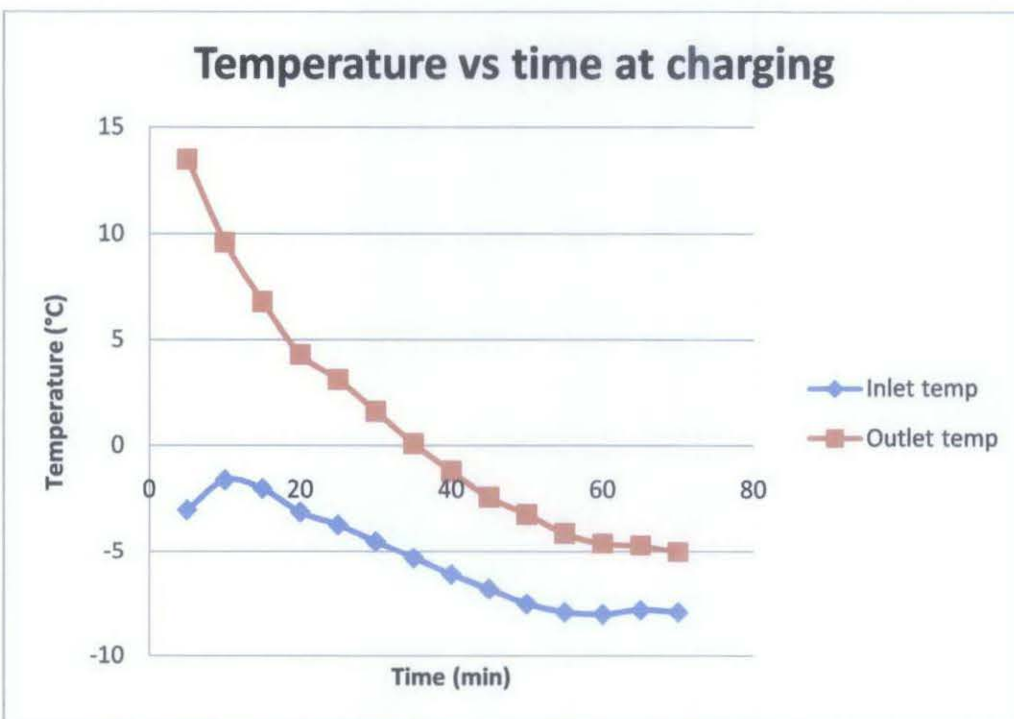

Figure 25: Graph of temperature vs. time at charging

In figure 25, the temperature difference is almost constant after 60 minutes (2.9°C~3.4°C). Say that the entire encapsulated ice storage was fully frozen or charged after 60 minutes of water chiller operation.

CTES performance

Performance efficiency, $\eta = \frac{output}{input} = \frac{CTES\ capacity}{cooling\ work}$

CTES Capacity

50 bottles filled with 180ml distill water

Total volume = 50 x 180ml = 9000ml

Q = m(cΔT+latent heat)

ΔT = 288.6K – 269.8K = 18.8K

Q = 9000ml x 1kg/1000ml x (4.184kJ/kg.K x (18.8K)+334kJ/kg)

Q = 3713.93kJ

It takes 60 minutes to cool the water from 15.6°C to -3.2°C

Refrigeration capacity = 70.405kJ/min

Cooling work = 70.405kJ/min x 60 min = 4224.30kJ

Performance efficiency, η = 3713.93/4224.30 = 0.879 or 87.9%

Several factors affect the CTES efficiency. The main factor is due to the insufficient of glycol solution circulation flow rate. The higher the circulation flow rate, the larger of heat load able to transfer from CTES to chiller storage, then remove by the chiller at evaporator. This would reduce the charging time required significantly, thus increase the performance efficiency. The prototype has huge room for improvements, there were discussed in the recommendation section.

4.6.2 CTES Discharging

In the CTES discharging experiment, a 1000 watts heater is used to demonstrate the application for CTES, discharging cold thermal energy from storage. The experiment objectives are:

- To evaluate the actual cold thermal energy stored
- To investigate time required for CTES to be fully discharged

<u>Procedure</u>

1. Water chiller unit is not operate in this testing
2. Charged CTES was connected to the water chiller storage tank as in charging testing
3. CTES circulation pump was switched on
4. A 1000 watts electric heater was inserted to the water chiller storage tank and switched on
5. Temperature for CTES inlet and outlet was monitored

Table 10: Inlet and outlet temperature for CTES

Discharging			
Time (min)	T in (°C)	T Out (°C)	Diff (°C)
0	-6	-5.0	1.0
5	-5	-4.1	0.9
10	3	-2.1	0.9
15	7	0.3	6.7
20	9	2.8	6.2
25	12	5.2	6.8
30	14	7.6	6.4
35	17	10.1	6.9
40	19	12.1	6.9
45	21	14.1	6.9
50	23	16.2	6.8

Initial bottle temperature: -3.0°C

Final bottle temperature: 13.7°C

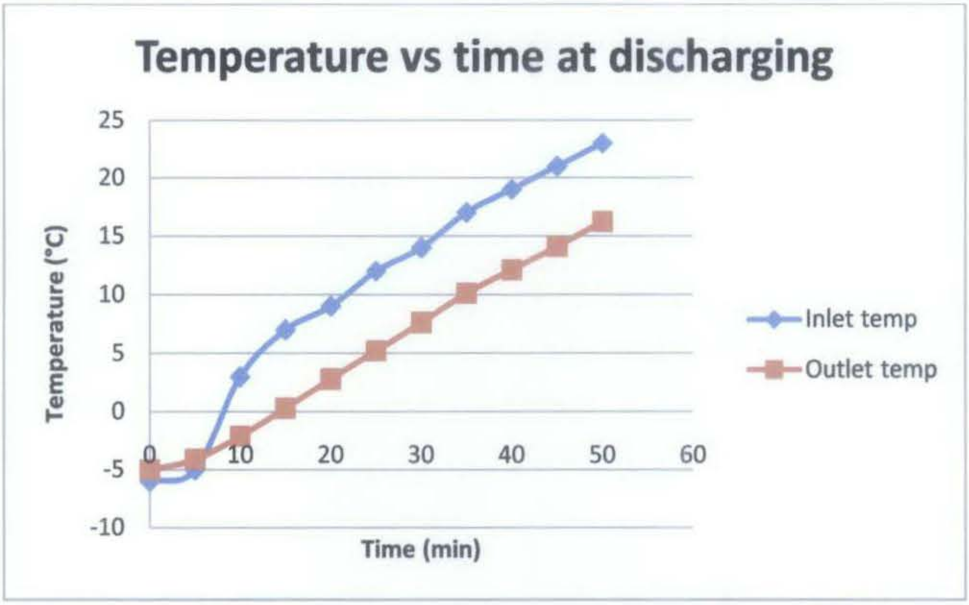

Figure 26: Graph of temperature vs. time at discharging

In commercial cold air distribution system, chilled water is supply at 5°C to 7°C. CTES is considered fully discharged when the outlet glycol temperature reached 6°C. In table 10, the temperature outlet from the CTES reached 7°C approximately after 30 minutes. CTES was fully discharged after 27 minutes.

Load = 1000watts = 1kJ/s

Total load applied = 1kJ/s x 27mins x 60s = 1620kJ

Total load applied = actual usable cold thermal energy stored = <u>1620kJ</u>

4.6.3 CTES Insulation Testing

In this experiment, CTES was fully charged and leave it unattended for a day. Initial temperature inside CTES tank is -5°C. After 24 hours, the temperature measured is 3°C or increase by 8°C. It still meets the requirement for cold air distribution system, which is chill water supply must within 5°C to 7°C. Most of the CTES does not required very long storage time, usually less than 12 hours. Chiller charges the CTES at off peak hour, usually during the night, and CTES discharges cold thermal energy from the storage tank during the peak hour, usually the next day. Improvement can be made by study alternative materials and designs for storage tank to reduce heat gain through infiltration and from the surrounding.

4.7 Comparison between CTES Using PCM and Non PCM

In this project, phase change material, ice is used to stored cold thermal energy supplied from the chiller. This section study the difference between using phase change material CTES and without phase change material CTES.

CTES tank store 9 litres of demonized distill water. Assuming in standard operation, chiller cool CTES from 21°C to -5°C during night, CTES supply chilled water at 6°C during daytime.

<u>Storage capacity for cold thermal energy storage with PCM</u>

Total volume = 50 x 180ml = 9000ml

$Q = m(c\Delta T + \text{latent heat})$

$\Delta T = 294K - 268K = 26K$

Q = 9000ml x 1kg/1000ml x (4.184kJ/kg.K x (26K) +334kJ/kg)

Q = <u>3985.056kJ</u>

<u>Storage capacity for cold thermal energy storage without PCM</u>

$Q = m\ (c\Delta T)$

$\Delta T = 294K - 268K = 26K$

Q = 9000ml x 1kg/1000ml x (4.184kJ/kg.K x 26K)

Q = <u>979.056kJ</u>

Capacity difference = (3985.056kJ – 979.056kJ) / 3985.056kJ x 100% = <u>75.43%</u>

CTES using phase change material will give an extra 75% of cold thermal energy storage in our case, with the same storage tank size. Cooling system incorporating ice storage has a distinct size advantage over equivalent capacity chilled water units because of large amount of energy to be stored as latent heat.

4.8 Costing Analysis

CTES have the potential to provide substantial operating cost effective in situations where cold air distribution is desirable. Chiller operate at off peak hour (usually at night) having the advantages of lower electricity tariff rate. The ambient temperature during night is also much lower than the day, thus reduce cooling work for chiller.

Table 11: Electricity tariff

Tariff category	Unit	Rates
Medium voltage commercial		
Maximum demand per month during peak period	RM/kW	36.6
kWh during peak period	sen/kWh	29.6
kWh during off peak period	sen/kWh	18.2
Medium voltage industrial		
Maximum demand per month during peak period	RM/kW	30.8
kWh during peak period	sen/kWh	29.6
kWh during off peak period	sen/kWh	18.2
High voltage industrial		
Maximum demand per month during peak period	RM/kW	29.6
kWh during peak period	sen/kWh	28
kWh during off peak period	sen/kWh	16.8

Table 11 shows the electricity tariff for several categories, adapted from Tenaga Nasional Berhad, Malaysia and effective since 1st July 2008. Assuming UTP demands 4000RT during weekdays for buildings in the campus, chiller to be operates for 10 hours in peak periods, from 7am to 5pm and consider UTP as a medium voltage commercial building. If CTES is used and chiller operation time move to 10 hours in off peak periods for charging CTES,

Power rating for water chiller compressor: 732W

<u>During peak period</u>

Tariff = 29.6sen/kWh

Operating cost = 0.732kW x 29.6sen/kWh = <u>RM0.2167/h</u>

During off peak period

Tariff = 18.2sen/kWh

Operating cost = 0.732kW x 18.2sen/kWh = RM0.1332/h

Saving per hour = RM0.2167/h – RM0.1332/h = RM0.0835/h

Assume laboratory water chiller was used

Chiller capacity: 0.846RT

Cost saving per RT = RM0.0835/h / 0.846RT = RM0.0987/RT.h

Estimated cost saving per day = RM0.0987/RT.h x 4000RT x 10h = RM3948

Consider demand only on weekdays, 20 weekdays in a month

Estimated cost saving per month = RM3948/day x 20days = RM78,960

Estimated cost saving per year = RM78,960/month x 12months = RM947,520

Installing a CTES system and moving the operation time for chiller from peak period to off peak period could save an electricity bill of RM947,520 per year. This is a significant saving of operating cost.

CHAPTER 5
CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

Thermal energy storage systems can play an important role as they provide great potential for facilitating energy savings and reducing environmental impact. Cold thermal energy storage reduce demand in peak season, lower capital and operating costs, increase usable space and minimum disruption.

The objectives of this project were achieved. It gives students additional equipment for study on CTES using ice as phase change material with the current available water chiller in laboratory. This project was completed with the use of appropriate and cost effective design and materials. CTES has a capacity to store cold energy of 3700kJ.

Prototype was tested and found has an efficiency of 88%. CTES required 60 minutes to be fully charged. CTES discharges cold energy at 6°C for 27 minutes with an application of 1000w heater. Temperature raises only 8°C after 24 hours in room temperature. Saving of RM947,520 per year for UTP is possible with the installation of CTES. This prototype successfully demonstrates CTES in real life application. Further study and modification can be made based on recommendation to increase the CTES performance and efficiency.

5.2 Recommendations

As this project was designed as an additional plug-in for the water chiller, many limitations must be taken care of. This project does not modify the current water chiller, but design a CTES which able to adapt to the chiller condition. These limitations reduce CTES performance and efficiency.

5.2.1 Glycol Circulation Flow Rate

From table 9 and table 10, it was noticed that the temperature difference between CTES inlet and outlet is large. Glycol circulation flow rate was limited to 1.90L/min, due to the restriction of chiller storage tank drain valve. The current installed drain valve had very small inner diameter, throttle glycol feeding into CTES. The higher the circulation flow rate, the faster the heat load from CTES transfer to chiller storage, then removes by the chiller at evaporator. Replacing the current drain valve with a larger inner diameter drain valve require modification on the current chiller. Further study can be made to find out other glycol feed in methods.

5.2.2 Fabrication of encapsulated ice storage

The current PET bottle for storing water to be frozen into ice as encapsulated ice storage was not vacuum, sealed and air tight. Observation from experiment found that a portion of encapsulated ice storage was not frozen. Sign of frozen only shown once bottle cap was opened and exposed to the atmosphere pressure. The reason may due to pressure build inside bottle during freezing process, volume expansion of ice. Glycol solution may seep into bottle through cap and mix with water in the bottle, thus reduce the water freezing point to a lower temperature. Thermal conductivity for PET bottle is low, as shown in table 7. The effect was observed in results from table 9 and 10. Temperature difference between water inside bottle and glycol solution is large. Further temperature reduce is needed to achieve water freezing point in bottle but the current water chiller in the lab only capable produces chilled glycol solution as low as -7°C. Further study can be made to select alternative bottle material and resolve technical issue such as sealing and vacuum.

Further study can be carried out to investigate any other possibility to increase CTES performance.

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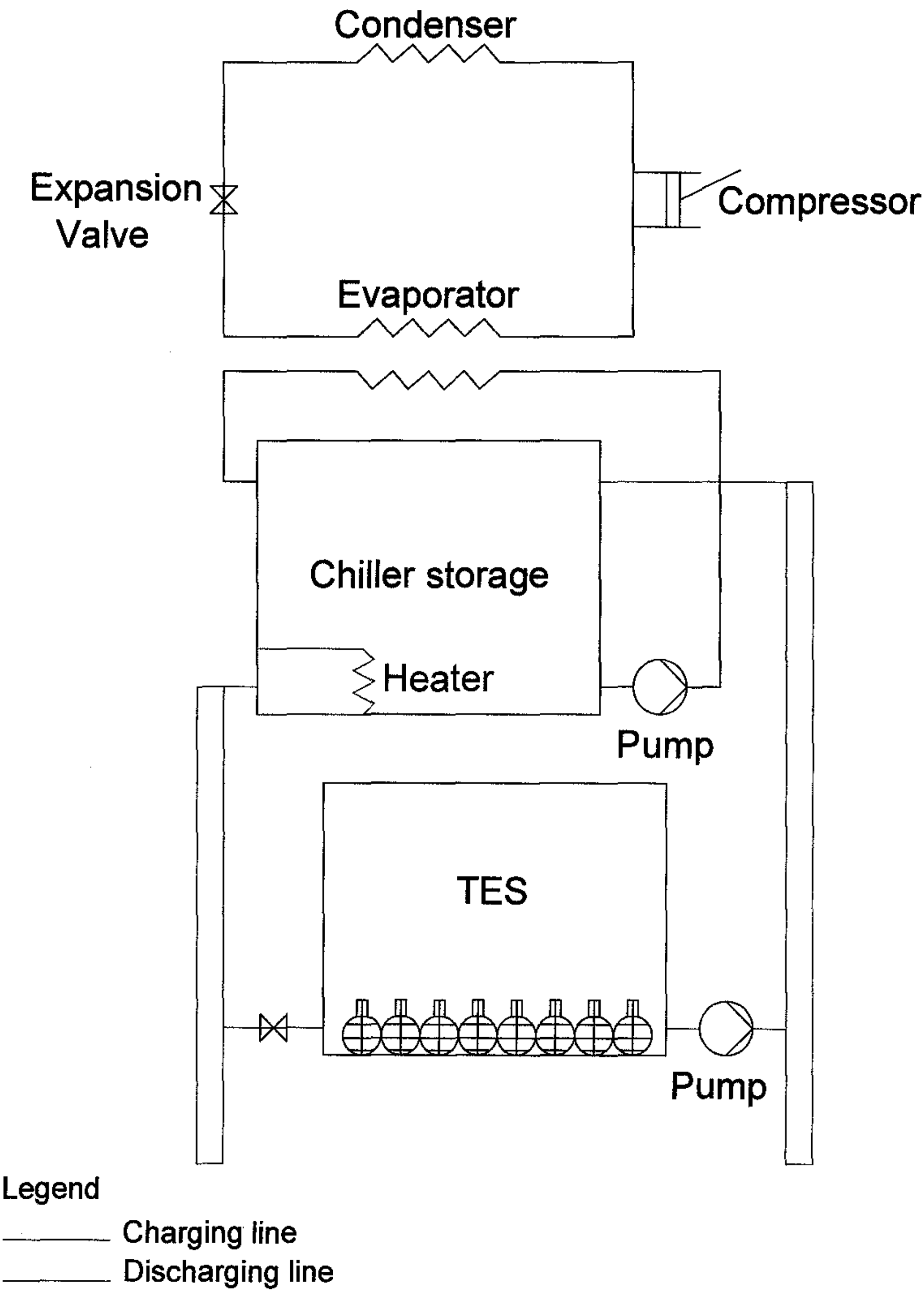
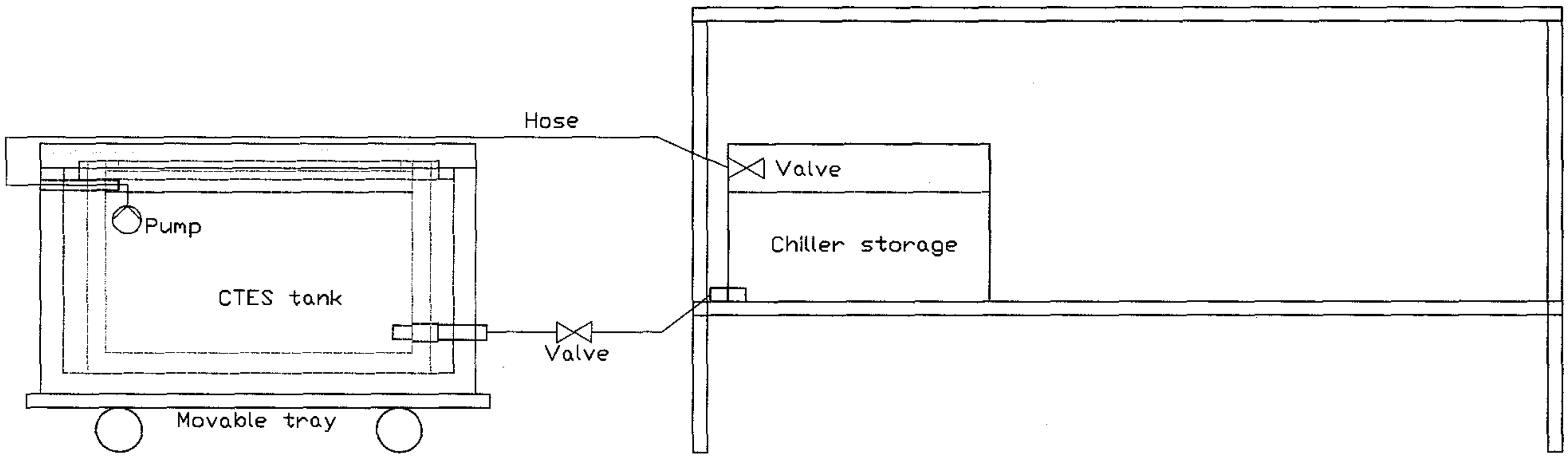
Appendix 1

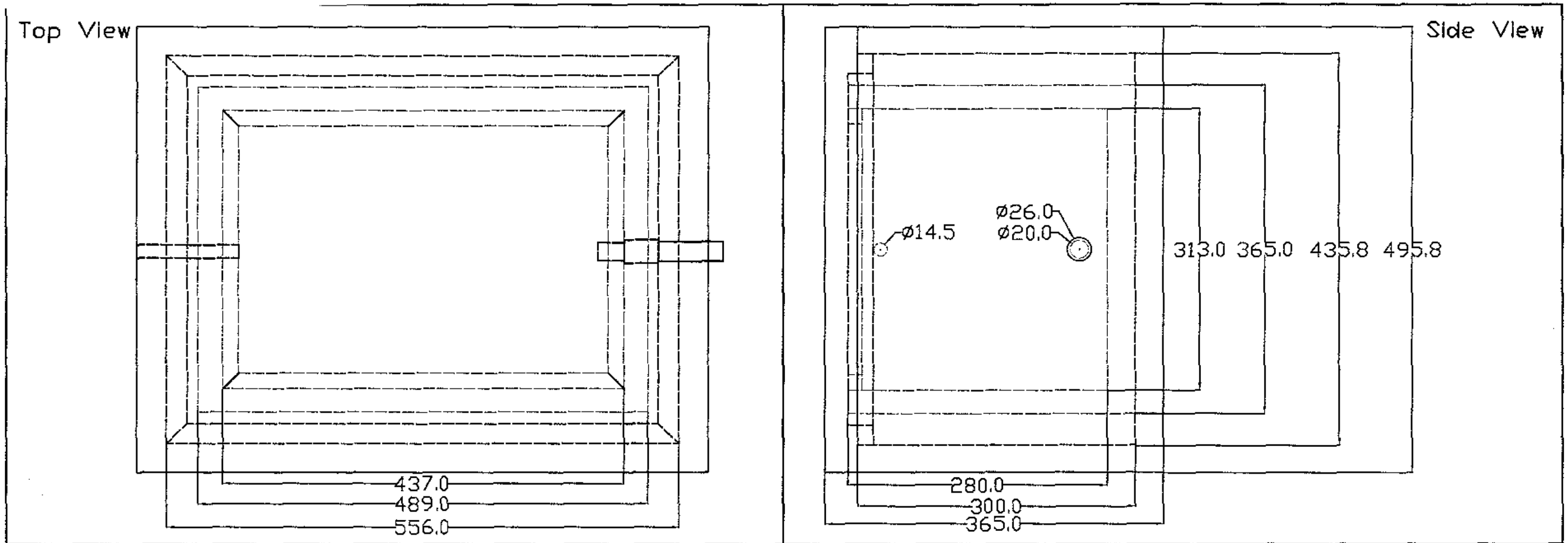


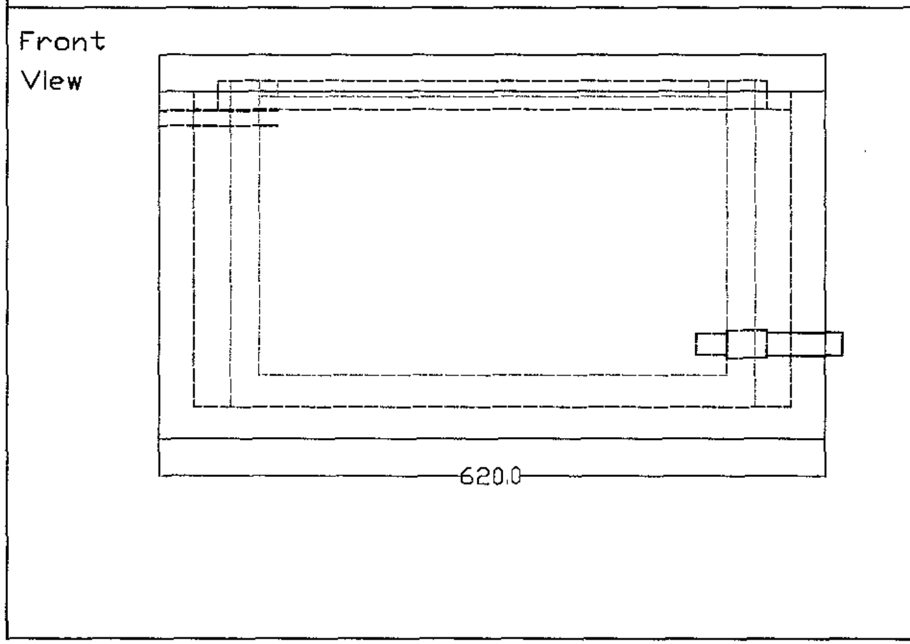
CTES schematic diagram

Appendix 2



Schematic diagram of CTES setup

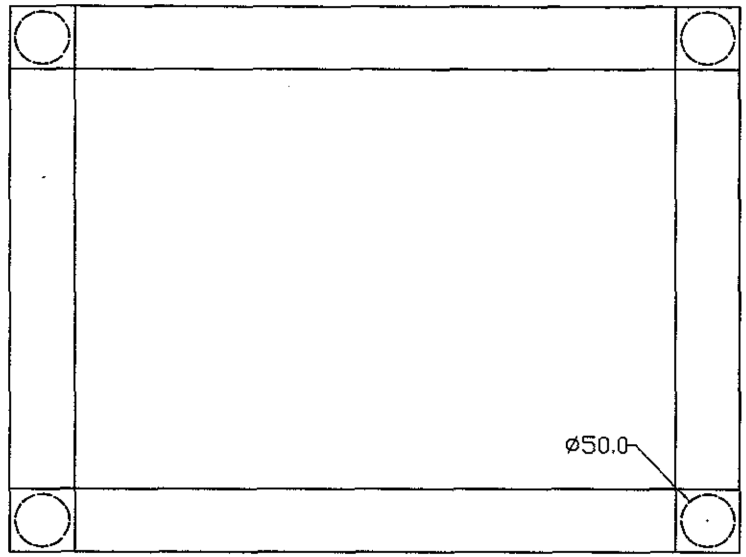




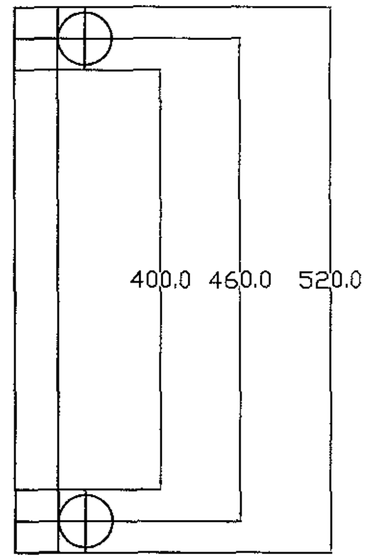
Appendix 3

Universiti Teknologi Petronas		
CTES Tank		Client Petronas
Scale 1:6		
Date 01-09-2008		
Drawn By:	Checked By:	Approved By:
DEE BOON HUEI 6410		

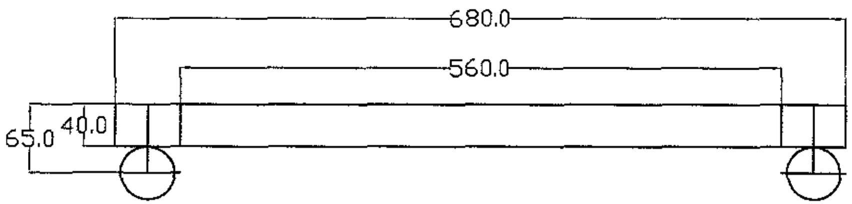
Top View



Side View



Front view



Appendix 4

Universiti Teknologi Petronas		
Movable tray	Client Petronas	
Scale 1:6		
Date 20-09-2008		
Drawn By:	Checked By:	Approved By:
DEE BOON HUEI 6410		

Appendix 5: Water chiller refrigeration and CTES data

Parameter	Units	Minutes								
		0	15	30	45	60	75	90	105	120
T1 Compressor suction temperature	°C	21.5	8.4	5.0	1.9	0.8	-1.6	-1.8	-2.0	-2.2
T2 Compressor discharge temperature	°C	21.9	59.0	62.2	66.4	69.4	71.6	74.9	77.0	80.2
T3 Condensed liquid temperature	°C	22.1	20.3	14.4	13.4	13.5	13.8	13.5	13.1	13.6
T4 Evaporator inlet (refrigerant)	°C	21.8	-5.0	-9.6	-13.2	-15.4	-20.9	-22.0	-22.9	-23.3
T5 Evaporator outlet (refrigerant)	°C	21.8	6.4	1.9	-2.5	-4.9	-10.9	-11.6	-12.1	-12.4
T6 Evaporator pressure regulator outlet	°C	21.7	6.5	1.9	-1.2	-3.4	-7.3	-9.0	-9.8	-10.0
T7 Condenser cooling water inlet	°C	23.5	15.9	11.8	11.5	12.0	12.2	12.4	11.9	12.0
T8 Condenser cooling water outlet	°C	23.4	18.1	14.1	12.9	13.3	12.6	12.5	12.3	12.5
T9 Evaporator water inlet	°C	21.6	7.6	2.6	-2.0	-4.5	-4.8	-5.2	-4.9	-4.8
T10/0 Evaporator water outlet	°C	21.5	5.4	0.0	-3.5	-6.4	-6.3	-6.6	-6.4	-6.8
Condenser pressure	kN/m^2	500	460	400	360	360	360	360	360	360
Evaporator pressure	kN/m^2	500	120	80	50	45	10	5	0	0
Refrigerant flow rate	g/s	0	12	10	8	6	4	3	4	3
Condenser water flow	g/s	299	295	290	295	291	293	293	292	293
Evaporator water flow	g/s	0	199	193	193	192	169	147	124	115
CTES inlet	°C	23	9	1	-2	-6	-7	-7	-7	-7
CTES outlet	°C	23	12	5	0	-4	-5	-6	-5	-5