CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Thermal energy storage may refer to a number of technologies that store energy in a thermal reservoir for later use. They can be employed to balance energy demand between day time and night time. The thermal reservoir may be maintained at a temperature above (hotter) or below (colder) than that of the ambient environment.

The principal application today is the production of ice, chilled water or eutectic solution at night which is then used to cool environment during the day. The thermal energy storage technologies store heat in an insulated repository for later use in space heating, domestic or process hot water or to generate electricity.

The most widely used form of this technology is in large building or campus-wide air conditioning or chilled water system. Air conditioning systems, especially in commercial buildings are the most significantly contributors to the peak electrical loads seen on hot summer days. In this application a relatively standard chillers is run at night to produce a pile of ice or chilled water. Water is circulated through the pile during the day to produce chilled water that would normally be the daytime output of the chillers.

The storage tank is naturally stratified type in which warm and cool water are stored together without any physical barrier. In the stratified tank, warmer, less dense water is stored at the top of the tank and the cooled water is stored in the bottom [1,2].

By thermal stratification; that is, water of a high temperature than the overall mixing temperature can be extracted at the top of the tank and water of a lower temperature than the mixing temperature can be drawn off from the bottom to make use even of short isolation periods and thus running the storage tank at a higher efficiency. In practice, perfect stratification is not possible since the water entering the tank will cause a certain amount of agitation and mixing. Moreover, there would be a certain amount of diffusion from the entering water (to the stored water) before it reaches the appropriate density level [2] .

Thermal stratification within thermal energy storage (TES) reduces temperature degradation. The degree of stratification is affected by the volume and configuration of the tank, the design of the inlets and outlets, the flow rates of the entering and exiting streams and the durations of the charging, storing and discharging periods. Increasing of stratification layers number improves TES efficiency relative to a thermally mixed-storage tank.

Universiti Teknologi Petronas (UTP) has its own thermal energy storage system at Gas District Cooling (GDC) plant as shown in the simplified process diagram in Appendix A [3]. TES is incorporated in UTP GDC. The TES is a vertically cylindrical tank type with height and radius of 15m and 22.3m respectively. The nominal volume of the tank is 5400m^3 and the holding capacity of the tank is 10000 RTh. There are 14 temperature sensors installed inside the tank which are used to monitor the temperature of warm and cold water in TES as per Appendix B. This TES stored chilled water produced by 4 units of 325 RTh electric chillers. The discharge at on-peak demand of TES is aimed to support supplying of chilled water from 2 units of 1250RT absorption chillers [1].

The thermal energy storage tank has two operating cycle namely the charging and discharging cycle. During the charging cycle, chilled water enters from the bottom part of the tank while the warmer water being withdrawn from the tank from the top part of the tank. For the discharge cycle, the chilled water being withdrawn from the bottom part of the tank while the warmer water enters from the top layer of the tank [1].

1.2 PROBLEM STATEMENT

The cooling demand for UTP has been increasing from day to day. This is due to increasing academic and co-curriculum activities. Due to these, there is a requirement to increase the supply chilled water to the campus. The electric chillers were design to charge the thermal energy storage tank at night. To assist in supplying the chilled water to the campus, the electric chillers need to operate during the day which increases the usage of electricity. Thus a study is required to evaluate the performance of the current thermal energy storage available at UTP GDC plant.

1.3 OBJECTIVE

The objective of this project is:

- To evaluate the performance of thermal energy storage of UTP GDC
- To develop a controlling strategy for enhancement of the performance of thermal energy storage of UTP GDC

1.4 SCOPE OF STUDY

The study covers thermal energy storage during the day and night for week days and weekends during the month of February 2010 and March 2010.

CHAPTER 2
LITERATURE REVIEW

2.1 THERMAL ENERGY STORAGE SYSTEMS

Thermal energy storage is an electrical load management and building equipment utilization strategy, which can reduce the utility electricity demand and equipment first-cost. Thermal energy storage is a temporary holding or storage of energy for later use.

Generally, there are two types of thermal energy storage system which are sensible and latent heat. In the sensible heat types of TES, water or rock are commonly used for their storage medium. For the latent type, it usually uses ice or eutectic salts as their storage medium. Dincer and Rosen [4] stated, "TES involves the storing of energy by heating or cooling, melting or vaporizing or solidifying or liquefying a material, or through thermo chemical reactions. (p.276)

Thermal energy storage system had been widely used in many applications mainly for heating and cooling purposes. Nowadays, some of the TES for heating is integrated with solar energy to provide heat at night and storage during the day. Dincer and Rosen [4] point out that "for cooling the heat removing heat can be via a chilled water network or directly from air system". (p.112). This type of TES needs to be insulated externally to avoid heat gain to the system from the environment.

2.2 THERMAL ENERGY STORAGE FOR COOLING

In a TES system application, the cooling capacity is stored in a thermal storage tank. The main components of a TES system are chillers, storage medium and storage tank. Figure 2.1 shows the difference between the configuration of conventional cooling system and TES system [5].

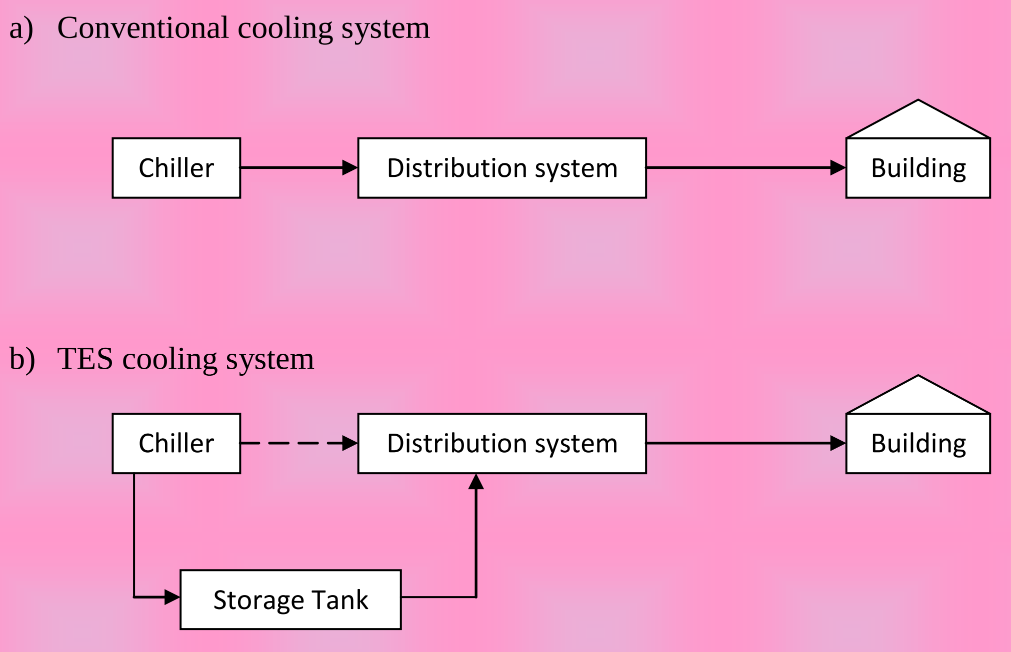

Figure 2.1: The conventional and TES cooling system

For most conventional cooling system, there are two major components:

i. Chiller – used to cool the cooling medium
ii. Piping system or distribution – to transport the cooling medium from the chiller to the building

For the conventional system, the chillers will only operate when cooling is needed. For a TES incorporated system, the chiller also operates at times other than when cooling is needed. Even though TES system is widely used by many applications, but all are designed to operate on a cyclical basis. By taking full advantage of the benefit of the TES system, we can optimize the system as follows [4]:

i. Increase generation capacity for TES during charging
ii. Shift energy purchase to low cost periods
iii. Increase system reliability
iv. Enable better operation of co-generation plants

2.3 STORAGE MEDIUM

The storage medium is an important factor that needs to be considered concurrence to determine and select the volume of the tank, the HVAC's configurations and amount of energy that can be stored. This is because different storage medium have different characteristic for energy storage. The three common medium that are widely applied for TES application which are chilled water, ice and eutectic salt or also known as phase change material (PCM) [6].

2.3.1 Chilled Water

This system normally operates at temperature ranges between 3.3ºC to 5.5ºC which is well suited with standard chillers. Chilled water TES uses the sensible heat in a body of water to store energy. Dincer and Rosen [4] found that this system requires larger storage tank. This system required more storage volume of water to absorb the energy compared to ice. Therefore, the storage tank for chilled water system would be bigger and the costing also will increase. The capacity of the tank is relative to its volume. For system that requires about 10000RTh or higher, the chilled water system can perform as good as the ice storage.

2.3.2 Ice

This kind of system uses smaller tanks and offers the potential for use of low temperature air system, but requires more complex chiller system. The storage medium uses the latent heat of fusion of water to store the cooling capacity. In this application, special ice making for low temperature service is used to charge the TES at temperature below the usual conventional. Several ice maker systems usually used in industrial application which are:

i. External-melt system
ii. Internal-melt system
iii. Ice-harvesting system

2.3.3 Eutectic Salts or Phase Change Material (PCM)

According to Dincer and Rosen [4], eutectic salt is a combination of inorganic salts, water and other elements to create a mixture that freezes at a desired temperature. This material is encapsulated inside plastic containers and stacked in the TES. The water come in to the tank will circulate this container. For most of the applications, the material mixture freezes at 8.3ºC. However, using this kind of storage medium will leads to higher discharge temperatures. These temperatures causing this kind of storage medium only can be used at full storage operation but, only if the dehumidification requirements are low. The beauties of this medium are easy to maintain, required smaller space and suitable for application which low temperature not really required.

2.4 STRATIFIED CHILLED WATER TES TANK

Stratified chilled water thermal storage tank are widely used since it can reduce the operating cost and refrigeration plant capacity requirement by having only one tank instead of two tanks that separates the chilled water and warm water [7].

In a stratified chilled water storage tank, warm and chilled water are stored together without an intervening physical barrier. A stable density gradient prevents mixing of the two volumes. The stable gradient is maintained during storage and operation by varying the direction of flow through the tank. Cool water is introduced and withdrawn at the bottom while the warm water is introduced and withdrawn at the top.

Typical temperature profile in a naturally stratified tank is show in Figure 2.2. A region of transition layer called thermocline forms between the warm and chilled water as a result of heat conduction across the interface. T_h shows the average warm water temperature while T_c indicates the average chilled water temperature. The profile consists of two curves that meet at point C. The midpoint position of the thermocline, C, defines the boundary line of chilled and warm water in the tank. The width, W_{TC} is identified as thermocline thickness [3,7].

Thermocline region thickness is an important design indicator of a stratified tank. A thinner thermocline is desired since thicker thermocline indicates larger degradation of stratification [3].

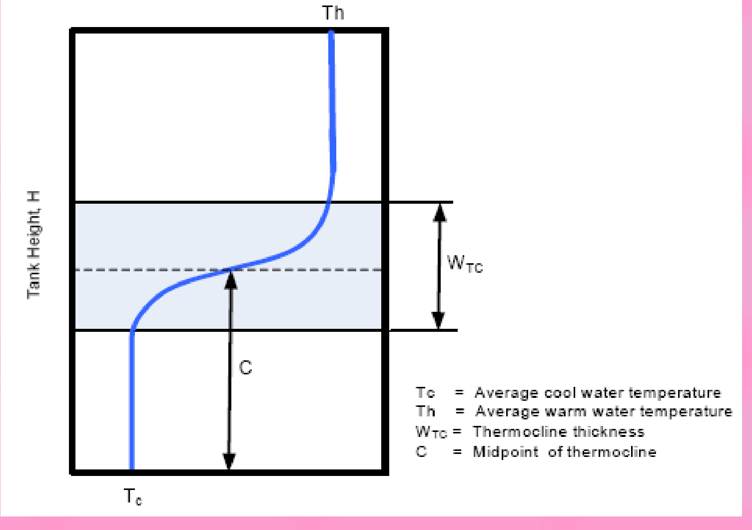

Figure 2.2: S-Curve of temperature profile

2.5 PERFORMANCE EVALUATION METHOD

Performance evaluation is a necessary and beneficial process, which assess a process or equipment in order to collect the current condition which can help in improving the performance. From several review of journals, there are quite a few ways in evaluating the performance of thermal energy storage for a district cooling plant.

2.5.1 Meeting Load Ratio

M Amin, Chalilullah and Joko [1], evaluated the performance of TES by calculating the meeting loads ratio. Meeting loads ratio to supply of chilled water is determined as the ratio of discharging amount of cooling potential over the total supply of chilled water during on-peak cooling demand. The total supply of chilled water is the amount of supply chilled water by discharging of TES and chilled water generated by electric chillers supply (EC) and absorption chillers (SAC).

$$\text{Meeting load ratio percentage, (\%)} = \frac{TES}{TES + EC + SAC} \qquad (2.1)$$

where

TES = discharging amount of chilled water from Thermal Energy Storage Tank

EC = discharging amount of chilled water from Electrical Chiller

SAC = discharging amount of chilled water from Absorption Chillers

Chilled water discharge by TES is determined as an accumulated value of discharging value, which can be derived from the difference of the value of the holding capacity at the start and the end of discharging mode. Chilled water generated by electric chillers (EC) and absorption chillers (SAC) are obtained as summation of multiplying of RT works each chiller with the time duration.

The data needed to do this investigation is the daily data operation of TES which consist of hourly time monitoring of holding capacity and temperature on each sensor since

TES have 14 temperature sensors installed. Holding capacity is defined as a parameter identifying of accumulated cooling potential stored in TES tank.

The result of the calculation done by Amin et al was tabulated as in Appendix C and Appendix D. The study was concluded with the percentage of meeting load ratio of TES to supply of chilled water during on-peak cooling demand as an average of 25.9% which is at the maximum academic activities while 26.8% at low academic activities.

2.5.2 Thermal Efficiency of TES

Study done by Bahnfleth and Amy Musser [7] stated that one of the ways to evaluate a stratified TES tank is measuring the cycle thermal efficiency which can be defined as the ratio of cooling capacity delivered during a complete discharge cycle to the capacity absorbed during a complete charge cycle. Represent in terms of summations of measurement,

$$\eta = \frac{[\sum mc\,(T_{in} - T_{out})\,\Delta t\,]_{Discharge}}{[\sum mc\,(T_{out} - T_{in})\,\Delta t\,]_{Charge}} \tag{2.2}$$

where m = mass flow rate over a time increment,

c = specific heat,

T_{in} = inlet temperature,

T_{out} = outlet temperature and

Δt = time increment.

The numerator of equation 2.2 is referred to as integrated discharge capacity while the denominator is integrated charge capacity.

2.5.3 Figure of Merit (FOM)

Bahnfleth and Amy Musser [7] stated that losses of availability in TES are due to mixing of warm and cool water in the stratified tank. This mixing results in loss of useable capacity and adds to the energy consumption of the refrigeration plant when the blended water is restored to its original temperature. A performance metric that reflects the losses of usable capacity in addition to ambient heat gain is the FOM. The FOM is the ratio of integrated discharge capacity for a given volume to the ideal capacity that could have been withdrawn in the absence of mixing and losses to the environment.

$$FOM = \frac{\left[\sum mc\,(T_{in} - T_{out})\,\Delta t \right]_{Discharge}}{Mc\,(T_{h*} - T_{c*})} \quad (2.3)$$

where
- m = mass flow rate over a time increment,
- c = specific heat,
- T_{in} = inlet temperature,
- T_{out} = outlet temperature,
- Δt = time increment,
- M = total mass cycled through the tank,
- T_{h*} = mass averaged discharge inlet temperature and
- T_{c*} = mass averaged inlet temperature during previous charge cycle.

The FOM gives a direct measure of the fraction of nominal capacity that can be delivered at a usable temperature for given charge and discharge inlet conditions. Consequently, it is generally regarded as a better indicator of performance than η. Because FOM includes not only capacity losses to the environment, but also losses due to mixing and conduction within the tank, it should always be less than η.

2.5.4 Integrated capacity

Integrated charge and discharge capacities are simply the net of thermal energy flows measured at the inlet and outlet of tank [7]. These quantities may be expressed as follows for the time series of temperature and mass flow measurements:

$$C_{Int} = \sum m\ Cp\ |\ T_{in} - T_{out}\ |\ \Delta t \qquad (2.4)$$

The theoretical capacity of one tank volume is proportional to the mass of water contained, the mass averaged temperature in the tank at the beginning of the cycle, and the mass averaged inlet temperature:

$$C_{Max} = m\ C_p\ (T_h - T_c) \qquad (2.5)$$

2.5.5 Half-cycle Figure of Merit

Bahnfleth and Amy Musser [7] stated, most useful cooling capacity in stratified tank is lost primarily through conduction across the thermocline and mixing near the diffuser. A more easily measured, enthalpy-based figure of merit (FOM) is often used to indicate the loss of cooling capacity of the stratified chilled water during the charging and discharging process in a complete storage cycle.

Half-cycle figure of merit is defined as the ratio of $C_{Int|charge} / C_{Max}$ and $C_{Int|discharge} / C_{Max}$ for half-cycle flow equal to one tank volume.

$$FOM_{1/2} = C_{Int} / C_{Max} \qquad (2.6)$$

For each of the tests performed, the half-cycle FOM exceeded 90% indicating that the tank stratifies well.

2.5.6 Effect of flow rates to TES efficiency

In his research paper [8], M.A. Karim concluded that the storage efficiency decreased with increasing flow rate due to the increased of mixing of warm and chilled water. This conclusion was made after undergoing a number of analysis and experiments. Karim used instrumentation method to get the data acquisition need for the analysis method.

In the instrumentation method, Karim used two vertical strings of calibrated thermocouples and put it on the side-wall and the other at the center of the tank. Each string consists of 38 calibrated thermocouples that are equally spaced at 5cm interval. These thermocouples are installed in order to monitor the movement of the thermocline. A number of calibrated thermocouples were also installed at the inlet, outlet of the storage tank, the inlet and outlet of the heater and inside of the water tank of the chiller. Calibrated electronic flow meters were used to measure water flow rate to and from the tank. Temperature controllers were used to control heater and chiller outlet water temperatures.

Using the data gained in the instrumentation method, Karim done an analysis using a derived equation as below.

$$Q = \int_0^{v_f} \rho c_p (T_h - T_l) dv \qquad (2.7)$$

Q is defined as integrated capacity of the tank, at maximum flow rate.

v_f is the total volume flow during the period of interest.

ρ is the density of water.

C_p is specific heat of water.

T_h is the fluid temperature at high port of the tank.

T_l is fluid temperature at the low port.

Using equation 2.7, Karim calculated the discharge and charge integrated capacity, Q_d and Q_c respectively. To calculate the storage efficiency equation below is used.

$$\eta_{st} = \frac{Q_d}{Q_c} \tag{2.8}$$

Storage efficiency is defined as the ratio of the cooling effect removed from the storage during a single complete discharge cycle to the cooling effect deposited during the immediately preceding complete charge cycle.

As mentioned earlier, M.A. Karim concluded that the storage efficiency decreased with increasing flow rate due to the increased of mixing of warm and chilled water.

2.5.7 Effect of Diffuser Design

As mentioned earlier [7], thermal stratification within a TES reduces temperature degradation. The degree of stratification is affected by the volume and configuration of the tank, the design of the inlets and outlets, the flow rates of the entering and exiting streams and the durations of the charging, storing and discharging periods. Increasing of stratification layers number improves TES efficiency relative to a thermally mixed-storage tank.

Diffuser design and layout primarily affected the mixing near the inlet diffuser and the extent of this mixing had primary influence on the shape of the thermocline [7]. The heat conduction through tank walls and through the thermocline caused widening of mixed volume which lowers the efficiency of TES tank.

As per study done by Karim [8], the diffuser should introduce water to the tank uniformly and at low velocity so that buoyancy forces create and maintain the thermocline. Diffusers in stratified tank must form and reform, a thermocline with minimum mixing between warm and cold water, and then ensure that the thermocline is not impaired by subsequent mixing. High velocity will overcome the buoyancy forces causing mixing. A nonuniform flow through the diffuser openings can cause swirling in the storage tank. This means that it is important to maintain the stability of the thermocline in order to have an efficient storage tank.

It is reported [8] that radial disk and circular diffusers are geometrically suited for cylindrical tanks, whereas slot and H-type diffusers are suitable for square and rectangular tanks. The thermocline formation can be ensured by designing the diffuser with the appropriate Froude number and by properly sizing diffuser openings. It was verified that Froude number of 1 or less proves that the buoyancy forces in the inlet flow is greater than the inertial force, and gravity current is formed. For higher Froude number, the inertial force creates jet-like flow immediately downstream of the inlet, resulting in unnecessary mixing. Froude number (Fr) is defined as:

$$Fr = \frac{u}{[g\beta(T_w - T_c)L]^{1/2}} \qquad (2.9)$$

where u is the average velocity of the flow at diffuser opening,

g is the acceleration due to gravity,

β is the coefficient of volumetric expansion,

T_w is the temperature of the warmer water in the tank,

T_c is the temperature of the cooler water in the tank and

L is the characteristic dimension of diffuser.

2.5.8 Percent cold recoverable (PCR)

Nelson et al [9] presented the percent cold recoverable method of performance measurement in his paperwork of experiments on stratified chilled water tanks. Percent cold recoverable (PCR) is defined as the ratio of the total cooling capacity of all the water elements whose temperature at any time is either equal to or less than T_j, to the cooling capacity of the stored water initially.

$$PCR = Q(t) / Q_0 \tag{2.10}$$

where $Q(t) = \sum Q(t)_j$ and

$Q_0 = M_T C_p (T_h - T_l)$

It is stated that the useful temperature considered by Nelson et al was that which does not rise above the low (cold) water charging temperature, T_l, by more than 20% of the initial temperature difference.

$$Q(t)_j = \begin{cases} 0 & \text{if } (T_j - T_l) / (T_h - T_l) > 0.2 \\ m_j C_p (T_h - T_j) & \text{if } (T_j - T_l) / (T_h - T_l) \leq 0.2 \end{cases} \tag{2.11}$$

CHAPTER 3

METHODOLOGY

3.1 FLOW OF WORK

Flows of work of the project are simplified as follows:

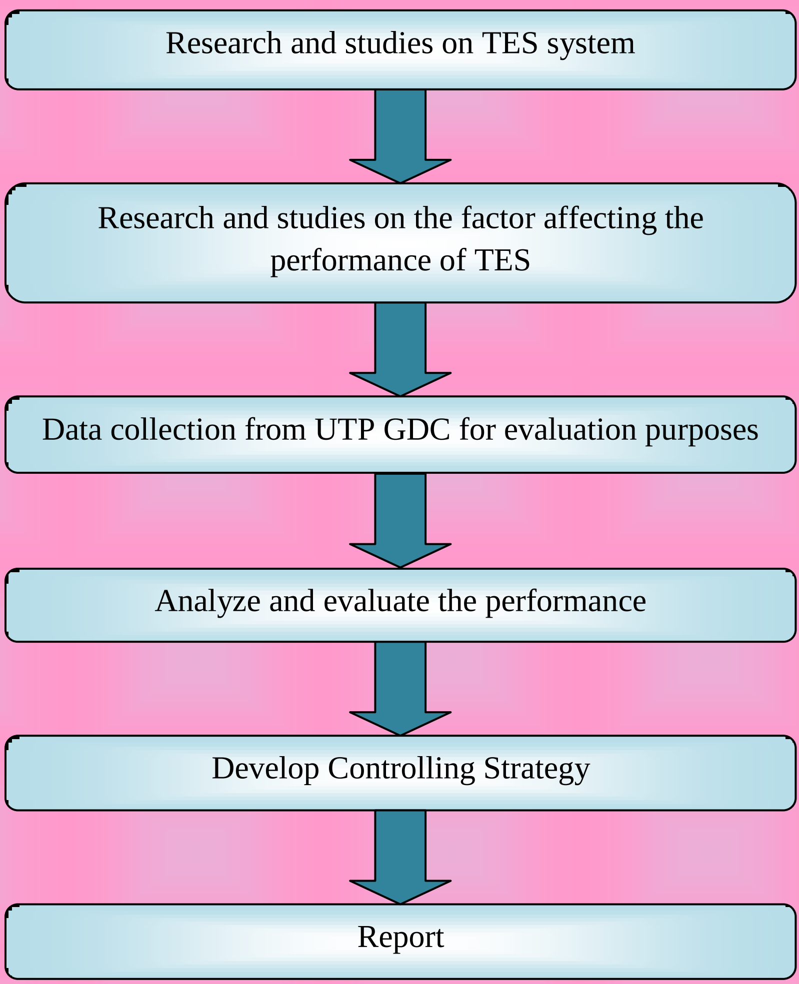

Figure 3.1: Flow of work

3.2 Research and studies on TES system

Research and studies was done on thermal energy storage system. The research covers on the introduction of TES system, different types of system and medium available, the working principle of the systems and the performance evaluation method used previously.

3.3 Research and studies on the factor affecting the performance of TES

Research and studies on the performance evaluation method was done first to identify the factors affecting the performance. Then research was done to know the factors affecting the performance of thermal energy storage are based on journals and research papers done by others.

3.4 Data collection from UTP GDC for evaluation purposes

Data collection for evaluation purposes was done during the visit to UTP gas district cooling plant. The data collected comprises the tank data sheet, UTP daily production report and the temperature for every layer in the stratified thermal energy storage tank for daily and monthly for the month of February 2010 and March 2010.

Data of the TES tank specification and the plant operations are extracted from the data sheet [13]. Temperature distribution and the holding capacity of thermal energy storage were extracted from the daily TES tank report for February 2010 and March 2010 [10]. While for the data of production of the chilled water was extracted from the daily electrical chiller report for February 2010 and March 2010 [11].

3.5 Analyze and evaluate the performance

The data collected are analyzed and the trending is evaluated. This analyzed data will be used to evaluate the performance of TES tank. The calculation of performance was done based on equation 2.4, 2.5 and 2.6.

Equation 2.4: $C_{Int} = \sum m\ Cp\ |\ T_{in} - T_{out}\ |\ \Delta t$

Equation 2.5: $C_{Max} = m\ C_p\ (T_h - T_c)$

Equation 2.6: $FOM_{1/2} = C_{Int} / C_{Max}$

The performance of thermal energy storage was calculated by calculating the integrated capacity for charging and discharging cycle using equation 2.4. The maximum capacity of the tank was taken as the design which is 10000RTh. The value calculated using equation 2.4 was then divided by the value of equation 2.5 as per equation 2.6. Thus the half-cycle figure of merit is obtained. The example of the calculation is shown in section 4.2.3.

3.6 Controlling Strategy

Controlling strategy to enhance the performance of thermal energy storage tank was proposed based on the calculation done using equation 2.4, 2.5 and 2.6.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter discusses the results of the research. The first step in the methodology is to research and study on the thermal energy storage system. This step was done and summarized in the introduction part where the principal application and related information on thermal energy storage was shared. The stratification aspects of the thermal energy storage are also cited in the introduction part. Primary factors that degrade the stored energy by reducing stratification are covered. This step was ended with a number of information of UTP GDC thermal storage system.

The second step of the methodology is research and studies on the aspect that effect the performance of thermal energy storage. As cited in the literature review section, the performance of thermal energy storage was affected by the flow rate of the water at the inlet and outlet section of the tank, the diffuser design, the stratification in the tank and several other aspects.

The next step is to collect the data needed and evaluate them. Data from the chilled water production for two weeks in 2010 were used to analyze the performances of the tank. The weeks selected were 22nd to 28th February and 1st to 7th March 2010. These weeks were chosen because it was typical working days at UTP and many events were conducted during these periods. Thus, we can see the variation of the chilled water production during the periods. Using the data collected, the performance of the tank was calculated and presented in the following sections.

4.1 UTILITY RATINGS

Below is some information that related to the TES and ECs in UTP GDC plant [12,13]. This information was taken into account for the whole research.

Table 4.1: Thermal Energy Storage tank ratings

Storage Capacity	10,000RTh
Storage Medium	Water (Stratified)
Type	Above-ground welded steel
Volume	5400 m^3
Dimensions	15m height x 22.3m diameter
Insulation	“Zincalume” cladding
Discharge capacity	1500Rth
Inlet temperature during charging	5ºC
Outlet temperature during charging	13.5ºC
Inlet temperature during discharging	13.5ºC
Limiting outlet temperature during discharging	6ºC
Usable tank volume	90%

The tank is an above-ground welded steel type. It can store about 5400 m^3 volume of water. The tank is about 15m (49.2ft) in height and 22.3m (73.8ft) in diameter. “Zincalume” cladding was installed externally on the wall and bottom of the tank to reduce energy loss to the ambient. The thickness of the insulation is about 100mm. During charging, the inlet temperature is 5ºC and outlet temperature is 13.5ºC. During discharging, the inlet temperature is 13.5ºC and the limiting outlet temperature is 6ºC. At these temperatures, the nominal capacity of the tank is 10,000RTh and the instantaneous discharge rate is 1500RTh. The system operates based on chillers priority through the collected data which is to cover the chilled water requirement that cannot met by the steam absorption chiller (SAC) during the on-peak period.

Table 4.2: Electric Chillers Ratings

Brand	Dunham-Bush
Capacity	325RTh
Type	Air Cooled Screw Chiller
Refrigerant	R-134a
Dimension	17.2m Length x 0.35m Wide x 0.46m Height
Flow Rate	131 m^3/h
Water Inlet (return)	12.6ºC
Water outlet (supplied)	5-6ºC
Quantity	4 units

Table 4.2 shows the rating of the ECs at the GDC plant. There are four units of ECs with capacity of 325RTh each. The ECs were manufactured by Dunham-Bush. These chillers use R-134a as their refrigerant to cool the water and use screw compressor to circulate the refrigerant. The flow rate of chilled water through the EC is at 131 m^3/h. Water inlet temperature to the evaporator of the ECs is 12.6ºC while the water outlet temperature is 5ºC. The temperature of water inlet and the water outlet are the designed value for these chillers. However these temperatures may be varied depending in the efficiency of the chillers and the temperature at the condenser.

4.2 RESULTS

As mentioned section 2.4, the principal operation of thermal energy storage tank is based on natural process of stratification. Temperature of the water inside the tank is measured by 14 sensors where the highest temperature of water lays at the top of the tank and the lowest temperature of water settles at the bottom of the tank.

The tank is equipped with 14 temperature sensors where were located at various elevation. The location of the sensors are represented by X variable. The X variable expresses the dimensionless elevation (*x*.N/H), where *x* is the elevation of the temperature sensors (in meter), H is the effective height of the tank content of water (14.025 m) and N number of stratified layers.

Based on this analyzation of data for February 2010 and March 2010, one typical graph on the hourly temperature distribution of chilled water in the tank is shown by Figure 4.1.

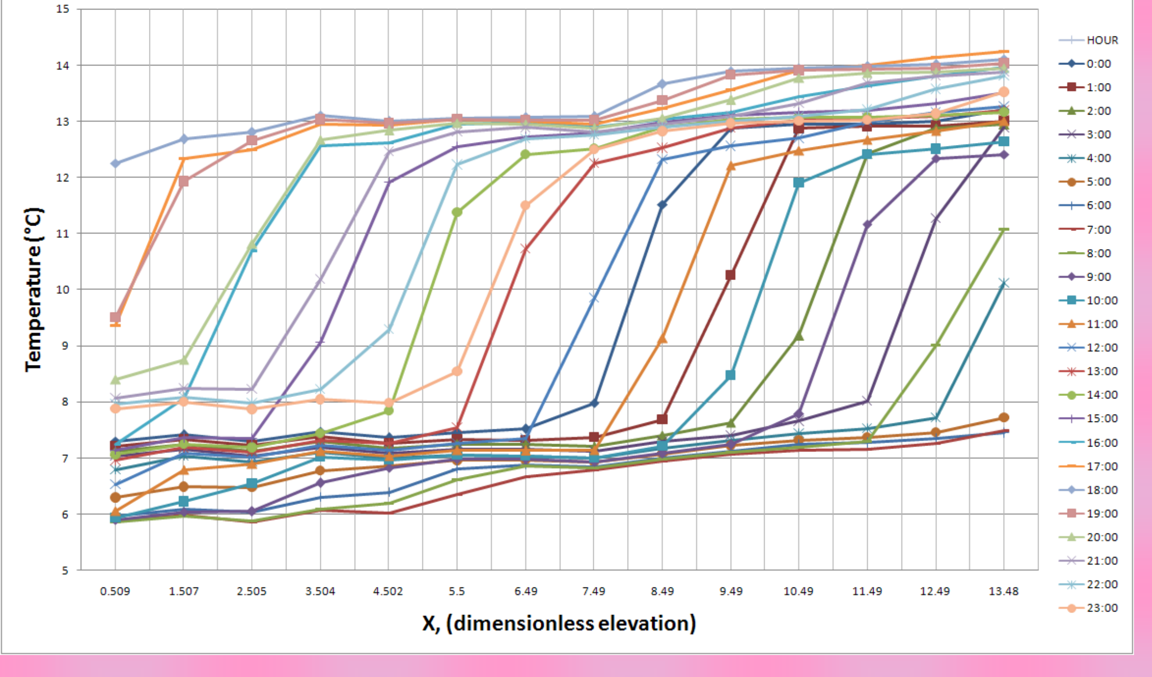

Figure 4.1: Temperature distribution of chilled water

From Figure 4.1, it can be seen that it follows the trend in Figure 2.2. Plots on Figure 4.1 indicate that the thermocline position moving upwards from the initial position as charging time increase. While the thermocline position moving downwards as discharging time increase.

Th above claim can be seen in Figure 4.1 where during the starting of charging duration (18:00 hours) the thermocline is at the bottom of the tank (0.509). After several hours of charging (22:00 hours) the thermocline are moving upwards (4.502). At the end of charging duration (07:00 hours), the thermocline settles at the top which is around 12.49 and 13.48.

For the discharging cycle, the thermocline is moving downwards. This can be seen when the discharging duration starts (07:00 hours) the thermocline is at the top of the tank which is around 12.49 and 13.48. After several hours of discharging (10:00 hours), the thermocline are moving downwards (9.49) and at the end of discharging duration (18:00 hours) the thermocline is at the bottom of the tank (0.509).

From the typical temperature distribution graph plotted above, the activities in thermal storage tank can be divided into two parts which are the charging and discharging. The time of charging and discharging are as follows:

- Charging cycle (chilled water are filled into the tank from the bottom diffuser replacing warm water) averagely starts from 6.00 pm to 7.00am (13 hours)
    - Starts at 6.00 pm (18:00 hours in Figure 4.1) the bottom of the tank (X=0.509) was having the temperature of 12.3ºC which shows that it was filled with warm water.
    - At 7.00 pm (19:00 hours) the temperature at bottom of the tank is lower, so as the temperature recorded at every sensors. This shows that the tank was charging.

- At 7.00 am (07:00 hours) the temperature at the top of the tank (X=13.48) was 7.5ºC, which shows that the tank was fully filled with chilled water.

- Discharging cycle (chilled water are withdrawn from the bottom diffuser of the tank and are replaced by warm water introduced at the top diffuser of the tank) averagely starts from 7.00 am to 6.00 pm (11 hours)
  - Starts at 7.00 am (07:00 hours in Figure 4.1) the top of the tank (X=13.48) was having the temperature of 7.5ºC which shows that it was filled with chilled water.
  - At 8.00 am (08:00 hours) the temperature at top of the tank is higher, so as the temperature recorded at every sensors. This shows that the tank was discharging.
  - At 6.00 pm (18:00 hours) the temperature at the bottom of the tank (X=0.509) was 12.3ºC, which shows that the tank was fully filled with warm water.

4.2.1 Analysis of Holding Capacity

Data collected for the week in February and March, 22nd February (Monday) until 28th February (Sunday) and 1st March (Monday) until 7th March (Sunday), are used for further analysis and sets of calculation. From these range of data, graphs (Figure 4.2 and Figure 4.3) were plotted to see the thermal energy storage holding capacity. The data for Figure 4.2 and Figure 4.3 are presented in Appendix E and F respectively.

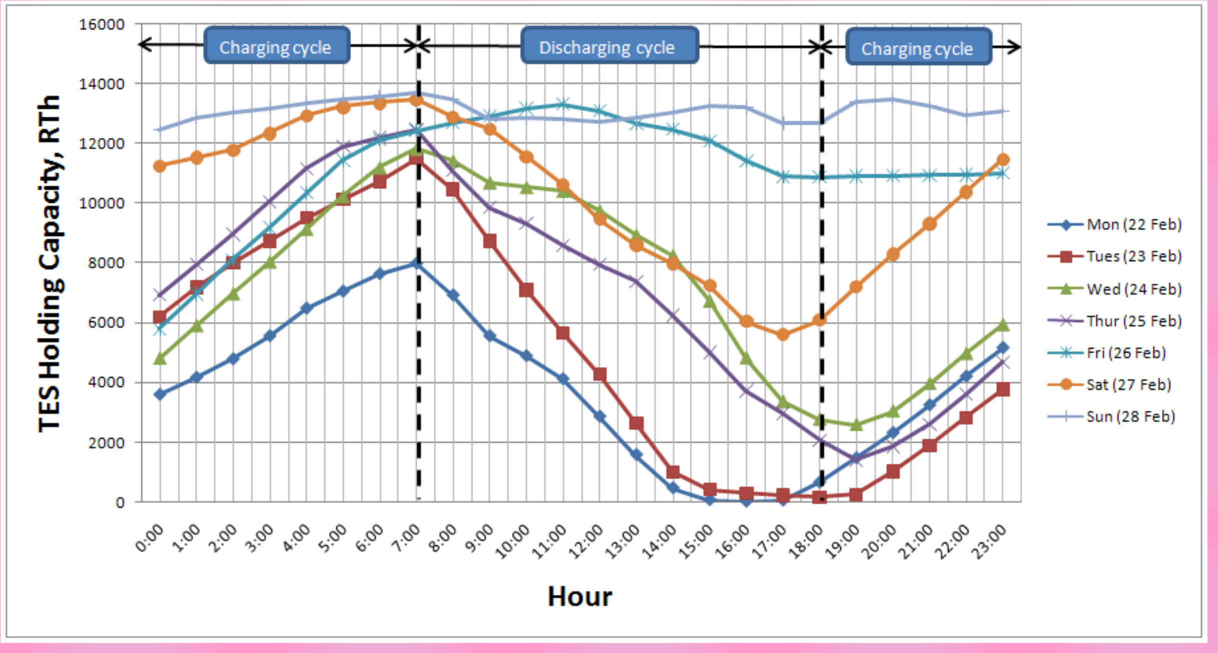

Figure 4.2: Thermal Energy Storage Holding Capacity, RTh for February 2010

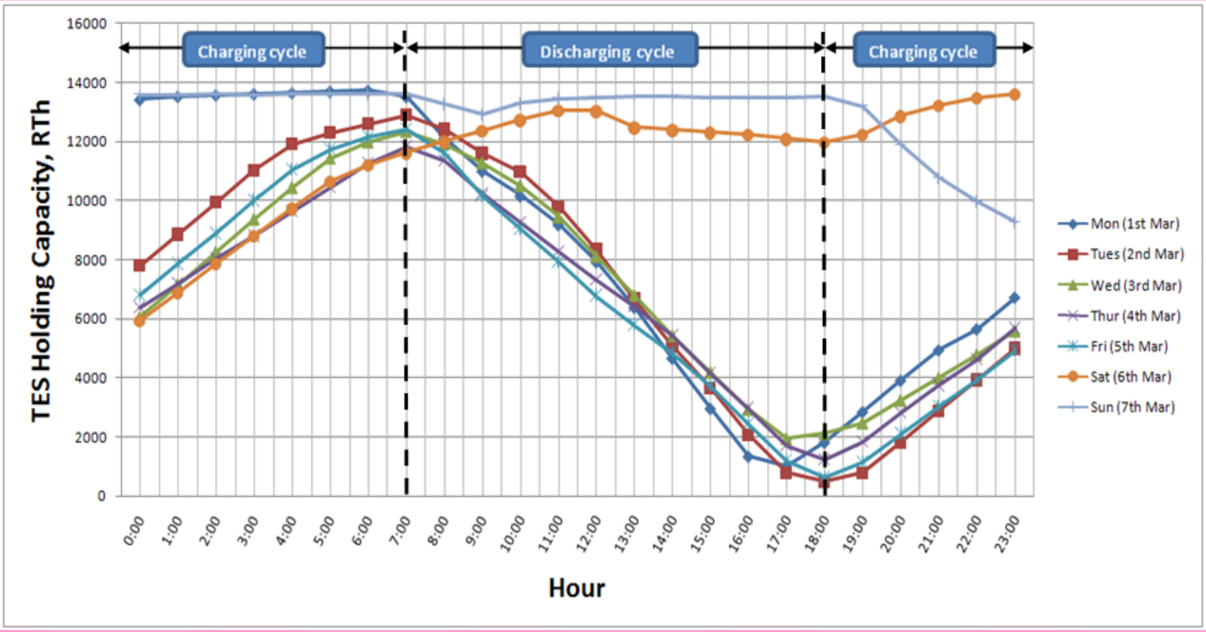

Figure 4.3: Thermal Energy Storage Holding Capacity, RTh for March 2010

a) In 1 week (22nd to 28th February), there are 7 charge cycles and 5 discharge cycles. For Friday and Sunday, there are only small amount of discharge made by TES tank. These means that TES tank completed one full cycle (charging and discharging) in a day.

b) During the week in March 2010 (1st until 7th March), there are 7 charge cycles and 5 discharge cycles. For Saturday and Sunday, there are only small amount of discharge made by TES tank. These means that TES tank completed one full cycle (charging and discharging) in a day.

c) From Figure 4.2 above, it can see that the holding capacity keep on increasing during the charging cycle (18:00 until 23:00 hours) and the capacity picked up for the next day during the charging cycle (00:00 until 07:00 hours). For example, for Monday the capacity was 661RTh at 18:00hours and increased to 5163RTh at 23:00 hours. This capacity then picked up at 00:00 hours on Tuesday where the capacity was 6191RTh. This pattern follows for everyday in the charging cycle.

d) From Figure 4.3 above, it is noted that the holding capacity keep on increasing during the charging cycle (18:00 until 23:00 hours) and the capacity picked up for the next day during the charging cycle (00:00 until 07:00 hours). For example, for Monday the capacity was 1816RTh at 18:00hours and increased to 6729RTh at 23:00 hours. This capacity then picked up at 00:00 hours on Tuesday where the capacity was 7785RTh. This pattern follows for everyday in the charging cycle.

e) The scheduling of charging and discharging processes were stable and fluctuating according to the demand from UTP campus. Averagely, the scheduling was stable on weekdays and fluctuating during the weekend. Based on Figure 4.2, during the weekdays (Monday until Thursday) the scheduling was stable. But for Friday the scheduling slightly varies, this is because it is a public holiday and the demand was low. On Saturday the scheduling was back to normal but with lower demand compared to the weekdays. And for Sunday, the scheduling was fluctuated again due to low demand on. For Figure 4.3, the scheduling of charging and discharging processes were rather stable on Monday until Friday. But for Monday morning, the holding capacity was quite high compared to other weekday’s morning.

f) From Figure 4.3, the discharging schedule on Saturday and Sunday was slightly varies with the scheduling during the weekdays. The chilled water demand from UTP during these days was low. However for Sunday, there was demand for chilled water where discharging was done during the night time.

4.2.2 Analysis of Electric Chillers

Figure 4.4 shows the hourly operation of electric chillers for the month of February and Figure 4.5 shows the hourly operation of electric chillers for the month of March.

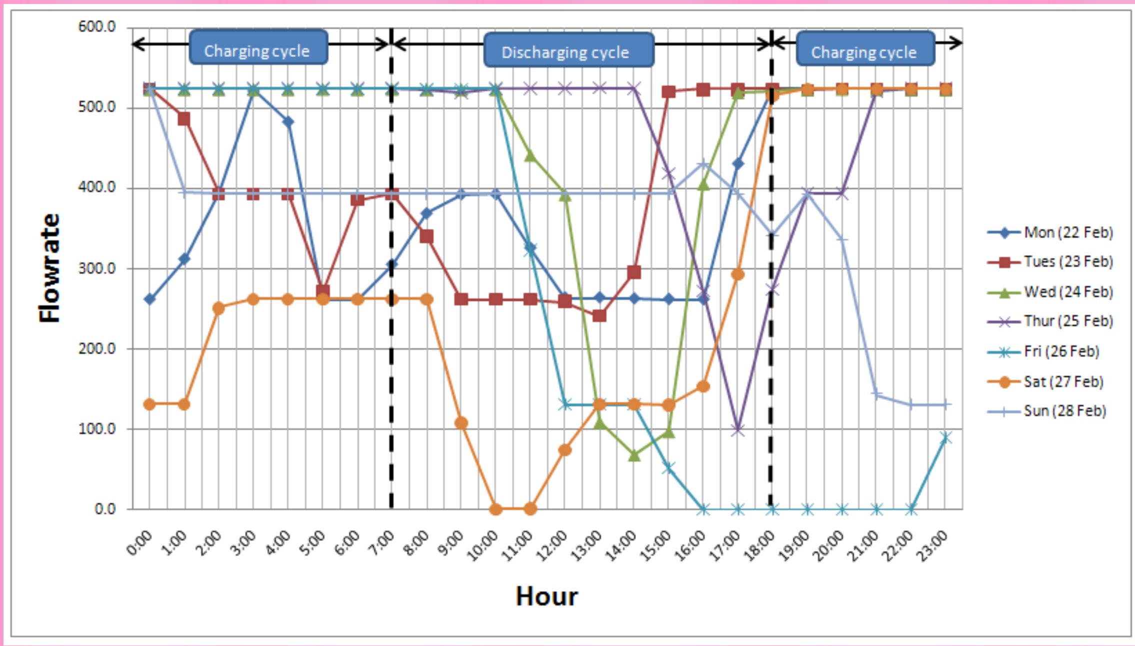

Figure 4.4: Hourly Operation of Electric Chillers for February 2010

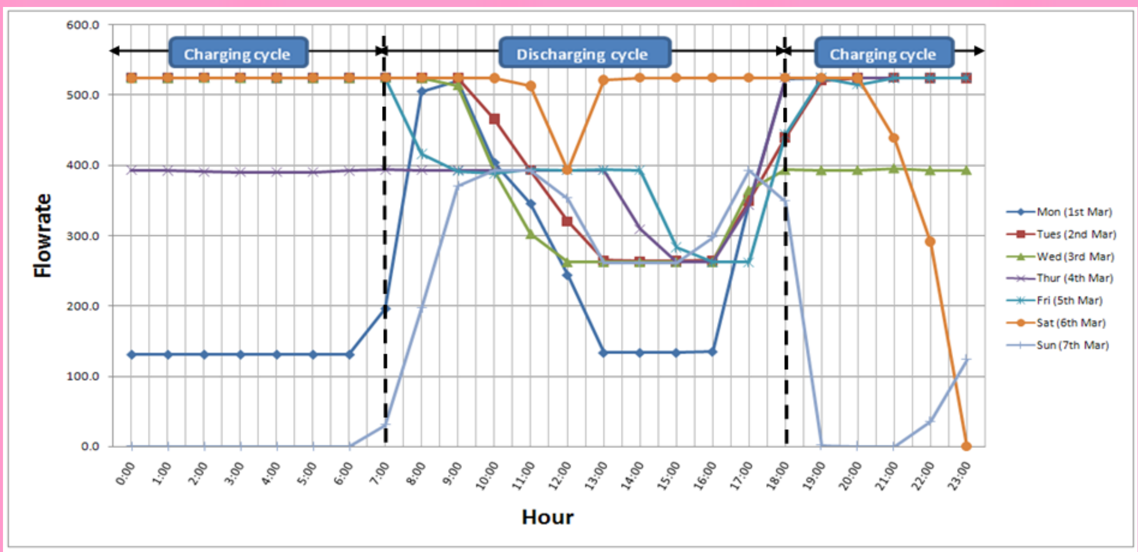

Figure 4.5: Hourly Operation of Electric Chillers for March 2010

a) UTP GDC thermal energy storage system was charged during the night time usually by 4 units of 325 RT electric chillers namely unit A, B, C and D. During the 1 week of performance analysis from 22nd until 28th February 2010, the output flowrate for each electric chiller was collected and the summation was presented in Figure 4.4

b) Figure 4.4 shows that there are four ECs were operated randomly during the night and day to meet UTP campus's requirement. Usually four ECs were running during the charging period which is the night time. But based on the graph plotted in Figure 4.4, the ECs were still running randomly during the day time. The chilled water produced during the day time was mostly used to add-on the chilled water demand that could not be met by the storage tank and the steam absorption chillers (SAC).

c) For the week in March 2010 (Figure 4.5), the apparent trend that the plant employed was by maximizing the chilled water produced by the ECs. During the charging cycle at the evening, most of the day (Monday, Tuesday, Thursday and Friday) was charged with the highest amount of flowrate which mean all 4 ECs were running. For Wednesday, charging schedule during the evening was not at the highest because only 3 ECs were running. For Saturday, the number of ECs running reduced by the hour. While for Sunday, only 1 EC were running towards the end of the evening.

d) In Figure 4.5, during the charging schedule at the early morning, most of the day (Tuesday, Wednesday, Friday and Saturday) was charged with the highest amount of flowrate which mean all 4 ECs were running. For Thursday, only 3 ECs were running. For Monday only 1 EC was running while no EC was running during Sunday. During the discharging period, the ECs were running randomly without any specific schedule.

4.2.3 Analysis on Performance

The summary of the performance of the TES tank during the week in February 2010 are included in Table 4.3 and for the week in March 2010 are included in Table 4.4. Base on the analysis, some points are noted:

Table 4.3: Summary of the performance of the TES tank for 22nd until 28th February 2010

Assessment/ Date	22-Feb	23-Feb	24-Feb	25-Feb	26-Feb	27-Feb	28-Feb	Avg	Max	Min
Charge duration, h	14	13	12	12	11	13	13	12.57	14	11
Discharge duration, h	10	11	12	12	13	11	11	11.43	13	10
Cint|char, RTh	2485.58	7403.98	7592.18	6338.72	5558.70	3877.14	2493.76	5107.15	7592.18	2485.58
Cint|disch, RTh	5546.78	7734.54	6886.35	6745.92	3632.80	5457.42	2614.91	5516.96	7734.54	2614.91
Avg charge rate, RT	556.30	764.80	897.15	824.67	742.63	200.31	549.14	647.86	897.15	200.31
Avg disch rate, RT	885.20	1030.00	770.17	921.33	362.00	787.60	214.00	710.04	1030.00	214.00
FOM1/2|char	0.25	0.74	0.76	0.63	0.56	0.39	0.25	0.51	0.76	0.25
FOM1/2|disch	0.55	0.77	0.69	0.67	0.36	0.55	0.26	0.55	0.77	0.26

Table 4.4: Summary of the performance of the TES tank for 1st until 7th March 2010

Assessment/ Date	1-Mar	2-Mar	3-Mar	4-Mar	5-Mar	6-Mar	7-Mar	Avg	Max	Min
Charge duration, h	12	13	13	13	13	16	16	14	16	12
Discharge duration, h	12	11	10	11	11	8	8	10	12	8
Cint|char, RTh	233.41	6980.42	7884.23	7890.05	8721.10	6194.61	1334.06	5605.41	8721.10	233.41
Cint|disch, RTh	7169.32	6724.64	7258.10	7561.45	7732.81	5343.34	1905.83	6242.21	7732.81	1905.83
Avg charge rate, RT	90.00	848.00	912.00	705.57	860.89	729.89	125.31	610.24	912.00	90.00
Avg disch rate, RT	1156.50	1143.50	1038.89	961.74	1071.90	152.98	269.98	827.93	1156.50	152.98
FOM1/2|char	0.02	0.70	0.79	0.79	0.87	0.62	0.13	0.56	0.87	0.02
FOM1/2|disch	0.72	0.67	0.73	0.76	0.77	0.53	0.19	0.62	0.77	0.19

a) From the result in Table 4.3, the average discharge duration of the TES tank from 22nd to 28th February was about 11.43 hours with a maximum of 13 hours and a minimum at 10 hours. For charging process, the average duration was 12.57 hours with a maximum of 14 hours and minimum of 11 hours.

b) The average of the integrated capacity during charging process was 5107.15RTh with a maximum at 7592.18RTh and minimum at 2485.58RTh. While the average for integrated capacity during discharging period was 5516.96RTh with a maximum of 7734.54RTh and minimum of 2614.91RTh.

c) The average charging rate from 22nd to 28th February was 647.86RTh with a maximum of 897.15RTh and minimum of 200.31RTh. For the discharging rate, the average was 710.04RTh with a maximum of 1030RTh and a minimum of 214RTh.

d) For the half-cycle figure of merit during the charging process, the average was 0.51 with a maximum of 0.76 and minimum of 0.25. While for the half-cycle figure of merit during the discharging process, the average was 0.55 with a maximum of 0.77 and minimum of 0.26.

e) From calculated result summarized in Table 4.4, the average charge duration for the week in March 2010 was 14 hours with a maximum of 16 hours and a minimum of 12 hours. While for discharging, the average duration was 10 hours with maximum 12 hours and minimum 8 hours.

f) The average integrated capacity during charging process was 5605.41RTh with a maximum at 8721.10RTh and a minimum 233.41RTh. While, the average integrated capacity during discharging period was 6242.21RTh with maximum of 7732.81RTh and minimum of 1905.83RTh.

g) From 1st to 7th March, the average charging rate was 610.24RTh with maximum at 912RTh and minimum at 90RTh. While the average discharging rate was 827.93RTh with a maximum of 1156RTh and minimum of 152.98RTh.

h) The average half-cycle FOM calculated for charging was 0.56 and 0.62 for discharging. For the charging cycle, the maximum half-cycle FOM was 0.87 and minimum of 0.02 while for discharging, the maximum was 0.77 and 0.19 was the minimum half-cycle FOM.

4.2.4 Calculation

From the data for the last week of February 2010 (22nd until 28th), the performance of the thermal energy storage tank was calculated. Below are sample of the calculation for 22nd February 2010 (Monday).

For charging cycle:

1) Integrated capacity for charging cycle

   $C_{Int|charge} = \sum m\, Cp \,|\, T_{in} - T_{out} \,|\, \Delta t$

   $= 2485.58$ RTh

   Value of m is the average of flow rate of the chilled water supplied by four electric chillers. Cp value for water is 4.2 kJ/ kg.K

2) Maximum capacity of the tank

   $C_{max} = 10\,000$ RTh

3) Half-cycle Figure of Merit

$$FOM_{1/2} = \frac{C_{Int|charge}}{C_{max}}$$

$$FOM_{1/2} = \frac{2485.58}{10\,000}$$

$$FOM_{1/2} = 0.25$$

4.3 DISCUSSION

a) As explained in the background study section, the principle of operation of thermal energy storage tank is based on the natural process of stratification, and hence the fluid flow within these tanks involves both forced and natural convection. The warm and cool water stored in the tank will naturally stratified themselves with the less dense water, warm water at the top and more dense water, chilled water at the bottom of the tank, while the mixing layer will be in between them. This process of stratification is proved by the plotted graph in Figure 4.1. From this graph, it can see that the temperatures are the highest at the top of the tank and lowest at the bottom of the tank. But these values vary from day to day since it depends on the number of chillers running, amount of chilled water produced, amount of cooling demand and other factors.

b) Charging and discharging value or thermal energy storage tank were based on daily requirements of chilled water from UTP

c) From the analysis of the data during the two weeks, it was noted that the ECs were operated during the whole discharging process or only for some period of the process. It was used to supplement the chilled water requirements that unable to be fulfilled by the steam absorption chiller and thermal energy storage tank.

d) The amount of chilled water discharged during weekends were small due to low demand from UTP, this were shown in the swerving of the graph.

e) During discharging process, a number of ECs were operated. The reason for this situation was because of the insufficient capacity of TES tank and SAC to serve the system during on-peak demand.

f) TES tank rarely made a complete discharged, this was evident from the holding capacity graph and the integrated capacity calculated. This remaining chilled water can still be used to serve the system.

g) The average of half-cycle figure of merit in February for charging was 0.51 and for discharging was 0.55, and in March for charging was 0.56 and for discharging was 0.62. Comparing this to the standard by Dorgan and Elleson (1993) in Bahnfleth and Amy Musser [7] stated “for a well stratified tank, the half-cycle figure of merit should be at least or exceed 90%”. The result calculated shows that GDC half-cycle figure of merit was low.

h) Analysis shows that the value of half-cycle figure of merit depends on

i. The duration of the charging and discharge cycles. The longer the time of cycle, the greater value of figure of merit. This is because sum of integrated capacity will be nearer to the value of maximum capacity of the tank.

ii. The number of electric chillers operated. This means higher flowrate of chilled water. By operating more chillers, the system can get higher value of half-cycle FOM for charging. However, it could lead to higher electrical cost.

4.4 CONTROLLING STRATEGY

From the result of the analysis of the data for the thermal energy storage tank and electric chillers operation during the two weeks, some problems and weaknesses are identified:

i. The operation of the chillers was random during the day. This leads to inconsistency of scheduling to the operation of the thermal energy storage tank and electric chillers.

ii. The capacity of the thermal energy storage tank was insufficient to meet the chilled water requirement. Thus, the plant was needed to run the electric chillers to supplement the chilled water demand during the day.

iii. Not all electric chillers were running during the charging cycle. Thus it took longer hours to charge the storage tank.

iv. From the result of integrated capacity, the charging process was unable to charge the tank fully at the current charging duration.

v. The half-cycle FOM was low. It indicates that there were large losses of cooling capacity during the charging and discharging cycles.

Possible solutions for this problem are described in details below:

i. Operate the ECs for longer period

Longer period of charging is needed to fully charge the thermal energy storage tank. It is because that not all ECs are running at the same time during the charging period. Thus, the production of chilled water is low. Based on the calculation done and summarized in Figure 4.6 below it shows that when the charging time is longer, the half-cycle figure of merit will be higher. This is consistent with the equation 2.4, 2.5 and 2.6. The tabulated results for Figure 4.6 are presented as in Table 4.5 below.

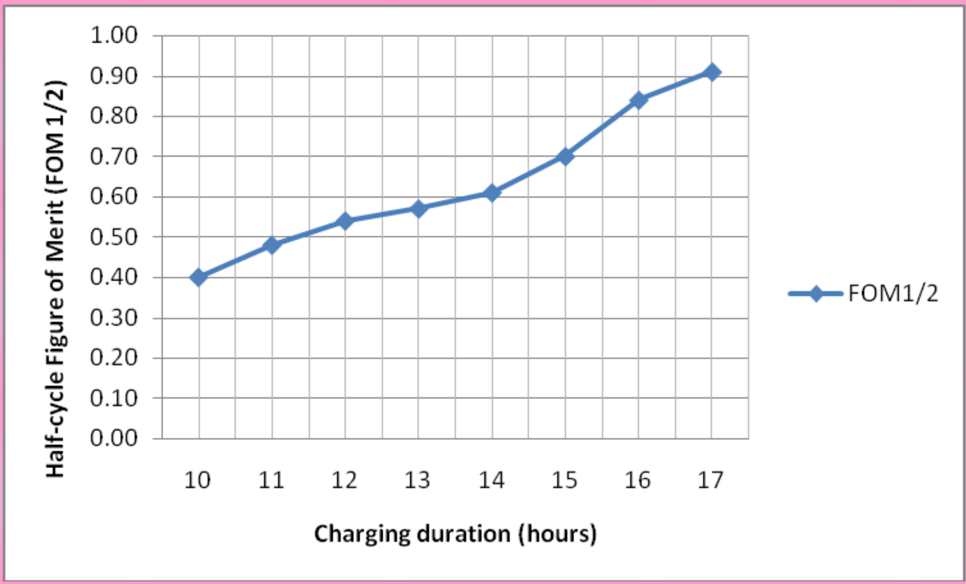

Figure 4.6: Summary of controlling by charging time.

Table 4.5: Summary of controlling by charging time

Charging Time	**$FOM_{1/2}$**
10	0.40
11	0.48
12	0.54
13	0.57
14	0.61
15	0.70
16	0.84
17	0.91

ii. Maximize chilled water flowrate

Based on equation 2.4, 2.5 and 2.6, integrated capacity will increase with higher flowrate of chilled water thus will increase the value of half-cycle figure of merit. Using those equations, a calculation was done and summarized as per Figure 4.7 below. From the graph, it can be seen that half-cycle figure of merit will be higher with higher flowrate of chilled water.

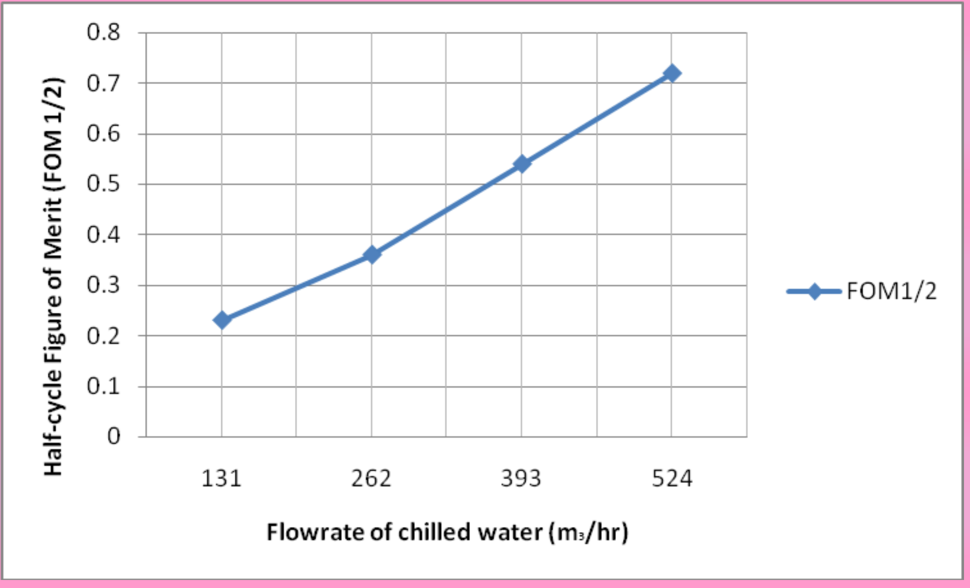

Figure 4.7: Summary of controlling by flowrate

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

a) Based on the design and the function of a stratified thermal energy storage tank, the top layer of the tank will be having the highest temperature while the bottom layer of the tank will be having the lowest temperature with a thermocline region in the middle. The range of temperature usually is around 15ºC at the bottom and 5ºC at the top of the tank.

b) The operating strategies of DGC were not fixed since the cycles were influenced by the varied demand from UTP. Hence, the scheduling sometimes changed.

c) During charging duration, not all 4 units of ECs were running. And during discharging duration, the ECs were operated randomly.

d) Integrated charge and discharge capacity for the tank was inconsistent. It was because the plant charged and discharged the thermal energy storage tank based on daily basis requirement of UTP.

e) The average of half-cycle figure of merit in February for charging was 0.51 and for discharging was 0.55, and in March for charging was 0.56 and for discharging was 0.62. Comparing this to the standard by Bahnfleth and Amy Musser [7] stated "for a well stratified tank, the half-cycle figure of merit should be at least or exceed 90%". The result calculated shows that GDC half-cycle figure of merit was low.

5.2 Recommendation

As discussed in chapter 4, the thermal energy storage system at GDC plant was not operated at its optimal scheduling. The scheduling can be enhanced by operating the electric chillers at longer period. Besides, higher flowrate of chilled water is also a viable option to get higher half-cycle figure of merit.

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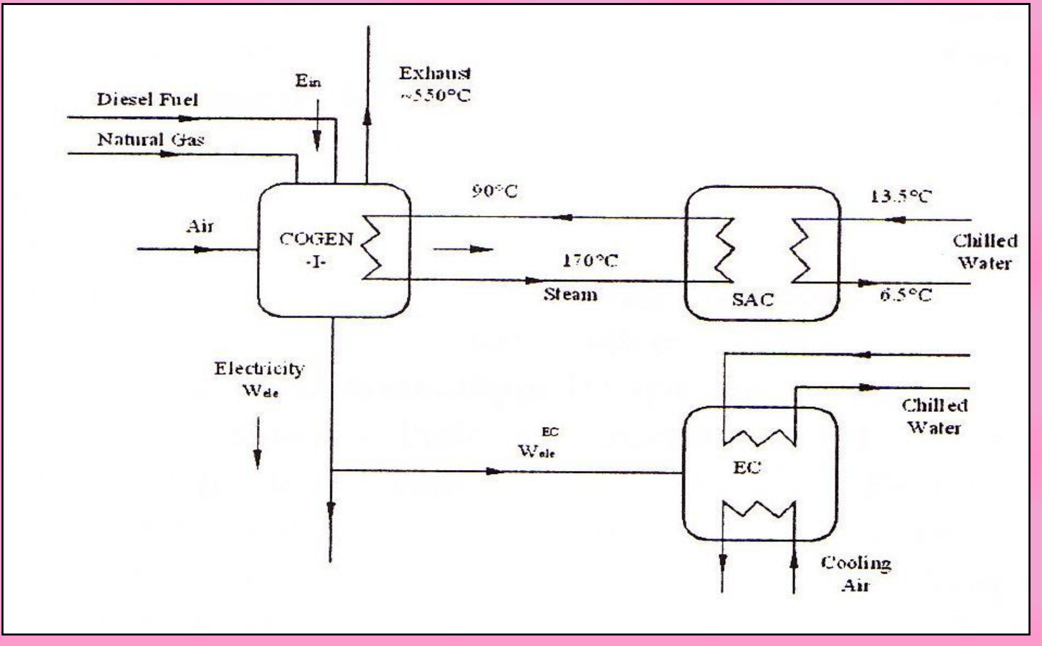
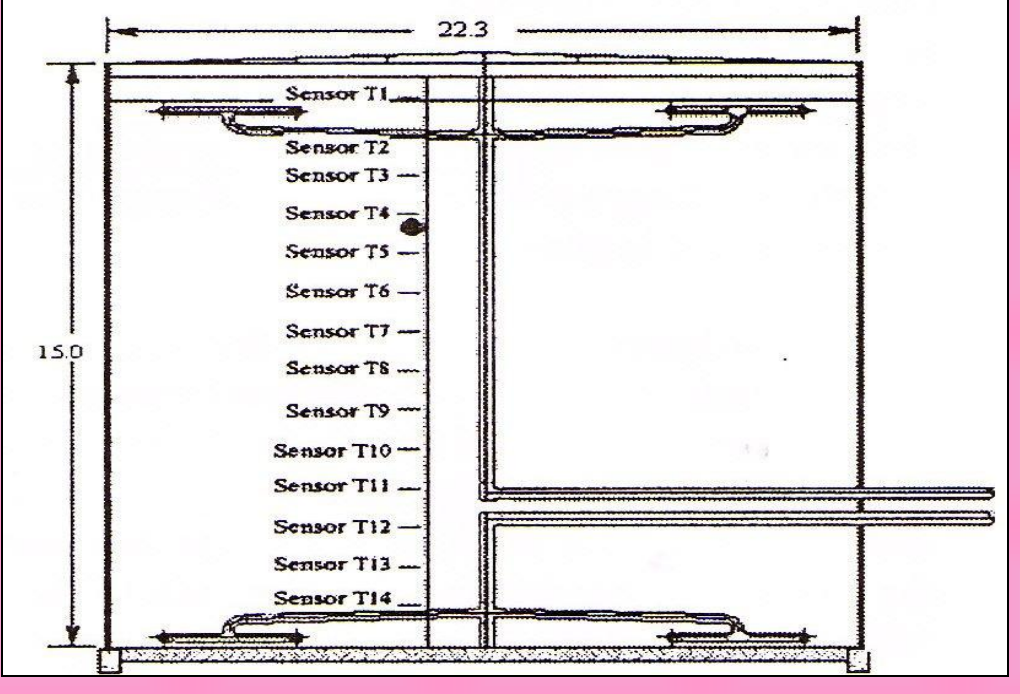
APPENDICES

Appendix A



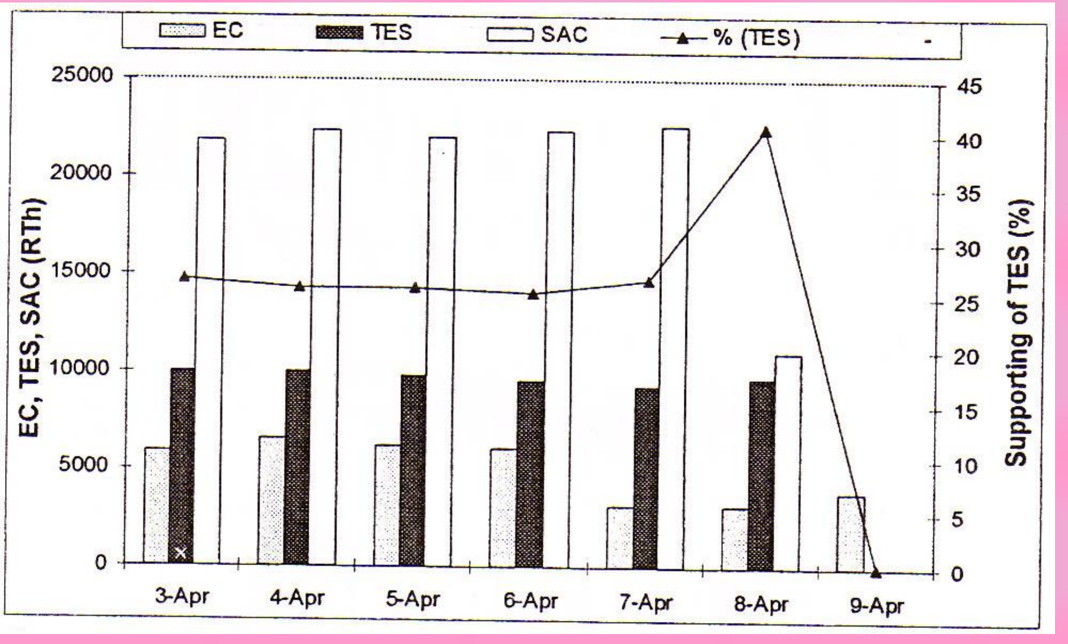
Simplified process diagram of UTP GDC [12]

Appendix B



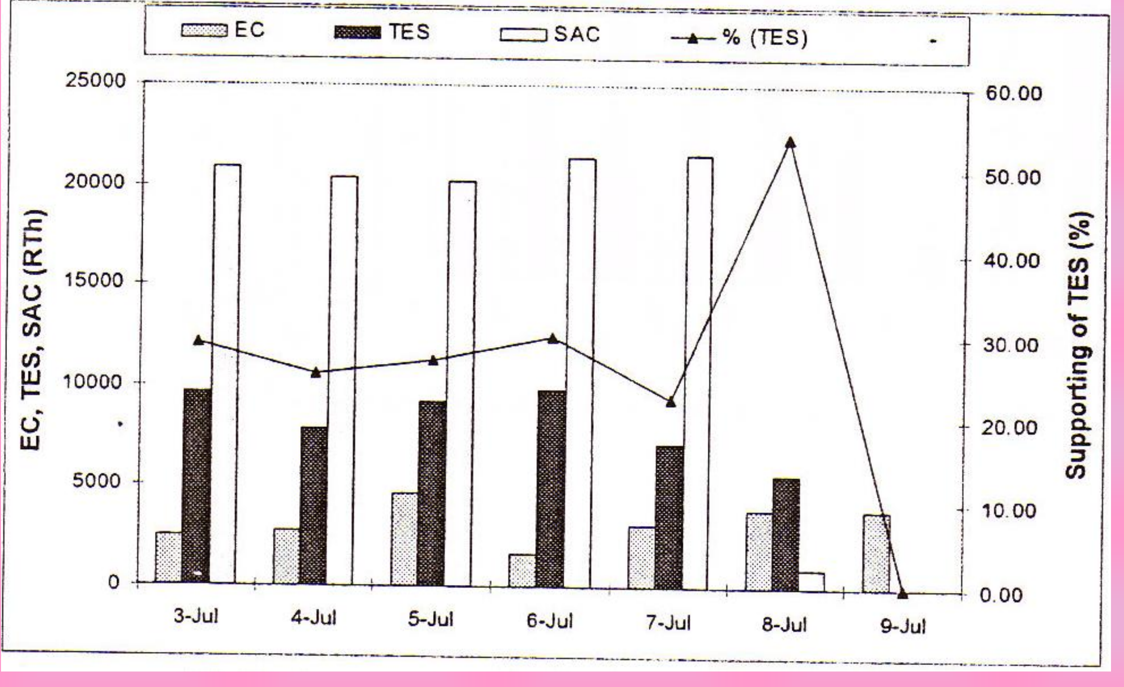
Configuration of TES tank dimension and location of temperature sensors [1]

Appendix C



Chilled water supply during on-peak cooling demand at the first week of April 2006 [1]

Appendix D



Chilled water supply during on-peak cooling demand at the first week of July 2006 [1]

Appendix E

Thermal Energy Storage Holding Capacity, RTh for February

	TES Holding Capacity , RTh						
Hour	Monday (22nd Feb)	Tuesday (23rd Feb)	Wednesday (24th Feb)	Thursday (25th Feb)	Friday (26th Feb)	Saturday (27th Feb)	Sunday (28th Feb)
0:00	3594	6191	4808	6945	5804	11255	12455
1:00	4170	7182	5901	7958	6967	11546	12880
2:00	4786	7989	6968	8963	8104	11802	13044
3:00	5559	8726	8037	10058	9176	12349	13188
4:00	6481	9489	9141	11168	10345	12959	13346
5:00	7051	10121	10230	11897	11429	13237	13487
6:00	7637	10719	11194	12225	12110	13373	13592
7:00	7985	11490	11823	12477	12435	13476	13708
8:00	6923	10460	11425	11116	12699	12908	13497
9:00	5560	8734	10695	9873	12923	12488	12809
10:00	4889	7083	10535	9341	13152	11570	12862
11:00	4119	5660	10417	8595	13306	10629	12825
12:00	2862	4266	9748	7957	13104	9463	12744
13:00	1585	2637	8932	7397	12665	8603	12857
14:00	469	998	8251	6260	12472	7974	13019
15:00	73	404	6721	5015	12088	7254	13279
16:00	18	297	4825	3741	11424	6048	13213
17:00	57	214	3355	2982	10893	5600	12696
18:00	661	160	2757	2070	10872	6095	12676
19:00	1471	240	2581	1421	10898	7183	13397
20:00	2315	1014	3037	1882	10929	8287	13495
21:00	3244	1880	3961	2619	10938	9316	13242
22:00	4204	2804	4963	3616	10956	10389	12950
23:00	5163	3758	5931	4695	11009	11473	13103

Appendix F

Thermal Energy Storage Holding Capacity, RTh for March

Hour	TES Holding Capacity , RTh						
	Monday (1st March)	Tuesday (2nd March)	Wednesday (3rd March)	Thursday (4th March)	Friday (5th March)	Saturday (6th March)	Sunday (7th March)
0:00	13420	7785	6044	6381	6805	5939	13584
1:00	13532	8844	7155	7200	7865	6873	13588
2:00	13580	9932	8252	8035	8894	7848	13608
3:00	13617	11018	9367	8800	10011	8801	13577
4:00	13651	11908	10433	9626	11073	9735	13609
5:00	13702	12297	11425	10455	11763	10654	13609
6:00	13733	12586	11979	11273	12165	11200	13604
7:00	13525	12884	12330	11819	12431	11613	13607
8:00	12116	12401	11903	11363	11628	12009	13255
9:00	11004	11583	11274	10252	10166	12371	12905
10:00	10161	10971	10501	9250	9044	12732	13289
11:00	9189	9775	9438	8273	7918	13049	13454
12:00	7932	8338	8103	7325	6787	13031	13498
13:00	6389	6676	6783	6409	5801	12477	13533
14:00	4664	5058	5423	5416	4855	12385	13535
15:00	2963	3644	4186	4149	3736	12306	13497
16:00	1341	2045	2923	2967	2448	12228	13500
17:00	1012	777	1941	1701	1196	12088	13496
18:00	1816	474	2108	1240	640	11978	13526
19:00	2846	775	2473	1823	1162	12231	13195
20:00	3914	1794	3240	2820	2110	12856	11895
21:00	4942	2867	3991	3746	3027	13222	10779
22:00	5655	3910	4774	4632	3953	13479	9976
23:00	6729	4982	5577	5676	4948	13604	9287