ENERGY MANAGEMENT IMPLEMENTATION IN AN OFFICE BUILDING VIA PEAK SHAVING METHOD

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Abstrak

Dewasa ini, penggunaan elektrik per capita telah menjadi rujukan utama bagi tahap pembangunan sesebuah negara. Penggunaan elektrik dalam negara-negara maju dan negara-negara membangun telah dikaji secara meluas dan hasil kajian telah menjadi sumber ilham bagi penentuan polisi untuk mengelakkan berlakunya sebarang pembaziran. Dalam semua jenis pengguna elektrik, bangunan bagi tujuan komersial merupakan pengguna kedua terbanyak di dunia, di mana sistem penyamanan udara menggunakan bahagian yang besar dalam konteks penggunaan elektrik. Secara tipikalnya, sistem penyamanan udara mengunakan 16%-50% daripada jumlah penggunaan elektrik. Keadaan ini bertambah kritikal dalam negara yang berada di iklim tropical seperti Malaysia di mana angka peratusan meningkat ke 57%. Bagi mengawal penggunaan elektrik, beberapa langkah telah diusahakan dalam pengurusan beban pendinginan di mana sistem direka dalam sifat yang akan membawa harmonik dalam produksi dan permintaan tenaga elektrik. Dalam kajian ini, penggunaan aplikasi penyimpanan sejuk tenaga haba dalam teknik pengurusan beban pendinginan melalui pemotongan puncak telah dianalisa secara kritikal dari pelbagai sudut, bermula dari penilaian thermodinamik sehingga impak alam sekitar serta taksiran ekonomi.

Dalam kajian ini, tinjauan medan telah dilakukan ke atas bangunan pejabat 10 tingkat yang baru selama 6 bulan untuk penghitungan corak permintaan elektrik secara mingguan. Permintaan elektrik, suhu di dalam dan luar bangunan, kelembapan dalam dan luar bangunan, keamatan cahaya, kepekatan gas CO dan CO_2 direkodkan secara berterusan dengan jeda masa yang singkat serta kejituan yang tinggi. Kejituan data yang direkodkan telah dianalisa dan ketidakpastian telah ditentukan. Hasil daripada tinjauan

medan ini ialah corak permintaan elektrik yang akan digunakan untuk menilai prestasi sistem pendinginan yang lazim dan mereka beberapa tatarajah sistem dengan menggunakan aplikasi penyimpanan sejuk tenaga haba.

Taksiran termodinamik menunjukkan aplikasi penyimpanan sejuk tenaga haba adalah berprestasi tinggi dalam erti kata kecekapan tenaga dengan kecekapan minima 93% dan maksima 98%. Walaubagaimanapun, kecekapan eksergi bagi sistem ini adalah jauh lebih rendah daripada kecekapan tenaga, dengan catatan kecekapan eksergi maxima sebanyak 18% bagi sistem ais pada gegelung (ice-on coil). Impak ekonomi hasil daripada penggunaan sistem penyimpanan sejuk tenaga haba disiasat dari dua segi yakni impak jangka pendek dan jangka panjang. Hasil kajian menunjukkan strategi penyimpanan penuh mampu mengurangkan kos elektrik sistem penyamanan udara sebanyak 35% setahun, manakala pengurangan sebanyak 8% bagi strategi pengarasan beban. Jangka masa bayaran balik strategi penyimpanan penuh adalah dalam jangka masa 3-6 tahun manakala 1-3 tahun bagi strategi pengarasan beban. Akhirnya, sistem yang dicadangkan telah diselakukan melalui perisian penyelakuan TRNSYS untuk meramal kelakuan sistem sepanjang tahun. Walaupun proses penyimpanan memerlukan lebih banyak tenaga pengepaman, tetapi dendanya boleh diabaikan dibandingkan dengan manfaat tenaga dan ekonomi yang luar biasa. Dari perspektif ini, maka ia boleh dikatakan penggunaan aplikasi penyimpanan sejuk tenaga haba boleh memainkan peranan yang penting dalam menggunakan sumber asli secara lebih cekap dan ekonomik, serta mesra alam sekitar dengan menukar corak penggunaan elektrik bagi mengatasi ketidakseimbangan penjanaan elektrik dan permintaan elektrik.

Abstract

In our today's world, one of the main indicators of a country's development is its electricity usage per capita. The electricity usage in developed and developing countries are critically being studied by the researcher and the results are being used by the policy makers in order to get the most from every drop of the valuable energy resources. Among all energy consumers, the commercial buildings are known as the second most electricity users around the world, in which the air conditioning (AC) systems have a significant share. Between 16% to 50% of the total electricity demand in the commercial buildings is dedicated to the AC systems, this share increased in tropical conditions of Malaysia up to 57%. In order to control the electricity demand, several methods have been established so far under the load management techniques in which the system is designed in a manner to bring more harmonic between electricity production and demand. In the context of this study, the application of utilizing cold thermal energy storage (CTES) system for building load management technique via peak shaving method is critically analysed through various viewpoints from thermodynamic evaluation to the environmental impact and economic assessment.

In the present work, a detailed field survey was conducted on a newly build 10-story office building for a period of 6 months to calculate the average weekly electricity demand pattern. The electricity demand, inside and outside temperature, inside and outside humidity, the light intensity, CO and CO_2 concentration levels were recorded continuously with short intervals and high accuracy. The accuracy of the recorded data was analysed and the uncertainty level was calculated. The resulted energy demand

pattern was used to evaluate the conventional system performance and to design various system configurations by utilizing CTES application.

The thermodynamic assessment shows that the CTES systems are highly efficient in terms of energy efficiency with minimum efficiency of 93% and maximum of 98%. However, the exergetic efficiencies were much lower than the energy efficiency, the maximum exergy efficiency for ice-on-coil system was obtained to be 18%. The economic impact of utilizing CTES systems was also investigated from two different viewpoints of short-term and long-term impacts. The result reveals that the full storage strategy can reduce the annual cost of the AC system up to 35% while this reduction is limited to around 8% for a load levelling strategy. The payback period of the full storage strategy varies between 3 to 6 years while the payback period for the load levelling strategy varies between 1 to 3 years. The energetic analysis reveals a potential for energy saving of up to 3.7% by implementing load levelling storage strategy that would consequently reduce the carbon footprint. Finally yet importantly, the proposed system was simulated via using TRNSYS simulation software in order to predict system behaviour throughout the year. The computer simulation was validated with the recorded data from the building. The validated model was used to calculate the potential energy saving by using CTES system. The results confirmed the approximate 4% energy saving potential of load levelling storage strategy. From this perspective, it can be stated that utilizing CTES system can play a vital role in consuming the natural resources in a more efficient, economic and environmentally benign way by changing the electricity consumption pattern to overcome the disparity between energy generation and energy demand.

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Behzad Rismanchi

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Table of contents

List of figures

List of tables

List of symbols and abbreviations

A	area (m^2)
AC	air conditioning
ACH	air change per hour
AHU	air handling unit
ARI	air-conditioning and refrigerating institute
ASHRAE	American society of heating, refrigerating and air-conditioning engineers
c	thermal conductivity
C	cost ($)
CFC	chloro-fluoro-carbons
CFL	compact fluorescent lamps
CI	confidence interval
CLF	cooling load factors
CLTD	cooling load temperature difference
CO	carbon monoxide
CO_2	carbon dioxide
COP	coefficient of performance
$\cos\varphi$	power factor
CRF	capital recovery factor
CTES	cool thermal energy storage
CWS	chilled water storage
DB	dry bulb
DE	district energy
DF	diversity factor
DR	mean daily temperature range
DSM	demand side management
e	electricity
E	energy
Ex	exergy
GWh	Giga Watt hour
h	hour / enthalpy

h_{fg}	latent heat of fusion
HVAC	heating, ventilating and air conditioning
I	current / irreversibility
i	interest rate (%)
IAQ	indoor air quality
ITS	ice thermal storage
JC	Johnson control
kW	kilo Watt
kWe	kilo Watt electrical
kWh	kilo Watt hour
kWt	kilo Watt thermal
lit	litter
LM	correction factor for different latitudes and months
m	mass / meter
M&E	mechanical and electrical
MWe	Mega Watt electrical
MWt	Mega Watt thermal
n	number of years
P_0	dead state pressure
PB	payback
PB	payback period
PCM	phase change material
PPM	parts per million
Q	heat flux
R	thermal resistance
RH	relative humidity (%)
RT	refrigeration tone
s	entropy
SC	shading factor
SCL	solar cooling load
$SHGF_{max}$	maximum solar heat gain factor
T	temperature
t	time

T_0	dead state temperature
TD	difference between indoor and outdoor temperature
TES	thermal energy storage
TMY	typical meteorological year
TNB	Tenaga Nasional Berhad
TOU	time of use
TRNSYS	transient systems simulation software
U	overall heat transfer coefficient
UM	University of Malaya
V	voltage / volume
w	humidity ratio
W	Watt / work

Greek symbols

μ	confidence interval
Δt	changing time
ε	effectiveness
η	energy efficiency
ρ	density
σ	standard deviation
ψ	exergy efficiency

Subscripts

amb	ambient
ch	charging
cond	condenser
dc	discharge
des	desired
evap	evaporator
f	fluid / liquid
final	final
g	glycol
ice	ice

ideal	ideal
in	inlet
inf	infiltration
initial	initial
l	latent
leak	leakage
max	maximum
ml	melting
op	operating
op	operating
out	outlet
ref	refrigerant mass
req	required
ret	return
room	room
s	sensible
st	storage
sup	supply
surr	surrounding
sys	system
T	tank
th	thermal
total	total
trf	tariff
uti	utility
vent	ventilation

Chapter 1. Introduction

1.1 Background

In our today's world, the main indicator of a country's development is its electricity usage per capita. The share of electricity usage in developed and developing countries are remarkably different, especially in industrial and commercial sectors. In the industrial sector, the motors are known as the main energy users. On the other hand, in the residential sector the electricity is mainly utilized for indoor air heating and/or cooling. Based on a research presented by (US Green Building Council, 2007), in the United States, buildings account for 38% of carbon emission that is more than the transportation or industrial sectors. This number is projected to grow even faster than other types over the next 25 years, with a rate of 1.8% per year through 2030. There are several ways to reduce the total electricity usage via electric load management techniques.

Air conditioning (AC) systems account between 16% to 50% of electricity use in many regions around the world, especially in hot and humid countries near the Equator in which the share of electricity consumption is relatively higher (Saidur et al., 2007a). In Malaysia, AC systems are the major energy consumers in office buildings with around 57% share (Saidur, 2009). Unlike other building electricity consumers, cooling is only required for a few hours of the day.

The accumulated energy demand of many customers shows a peak during certain times during the day, since customers are exposed to roughly the same ambient conditions and will have similar occupation profiles (due to similar business hours). The peak usually occurs in the late afternoon on regular workdays. The utility providers have to provide the necessary peak capacity to satisfy its customers, but during most hours of the days the required energy is significantly lower than the peak capacity. Therefore, the equipment operates at a low fraction of their capacity (part load ratio). The utility's average power generation effectiveness (the fraction of electric energy produced over the amount of primary energy used) will therefore be lower if there were fewer capacities and a higher daily part load ratio. This, in turn, means higher cost of electric energy. Generally, electricity usage is divided into two operating periods of daytime (peak hours) and night-time (off-peak hours) when electricity is cheaper and often the ambient temperature is lower.

Demand side management (DSM) is defined as the planning, implementation and monitoring of distribution network utility activities that are designed to influence the customer use of electricity in ways that will produce desired changes in the load shape, for instance, change the pattern of electric use. DSM techniques are generally categorized into six categories of flexible load shape, strategic load growth, strategic conservation, load shifting, peak clipping and valley filling that are presented in Figure 1.1. There are several options that can be implemented to make the energy demand follow the energy production pattern, among them the load shifting technique is the most applicable method for the residential sector. In this strategy, the energy demand is shifted from the peak to the off-peak hours. This technique is also called "peak shaving method".

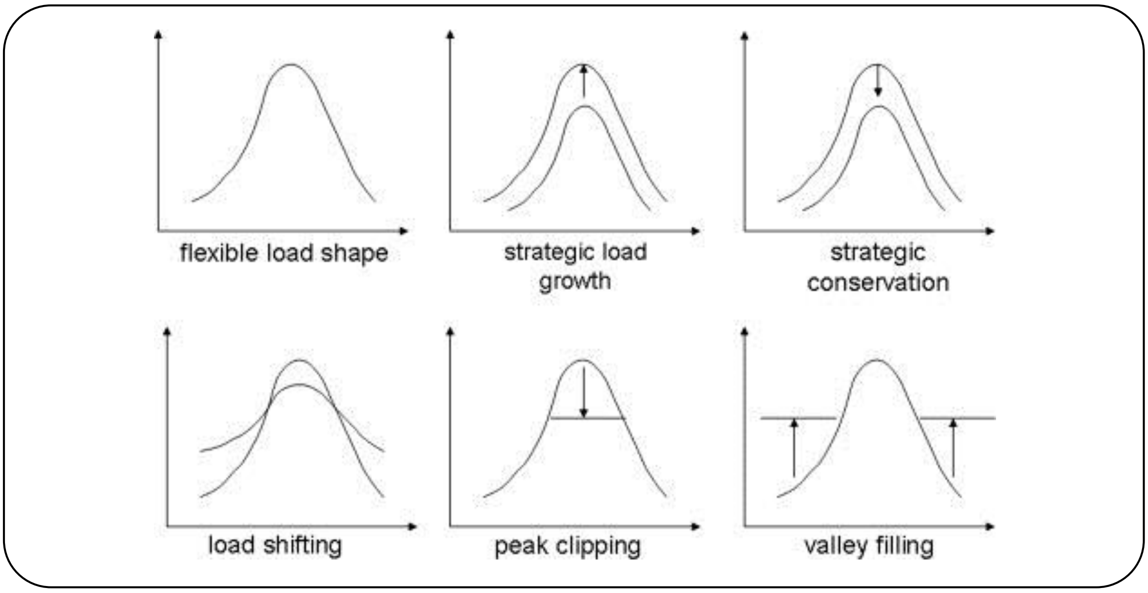


Figure 1.1: Demand side management categories (Arteconi et al., 2012).

One of the promising methods for levelling the energy demand and production in the residential buildings is utilizing cold thermal energy storage (CTES) systems. Generally, thermal energy storage systems refer to a number of technologies that store energy in a thermal reservoir for later reuse. They can be employed to balance energy demand between daytime and night-time. The thermal reservoir may be maintained at a temperature above (hotter) or below (colder) than that of the ambient environment. CTES is a technology whereby cool energy is stored in a thermal reservoir during off-peak periods. The stored cooling is later used to meet an AC or process cooling load (Dincer and Rosen, 2002; 2007b). Consequently, the offset in electricity demand is accompanied by an improved system performance (MacCracken, 2003) and reduced total cost (Tabors Caramanis and Associates, 1996). The gradual development of CTES technology over the past decade has allowed for wide deployment in many countries, and it is now considered as one of the best energy saving approaches for AC systems.

Nowadays, many electricity providers have recognized the potential of CTES systems to change electricity demand pattern, and now offer special pricing structures as incentives for energy users to deploy CTES systems. CTES systems are widely used for different building applications that are mainly occupied during the working hours. Figure 1.2 illustrates the general differences between conventional AC systems and CTES systems. The most common medium for storing cold energy are ice, chilled water or eutectic salt phase change materials (PCM) (Al-Rabghi and Akyurt, 2004). Hence, CTES systems are generally categorized into three major types of; ice thermal storage (ITS), chilled water storage (CWS) and eutectic salt thermal energy storage systems (Dorgan and Elleson, 1994). Although CTES is a mature technology, considerable potential exists to further optimize their performance.

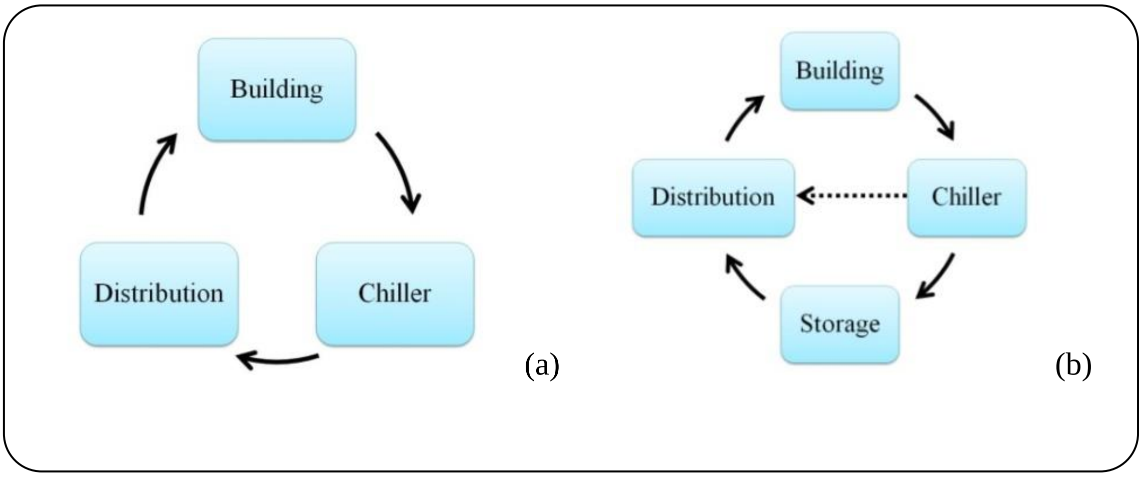


Figure 1.2: The difference between (a) a conventional AC system and (b) a CTES system.

Depending on the utility's time of use (TOU) rates and system operational strategy, and assuming that the storage system is well designed for the customer's needs, the customer's electricity bill can drop significantly, paying off the investment for the storage system within a few years.

1.2 Problem statement

Malaysia is a country located near the equator with around 329,733km^2 area and a tropical climate with an average temperature varied from 20°C to 32°C and an average rainfall of about 3540mm per annum (Electricity Supply Department, 2005). Like any other developing country, Malaysia has experienced a rapid economic growth in the past decade. In the past 50 years the statistical data (Electricity Supply Department, 2005; UNDP, 2006) showed that residential electricity consumption has increased dramatically in a way that the number of AC systems used increased from 13,251 units in 1970 to 253,399 in 1991 and it is predicted that the number will reach to around 1.5 million in the year 2020 (Mahlia et al., 2002a; Mahlia et al., 2002b). The total energy usage of AC systems is increased from 1237GWh in 1999 to around 2277GWh in 2009 and it is predicted to reach to around 3055GWh in 2015 (Saidur et al., 2007b).

Total energy demand breakdown of electrical appliances utilized in an office building in Malaysia shows that AC systems are the major energy users (57%) followed by lighting (19%), lifts and pumps (18%) and other equipment (6%) (Saidur, 2009). It is estimated that a considerable amount of energy can be saved and a remarkable reduction of emissions can be achieved through the application of advance glazing, compact fluorescent lamps (CFL), peak shaving, thermal energy storage, insulation and controlling the thermostat set point temperature.

Distributing the energy to the buildings at night-times when line losses are low and production efficiencies are high, reduces the use of old power plants and consequently reduces emission production. CTES system reduces peak electric demand and it stores what that demand is normally needed for, which is cooling. On the other hand, CTES system reduces source-energy use, which means that energy providers will generate fewer polluting emissions. In numerous studies, it is proved that electricity is produced and delivered much more efficiently during off-peak hours than during peak periods. For every kilowatt-hour of energy that is shifted from peak to off-peak period, there is a reduction in the amount of the source fuel needed to generate it. The reduction in source fuel normally results in a reduction of greenhouse-gas emissions produced by the power plant.

In this study, a fieldwork survey was conducted on a newly build 10 story office building in University of Malaya for a period of 170 days. The fieldwork data were used to evaluate the system performance, also the data were used to design and propose different CTES systems to reduce energy demand and save the electrical fee. The proposed system was critically analyzed from different aspects such as; thermodynamic assessment (energy and exergy analysis), the economic impact, and the long term benefits of utilizing CTES systems.

1.3 Research objectives

The main objectives of this research are as follows:

a) To analyse different methods of storing cold thermal energy for residential sector that can be used for peak shaving purpose,
b) To develop design procedure for CTES systems, and evaluate the trend of electricity demand, the peak and off-peak hours, and the electricity tariff rates in Malaysia,
c) To conduct a fieldwork survey in a newly build office building in Malaysia to assess its energy demand through a complete energy management analysis,

d) To calculate the performance of different CTES techniques through thermodynamic assessment and evaluate the possible energy saving potential,

e) To evaluate the economic and environmental impact of using ITS for office building application for various cooling demand capacities, and to assess the cost-benefits of retrofitting ITS systems in building applications on the Malaysian economy,

f) To develop a computer model to simulate ITS system behaviour based on the Malaysian climates to calculate the possible energy saving potential.

1.4 Contribution of the thesis

Considering the great potential of the Malaysian residential sector to utilize the DSM programs, the results from this survey can be used for various buildings in the country. In this regard, a newly built office building in the University of Malaya (UM) is selected to evaluate its potential for energy saving, cost saving and pollution reduction by utilizing the methodology presented in this research. The results are presented as different strategies to minimize thermal losses, reduce total cost and decrease energy demand.

1.5 Thesis organizations

This thesis is composed of five chapters. The introductory chapter places the work broader context and provide basic information about the topic. The relevant background information and a comprehensive review on recent works on the field are presented in Chapter 2. Chapter 3, address the methodological approach of the work and presents the applied models and governing equations, in addition, the systematic fieldwork procedure required to obtain the baseline data is discussed, and finally the computer simulation method is described in details. Chapter 4 summarises the results and the main insights of the work. The main findings of the work are summarized and further research suggestions are presented in Chapter 5. All the other materials used in this work are presented in the Appendixes. Figure 1.3 shows the overall thesis organization graphically.

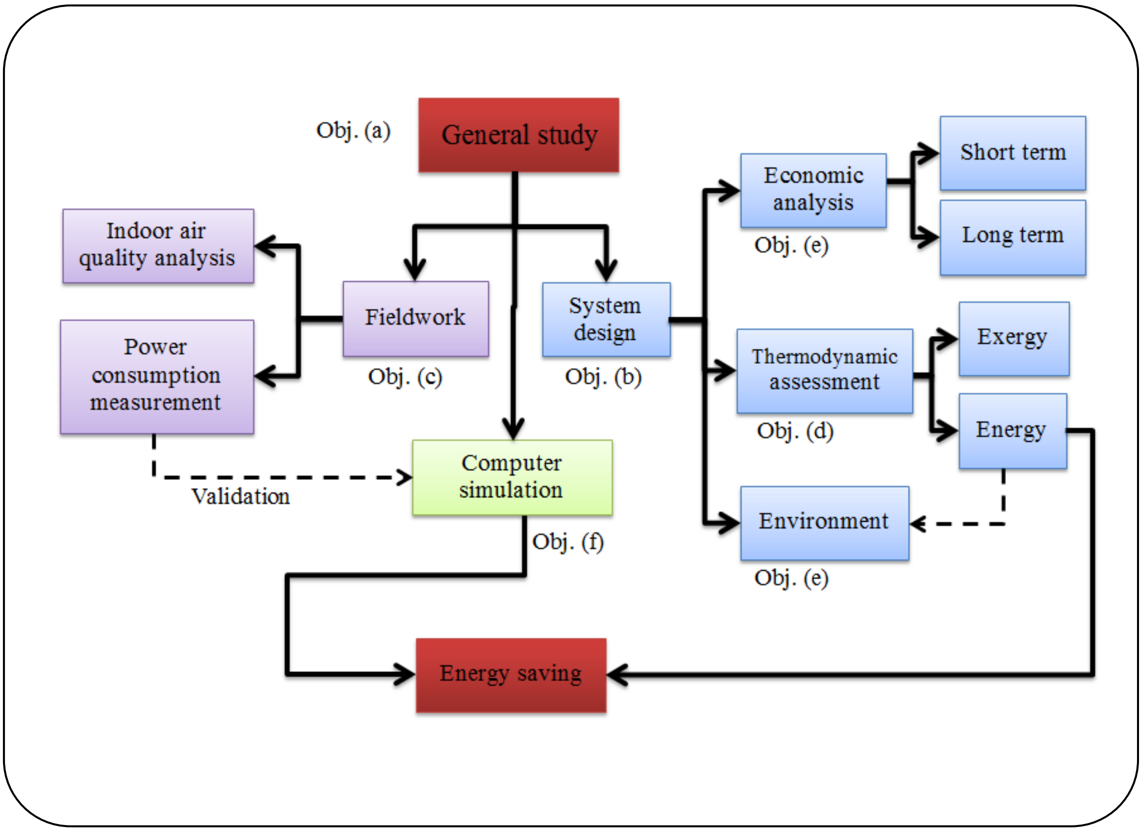


Figure 1.3: The graphical demonstration of thesis organization.

Chapter 2. Literature review

People have taken advantage of natural cooling for thousands of years. Caves, holes dug in the ground, springs, ice, snow and evaporative cooling have all been used to cool foods and drinks. However, natural cooling has limitations and its availability depends on location, weather conditions, and it has never been adequate to chill large quantities for long periods. Before the 19th century as there was no mechanical refrigeration system, any artificially cooling would be possible by using natural phenomena like ice, snow, underground cold water or natural evaporating cooling (Nagengast, 1999). Nowadays, as the cool generator systems are becoming more developed, the existence of the storage devices is unavoidable. Generally, thermal energy storage (TES) systems help reserving the energy in thermal reservoirs for later usage. They are designed to store either the higher (heat) or the lower (cold) temperature in comparison with their environment (Dincer and Rosen, 2002). The energy might be charged, stored and discharged daily, weekly, yearly or in the seasonal cycles (ASHRAE, 2007b).

The cool energy is usually stored in the form of ice, chilled water, phase change materials or eutectic solution during the low electricity demand hours (Al-Rabghi and Akyurt, 2004; Bahnfleth and Song, 2005). The heat TES system frequently stores the collected heat from solar collectors in the packed beds, steam storage tanks or solar ponds to be used later in the domestic hot water process or for electricity generation applications (Karakilcik et al., 2006; Guo and Zhang, 2008; Regin et al., 2009). The TES systems can be employed to balance the energy demand between the peak and off-peak hours (normally days and nights). There are also small but growing numbers of seasonal TES systems that store the summer heat for the purpose of space heating during the winter and store the winter cool for summer cooling. They have been perused in previous studies and have been found as a practical application (Ucar and Inalli, 2008; Karacavus and Can, 2009; Novo et al., 2010; Wang et al., 2010).

2.1 Cold thermal storage system

Reserving cold thermal energy for later use is not a new concept, during the past century people harvest ice from the natural ice caves or from frozen rivers to keep themselves cold during the summer or to preserve their stored food. The primary benefit of employing CTES systems is to shift the power consumption from the peak to the off-peak periods, especially in cases when electricity is used, thus they are often named as "off-peak cooling" systems. Besides, due to the constant and comparatively lower temperature during the nights, usually they would consume less operating energy compared to the conventional air conditioning systems. It is important to know that reserving cool is significantly cheaper than storing electric power to make cooling (MacCracken, 2010). Based on the report of the California energy commission (Tabors Caramanis and Associates, 1996), producing off-peak electricity would consume less fuel that makes it cheaper.

Many applications of CTES systems have been employed in the industry. Many of them have focused on different technologies and strategies to store the cool-energy for building applications by using thermal reservoirs or by pre-cooling control systems (Morgan and Krarti, 2007). Another well-known application of CTES systems is the preservation and shipment of temperature sensitive materials (Cabeza et al., 2002;

Kowata et al., 2002). Designers should consider selecting a CTES system when any of the following criteria are applied:

- The maximum cooling load of the facility is significantly higher than the average load. This is true for most of nonindustrial facilities.
- The electric utility rate structure includes high demand charges, a significant differential between peak and off-peak rates, or special rebates or incentives for cool storage installations.
- An existing cooling system is undergoing expansion.
- An existing tank suitable for cool storage use is available.
- Cooling is needed for an application in a remote region.
- Electric power available at the site is limited.

A comprehensive review paper on cold thermal storage technologies has been presented by Hasnain (1998). He demonstrated the advantages and disadvantages of the CTES system over the conventional AC systems. Normally, these systems shift the electricity consumption from the daytimes to the nights when the ambient temperature (T_{amb}) is considerably lower. It would consequently, improves the chiller efficiency (MacCracken, 2003). In addition, the constant cooling generation ensures efficient operation of the plant. The significant air temperature difference across the air-handling unit (AHU) also reduces the required circulated air volume. Therefore, smaller AHUs, less duct working and less electrical equipment are required. Moreover, as the chiller capacity reduces, fewer gas charge refrigerants are required, which can decrease the emission of harmful CFCs into the atmosphere. Conversely, as the chiller produces chilled water at lower temperature its performance is reduced significantly.

The performance of a TES system is commonly described by its coefficient of performance (COP) that is defined as the ratio of the net refrigerating divided to the input power. The COP of a system during peak and off-peak hours is defined by the chiller and compressor design. However, the actual operating performance of a system is assessed through a real time fieldwork study. For this purpose, the net cooling capacity and required energy should be recorded continuously by using a numerator and a denominator. The COP of a chiller operating with ITS system during the charging period decreases because of the low-temperature of chilled water production (around -5°C) compared to the conventional AC systems. In 1992, it was assumed that the COP of the chiller throughout the charging period is around 23% lower in comparison to the normal operation conditions (Beggs and Ward, 1992). However, the real percentage of the TES system completely depends on the system configuration, storage strategy and the localized parameters. Generally, TES systems are considered as cost effective techniques (MacCracken, 2004).

CTES systems are generally categorized into three types, which are chilled water, ice storage and eutectic salt TES systems (Hasnain, 1998). More details of each system are described herein. Among these techniques, the CWS and ITS systems are the most promising ones in case of the normal applications. Table 2.1 shows some of the main differences between these three cool storage systems.

Table 2.1: Primary features of cool storage systems (Hasnain, 1998; Incropera and DeWitt, 2002; Washington State University, 2003).

Parameter	Chilled water	Ice storage	Eutectic Salt
Specific heat (kJ/kg K)	4.19	2.04	-
Latent heat of fusion (kJ/kg)	-	334	80 - 250
Chiller type	Standard Water cooled	Low temperature Secondary coolant	Standard Water cooled
Chiller cost per kW ($)	57 - 85	57 - 142	57 - 85
Tank volume (m^3/kWh)	0.089 - 0.169	0.019 - 0.023	0.048
Storage installed cost per kWh ($)	8.5 - 28	14 - 20	28 - 43
Charging temperature (ºC)	4 – 6	(-6) - (-3)	4 - 6
Chiller charging efficiency (COP)	5.0 - 6.0	2.7 - 4.0	5.0 - 6.0
Discharge temperature (ºC)	1 – 4 above charging	1 - 3	9 - 10
Discharge fluid	Water	Secondary coolant	Water
Tank interface	Open tank	Closed system	Open tank
Maintenance	High	Medium	Medium

It can be clearly observed from Table 2.1 that the ITS system has the advantage of larger storage volume in comparison with the two other systems. However, as mentioned earlier the COP of the ITS system is much lower than other techniques. Thus for a proper selection, further investigations on localized parameters such as the electricity demand trend, the peak and off-peak hours, the climate change profile, the electricity tariff rate and the system set-up costs are the key elements that varied place to place. To investigate different parameters that affect the performance of a CTES system many case studies have been conducted around the world and the results have published in the open literature.

In the past decades, the use of cool storage systems has been widely developed in the commercial and industrial scales thus plenty of information relating to these systems and developed technologies are presented. The American society of heating, refrigerating and air conditioning engineers (ASHRAE) have tabulated the available processes into the handbook where different geometries are described

(ASHRAE, 2007b). Various manufacturers have used these geometries on their production line such as; Baltimore Aircoil company (Ice Chiller), Ciat Co. (Cristopia), Calmac Co. (Ice bank) and Sedical Co.

The statistical study shows that in the early 1990s around 1,500 to 2,000 units of CTES systems were employed in the United States. Most of them were installed in the office buildings, schools and hospitals. The results show that ITS systems had the largest proportion of around 80% to 85% followed by the chilled water applications with 10% to 15% and the rest 5% were eutectic salt systems (Potter et al., 1995).

Saudi Arabia is one of the countries that has employed plenty units of ITS systems. The available applications and their economic effects in that region have been represented in a work done by Hasnain et al. (1999). A list of various types of installed units has been presented, and it was found that the TES system could decrease around 30% to 40% of the peak cooling-load demand and 10% to 20% of the peak electrical demand (Hasnain and Alabbadi, 2000). In another work, Hasnain et al. (2000) have forecasted the cold thermal storage utilization based on two scenarios. They found that their proposed partial ITS model could decrease the peak electrical load for the first and second scenarios by 15% and 23%, respectively. In the following sections, different types of CTES systems will be described in details and some of the available studies will be discussed briefly.

2.1.1 Chilled water storage techniques

Employing chilled water to store cold thermal is a well-known strategy in many countries to save energy by shifting power consumption from the peak hours of the day to the night-times (Mackie and Reeves, 1988). During the past decade, many different types of CWS designs were developed and employed in the field prior to the successful evolution of thermally stratified systems. Primarily designs were in the manner to avoid temperature mixing of chilled water with return water. However, they often require complex tank configurations or piping systems that are expensive and difficult to operate. The CWS systems currently in use can be classified as labyrinth, baffle, tank series, multiple tanks with an empty tank, membrane and thermally stratified systems. Some of them are schematically illustrated in Figure 2.1.

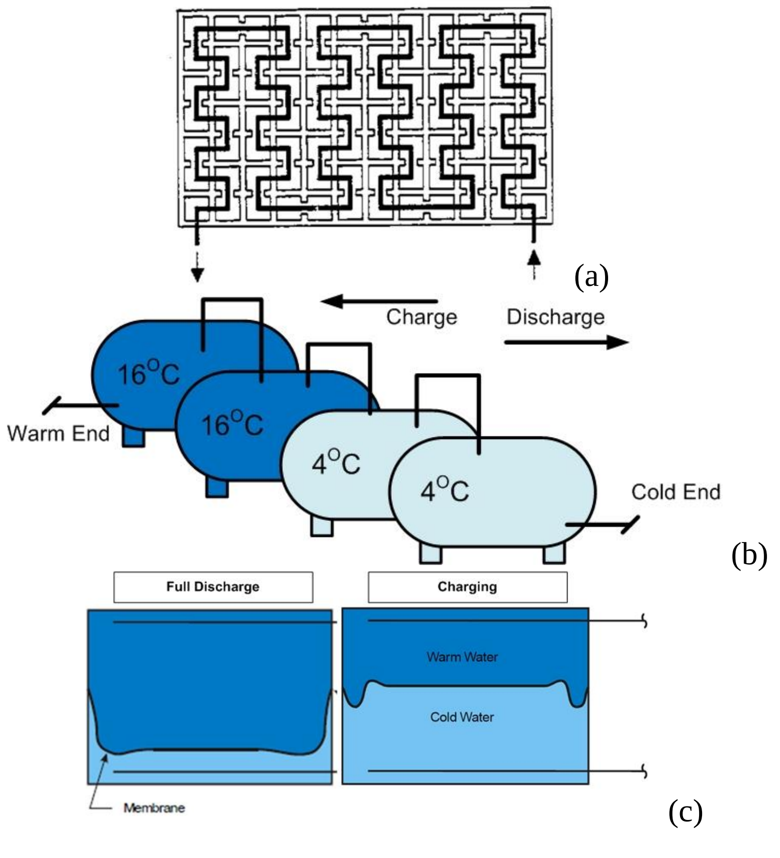


Figure 2.1: (a) labyrinth tank (Mackie and Reeves, 1988), (b) series tank and (c) membrane tank (Electric power research institute (EPRI), 2000). (The figures are used with the publisher's permission).

In 1999, Sohn et al. have presented a report of an installed CWS tank with 8,517m^3 volume by the US Army. The system shifts more than 3MWe of the electrical demand to the off-peak hours. Andrepont (2006) has studied on a 10 year old district energy (DE) system in Chicago. The system was considered as one of the largest units in the world with a peak discharge rate of 25k tons and a storage duty of around 123k ton-hours. In another study, Sebzali and Rubini investigate the performance effects of using CWS systems on the conventional AC system performance based on Kuwait's climate (Sebzali and Rubini, 2007). They found that in that province the CWS system can approximately decrease the peak electrical load up to 100% and decrease around 33% of the nominal chiller size.

Osman et al. (2008) have used a three dimensional numerical modelling to determine the correlation between the chilled water thermal stratification and the tank size. In a recent work, Boonnasa and Namprakai (2010) have presented a methodology for determining the optimal capacity of the CWS tank. They have presented the results of their study for the King Mongkut's University of Technology North Bangkok (KMUTNB) and they pointed out that for a CWS system consisting of two chiller units (of 450RT) operating continuously, a TES of 9,413RT-h and 5,175m^3 volume, was the best combination. Based on these configurations over two times of the mechanical chiller capacity and around 31% of the peak demand could be reduced.

2.1.2 Ice thermal storage technique

Among all the available CTES systems, the use of ice due to its high latent heat of fusion [h_{fg}=334 kJ/kg (Incropera and DeWitt, 2002)] was considered as the most popular technique during the past decade, especially when the available space is limited. By employing the ice, the greater part of the base load can be stored for further use (ASHRAE, 2007b). Obviously, even though the storage volume is determined based on the applied technology, it generally varies between 0.019 to 0.027m^3/kWh (Dorgan and Elleson, 1994). Assuming a reasonable temperature difference of 15°C between the water supply and return temperature for a liquid water storage system as well as for an ice storage system, it is obvious that ice storage needs considerably less storage volume to store the same amount of energy.

$$\frac{Q_{ice}}{Q_{water}} = \frac{V_{ice}\rho_{ice}(c_p\Delta T + h_{fg})}{V_{water}\rho_{water}c_p\Delta T} = \frac{V_{ice} \times 970(4.19 \times 15 + 334)}{V_{water} \times 1000(4.19 \times 15)} \tag{2.1}$$
$$\Leftrightarrow V_{water} = 6.1 \times V_{ice}$$

Practically, the necessary volume for ice storage is about 1/5 to 1/8 of the volume of a comparable water storage system. Figure 2.2 shows the configurations of ITS heat exchangers of three reputable manufacturers. The air conditioning and refrigerating institute (ARI) has established special standard (Air Conditioning and Refrigeration Institute, 2004) and guideline (Air Conditioning and Refrigeration Institute, 2002) for TES equipment that defines the classifications, tests and rating requirements.

(a) (b) (c)

Figure 2.2: ITS heat exchangers configuration, (a) Calmac Co. (Ice bank), (b) Fafco Co. and (c) Dunham Bush Co. (Ice tank)

As the thermal energy in this technique is stored in the form of ice, thus the supplied chiller must be able to produce charging temperature in the range of (-6)ºC to (-3)ºC, which are considerably lower than the normal range of the conventional chillers. The heat transfer fluid that is used in the ITS system might be either a refrigerant or a secondary coolant. Due to the reliability and simplicity of this technique, it has been widely used in buildings that are mainly occupied during the working hours such as office buildings (Chaichana et al., 2001), schools (Haughey, 2003; Morgan and Krarti, 2010), store building (Crane and Dunlop, 1994), campus buildings (Engineered Systems, 2000a), court-hall (Engineered Systems, 2000b), hospitals (Collins et al., 2000; Gopal et al., 2000), subway station (Onishi, 2002), churches and mosques (Habeebullah, 2007). In 1991, Landry and Noble found that employing the ITS system would help to downsize the cooling generation devices such as pipes, ducts and AHUs and consequently would lead to lower the primary cost of the HVAC system. During the past decade various studies on the issues of storing energy in the form of ice have been presented and variety of CTES systems had been built and studied (Ismail, 1998; Velraj et al., 2002). Comprehensive reviews on the TES (Zalba et al., 2003) and especially on the CTES (Saito, 2002) have been presented based on the works done before the year 2003.

The ice formation profile during charging is one of the key challenges that can influence the system performance. It is believed that adding side fins on the surface of the tubes would improve the thermal resistance. The melting of n-octadecane (n-C18H38) around a finned tube has been first studied by Lacroix (1993). Zhang and Faghri (1996b) found that by using internal fins the performance of a system with low thermal conductivity fluid could be improved up to 15%. They also investigated a similar study for the systems with external radial finned tubes and they found that by increasing the fin’s height the molten volume fraction (MVF) consequently increases (Zhang and Faghri, 1996a). In another work, Lacroix and Benmadda (1997) presented the results of their study on the melting from a finned vertical wall. They found that as the fine numbers increase, the solidification rate improves. (Ismail et al., 2000; Ismail and de Jesus, 2001) carried out parametric studies on solidification of PCM around a cylinder for storing ice. Teraoka et al. (2002) investigated about the characteristics of ice crystalation in a super-cooled solution. (Kayansayan and Acar, 2006) performed an experimental study to investigate the temperature profile and the phase front distribution across the tube.

The ITS systems are generally categorized by their different combinations of storage media, charging or discharging mechanism. Typically, ITS system consists of a large tank of water or salt-water or small capsules of water or any material with solidification temperature lower than the available chilled water temperature of a building (Roth et al., 2006). They are generally categorized into ice harvesting, ice-on-coil, ice slurry or encapsulated ITS systems (Dorgan and Elleson, 1994). In another point of view, they can be divided as either dynamic or static storage devises. In the static types, ice is formed directly on the chilling surface but in the dynamic types, the ice is formed and moved out of the cooling surface (Ho and Tu, 2008).

Henze et al. (2003) performed a comprehensive study on two types of ice-on-coil and ice harvester systems to evaluate the bill saving effects of different strategies. In some recently proposed techniques, the air is cooled down by having a direct contact with the ice, as shown in Figure 2.3 (Ho and Wang, 2002; Ho et al., 2005). Due to the low thermal resistance, the heat transfer rate of the free surface increases. However, Clark (2010) has mentioned in his report that although the ITS systems can successfully reduce energy costs, but they cannot be clearly considered as green systems. Conversely, MacCracken (2003) categorized the TES systems as green technologies due to their lower impact on the environment, which is the basic principle of being green.

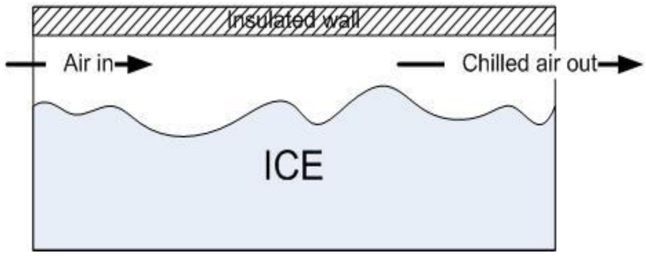


Figure 2.3: Schematic diagram of a direct chilled air production system.

The studies on different kinds of ITS systems are reviewed hereinafter.

2.1.2.1 Ice harvesters

The ice harvester system is classified as a dynamic type of ITS systems, which is usually consists of an open insulated storage tank and a vertical plate surface positioned above the tank. During the charging period, the ice is formed on the plate's surface of the evaporator. A circulating pump brings the water at a temperature of 0°C on the outer surface of the evaporator, which is fed internally with liquid refrigerant. Normally, thickness of the produced ice varies between 8mm to 10mm depending on the length of the freezing cycle. The ice would then be harvested by feeding a hot gas to the evaporator. The outer surface temperature rises to about 5°C causing the ice in contact with the plates to melt and fall into the storage tank. During the discharging period, the chilled water that circulates through the storage tank, further reducing the water temperature to cope with the load (Chan et al., 2006). An Ice harvesting system diagram is illustrated in Figure 2.4.

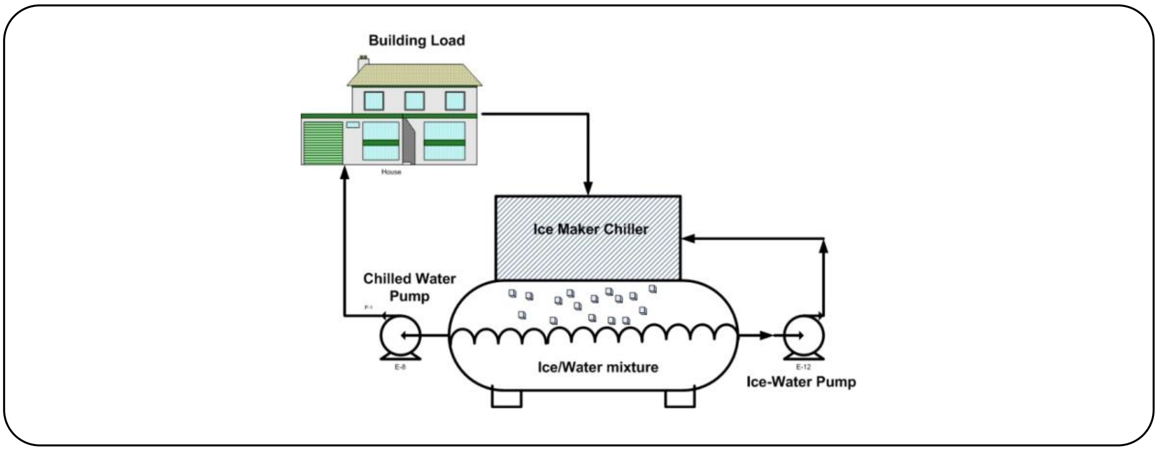


Figure 2.4: Schematic diagram of a typical ice harvesting ITS system.

Applying a simulation model, Knebel (1995) has evaluated the system performance of an ice harvesting TES system. Ohira et al. (2004) studied on the characteristics of ice melting in the ice harvesting system. They investigate the effects of the inlet water spraying method, the position of inlet water release and the water replacement time. They found that the characteristics of the ice melting in an actual tank could be evaluated by the average modified Stanton number. However, due to the system complexity, only a few manufacturers are involved with these systems, which are normally employed only in special applications.

2.1.2.2 Ice slurry

In this technique, the ice is formed by passing a weak glycol/water solution through the pipes submerged in an evaporating refrigerant. Figure 2.5 illustrates a schematic drawing of the ice slurry system. The evaporating refrigerant would cool the solution and produce a suspension of ice crystals. The small ice particles are pumped or dropped directly into the storing tank. During the discharging process, the cold solution circulates from the tank either directly or indirectly through the AHUs (Tanino et al., 2001b; Tanino et al., 2001a; Kozawa et al., 2005). Kitanovski and Poredos (2002) studied on the viscosity and concentration scattering of ice slurry in heterogeneous flow.

Bellas et al. (2002) investigated the pressure drop and heat transfer behaviour of the ice slurry system. They found that by increasing the ice-fractions from 0% to 20% the pressure drop increases around 15%. They also found that the heat transfer capacity of the heat exchanger with melting the ice slurry is around 30% more than conventional chilled water flow systems. In another survey, (Yamada et al., 2002) proposed the oscillatory rotating cooled tube as a production method of the ice slurry. Egolf and Kauffeld (2005) conducted their work on the physical properties of ice slurries and they found that if the ice fraction maintained below 15% to 20% the fluid would have the Newtonian fluid behaviour.

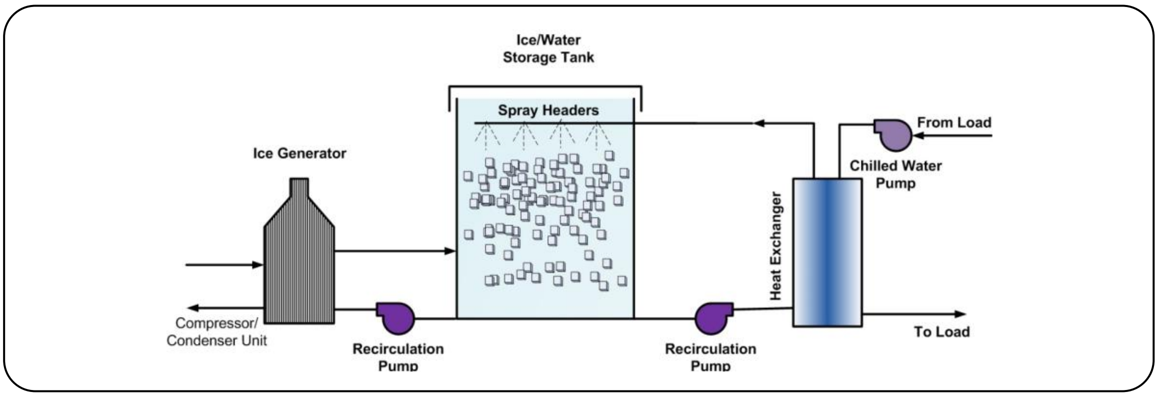


Figure 2.5: Schematic diagram of an ice slurry storage system.

2.1.2.3 Encapsulated ice

An encapsulated ice storage system consists of numbers of spheres or rectangular plastic capsules of water immersed in a secondary coolant such as ethylene glycol in a steel or concrete tank. In the United States, rectangular containers of approximately 0.017m^3 and 0.0042m^3 size and dimpled spheres of 100mm diameter capsules are available. However, in Europe, spheres of 95mm and 75mm diameters are utilized (Dorgan and Elleson, 1994) (see Figure 2.6). The capsules are usually made of a high-density polyethylene that is able to bear up the pressure due to the water expansion. During the charging period, a low temperature solution (-6°C to -3°C) passes through the tank and freezes the water inside the capsules. In the discharging period, the warm solution returns from the load to the tank and melts the ice. Figure 2.7 shows the charging and discharging procedure of the encapsulated ITS system (Erek and Dincer, 2009; Fang et al., 2010). Saitoh and Hirose (1986) performed experimental and numerical investigation to evaluate the thermal specification of the encapsulated thermal storage tank. They indicate that the size and material of the capsule as well as coolant temperature and flow rate are the main parameters that determine the charging and discharging duration.

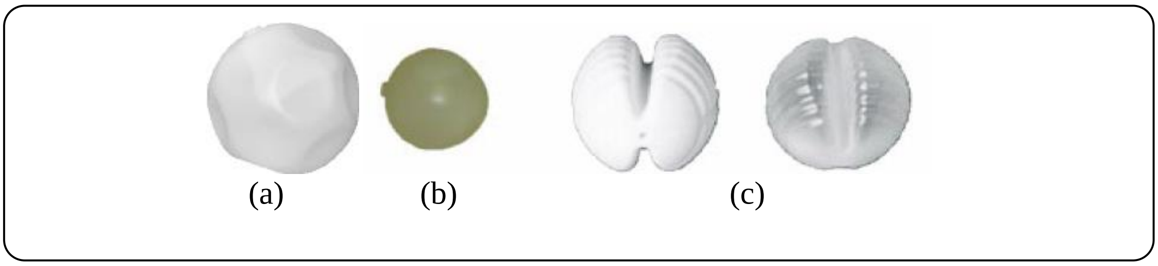


Figure 2.6: Samples of encapsulated ice containers; (a) (Cryogel), (b) Crystopia, (c) Ice-Bon (Electric power research institute (EPRI), 2000).

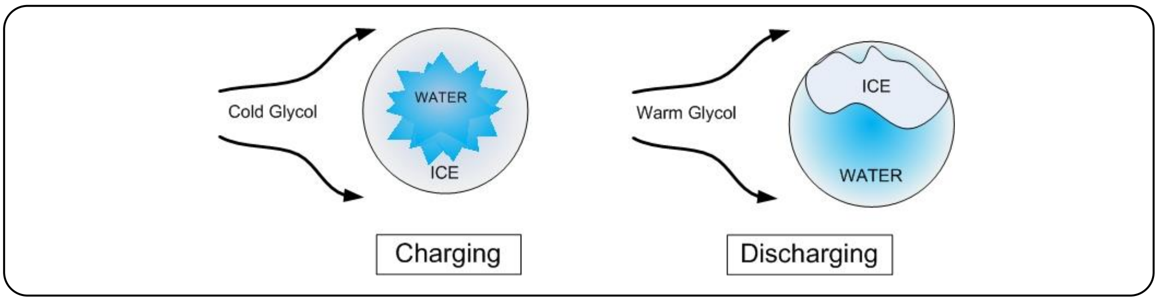


Figure 2.7: Charging and discharging procedure of an encapsulate ice storage.

There is a special kind of paraffin that can be used in the spherical capsule as its melting temperature is higher than water but has the same latent-heat capacity with the average heat transfer coefficient of around 40% higher than water (Cho and Choi, 2000). Regin et al. (2008) presented a complete review on heat transfer characteristics of the TES system utilizing the PCM capsules. In a recent work Bedecarrats et al. (2009)

investigated the charging and discharging performance of the encapsulated ITS system experimentally.

Chen et al. (2000) carried out an experimental investigation on both the pressure drop and the thermal performance during the charging process of an encapsulated thermal storage tank. They indicate that by decreasing the inlet coolant temperature and increasing its flow rate, the efficiency of the storage tank improves. Eames and Adref (2002) performed an experimental study to investigate the phases changing processes (freezing and melting) in spherical capsules. They proposed a semi empirical equation to predict the mass of ice, which forms into a sphere during the charging and discharging period. The optimum charging mode was captured in the vertical arrangement as the natural and forced convections were in a same direction (Kousksou et al., 2005).

2.1.2.4 External melt-ice-on-coil storage systems

The external melt ice-on-coil TES system is sometimes referred to the ice builder because in this storage system the ice is formed on the outer surface of the heat exchanger coils submerged in an insulated open tank of water as shown in Figure 2.8 (Lee and Jones, 1996a; Lee and Jones, 1996b). During the charging procedure, a liquid refrigerant or a glycol solution circulates inside the heat exchanger coils and produces ice on the outer surface of the coil. The ice thickness usually varies between 40mm to 65mm depending on the application. Thinner layer is suitable where higher charging temperatures (-7°C to -3°C) is required and thicker layer is used for applications where lower charging temperatures (-12°C to -9°C) is required. During the discharging process, the returned water from the load, circulates while passing through the ice tank and cooled down by direct contact with the ice (Shi et al., 2005). The charging and discharging processes of the external melt ice-on-coil is illustrated in Figure 2.9.

Figure 2.8: A photograph of an external melt ice-on-coil system (sub-systems of an Ice-Bear® unit) (ice-energy).

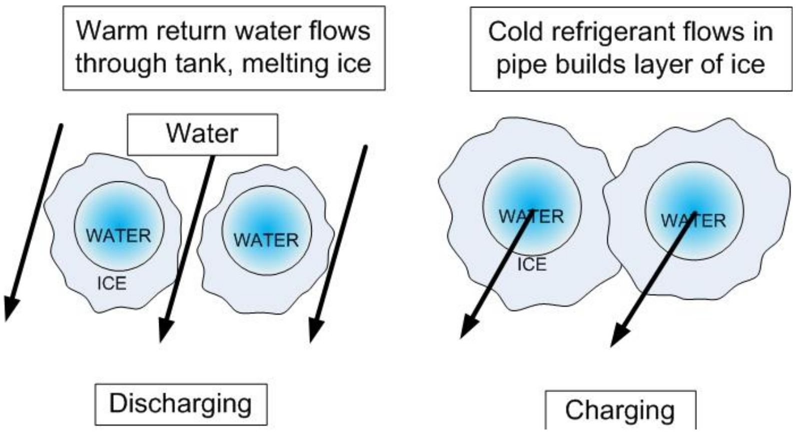


Figure 2.9: The charging and discharging procedure of an external melt ice storage system (ASHRAE, 2007b).

Soltan and Ardehali (2003) numerically simulated an ice-on-coil TES system to determine the approximate duration of water solidification around a circular cross-section coil. They found that it takes approximately 2,600 seconds to form 10mm of ice around a pipe of 20mm diameter.

2.1.2.5 Internal melt ice-on-coil storage systems

In the internal melt ice-on-coil storage systems, the heat transfer fluid such as the glycol solution circulates through winding coils submerged in tanks filled with water. During charging, the low temperature glycol solution (-6°C to -3°C) flows through the coils inside the tank and produces ice on the coil's outside surface. During the discharging process, the warm glycol solution flows through the coils causing ice to melt from the inside out (Zhu and Zhang, 2001). Silvetti (2002) provided the fundamental methodology for sizing an internal melt system. Figure 2.10 shows the schematic charging and discharging processes of an internal ice-on-coil storage system.

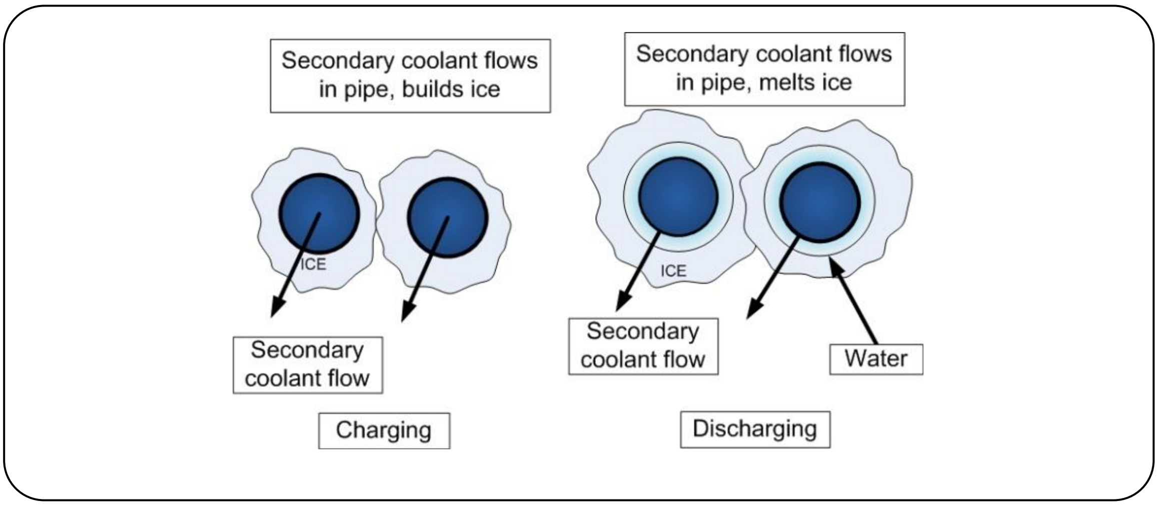


Figure 2.10: Charging and discharging procedure of an internal ice-on-coil storage system (ASHRAE, 2007b).

2.2 Operation strategies of CTES systems

The CTES system strategies are generally classified into two major divisions of full or partial storages indicating the sum of shifted cooling load from the peak to the off-peak periods. The partial storage strategy could be further categorized as chiller priority or storage priority types. It should be mentioned that the relationships between the electric rate structure, building load profile and the costs of equipment and storage are critical in determining the most cost effective mode of operation.

2.2.1 Full storage strategy

In the full storage strategy, all the required building loads will be transferred from the peak to the off-peak periods (usually from days to the night-times). Thus, the chiller operates at its maximum capacity when the cooling load is at the minimum and charges the storage tanks. Since the full storage strategy provides the whole demand load during the off-peak periods, thereby, in comparison to the partial storage strategy, the chiller size is significantly higher and is approximately equal to the non-storage condition. This strategy is suitable for conditions that the peak load occurred in a short period or there are small overlaps between peak energy hours and peak loads (Dincer, 2002).

2.2.2 Partial storage strategy

In the partial storage strategy, chillers will supply part of the required cooling load while the stored cooling provides the rest, thus the chiller size is usually smaller than the design load. This is an interesting approach for many designers as there are numbers of successful designs with a total cost of equal or even less than the non-storage conventional AC system.

This strategy is further categorized based on the selected operation strategies as the load levelling (the chiller operates at full load for 24 hours and the storage provides the extra required cooling) or demand limiting operations (the chiller operation is controlled during the daytime in order to keep the electricity cost as low as possible). The load levelling strategy is proper for cases that the maximum load is significantly more than the average load. However, in this strategy the electricity demand reduction is less than the full storage strategy. Figure 2.11 shows the difference of just mentioned strategies. Table 2.2 illustrates how the different storage strategies could affect the performance of a sample CWS system (Mackie and Reeves, 1988).

The chiller priority or storage priority is another way of categorizing the partial storage strategies. In the just mentioned operating strategies, either the chillers or the storage system provides the required building cooling load. The main difference between the storage and chiller priority strategies is the device that supplies the main proportion load, which is storage tank and chiller, respectively. Generally, the storage size and the chiller capacity in the storage priority strategy are larger with more complex control, which helps them to consume lower energy (Simmonds, 1994).

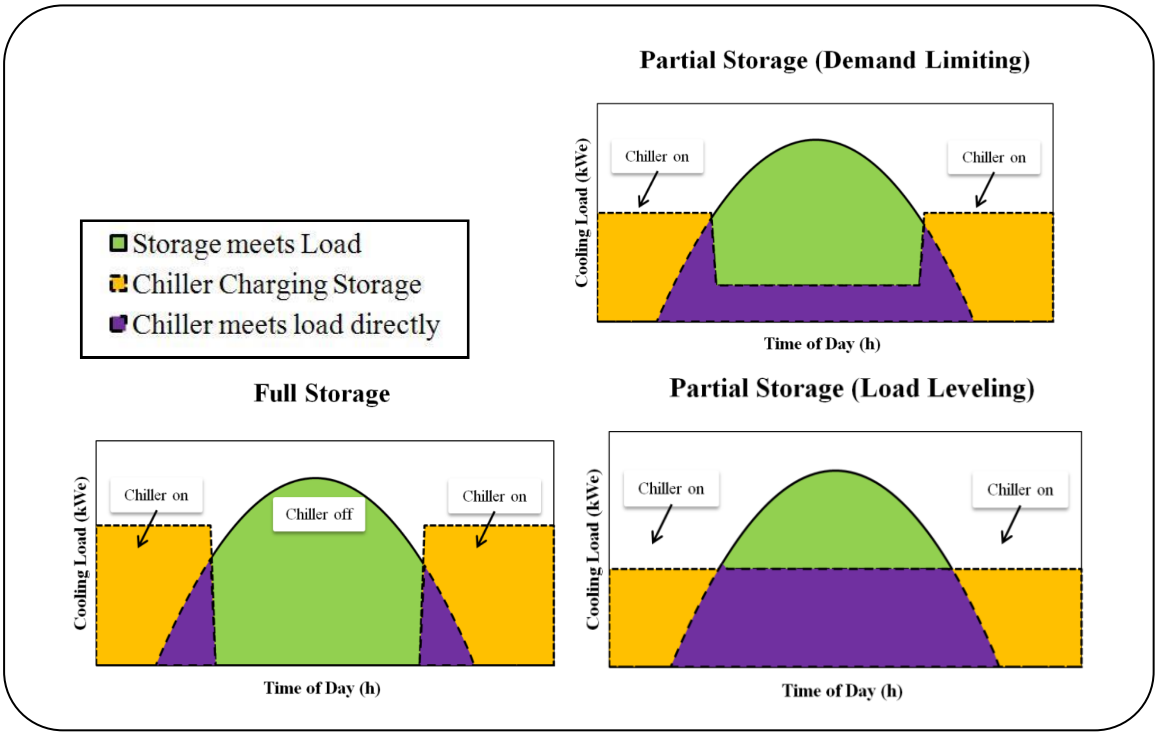


Figure 2.11: Comparison of different operating strategies of CTES system (Dorgan and Elleson, 1994).

Table 2.2: The effects of different storage strategies on a sample CWS system during a peak day (Electric power research institute (EPRI), 2000).

System	Chiller	Storage	Chiller - Peak	
	Size - Tons	Ton Hours	kW	kWh
No Storage	120	0	96	960
Full Storage	90	1200	0	0
Partial Storage (Demand Limited)	70	980	0	220
Partial Storage (Load Levelling)	50	700	40	400

2.3 Thermodynamic evaluation

A powerful tool to evaluate the performance of the CTES system is energy and exergy analysis on the basis of thermodynamics laws. Exergy analysis is used to determine the exergy destruction sources and to improve the exergetic efficiency of the system. The mathematical formulation and performance analysis of a two-stage unit of the thermal energy storage system, during the charging and discharging stages were evaluated by Domanski and Fellah (1996). Applying the definition of entropy generation which was presented by Ho et al. (2007), the exergy efficiency was calculated. Investigating the effect of mass velocity on the exergy efficiency it was found that increasing the mass velocity would decrease the exergy efficiency. It was also pointed out that the best exergy efficiency would be obtained when the melting temperature of the downstream unit was closed to the ambient temperature. The performance of four different ice TES case studies based on the first and second law of thermodynamics was assessed by MacPhee and Dincer (2009). The reported total energy efficiency for full storage is a little higher than the partial storage. The maximum energy efficiency was reported to be 99.02% for ice slurry storage system that was followed by ice on coil (internal melt) and encapsulated ice storage system with 98.92%. The exergy efficiency was defined as the ratio of desired exergy to the required exergy. The variable of the presented case studies is similar to the study that was conducted by Dorgan and Elleson (1994) and Wang and Kusumoto (2001). The total exergy efficiency of ice on coil (internal melt) was reported to be the maximum and was equal to 14.05% during full storage load and 13.9% during the partial storage load.

2.4 Case studies of utilizing CTES systems

Office building, Dallas, Texas, USA, 1989: An internal ice-on-coil storage system was installed in an office building located in Dallas, in order to shift about 800kWe electric demands from the daytime to the night-time and to save an estimated of US$55,000 per annum (Tackett, 1989). For this purpose, different cooling strategies have been studied and it was found that by using the load levelling partial storage strategy, smaller chiller and storage system are required in comparison with the full storage strategy. The study on the demand limiting partial storage strategy shows that the size of the chiller and storage system was fallen somewhere between those of full storage strategy and load levelling partial storage. Tackett (1989) reports that the system has a payback period of 0.34 years for the load levelling partial storage, 2.35 years for the demand limiting partial storage and 1.34 years for the full storage strategy systems.

Dental clinic, Texas, US, 1991: In 1991, the ice harvester TES system was installed in a dental clinic at Fort Bliss, Texas, (Sohn, 1991). The design cooling-load of the building varied from 197kWt (from 12:00 to 13:00) to 204kWt (from 15:00 to 16:00). The ice harvester system consists of a 91.4kWt icemaker and 1.1MWt steel storage tank. The ice harvesting system operates from 20:00 to 5:00 while all the AHUs were shut down and during this period, the building was not cooled. The system was shut down from 5:00 to 12:00 and the existing conventional chillers were switched on to directly cool the building. From 12:00 to 16:00, the chillers were switched off and the building cooling was met only by the stored ice. Finally, from 16:00 to 20:00 the chillers were switched on again and directly cool the building. The ice harvester system shifted the electric power consumption to the off-peak hours. However, the use of the ice harvester system consumes about 29% more electrical energy than the conventional AC system.

Department store, Oxford Street, London, 1994: An external melt ice-on-coil storage system was installed in a store in Oxford Street, London (Crane and Dunlop, 1994). The system was designed to supply half of the required building load of a day design. The system was operated based on the storage priority control strategy, thus there was no need to increase the chiller size. The existing AC system was consisted of three screw chillers providing 3.0°C chilled water during the daytime (603 kWt) and -6.0°C during the night-time (450 kWt). The ITS system provides around 9.3MWt of cooling during the discharging period. The chillers were designed to start charging the storage tank in 10 hours starting at 9:00. During the discharging cycle, the stored ice provides the required cooling load as much as possible and the remaining load was supplied by the chiller. For days closer to the design day conditions with a peak load of 2.6MWt and total integrated load of 17.4MWt, the discharging cycle starts at 9:00 and finished at 17:00. The stored ice provides about 9.2MWt of the base cooling load and the rest of 8.2MWt was handled by chillers. The results of this case study show that the ITS system has significantly reduced the ongoing charges by shifting part of the demand electricity load to the off-peak hours.

Fort Jackson, 1996: In 1996 an investigation has been conducted in Fort Jackson, US, to design, construct and operate a massive CWS system (Sohn et al., 1998). A large capacity (2.25Mgal) CWS system has been constructed that could serve more than half of the Fort Jackson's cooling load. The reported results of a two-year operation show that the system could save annually around $0.43M of electrical utility cost for Fort Jackson. Figure 2.12 shows the installed chilled water storage tank in Fort Jackson, SC.

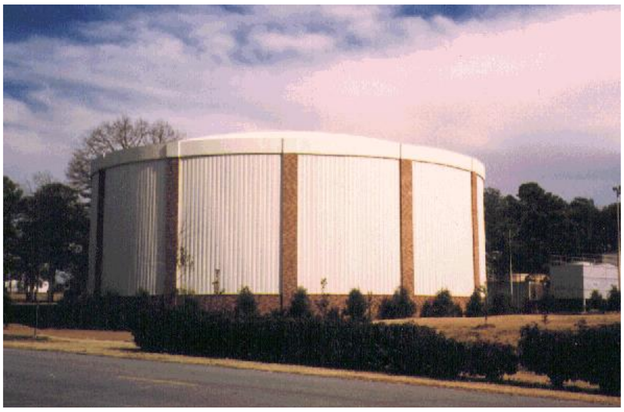


Figure 2.12: The 2.25Mgal chilled water storage tank installed at Fort Jackson, SC (Sohn et al., 1998).

Typical office building, Thailand, 2001: Chaichana et al. (2001) presented the results of their case study in a typical office building in Thailand. An internal ice-on-coil ITS system was simulated based on the model presented by (Neto and Krarti, 1997). The results show that under Thailand's electricity tariff rates the full storage strategy is able to save up to 55% of the required cooling electricity cost monthly. It was also found that by using this strategy the total energy consumption reduces around 5%.

A clinic building, Kuwait, 2005: Due to the hot climates, considerably long summer and low energy costs in Kuwait, the AC systems consume around 61% of the peak electrical duty and around 40% of the total electricity consumption. Sebzali and Rubini (2006) conducted their case study on a clinic building. They examined different storage strategies through a computational modelling. They found that incorporating full storage strategy results to the highest electricity reduction for the selected building, but the size of the required chiller and storage system is higher in comparison to the other strategies.

They show that by transferring the charging periods from 18:00 to 20:00 the total energy usage can be reduced due to the benefit of the lower dry bulb (DB) temperature. The full storage operation strategy requires larger chiller and higher storage capacity while the partial storage strategy (load levelling) requires smaller chiller and storage capacities.

Mosque of Makkah, Saudi Arabia, 2007: Habeebullah (2007) conducted an investigation on the economic feasibility of using the ITS systems in the AC plant in the Mosque of Makkah. The results indicate that as the existing electricity rate is fixed (0.07$/kWh), the ITS system does not have any gain neither for the partial nor for the full storage strategy. However, the author found that by employing the energy storage system via full load storage strategy combined with an incentive time structured rate, the electricity cost could be reduced significantly.

Fossil Ridge High School, southeast Fort Collins, 2008: The innovative design of the school building has won multiple awards; the AC system is cost effective and provides an exceptional environment for occupants (Watts, 2008). The system consists of a 135ton chiller and the partial ITS system combines with an interactive direct digital control system that manages all the equipment to maintain a comfortable environment. The school consumed around US$100,000 less in energy costs between the years 2004 to 2005 in comparison with its sister school.

Elementary school, Colorado, 2010: Morgan and Krarti (2010) presented the results of their field survey on an elementary school with total floor area of 6040m^2 in two levels (4460m^2 on the ground level and 1625m^2 on 2nd floor). They investigated the influences of using active and passive TES systems to shift the peak cooling loads to the nights and reduce building energy costs. The set point temperature during the occupied periods

(8:30 to 17:00) was 24°C and it was 32°C during unoccupied periods. A 50ton scroll compressor operates during the night (from 2:00 to 8:00) and charges three ice-tanks with a total capacity of 570 tons/h using the internal melt ice-on-coil system. In the discharging period, the chiller was kept in assist mode to handle any unexpected cooling loads. They found that around 47% of the annual electricity cost could be saved by employing the TES systems. This huge cost saving is due to the incentive utility rate of \$0.0164/kWh as a flat consumption rate and a demand charge of \$11.24/kW.

Library building, Malaysia, 2010: A recent simulation case study conducted in a typical library building situated in the tropics by Yau and Lee (2010). They used a typical meteorological year (TMY) weather profile of Kuala Lumpur with the aim of the Transient Systems Simulation Program (TRNSYS) software. They employed the ice-slurry cooling storage system in their simulation and they found that by employing the ITS system with the full storage strategy, the cumulative energy consumption would be increased by 20% due to the higher chiller energy consumption and the longer water pump usage compared to the baseline design. However, with considering the electricity tariff rate of Malaysia, using the ITS system would reduce the bill costs around 24%.

2.5 Chapter summary

A comprehensive review has been carried out to investigate different types of the CTES systems, in this regards some of the various available cases have been briefly described and some of the basic technologies have been discussed. The review reveals the advantages and disadvantages of different types of the CTES techniques and the storage strategies. However, due to the simplifications and approximations made by the authors, not all of the presented results could provide accurate guidance. A comparison study between the available systems shows that the ITS system has the advantages of larger storage volume capability, but it has a comparatively lower COP than other available techniques. Therefore, in order to choose the best TES system further investigations based on the local situation are highly recommended.

Chapter 3. Methodology

In this chapter, the essential theoretical backgrounds for the design capacity of CTES systems in humid tropical climates are presented. The energy and exergy analysis and economic evaluation are conducted in detail for a system comprising of a chiller and a storage tank. The vital design parameters and limitations of CTES systems are presented regardless of the specific storage medium or storage technology. A case study based on the Malaysian climatic conditions is presented to demonstrate the design procedure. Last but not least, a computer simulation is performed to predict the system behaviour year round.

3.1 Cooling load profile calculation

Normally, for the non-storage systems the building load profile is calculated based on the peak hourly load in a design day. However, a period of 24 hours or more should be considered when calculating the cooling load profile for a CTES system. The total system capacity in the non-storage system is simply 24 times the peak hourly load. At the same time, the CTES system must be designed in a way that meets the peak load and the extended load over time. Therefore, an accurate load profile calculation over the complete storage cycle is the most important part of the design process (Dorgan and Elleson, 1994).

3.1.1 Design weather conditions

Selecting the design ambient temperature conditions for CTES systems requires the same considerations as do a non-storage system. However, in the event that the design load exceeds the maximum design load, the CTES systems have less capacity to recover than the non-storage systems. Therefore, designers must be more conservative in their selection of the design temperature range for CTES systems. The ambient temperature profile of the design day can be predicted by using the method presented in the ASHRAE Handbook (ASHRAE, 2007a). For the systems with weekly cycles, it is recommended to design for at least five consecutive days with peak temperature profiles. If such a trend occurs rarely in the region, it is sufficient to consider a week with two or three peak days. Nowadays, most load calculations are performed with the aid of computer programs. The TRNSYS software program (*TRaNsient SYstem simulation program*) is commonly used by many designers worldwide (TRNSYS Simulation Studio, 2009).

Since Malaysia is located on the Equator, the ambient temperature profile does not show significant seasonal fluctuations during the year. The ambient temperature records show that the diurnal temperature varies between 22 and 36ºC, whereas the RH varies from 51 to 100 % and there are no distinct seasonal variations to this pattern. The average fluctuations in the ambient temperature profile for Kuala Lumpur for one year (8760 hours) is illustrated in Figure 3.1.

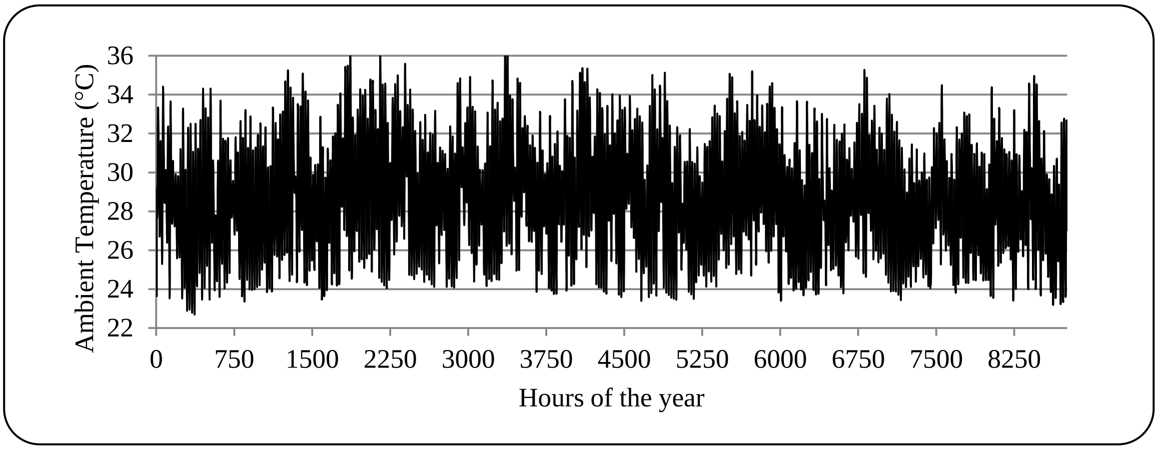


Figure 3.1: Average annual ambient temperature fluctuations for Kuala Lumpur.

The hottest temperature occurred on day 140 (May 20th), which is shown in Figure 3.2.

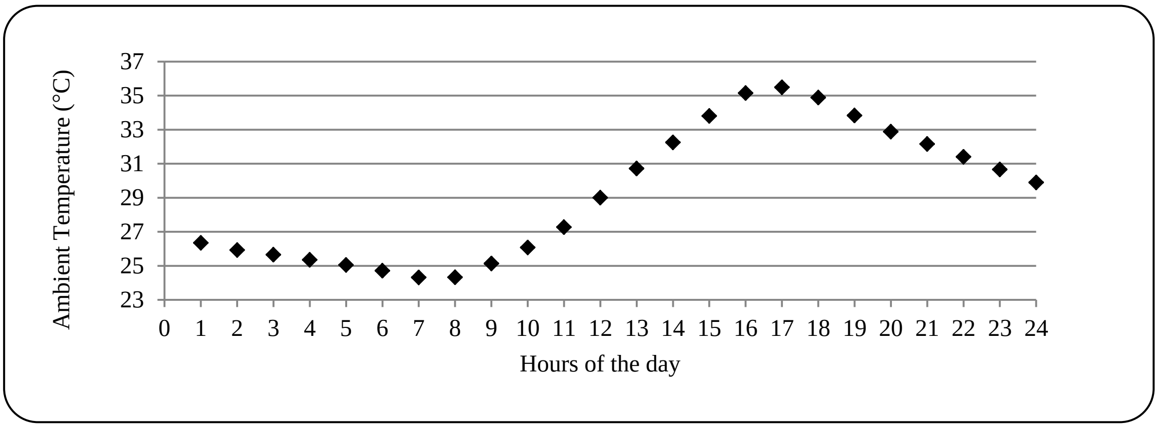


Figure 3.2: Ambient temperature profile of May 20th for Kuala Lumpur.

3.1.2 General considerations for load calculation

As mentioned above, the load profile should be calculated for the entire charging, storage and discharging cycle of the CTES system. The minimum cycle is 24 hours, but the recommended cycle is at least one week. Longer cycles may be required for special conditions. To calculate the load profile, an accurate estimate of occupancy schedules, lighting and equipment is required. All heat sources within the conditioned space have to be considered. Even relatively small heat sources can have a significant effect on the integrated daily load. In a non-storage system, cooling is only required when the building is occupied. Therefore, all the unoccupied heat gains (referred to as the *pull-down load*) are generally met during the first operating hours. However, in CTES systems, the pull-down load does not have such a significant effect on sizing calculations, but it should instead be considered as part of the weekly load profile.

Thermal losses during the charging, storage and discharging processes are another relatively small load that should be considered during the calculation. If the storage tank is properly insulated and not exposed to direct sunlight or other heat sources, the amount of heat loss normally varies from 1% to 5% of the total storage capacity per day, depending on system characteristics, such as tank shape, storage medium and insulation material.

3.1.3 CLTD/SCL/CLF method

The cooling load temperature difference (CLTD) method is basically a manual approach used to calculate the building load profile on an hourly basis. The CLTD value of this approach is applied to walls and roofs, while the cooling load factor (CLF) is employed to calculate internal heat sources, and the solar cooling load factor (SCL) is employed for window solar heat gain calculations. These values are time dependent and they are also functions of environmental conditions and building parameters (McQuiston et al., 2005). The following methodology and general formulations are taken from the ASHREA Handbook (ASHRAE, 2007a).

The total building load is divided in two parts: *latent heat gain* and *sensible heat gain*. Moist air from ventilation, infiltration and occupants mainly causes the latent heat gain. Sensible heat gain results from heat conduction via roofs, walls, windows, occupants (as heat sources), lighting and electrical equipment. Equation (3.1) is used to compute the hourly cooling load owing to conduction:

$$Q = U \times A \times CLTD_{corr} \tag{3.1}$$

Where, U represents the overall heat transfer coefficient, A is the effective area and $CLTD_{corr}$ is the corrected equivalent temperature difference. In order to normalize the CLTD for various latitudes, months and design conditions, the $CLTD_{corr}$ presents as follows:

$$CLTD_{corr} = CLTD + LM + (78 - T_{room}) + (T_{avg} - 85) \tag{3.2}$$

Where, LM is the correction factor for different latitudes and months, T_{avg} is the average outside temperature (T_{avg}=T_{amb} - DR/2) and DR is the mean daily temperature range. The cooling load through the glasses can be divided into radiant and conductive, where the conductive part is calculated based on Equation (3.1) and the radiant part is calculated as follows, Equation (3.3):

$$Q = SHGF_{max} \times SC \times CLF \times A \tag{3.3}$$

Where, $SHGF_{max}$ is the maximum solar heat gain factor and SC is the shading coefficient. The heat gain from occupants, lighting, and equipment can be determined using Equation (3.4).

$$Q = q_s \times CLF + q_l \tag{3.4}$$

The heat gain from infiltration and ventilation is also divided into latent and sensible heat gain. The sensible heat gain is determined by the following Equation (3.5):

$$Q_s = 1.1 \times CFM \times TD \tag{3.5}$$

Where, CFM is the airflow rate for cooling and TD represents the difference between indoor and outdoor temperature. Latent heat gain owing to ventilation and infiltration is determined as follows:

$$Q_l = 0.68 \times CFM \times (w_{amb} - w_{room}) \tag{3.6}$$

Where, w_{amb} and w_{room} are the humidity ratio of outdoor and indoor air. The quantity of air infiltrating into the room is calculated from following equation:

$$CFM = ACH \times (\frac{V}{60}) \tag{3.7}$$

Where, *ACH* is the number of air changes per hour and *V* represents the room volume.

3.1.4 Existing load profiles

In the retrofit projects where a CTES system is added to an existing non-storage cooling system, the building load profile can be estimated by direct load measurement with accurate instruments or from the historical logs of the building control system over a number of design weeks. It should be noted that there are normally major deviations between real situations and design conditions. Therefore, a combination of field measurement and computer simulation will obtain the most accurate building load profile of the existing AC system (Mackie and Reeves, 1988).

The energy use of the system can be measured directly by recording the compressor power input with an inline power-meter, which gives direct readings in kW. If an inline power-meter is not available, then the power for a three-phase system can be calculated by measuring the current and voltage separately and then using the following equation to calculate the power consumption, Equation (3.8). The “real power” is equal to the “apparent power” multiplied by $\cos\varphi$. Hence, for a three-phase system, the real power is (Bird, 2007):

$$\text{Power (kW)} = \sqrt{3}\text{V} \times \text{I} \times \cos\varphi \tag{3.8}$$

3.1.5 Sizing the cooling plant and storage tank

A conventional AC system rarely works at full load during the entire daily cooling cycle, and the peak normally occurs between 13:00 to 16:00 hours. The schematic load profile of an office building is presented in Figure 3.3.

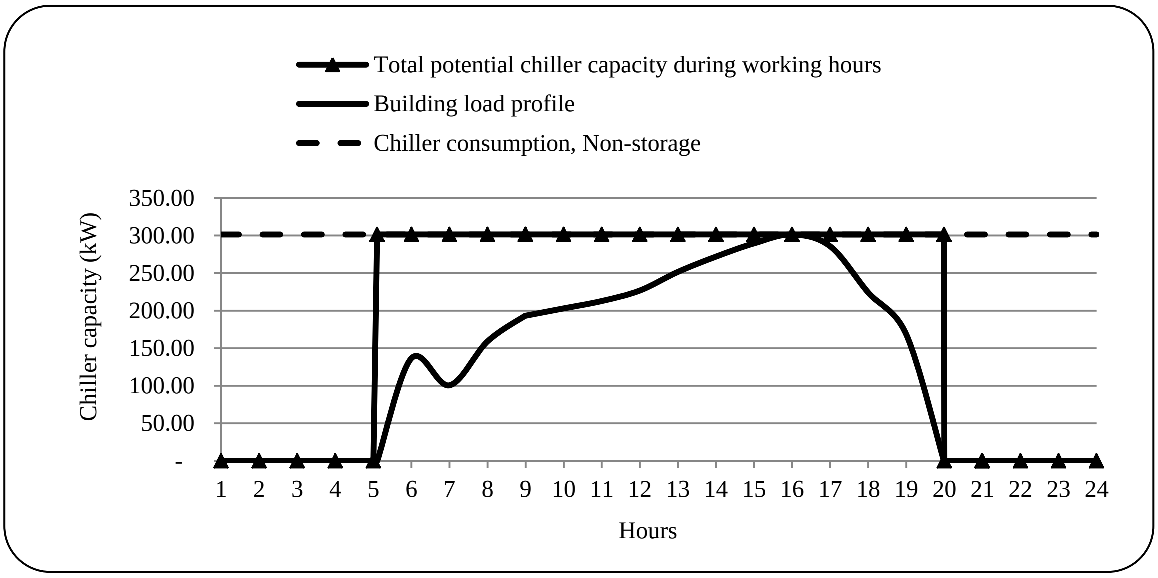


Figure 3.3: A typical building AC load profile during the working day.

It can be clearly observed that the full chiller capacity is only required for around two hours (from 15:00 to 17:00); less chiller capacity is needed during the rest of the day. In a conventional AC system design, the chiller must be able to meet the maximum peak cooling load of the design day. The "diversity factor" (DF) is defined as the ratio of the actual cooling load to the total potential chiller capacity (Calmac, 2002). A low DF means that the system has low efficiency and a high potential to benefit from employing

CTES. By shifting the AC load to off-peak hours, less chiller capacity is required and a DF of around 100 % is achievable.

$$\mathrm{DF}(\%) = \frac{\text{Actual cooling load}}{\text{Total potential chiller capacity}} \qquad (3.9)$$

By applying Equation (3.9) to the results shown in Figure 3.3 a DF of 70% is achieved. Therefore, the potential benefit of installing a CTES system in this building is considerable. While CTES system can supply any portion of the building load, ideal selection is typically limited to the economic and practical parameters and reasonable payback periods.

In conventional AC systems, the cooling load is described as the "kW of Refrigeration", whereas in CTES systems the building load is measured in "kWh" over the entire operating cycle. Chiller operating time is divided into two periods, daytime (peak hours) and night-time (off-peak hours). Hence, the total chiller capacity is calculated by Equation (3.10), (Silvetti, 2002).

$$\text{total kWh} = \text{chiller day kWh} + \text{chiller night kWh} \qquad (3.10)$$

The total “chiller day” capacity is equal to the chiller capacity (kW) multiplied by the number of daytime working hours. Similarly, the total “chiller night” capacity is equal to the chiller capacity multiplied by the number of night-time (off-peak) operating hours. Because the chiller capacity during ice making is lower than its capacity during direct cooling, a *derating factor* is applied to the chiller capacity to obtain its capacity during the charging process. The derating factor is directly related to the system design and manufacturer’s standards. Generally, it varies from 65% to 72% for compressor type chiller. Hence, chiller capacity can be calculated as follows:

$$\text{chiller kW} = \frac{\text{total kWh}}{\text{day hours} + \text{derating factor} \times \text{night hours}} \tag{3.11}$$

However, the total building load (kWh) is equal to the storage capacity plus the chiller "day capacity". Therefore, the total storage capacity can be derived from Equation (3.12).

$$\text{storage kWh} = \text{total kWh} - \text{chiller day capacity} \tag{3.12}$$

The required chiller and storage tank sizes will vary with different storage strategies. The simplest strategy is full storage, whereby the chiller operates only during off-peak hours. Based on the latest information released by Tenaga Negara Berhad (TNB) Malaysia, the main Malaysian electricity provider, the peak period for medium voltage commercial use (C2) is from 8:00 to 22:00 (14 peak hours per day). However, to encourage customers to shift their electricity use to off-peak hours, TNB offers special rate structures for those using TES systems. Based on the special rates, the peak period is reduced by two hours (from 9:00 to 21:00), creating 12 peak hours and 12 off-peak hours each day.

3.2 Fieldwork survey

Fieldwork study was conducted to evaluate the energy usage of the operating systems of the Canseleri building. The building was chosen as the case study for this project, because it is newly built and it has standard design criteria and the most important point is that the building uses central chiller as the main cooling system. The following steps were considered during the fieldwork study.

- The existing HVAC system design has been studied through the mechanical and electrical (M&E) drawings as well as architectural drawing of the building.
- The fieldwork measurement was conducted by using equipment's such as power analyser, thermometer, hygrometer, anemometer, electronic Micromanometer, luxmeter, total volatile gas monitor and indoor air quality meter.
- The total electricity consumption of the chiller plant room and the building was measured and recorded during the fieldwork period. The electricity consumption pattern was used as the baseline for the system calculation and simulation.
- The fieldwork was started on Friday February 24th, 2012, 5:15 PM and continued for almost half a year until Sunday August 12th, 2012 8:00 AM (170 days).

3.2.1 Building description

The Canseleri building is a newly constructed 10 story building located in the middle of the University of Malaya campus near the lake. The building is slightly oriented west along the north-south axis. It has almost no neighbour and hence all faces are subjected to direct sunlight.

The building comprises of 10 floors and 1 underground floor with a total floor area of 17280m^2. The underground floor is assigned as the parking area and the remaining floors are allocated to office spaces. The engineering installation room is located nearby the main building. On average 470 people work in building while an average of 300 people visit the building every working day. The north and south faces of the building are glazed and the building is embellished with an elegant shading on both sides. Figure 3.4 shows the northern and southern faces of the building and the underground floor.

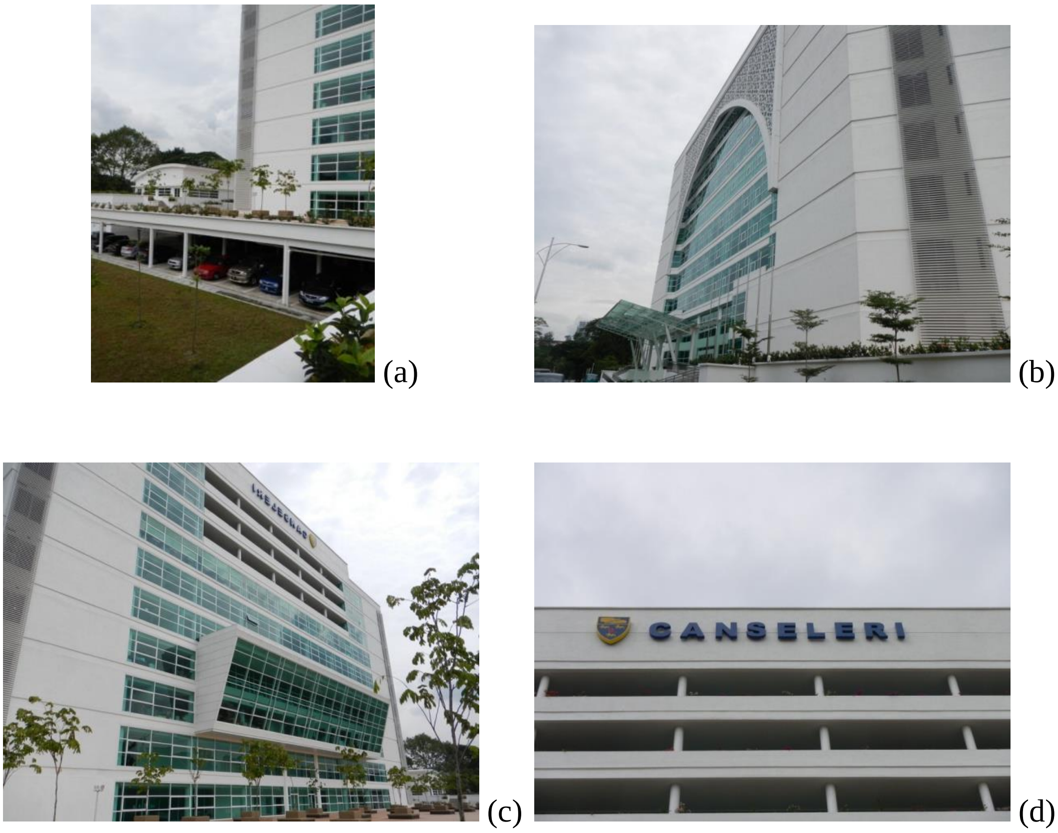


Figure 3.4: (a) Northern face, (b) Southern face and (c) the underground of the building.

3.2.2 Occupancy period and activity level

The Canseleri building is typically an office building. Therefore, the people who work in the building follow the usual office hours. The working hours from Monday to Thursday are from 8:30 to 13:00, 14:00 to 17:30 and on Fridays it is from 8:30 to 12:15, 14:45 to 17:30. As a result, the occupancy period during weekdays is from 8:00 to 19:00 and it is usually low in nonworking periods or during weekends.

Activity level code is moderate activity, office work. Inside the conditioned space, the most significant electricity consumers are AHUs, FCU, mechanical cooling systems, lifts and computers. The number of computers in operation is mainly dependent upon the number of occupants inside the office.

Table 3.1: Average occupancy of different levels.

Level	Staff	Visitors per day
Level 1 - Lobby	50	100
Level 2 – Main bursar office	100	20
Level 3 – Bursar office and Bright Spark unit	80	30
Level 4 - Meeting rooms	45	20
Level 5 – Gallery	50	10
Level 6 – Human resource	70	50
Level 7 – Quality management & Enhancement centre	80	20
Level 8 – Deputy Chancellor office	65	30
Level 9 – Chancellor office	60	20
Total	470	300

3.2.3 Main power supply

The building is supplied with a 3-phase 11kV medium-voltage power by means of a private transforming system. A diesel standby generator set is also installed that can provide emergency electric power if required. The main distribution cabinet is shown in

Figure 3.5. The cabinet is supplied with two main inlets, one of them is dedicated to the mechanical plant room and the other one directly provides electricity for the appliances inside the building. The power readings were done at chiller supply and building supply line, separately.

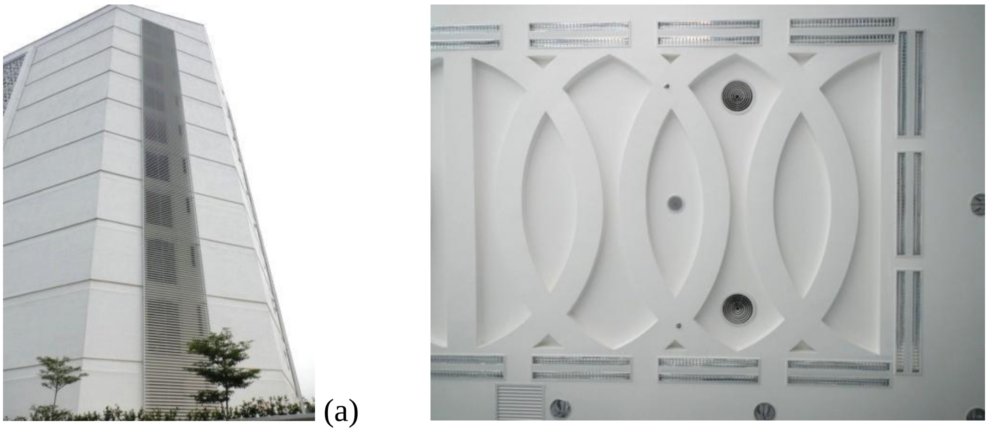
Figure 3.5: The main distribution cabinet.

3.2.4 Lighting

The building is designed in such a way to maximise the natural lighting of the building while at the same time minimising the amount of incident sunlight radiation through the building's windows. However, the direct incident of the sunlight passes through the southern windows during the afternoon hours. Therefore, a flexible window cover is provided for the northern and southern faces in order to reduce the direct incident from these angels as shown in Figure 3.6. The natural lighting covers the northern and southern parts of the building during daytimes.

Figure 3.6: Artificial flexible window shading of the southern face.

The artificial lighting system is intended to work as a backup to the natural lighting of the building. The lights are generally kept “off” during the morning when the natural light is sufficient and convenient. The walls are painted with light colours (white) to maximise the light diffusion. Most spaces are equipped with high efficiency fluorescent luminaries as shown in Figure 3.7 (b).



(a) (b)

Figure 3.7: (a) Western face of the building, (b) Artificial lighting inside the building.

The numbers of lights used in the building are listed in Table 3.2.

Table 3.2: The number of lighting balls and their distribution inside the building.

Level	Type / Power (W)														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
	14 W	28 W	56 W	28 W	56 W	42 W	84 W	110 W	52 W	26 W	26 W	70 W	18 W	50 W	84 W
Parking	111	-	107	14	-	-	11	-	9	-	7	11	-	-	-
Lobby	17	-	67	10	22	-	89	-	63	-	12	-	108	-	-
Level 1	-	19	-	6	-	3	121	-	25	-	12	-	28	-	-
Level 2	-	19	10	6	-	1	202	-	34	-	12	-	28	12	-
Level 3	-	19	8	6	-	2	184	-	50	-	12	-	28	9	-
Level 4	-	19	41	6	-	-	89	6	109	-	12	-	28	27	-
Level 5	-	19	-	6	-	2	197	-	23	-	12	-	28	-	-
Level 6	-	19	12	6	-	-	195	-	23	-	12	-	28	12	-
Level 7	-	19	22	6	-	1	184	-	42	-	12	-	28	18	4
Level 8	-	19	8	6	-	2	185	-	52	-	12	-	28	6	4
Level 9	-	19	8	6	-	-	166	-	28	-	12	-	28	9	4
Service	-	1	-	17	-	-	-	-	-	21	-	-	-	-	-

Based on the above mentioned details, if all the lights are switched on around 204kW would be used by all types of the lamps.

3.2.5 Cooling system

The AC system consists of a centralized chilled water system using electrical driven rotary screw chillers producing chilled water. The produced chilled water is channelled to the main building using pre-insulated chilled water pipes. The chilled water AHUs and FCUs serves as heat exchangers to cool various parts of the building. The required fresh air is provided via AHUs on each floor. The natural ventilation is provided via manual window openings in the southern and northern faces of the building. The extra ventilation is also possible through internal doors and windows. The chiller plant room is located in the mechanical room on the lower ground floors outside the main building. The main equipment of the AC system are listed in Table 3.3.

The chilled water system is designed to operate in two modes, “Auto” or “Manual”. For Auto mode, the operation of the AC plant is computerized using the chiller sequencing and monitoring through the chiller microprocessor, which is linked as a network using hard wire interlocking to the main chiller switchboard. The chiller sequencing provides a more flexible and effective operation and control of the chillers and the whole system is selected to run according to the actual load requirement, thus resulting in better efficiency and energy saving. Optionally, the system can be operated manually by selecting at the starter panels in manual mode. In this mode, the maintenance personnel have to go to each equipment starter panel located in the equipment room to run the particular equipment.

Table 3.3: List of main equipment of AC system.

Unit	Description	Manufacturer	Qty
Chiller	Water cooled rotary screw chiller, R-134A	York	3
Pumps	Horizontal split casing primary chilled water pump	Ebara	3
Pump	Horizontal split casing secondary chilled water pump	Ebara	3
Pump	Horizontal split casing condenser water pump	Ebara	3
Cooling tower	450RT, 2 cells Fiber-Reinforced Polymer, square type, low noise, induced draft, cross flow cooling tower	Genius	3
AHU	The size capacity is presented in detail in following section	York	21
FCU	The size capacity is presented in detail in following section	York	38
Split unit	The size capacity is presented in detail in following section	Acson	11

3.2.5.1 Chiller characteristics

The system is designed to meet the required cooling load with the aim of 3 York water cooled screw chillers model YRXCXBT3555C. The chiller is producing cooling capacity of 360 RT, two units are on duty to meet the required load and one unit is considered to be in standby condition. All three chillers shall be placed under a monthly sequence change to spread the running hour of each chiller equally. The actual numbers of chiller operating will depend on the load required. The chiller is used R-134A as refrigerant. The chillers are designed for chilled water inlet/outlet temperature of 12.2/6.6°C (54/44°F) and condenser water inlet/outlet temperature of 35.5/30.5°C (96/87°F), respectively. Each chiller compressor is equipped with built-in refrigerant-cooled electric motor of 415V/3P/50Hz. The chiller is also equipped with built-in factory assemble part-winding starter. The summary of the chiller characteristics is presented in Table 3.4.

Table 3.4: The chiller characteristics.

Item	Description
Type	Water cooled chillers
Brand	York
Unit Model	YRXCXBT3555C
Compressor Model	YR82221CB55
Capacity	360 RT
Refrigerant	R-134A
Power supply	415V/3P/50 Hz
Power	211kW
Chilled water inlet	12.2 °C (54°F)
Chilled water outlet	6.6 °C (44°F)
Condenser water inlet	30.5°C (87°F)
Condenser water outlet	35.5 °C (96°F)
Refrigerant charge	658 (kg)
Inrush current during start	18.40 A
Operating current	20.5 A
Evaporator inlet chilled water temperature	11.1°C (52°F)
Evaporator outlet chilled water temperature	6.6°C (44°F)

The chiller is controlled by a Johnson control (JC) controller that is connected to the chiller and the electrical switchboard. The JC controller acts as the master of the plant room. It decides which chiller is on duty and which one is on standby. If the leaving chilled water set point is not achieved, then the JC controller shall monitor the full load amperes of the running chiller. If the chiller has been running above 90% of full load amperes for more than 30 minutes, then the second chiller shall be turned on. If both chillers are operating, the full load amperes or leaving chilled water temperature are used to control the system. If both chillers are in operation at below 60% full load amperes or leaving water temperature below 6.7°C over 30 minutes is achieved then one of the chillers shall be turned off to save energy consumption.

3.2.5.2 Primary and secondary chilled water pump

There are three units of primary chilled water pumps of 3294 lit/m and three units of secondary chilled water pump of 3294 lit/m. Two units are normally on duty and one is on standby. Both of the chilled water pumps are horizontal split casing pump with mechanical seal. Each pump is run using 3-phase squirrel-cage induction motor. The pump motor is started by way of auto-trans starter system.

There are also three units of cold water pump of 5000 lit/m. Two are on duty and one is on standby. The condenser water pump is horizontal split casing pump with mechanical seal. Each pump is run using 3 phase squirrel-cage induction motor. The pump motor is started by way of auto-trans starter system.

Figure 3.8: Horizontal split casing pump.

3.2.5.3 Cooling tower

The cooling tower is designed to cool down the condenser water temperature. There are 3 units of cooling tower serving the chiller. The cooling tower model is GPC 450, square type, Fiber-Reinforced Polymer, induced draft and cross-flow type. Each cooling tower has 2 cells. Each cooling tower equipped with a low noise belt-driven propeller fan, which operate proportionally in according with the condenser water pump. Figure 3.9 shows the installed cooling tower during maintenance of the actuated valve on 28/3/2011, 10:48 AM and its characteristics are summarized in Table 3.5.

Figure 3.9: Cooling tower, during maintenance.

Table 3.5: The cooling tower characteristics

Item	Description
Type	Square type, FRP, induced draft and cross-flow
Manufacturer	Genius
Location	Roof top
Model	GPC 450
Power	5.5 × 2 kW
RPM	360
Starting current	30
Operating current	10

3.2.5.4 Air Handling Unit

A total number of 21 units of AHU are used to serve the main building. Figure 3.10 shows the installed AHU in level 2.

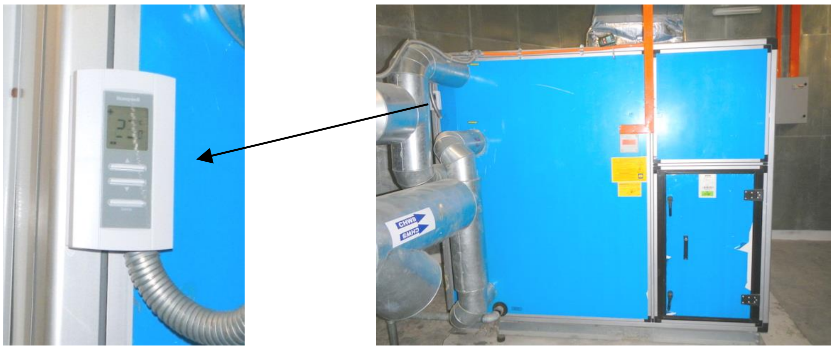


Figure 3.10: AHU, level 2, set point temperature of 23ºC on 29/3/2012, 10:12 AM.

Table 3.6 presents the detail of the AHUs installed in the building.

Table 3.6: The AHUs characteristics.

Label	Level	Model	Type	Power kW	RPM	CFM	Starting Amps	Running Amps
AHU-B-1	G*	YSM 50 X 50	500 FC	7.5	1450	12630	31.7	15
AHU-B-2	G	YSM 30 X 60	450 FC	7.5	1450	9955	31.4	13
AHU-M-1	1	YSM 40 X 80	630 FC	15	1460	13970	59.6	25.8
AHU-M-2	1	YSM 40 X 80	630 FC	15	1460	13405	55.6	25.7
AHU-1-1	2	YSM 50 X 60	560 FC	11	1460	16689	77.3	16.7
AHU-1-2	2	YSM 40 X 80	560 FC	11	1460	19755	81.2	22.1
AHU-2-1	3	YSM 40 X 70	500 FC	15.5	1450	11980	31.6	15
AHU-2-2	3	YSM 40 X 60	500 FC	7.5	1450	12468	30.2	13
AHU-4-1	4	YSM 50 X 50	500 FC	11	1460	12355	72.3	13.1
AHU-4-2	4	YSM 40 X 70	560 FC	7.5	1450	15721	32.3	15.3
AHU-5-1	5	YSM 40 X 60	560 FC	11	1460	12795	88.1	15.5
AHU-5-2	5	YSM 40 X 70	560 FC	11	1460	16165	83.2	18.9
AHU-6-1	6	YSM 50 X 50	500 FC	7.5	1450	12331	30.1	12.8
AHU-6-2	6	YSM 50 X 50	500 FC	7.5	1450	11797	29.3	12.6
AHU-7-1	7	YSM 40 X 50	500 FC	7.5	1450	12448	30.1	13.2
AHU-7-2	7	YSM 40 X 60	500 FC	7.5	1450	12596	31.3	12.7

3.2.5.5 Fan coil unit

A total number of 38 units of FCU are used to serve the main building. Table 3.7 presents the detailed description of the installed FCUs.

Table 3.7: The FCUs characteristics.

Label	Model	Temperature, °C	Power, W	CFM	Running Amps
FCU-BT	YORK	22/17	65×2	572	0.9
FCU-B-1	YORK	21/16	150 ×2	752	2.3
FCU-B-2	YORK	20/17	65 ×2	761	2.2
FCU-M-1	YORK	20/17	150 ×2	1166	2.3
FCU-1-1	YORK	21/17	70 × 2	309	0.9
FCU-1-2	YORK	21/17	135 ×1	492	1.6
FCU-1-3	YORK	21/16	70 × 2	298	0.9
FCU-2-1	YORK	21/17	150 × 2	2709	2.4
FCU-2-2	YORK	21/17	135 ×1	356	0.8
FCU-2-3	YORK	20/17	150 × 2	1237	2.2
FCU-2-4	YORK	21/17	135 ×1	301	1.6
FCU-2-5	YORK	21/16	135 ×1	490	1.6
FCU-4-1	YORK	20/16	65 × 2	1015	2.2
FCU-4-2	YORK	21/17	25 ×1	218	0.4
FCU-4-3	YORK	21/17	25 × 1	229	0.4
FCU-4-4	YORK	20/17	25 × 1	309	0.3
FCU-4-5	YORK	21/16	65 × 1	298	0.4
FCU-4-6	YORK	21/16	65 × 1	289	0.4
FCU-4-7	YORK	20/16	65 × 1	268	0.5
FCU-4-8	YORK	22/17	135 ×1	428	0.9
FCU-5-1	YORK	21/16	135 ×1	439	1.6
FCU-5-2	YORK	22/17	20 ×1	180	0.4
FCU-5-3	YORK	21/17	20 ×1	203	0.4
FCU-5-4	YORK	21/16	20 ×1	162	0.3
FCU-5-5	YORK	21/16	20 ×1	198	0.4
FCU-6-1	YORK	20/16	65 × 1	298	0.9
FCU-6-2	YORK	20/17	135 × 2	452	2
FCU-7-1	YORK	20/17	65 × 1	342	0.9
FCU-7-2	YORK	20/17	135 × 1	301	1.6
FCU-7-3	YORK	21/17	65 × 2	299	0.9

3.2.5.6 Mechanical ventilation system

The mechanical ventilation system is designed to serve mainly the toilets, kitchens, LV room, transformer room and chiller plant room. Table 3.8 presents the detail of the mechanical ventilation system installed in the building.

Table 3.8: Mechanical ventilation details.

Label	Location	Power kW	Full load AMPS	CFM	Starting AMPs	Running AMPs
EX-BT-TRANS-1	Transformer room	0.55	1.36	3035	6.1	1.2
EX-BT-TNB-1	TNB room	0.55	1.36	3024	5.4	1.2
EX-BT-TNB-1	TNB room	0.55	1.36	3024	5.4	1.2
EX-BT-LV-1	LV room	1.1	2.7	5969	8.8	2.2
EX-B-TM-1	Toilet male 1	0.37	1.02	978	*	
EX-B-TF-1	Toilet female 1	0.37	1.02	1134	*	
EX-B-TM-2	Toilet male 2	0.37	1.02	1025	*	
EX-B-TF-2	Toilet female 2	0.37	1	1016	*	
EX-2-TM-1	Toilet male 1	0.37	1.02	1032	*	
EX-2-TF-1	Toilet female 1	0.37	1.02	1032	*	
EX-2-TM-2	Toilet male 2	0.37	1.02	973	*	
EX-2-TF-2	Toilet female 2	0.37	1.02	1018	*	
EX-4-TM-1	Toilet male 1	0.37	1.02	1026	*	
EX-4-TF-1	Toilet female 1	0.37	1.02	1033	*	
EX-4-TM-2	Toilet male 2	0.37	1.02	996	*	
EX-4-TF-2	Toilet female 2	0.37	1.02	1035	*	
EX-5-TM-1	Toilet male 1	0.37	1.02	1039	*	
EX-5-TF-1	Toilet female 1	0.37	1.02	983	*	
EX-5-TM-2	Toilet male 2	0.37	1.02	1027	*	
EX-5-TF-2	Toilet female 2	0.37	1.02	1012	*	
EX-6-TM-1	Toilet male 1	0.37	1.02	1003	*	
EX-6-TF-1	Toilet female 1	0.37	1.02	988	*	
EX-6-TM-2	Toilet male 2	0.37	1.02	976	*	
EX-6-TF-2	Toilet female 2	0.37	1.02	1062	*	
EX-7-TM-1	Toilet male 1	0.37	1.02	1028	*	
EX-7-TF-1	Toilet female 1	0.37	1.02	979	*	
EX-7-TM-2	Toilet male 2	0.37	1.02	1026	*	

Table 3.8 continue.

EX-7-TF-2	Toilet female 2	0.37	1.02	1032	*
EX-8-TM-1	Toilet male 1	0.37	1.02	890	*
EX-8-TF-1	Toilet female 1	0.37	1.02	790	*
EX-8-TM-2	Toilet male 2	0.37	1.02	730	*
EX-8-TF-2	Toilet female 2	0.37	1.02	720	*

*Interlocked with lamp

3.2.5.7 Make-up water and expansion tank

One unit of make-up water tank with the capacity of 72,700 litters to supply the make-up water for cooling tower is installed. The tank is made of pressed steel hot dip galvanized material. This building is also equipped with one expansion tank located in the service floor at the main building with the dimensions of 1.2m × 1.2m × 1.2m. The expansion tank is equipped with a float valve to ensure water is fed when it is at low level.

3.2.5.8 Air cooled split unit (ACSU)

The ACSUs used in the building are Acson brand and they are controlled by 24h timer for auto changeover at MDF room, LGF and PABX room. They also can operate manually by the built in on-off switch. The room temperature can be controlled by the thermostat that comes along with the units. Table 3.9 presents the capacity of the installed ACSUs.

Table 3.9: Air cooled split units.

Location	Capacity kW	Qty	Location	Capacity kW	Qty
Driver room, LGF	5.2	1	PABX room, LGF	2.6	2
MA room, LGF	7.0	1	Cafeteria, GF	14.5	3
MA room, LGF	2.6	1	Server Area, GF	11.7	1
MDF room, LGF	2.6	2			

3.2.6 Equipment and monitoring procedures

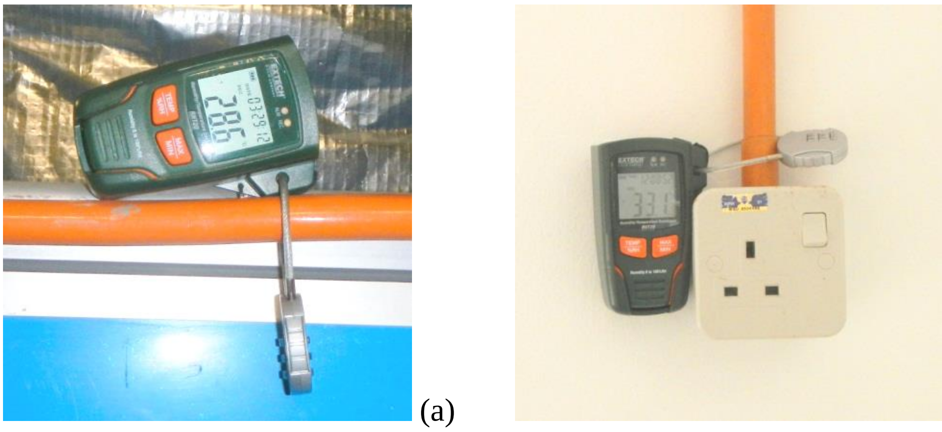
The monitoring of the Canseleri building was carried out from Friday February 24th, 2012, 5:15 PM and continued for almost half a year until Sunday August 12th, 2012 8:00 AM (170 days). All the instruments were calibrated over the range of test readings for the measurement of following parameters. The following values were continuously monitored during this period, Table 3.10:

Table 3.10: The monitored parameters.

Parameter	Description	Instrument	Accuracy
Outside dry bulb temperature	The temperature was monitored at 2 selective points in the shade with 5 minute interval	Extech RHT20	±1°C
Outside humidity ratio	The humidity ratio was recorded at the same points as the temperature with 5 minute interval	Extech RHT20	±3%
Inside dry bulb temperature	The temperature was monitored at 3 selective points inside the building with 5 minute interval	Extech RHT20	±1°C
Inside humidity ratio	The humidity ratio was recorded at the same points as the temperature with 5 minute interval	Extech RHT20	±3%
Power demand	The electricity consumption of the building was recorded with 15 minute interval	Siemens power meter PAC3200	V: ± 0.5% A: ± 0.3%
Air velocity	Air velocity was measured in selective points	Extech 451112-NIS	2%
Carbon dioxide concentration	CO and CO_2 concentrations were measured in selective points	TSI 8554 Q-Trak Plus IAQ meter	1 ppm
Room light level	The level of light was measured in selective points	Extech Model 403125	±5%

3.2.6.1 Temperature and humidity measurement

The temperature and humidity were measured with an Extech RHT20 temperature and humidity data logger. The recordings were conducted inside and outside of the building. For inside the recordings were conducted in three different zones, the first zone is in the lobby, which has the highest air leakage from outside. The second zone is at level 2 that has the highest level of activity and the third zone is chosen to be level 8 that has a very low number of visitors and working staffs. The outside temperature was recorded in the shade, for convenient the data logger was installed in the electrical room, since there is no cooling system and it can represent the outside condition. Figure 3.11 shows the installed data logger in Level 2 and inside the electrical room.



(a) (b)

Figure 3.11: Temperature and humidity measuring points via Extech RHT20 (a) inside the AHU of level 2, and (b) inside the electrical room.

The sample recorded data from the temperature and humidity meter is presented in Figure 3.12.

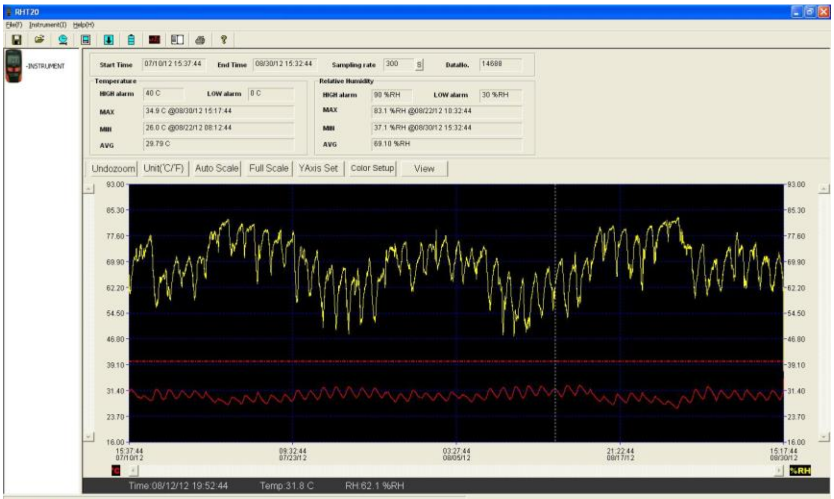


Figure 3.12: Sample outside data recorded during 10th July to 30th August.

3.2.6.2 Air velocity measurement

The air velocities were measured inside the building in random locations, the measuring was conducted manually using an Extech portable thermo-anemometer with an accuracy of 2%. Figure 3.13 shows the used equipment.

Figure 3.13: Extech portable thermo-anemometer.

3.2.6.3 Indoor air quality measurement

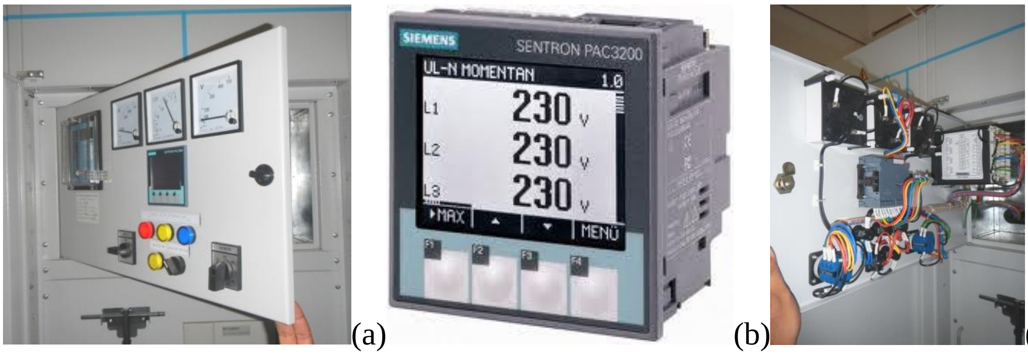
Carbon dioxide is a normal constituent of exhaled breath and is commonly measured as a screening tool to evaluate whether adequate volume of fresh outdoor air is being introduced into indoor air. The CO_2 concentration of fresh air usually varies from 300 to 400 parts per million (ppm). The CO_2 level was monitored with a TSI 8554 Q-Trak Plus IAQ meter that measured temperature, humidity, CO and CO_2 concentrations with 1 ppm resolution for CO and CO_2 concentration measurement. The measurements were conducted at three different heights of 0.3m, 1.0m and 1.6m at each point.

Figure 3.14: Indoor air quality meter.

The data were taken manually from randomly selected diffusers with the distance of 1 meter below the diffuser and the supply air temperature was measured from the opening of diffusers. Figure 3.14 shows the used IAQ meter.

3.2.6.4 Power supply

The electricity consumption of the building was recorded from two Seimens- Sentron PAC3200 power analysers installed on the main distribution cabinet, Figure 3.15.



(a) (b) (c)

Figure 3.15: Power consumption monitoring device (Siemens PAC3200).

The monitoring interval is set to every 15 minutes. During the system start-up, all of the equipment will start operating in less than 40 seconds therefore the start-up amperes cannot be detected by the instrument. The power analysers were connected to the laptop located inside the electrical room to log the data as shown in Figure 3.16. The power analyser in the left hand side of the figure is dedicated to the mechanical plant room and the right hand side power meter is dedicated to the building. Two network cables were connected to a switch and the switch was connected to the laptop. The channel 1 represents the electricity consumption of chiller and channel 2 shows the building's electricity consumption. The total energy usage of the building is consequently equal to the sum of both channels.

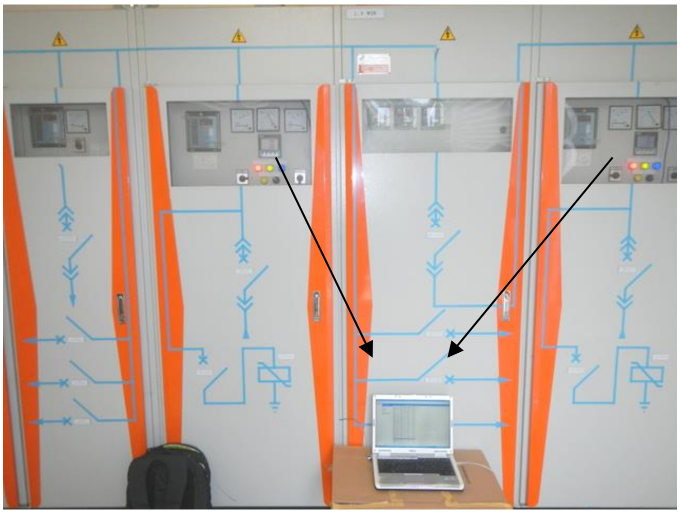


Figure 3.16: The power monitoring system setup inside the electrical room. The computer is logging the data from two PAC3200 power analysers.

The power analyser software compatible with the power meters were purchased and used to record the data from the instrument. Figure 3.17 shows the software interface taken on March 25^{th}, 2012, 11:37 am.

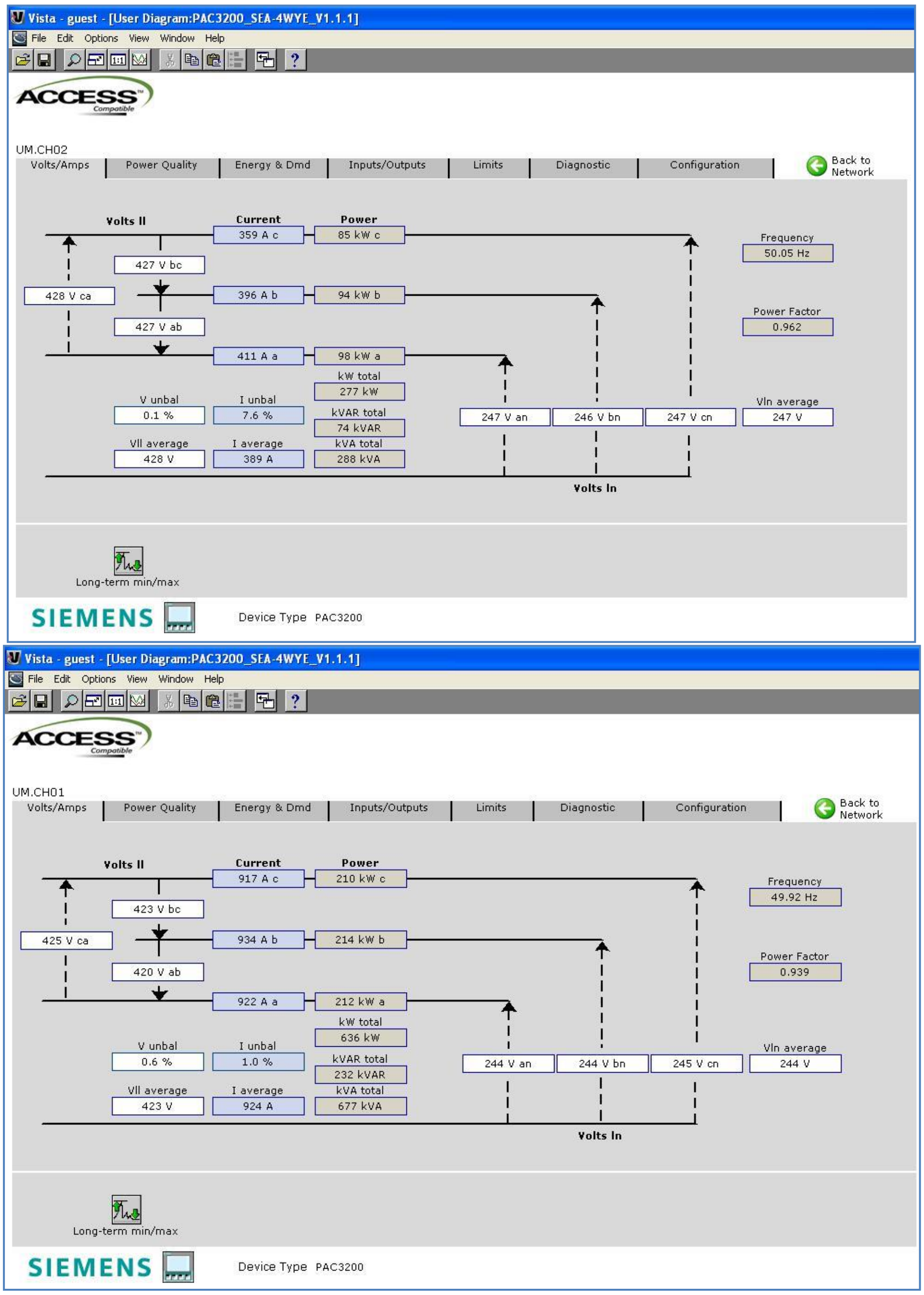


Figure 3.17: Power monitoring software interface taken on March 25th, 2012, 11:37 am, top: Channel 1 (chiller), below: Channel 2 (building).

3.3 Data analysis

Uncertainty measurement is a numerical expression of the quality of the measurement result. Any result of measurement is more or less uncertain. There is no doubt that, the actual value of the physical quantity exists, but it cannot be found out by measurement. In the best case, one can estimate the uncertainty of the measurement and determine the range of values for which can be said: there is a high probability that the actual value of the measured quantity is in this range. The source of errors can be categorized as rough errors, systematic and random errors. Rough errors occurred by personal errors, systematic errors arise due to the imperfection of the measuring equipment and procedure. Most of the systematic errors have permanent value, hence, they can be quantified and taken into account during analysis of the measurement results. Systematic errors can be minimized by calibrating the equipment.

The uncertainty caused by recording instruments and the errors due to manual calculation are calculated in this research. Most of the plotted data are considered with the confidence level of 95%. The methodology to obtain the mentioned confidence region is described hereinafter.

3.3.1 Standard deviation

Standard deviation (σ) shows how much variation or "dispersion" exists from the average (mean, or expected value). A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data points are spread out over a large range of values. Consider two numbers, X_1 and X_2 ($X_1 > X_2$). Their mean number $\overline{X}$ is the midpoint and the standard deviation σ is the distance from each of the numbers to $\overline{X}$. So $\overline{X}$ and σ satisfy the equations

$$\overline{X} = \frac{(X_1 + X_2)}{2} \tag{3.13}$$

$$\sigma = \frac{(X_1 - X_2)}{2} \tag{3.14}$$

These expressions are generalized to the case where "n" represents the numbers of involved recording data.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}} \tag{3.15}$$

Where, X_i is the value of sample i, $\overline{X}$ is the mean of sample values and n is the number of samples.

3.3.2 Confidence level

The confidence interval (CI) is a kind of interval estimate of a population parameter and is used to indicate the reliability of an estimate. If confidence intervals are constructed across many separate data analyses of repeated (and possibly different) experiments, the proportion of such intervals that contain the true value of the parameter will match the confidence level. Confidence regions generalize the confidence interval concept to deal with multiple quantities. Such regions can indicate not only the extent of likely sampling errors but can also reveal whether (for example) it is the case that the estimate for one quantity is unreliable then the other is also likely to be unreliable. In applied practice, confidence intervals are typically stated at the 95% confidence level. In the present work, the confidence level of 95% is taken into account during data analysis. Therefore, the confidence interval (μ) for the confidence level of 95% is calculated as follows:

$$\overline{X} - 1.96\frac{\sigma}{\sqrt{n}} < \mu < \overline{X} + 1.96\frac{\sigma}{\sqrt{n}} \tag{3.16}$$

3.3.3 Uncertainty analysis

The uncertainty analysis is used to evaluate the experimental uncertainty of a derived quantity, based on the uncertainties in the experimentally measured quantities. It has two components, namely, bias (related to accuracy) and the unavoidable random variation that occurs when making repeated measurements (related to precision). The bias uncertainty is mainly caused due to the non-uniformity of the collected data. Its value can be calculated as follows:

$$\mathrm{B_{uncertainity}} = \frac{(\mathrm{X_{maximum}} - \mathrm{X_{minimum}})}{\text{Number of measurements}} \tag{3.17}$$

Where, $\mathrm{X_{maximum}}$ and $\mathrm{X_{maximum}}$, represent the maximum and minimum recorded value of a certain parameter.

3.4 Thermodynamic assessment of different CTES systems

In a CTES process, the chilled water produced in the evaporator flows through the tank and transfers the heat from the tank to the refrigerating cycle until the temperature of the tank drops to the inlet temperature. The stored cold energy will be kept in the tank for a period of time, which is called the storing process. Challenges arise in evaluating the energy and exergy efficiency of this process because the efficiency is directly depending on the process timing. The thermophysical properties of ice and water are considered at -5ºC and 5ºC, respectively. The required data for conducting the energy and exergy analysis are tabulated in Table 3.11.

Table 3.11**:** Data used for energy and exergy analysis (Wang and Kusumoto, 2001).

CTES technique	COP	Charging temperature (ºC)	Discharging temperature (ºC)	Maximum cooling density (kWh/m^3)
Ice on coil-internal	2.9 to 4.1	-6 to -3	2	48.1
Ice on coil-external	2.5 to 4.1	-9 to -4	1	43.5
Ice slurry	2.4	-12 to -10	-3	46.5
Encapsulated ice	2.9 to 4.1	-6 to -3	1	52.6
Ice harvesting	2.7 to 3.7	-9 to -4	1	39.3

Generally, the cool energy production cycle can be simplified by considering the ideal vapour-compression refrigeration cycle (Figure 3.18).

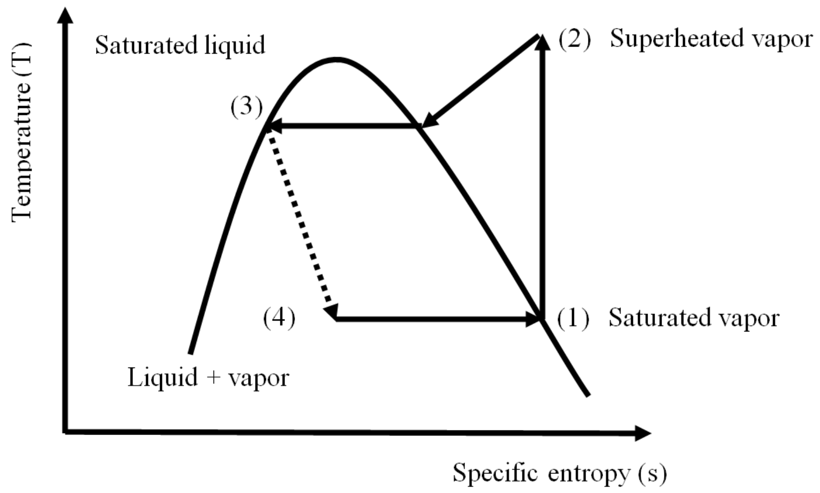


Figure 3.18: Cycle description for an ideal vapour-compression refrigeration cycle (Çengel and Boles, 2011).

In order to simplify the calculation some minor assumptions were taken into account. By neglecting the expansion valve and pipe heat losses and considering the chiller and thermal reservoirs as a single lumped system, the process can be simplified. Furthermore, the following assumptions are made during system analysis, Table 3.12:

Table 3.12: General assumptions made during the calculation.

General considerations	- The temperature of the storage tank is constant at each time point. - All of the thermal energy is reserved in the storage medium. - Thermophysical properties remain constant at their given values.
Charging	- Compressor work is the only input to the system. - The only interaction with the ambient air is heat transfer between the tank and the environment.
Storing	The only interaction with the surroundings is heat leakage to the storage media.
Discharging	The discharge process only involves cooling the antifreeze solution.

By considering these assumptions, the energy and exergy evaluation can be conducted.

3.4.1 Energy evaluation

The overall energy balance of the whole process is described as follows (MacPhee and Dincer, 2009):

$$\Delta \mathrm{E_{system}} = \mathrm{E_{final}} - \mathrm{E_{initial}} = \mathrm{E_{in}} - \mathrm{E_{out}} \qquad (3.18)$$

The general energy efficiency formula is defined as the ratio of the desired to the required energy. This ratio is calculated for the charging, storage and discharging cycles individually.

$$\eta = \frac{\mathrm{E_{des}}}{\mathrm{E_{req}}} \qquad (3.19)$$

3.4.1.1 Charging

During the charging process, the compressor work (W_{in}) is the only input. The outputs from the system are the condenser heat transfer (Q_{cond}) and the heat leakage from the surroundings ($Q_{leak,ch}$), illustrated in Figure 3.19.

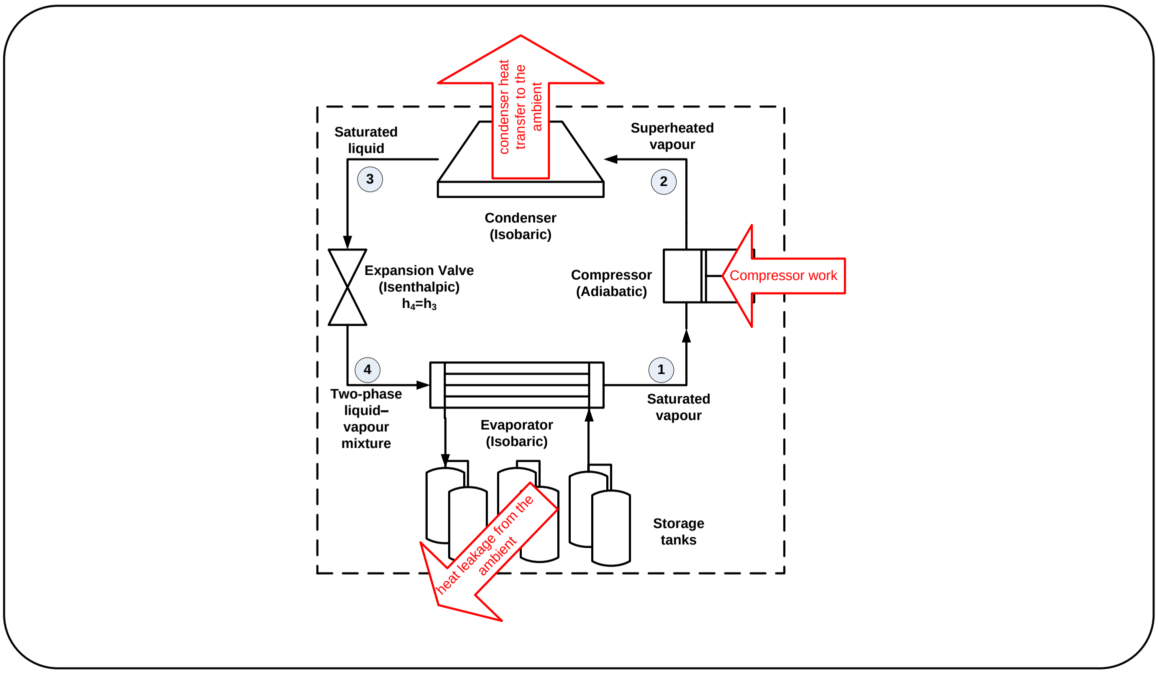


Figure 3.19: Schematic energy balance during the charging process.

The energy change of the system is equal to the amount of energy accumulating in the evaporator during charging process. Hence, the energy balance can be described as follows:

$$E_{final} - E_{initial} = E_{in} - E_{out} \tag{3.20}$$

$$0 - Q_{evap} = W_{in} - Q_{cond} - Q_{leak,ch} \tag{3.21}$$

$$E_{total} = Q_{evap} = Q_{cond} + Q_{leak,ch} - W_{in} \tag{3.22}$$

Where E_{total} is the known value of the total stored energy during the charging process. The desired energy during charging is equal to the total energy moved from the cold source to the ambient environment (the hot source), and the required energy to do so is equal to the input work of the compressor. Hence;

$$E_{des,ch} = Q_{cond} - Q_{evap} \tag{3.23}$$

$$E_{req,ch} = W_{in} \tag{3.24}$$

$$\eta_{ch} = \frac{Q_{cond} - Q_{evap}}{W_{in}} \tag{3.25}$$

The COP of the refrigeration cycle is defined as the ratio of the heat transferred to the hot sources into the required work. The COP of the cold storage system is a known parameter, which is presented in Table 3.11 and is defined by the manufacturer. Hence, the input work of the compressor can be calculated by considering the known value of COP and E_{total} as follows:

$$W_{in}(\mathrm{kWh}) = \frac{Q_{evap}\,(\mathrm{kWh})}{\mathrm{COP}} = \frac{E_{total}\,(\mathrm{kWh})}{\mathrm{COP}} \tag{3.26}$$

From thermodynamics, the energy rejected from the evaporator is defined as:

$$Q_{evap} = m_{ref} \times (h_1 - h_4) \tag{3.27}$$

Hence, by rewriting the equation for m_{ref}, the refrigerant mass can be calculated.

$$m_{ref}\,(\mathrm{kg}) = \frac{Q_{evap}\,(\mathrm{kWh}) \times 3600(\mathrm{kj} / \mathrm{kWh})}{(h_1 - h_4)(^{\mathrm{kj}}/_{\mathrm{kg}})} \tag{3.28}$$

The work input to the compressor depends on the enthalpy change during the compression process, between points 1 and 2, as defined below and, from that figure, the unknown enthalpy value h_2 can also be defined,

$$Q_{evap} = m_{ref} \times (h_2 - h_1) \tag{3.29}$$

$$h_2\left(\frac{\mathrm{kj}}{\mathrm{kg}}\right) = \frac{W_{in}(\mathrm{kWh}) \times 3600\left(\frac{\mathrm{kj}}{\mathrm{kWh}}\right)}{m_{ref}(\mathrm{kg})} + h_1\left(\frac{\mathrm{kj}}{\mathrm{kg}}\right) \tag{3.30}$$

In order to calculate the energy loss via leakage during charging process the temperature distribution within the storage tank is assumed to be constant. Generally, thermal storage tanks are designed with a cylindrical shape. The tank volume can be calculated from its maximum thermal storage density ($\rho_{th,max}$) as follows (MacPhee and Dincer, 2009):

$$V(m^3) = \frac{E_{total}(kWh) \times 3.6(\frac{Mj}{kWh})}{\rho_{th,max}(\frac{Mj}{m^3})} \quad (3.31)$$

Therefore, the tank surface area will be calculated as below:

$$A = 6\pi(\frac{V}{2\pi})^{2/3} \quad (3.32)$$

By having the tank's geometry, its heat leakage Q_{leak} can be calculated using Equation (3.33) (MacPhee and Dincer, 2009). The average charging temperature is taken to be equal to the average storage temperature (T_{ch}=T_{st}).

$$Q_{leak,ch} = A\frac{T_{amb} - T_{st}}{R_T}\Delta t_{ch} \quad (3.33)$$

Where A is the tank surface area, R_T (m^2/kW.K) is the tank's thermal resistance and Δt_{ch} represents the changing time. Once we obtain the leakage during charging process the condenser heat transfer can be computed:

$$Q_{cond} = Q_{evap} - Q_{leak,ch} + W_{in} \quad (3.34)$$

Now adequate information is available for obtaining the storage efficiencies during charging process.

3.4.1.2 Storage

During the storage process, the only interaction between system and surrounding is heat leaked from the ambient. The schematic diagram is shown in Figure 3.20.

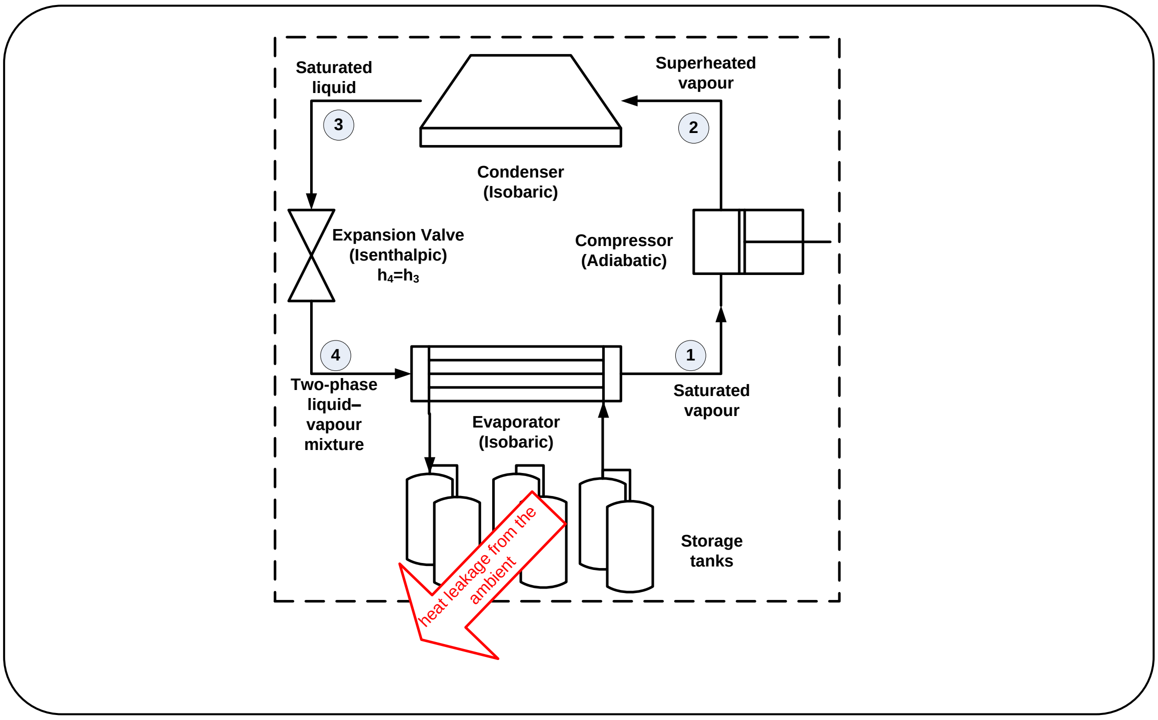


Figure 3.20: The schematic energy balance diagram during the storage process.

The required and desired cool energy during the storage process can be defined as follows:

$$E_{des,st} = E_{total} - Q_{leak,st} \tag{3.35}$$

$$E_{req,st} = E_{total} \tag{3.36}$$

Where $Q_{leak,st}$ is the heat leakage through the walls during storage process, which can be derived in the same fashion as during the charging stage, taking T_{st} as the storage temperature and Δt_{st} as the storage time.

$$Q_{leak,st} = A\frac{T_{amb} - T_{st}}{R_T}\Delta t_{st} \tag{3.37}$$

3.4.1.3 Discharging

The only loss during the discharging process is heat leakage through the walls. Thus, the amount of desired and required energy contents can be given by the following equations:

$$E_{des,dc} = E_{total} - Q_{leak,ch} - Q_{leak,dc} \tag{3.38}$$

$$E_{req,dc} = E_{total} - Q_{leak,ch} \tag{3.39}$$

$$Q_{leak,dc} = A\,\frac{T_{amb}-T_{dc}}{R_T}\,\Delta t_{dc} \tag{3.40}$$

Finally, the overall energy efficiency can be derived by multiplying the efficiency of each individual process (Çengel and Boles, 2011):

$$\eta_{overall} = \eta_{ch} \times \eta_{st} \times \eta_{dc} \tag{3.41}$$

3.4.2 Exergy evaluation

Unlike energy, exergy is a property which represents a combination of the system and its environment. When the system is in equilibrium with its environment, the physical exergy value is zero. This condition is called "dead state" and is defined normally at T_0=25ºC and P_0=1atm. The change in exergy of the closed system from the initial to the final state is equal to the difference between inlet and outlet exergy flows, minus the exergy destroyed. Hence, the overall exergy balance of the system can be defined as follows:

$$\begin{pmatrix}\text{Change in the}\\ \text{total exergy}\\ \text{of the system}\end{pmatrix} = \begin{pmatrix}\text{The net}\\ \text{exergy}\\ \text{input}\end{pmatrix} - \begin{pmatrix}\text{The net}\\ \text{exergy}\\ \text{output}\end{pmatrix} - \begin{pmatrix}\text{Total}\\ \text{exergy}\\ \text{destroyed}\end{pmatrix} \tag{3.42}$$

By applying Equation (3.42) to the CTES system, the overall exergy balance will be as follows:

$$\Delta Ex_{sys} = Ex_{in} - Ex_{out} - I \tag{3.43}$$

Where, Ex_{out} consist of exergy output through fluid flow and exergy transfer due to heat penetration ($Ex_{l,i}$) and I is the system's irreversibilities. The exergy transferred by boundary work can be expressed as follow (Çengel and Boles, 2011):

$$\mathrm{Ex_{work}} = \mathrm{W} - \mathrm{W_{surr}} \tag{3.44}$$

Where $W_{surr}=P_0(V_2-V_1)$, V_1 and V_2 are initial and final volumes of the system. As the system has fixed boundaries ($V_1=V_2$), hence, $Ex_{in}=W_{in}$. The maximum work that can be achieved from energy transfer from a heat source at T to T_{amb} is equal to the work produced by a Carnot heat engine working between the same conditions. Therefore, the general formulation for obtaining exergy transferred by heat transfer is described below:

$$\mathrm{Ex_{heat}} = \mathrm{Q} \times \text{Carnot efficiency} = \mathrm{Q}\left(1 - \frac{\mathrm{T_{amb}}}{\mathrm{T}}\right) \tag{3.45}$$

The exergy efficiency (ψ) is defined in a same fashion as energy efficiency as the ratio of the desired exergy output to the required exergy input.

$$\psi = \frac{\mathrm{Ex_{des}}}{\mathrm{Ex_{req}}} \tag{3.46}$$

Since the charging, storage and discharging process are quite different, the exergy efficiency of each of them will be defined and calculate separately.

3.4.2.1 Charging

The input exergy during charging is the input work and the output exergy is the exergy output due to the heat transfer from condenser and the heat leakage to the storage tank from surrounding. The exergy balance equation for charging process can be written as follows:

$$\Delta\mathrm{Ex_{sys,ch}} = \mathrm{W_{in}} - (\mathrm{Ex_{cond}} - \mathrm{Ex_{leak,ch}}) - \mathrm{I_{ch}} \tag{3.47}$$

Where, exergy of the condenser and the exergy transferred by the heat leakage are calculated based on the following equations. It is assumed that the tank is charged at T_{st}. T_{cond} is set equal to the average of ambient and compressor outlet temperatures.

$$Ex_{cond} = Q_{cond} \times \left(1 - \frac{T_{amb}}{T_{cond}}\right) \tag{3.48}$$

$$Ex_{leak,ch} = Q_{leak,ch} \times \left(1 - \frac{T_{amb}}{T_{st}}\right) \tag{3.49}$$

The desired exergy is equal to the exergy stored in the tank during charging and the required exergy is the equals to the net work input. Hence, $Ex_{des,ch}$ and $Ex_{req,ch}$ can be shown as follows:

$$Ex_{des,ch} = \Delta Ex_{sys,ch} = \Delta E_{sys,ch} - T_{amb}\Delta S_{sys,ch} \tag{3.50}$$

$$Ex_{req,ch} = W_{in} \tag{3.51}$$

$$\Delta E_{sys,ch} = W_{in} - Q_{cond} - Q_{leak,ch} \tag{3.52}$$

The charging process starts from T_{dc} to T_{ml} (melting temperature) and after solidification continues from T_{ml} to T_{st}. The mass of media in the storage tank can be calculated as below:

$$m_{PCM} = \frac{Q_{evap}}{C_f(T_{dc} - T_{ml}) + h_{fg} + C_{ice}(T_{ml} - T_{ch})} \tag{3.53}$$

Where C_f is the specific heat of liquid and C_{ice} is the specific heat of the frozen media. Since all the system's energy is assumed to be contained within the water/ice portion of the tank, this entropy change will consist of sensible (both liquid and solid) and entropy of phase change.

$$\Delta S_{sys,ch} = m_{PCM}\left[C_W \ln\left(\frac{T_{ml}}{T_{dc}}\right) - \frac{L}{T_{ml}} + C_{ice}\ln\left(\frac{T_{st}}{T_{ml}}\right)\right] \tag{3.54}$$

The system irreversibility during charging is equal to:

$$I_{ch} = W_{in} - Ex_{cond} - Ex_{leak,ch} - \Delta Ex_{sys,ch} \tag{3.55}$$

3.4.2.2 Storage

During the storage process, the only interaction between system and surrounding is the heat leakage from outside of the storage tank. It is assumed that the tank's temperature during the storage period has a small fluctuation shown as ΔT_{st}. The exergy balance for this process can be simplified as the following form:

$$\Delta Ex_{sys,st} = -Ex_{leak,st} - I_{st} \tag{3.56}$$

The exergy transferred due to heat leakage can be calculated in the same fashion as the charging process:

$$Ex_{leak,st} = Q_{leak,st} \times \left(1 - \frac{T_{amb}}{T_{st}}\right) \tag{3.57}$$

By having the amount of heat leaked to the tank during the storage process ($Q_{leak,st}$), the temperature drop can be calculated as well:

$$\Delta T_{st} = \frac{Q_{leak,st}}{m_{pcm} C_{ice}} \tag{3.58}$$

The irreversibilities due to the entropy generation is defined as follows:

$$I_{st} = m_{ice} C_{ice} T_{amb} \ln\left(\frac{T_{st} + \Delta T_{st}}{T_{st}}\right) \tag{3.59}$$

where, m_{ice} is the mass of frozen media stored inside the storage tank, C_{ice} is the ice specific, T_{st} is the average temperature of the storage tank and ΔT_{st} is the sensible temperature change of ice due to heat leakage. The desired exergy for the storage process is equal to the desired exergy of charging minus the exergy destroyed during storage. Obviously, required exergy is equal to the stored exergy:

$$Ex_{des,st} = Ex_{des,ch} - Ex_{leak,st} - I_{st} \tag{3.60}$$

$$Ex_{req,st} = \Delta Ex_{sys,ch} \tag{3.61}$$

3.4.2.3 Discharging

For the discharging process, there will be a glycol solution entering the storage vessel at room temperature and cooled by the ice storage. The glycol solution is assumed to leave at a specified discharge temperature. For the discharge process, the exergy balance equation is as follows:

$$\Delta Ex_{sys,dc} = Ex_{in} - (Ex_{out} - Ex_{Q,dc}) - I_{dc} \tag{3.62}$$

The desired exergy output for the discharge process is the difference in flow exergy in the glycol solution as it gives heat to the storage tank.

$$Ex_{des,dc} = Ex_{in} - Ex_{out} = m_g C_g \left(T_{in} - T_{out} - T_{amb} \ln\left(\frac{T_{in}}{T_{out}}\right)\right) \tag{3.63}$$

The required exergy output for discharging process is equal to the exergy accumulation during charging and storage and can be illustrated as follow:

$$Ex_{req,dc} = \Delta Ex_{ch} + \Delta Ex_{st} \tag{3.64}$$

However, in order to evaluate the above equation, the total mass of glycol used will depend on the total energy transferred to the glycol, as well as the temperature change:

$$m_g = \frac{E_{req,dc} - E_{l,dc}}{C_g (T_{room} - T_{dc})} \tag{3.65}$$

Now, the exergy transferred from the system by heat leakage will be addressed in similar fashion as was done earlier:

$$\mathrm{Ex_{leak,dc}} = \mathrm{Q_{l,dc}}\left(1 - \frac{\mathrm{T_{amb}}}{\mathrm{T_{dc}}}\right) \tag{3.66}$$

So, finally, all terms and efficiency equations can be calculated for the discharging case. The overall exergy efficiency can be calculated using Equation (3.67).

$$\psi_{overall} = \psi_{ch} \times \psi_{st} \times \psi_{dc} \tag{3.67}$$

3.5 Economic analysis

For a system consisting of a chiller and a storage tank, the total annual cost, C_{total}, is a function of the capital cost for the chillers, C_{ch}, capital cost for the storage system, C_{st}, and the utility costs, C_{uti}. The utility cost itself is a function of operating time, t_{op}, total energy consumption, E, and the localized electricity tariff rate, e_{trf} ($/kWh) (Habeebullah, 2007).

$$\mathrm{C_{total}} = \mathrm{f(C_{ch}, C_{st}, C_{uti})} \tag{3.68}$$

$$\mathrm{C_{uti}} = \mathrm{f}\left(\mathrm{t_{op}, E, e_{trf}}\right) \tag{3.69}$$

To calculate the annual repayment of the chiller and storage system to pay back the investment in a specified period, the capital costs must be multiplied with the capital recovery factor (CRF). The CRF is defined as the ratio of a constant annuity to the present value of receiving that annuity for a given length of time (Park, 2008).

$$\mathrm{CFR} = \frac{\mathrm{i(1+i)^n}}{\mathrm{(1+i)^n - 1}} \tag{3.70}$$

Where i is the interest factor and *n* is the number of years. Therefore, by substituting Equations (3.70) and (3.69) in to (3.68) the total annual cost can be expressed as follows:

$$C_{total} = \frac{i(1+i)^n}{(1+i)^n - 1}[C_{ch} + C_{st}] + \int_0^{t_{op}} e_{trf} E dt \tag{3.71}$$

In Equation (3.71) the total energy demand, E, is a function of climate condition, building geometry, occupancy profile, activity level, and etc.

3.5.1 Payback period

Payback (PB) period is defined as the period of time required for the profit or other benefits of an investment to be equal to the cost of the investment (Park, 2008).

$$PB = \frac{\text{Intial cost}}{\text{Uniform annual benefit}} \tag{3.72}$$

For the ITS system, the initial cost includes supply and installation of chillers, pumps, cooling towers, piping and valve fittings, electrical and control system cost and chemical treatment. The annual cost saving is the difference between the on-going costs of a conventional AC system and the on-going costs of an ITS system working in the same condition. It was assumed that Malaysia will experience a steady and constant interest rate of 7% over the next 20 (Masjuki et al., 2001).

3.5.2 Localized costs for installation and maintenance

The installation cost of the conventional AC systems is mainly nominated by the total system capacity. Generally, in Malaysian market if the total system capacities are 1,000ref.ton and above, a rule of thumb of \$1,166/ref.ton (RM3,500/ref.ton) can be adopted, which includes supply and installation of chillers, pumps, cooling towers, piping and valve fittings, electrical and control system cost and chemical treatment. For the system capacities less than 1,000 ref.ton the installation costs vary between \$1,666

(RM5000) to $2,333 (RM7,000) per ref.ton. The same rule of thumb may also be applied for the installation cost of the ITS systems. If the total system capacities are 1,000 ref.ton and above, the installation cost of $2,000/ref.ton (RM6,000/ref.ton) can be adopted, which includes supply and installation of chillers, pumps, cooling towers, ice tanks, piping and valve fittings, electrical and control system cost, glycol and chemical treatment. For system capacities less than 1,000ref.ton, the price varies from $2,666 (RM8,000) to $3,333 (RM10,000) per ref.ton. Figure 3.21 is generated based on the above rule of thumb. A curve fitting shows that the best relation between installation cost and total system capacity can be defined by the power order equation as follows where a and b are constant values.

$$\text{Approximate installation cost} = \text{a}(\text{Total system capacity})^{\text{b}} \qquad (3.73)$$

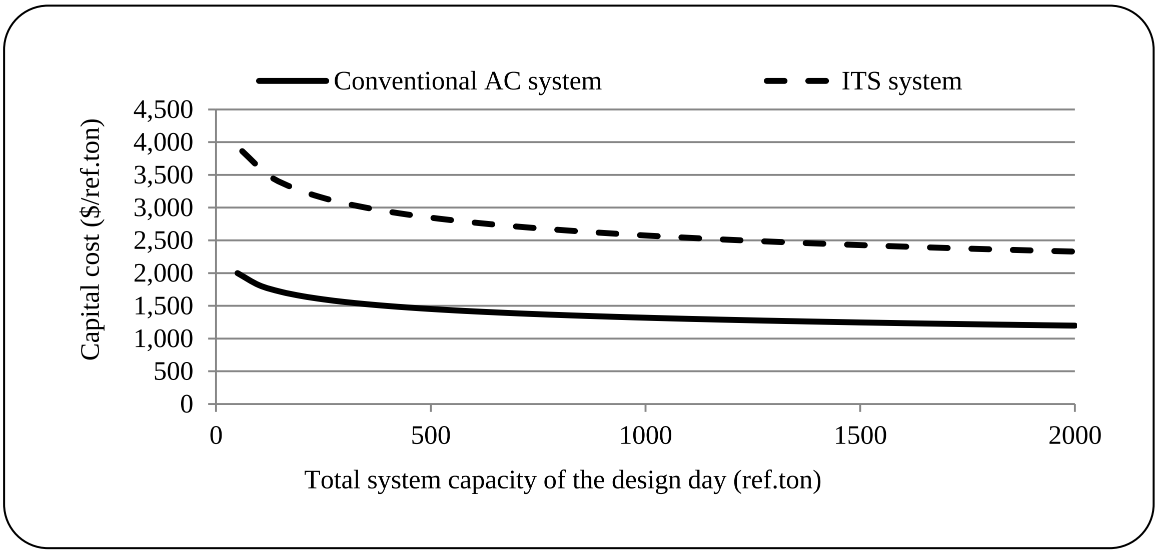


Figure 3.21: Capital cost trend for conventional AC system and ITS system.

The annual maintenance costs for ice tanks alone are low, it can be assume for $1.6/ref.ton/year. The annual cost of maintenance for the conventional AC system can be adapted with the rule of thumb of $6.6/ref.ton/year and for the ITS system is around $8.3/ref.ton/year.

3.5.3 Tariff rate structure

The ambient temperature records from different cities of Malaysia show that diurnal temperature varies between 19ºC to 36ºC, whilst relative humidity (RH) varies from 51% to 100% and there are no distinct seasonal variations to this pattern (ASHRAE, 2009). For estimating the daily cooling load profile inside the conditioned space, both demographical and climate data are considered.

Based on the latest information released by TNB, the peak period for medium voltage commercial use (C2) is from 8:00 to 22:00 (14 peak hours per day). However, to encourage customers to shift their electricity use to off-peak hours, TNB offers special rate structures for those using thermal energy storage systems. Based on the special rates, the peak period is reduced by two hours (from 9:00 to 21:00), creating 12 peak hours and 12 off-peak hours each day. The electricity tariff rate and the maximum demand charge for the conventional AC system and for the ITS system is presented in Table 3.13.

Table 3.13: Comparison between normal and Special rate structure for medium voltage commercial (C2).

Descriptions	Normal rate per kW	Special rate per kW	
Peak hours	8:00 to 22:00	9:00 to 21:00	
Peak duration	14 hours	12 hours	
Tariff rate	$0.104 (RM0.312*)	During peak hours:	During off-peak hours:
		$0.104 (RM0.312)	$0.06 (RM0.182)
Maximum demand charges	$8.633 (RM25.90)	$12.86 (RM38.60)	

*$1 is equal to RM3.0 (Universal Currency Converter)

The latest tariff tare structure provided by TNB is presented in Appendix B.

3.6 TRNSYS Simulation

TRNSYS is a transient systems simulation program with a modular structure. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. The TRNSYS library includes many of the components commonly found in thermal and electrical energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results. The modular nature of TRNSYS gives the program flexibility, and facilitates adding mathematical models that are not included in its standard library. TRNSYS is well suited to detailed analyses of any system whose behaviour is dependent on the passage of time (TRNSYS Simulation Studio, 2009).

In order to model the building in TRNSYS simulation software numbers of inputs and parameters are required such as; Meteorological data, building characteristics (Orientation, Thermal characteristics of components etc.), air conditioning and ventilation requirements, internal thermal gains and etc.

3.6.1 Building modelling equations

The building model used in this simulation is the typical multi-zone building component (Type 56). Detailed theories about this component is presented in TRNSYS user manual (TRNSYS Simulation Studio, 2009). Herein a fundamental mathematical frame is presented through a series of equations and illustrations.

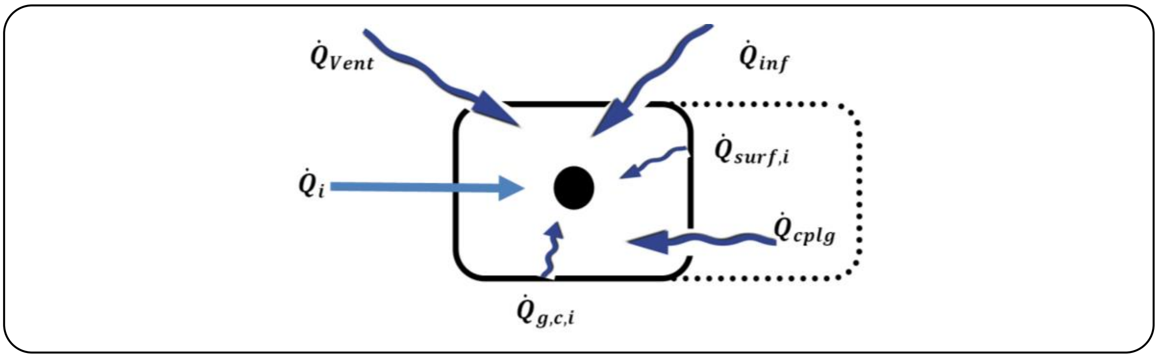


Figure 3.22: Heat balance on the zone air node.

The building model in Type56 is a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and capacities that are closely connected with the air node, hence the overall energy balance can be illustrated as follows:

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g.c,i} + \dot{Q}_{cplg,i} \qquad (3.74)$$

Where $\dot{Q}_{surf,i}$ is the convective heat flow from all inside surface, $\dot{Q}_{inf,i}$ is the infiltration gain from outside air flow, $\dot{Q}_{vent,i}$ is the ventilation gains from HVAC system, $\dot{Q}_{g.c,i}$ denotes the internal convective gains (by people, equipment, illumination, radiators, etc.), and $\dot{Q}_{cplg,i}$ is the gains due to (connective) air flow from zone I or boundary condition. The rate of change of internal energy for thermal zone is equal to the net heat gain, therefore their relations are expressed by the following equation:

$$C_{zi}\frac{dT_i}{dt} = \dot{Q}_i \qquad (3.75)$$

Where C_{zi} denotes the thermal capacitance of zone i. The equation (3.75) indicates that the net heat gain $\dot{Q}_i$ is a function of T_i and the temperature of all other zones adjacent to zone i. Heat fluxes through current internal wall surfaces depend on inside and outside air and surface temperatures as well as inside and outside heat fluxes. Therefore, transient response of the building envelope is typically modelled by transforming the heat diffusion equation into a conduction transfer function, where the inside and the outside surface heat fluxes are determined with surface temperatures and coefficients of the time series.

$$\frac{\partial T_z}{\partial t} = \alpha \frac{\partial^2 T_z}{\partial x^2} \tag{3.76}$$

The walls are modelled according to the transfer function relationships of Mitalas and Arseneault (1972) defined from surface to surface. For any wall, the heat conduction at the surfaces is:

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{bs}} b_s^k\, T_{s,o}^k - \sum_{k=0}^{n_{cs}} c_s^k\, T_{s,i}^k - \sum_{k=0}^{n_{ds}} d_s^k\, T_{s,i}^k \tag{3.77}$$

$$\dot{q}_{s,o} = \sum_{k=0}^{n_{as}} a_s^k\, T_{s,o}^k - \sum_{k=0}^{n_{bs}} b_s^k\, T_{s,i}^k - \sum_{k=0}^{n_{ds}} d_s^k\, T_{s,o}^k \tag{3.78}$$

These time series equations in terms of surface temperatures and heat fluxes are evaluated at equal time intervals. The superscript k refers to the term in the time series. The current time is k=0, the previous time is for k=1, etc. The time-base on which these calculations are based is specified by the user within the TRNBUILD description. The coefficients of the time series (a_s, b_s, c_s, and d_s) are determined within the TRNBUILD program using the z-transfer function routines of reference. Figure 3.23 shows the heat fluxes and temperatures that characterize the thermal behaviour of any wall or window.

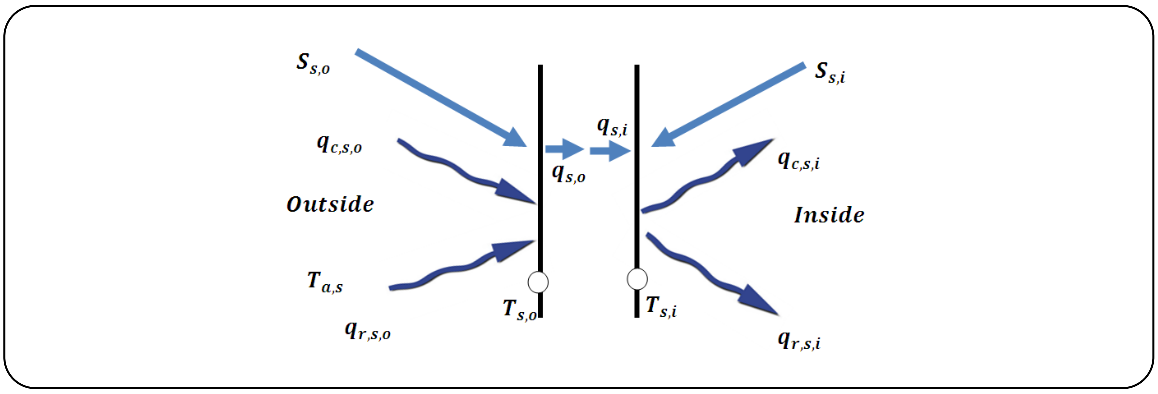


Figure 3.23: Surface heat fluxes and Temperatures.

The nomenclatures used in this figure are defined as follows:

$S_{s,i}$ is the radiation heat flux absorbed by the inside surface (solar and radiative gains), $S_{s,o}$ is the radiation heat flux absorbed by the outside surface (solar gains), $\dot{q}_{r,s,i}$ is net radiative heat transfer with all other surfaces within the zone, $\dot{q}_{r,s,o}$ is net radiative heat transfer with all surfaces in view of the outside surface, $\dot{q}_{w,g,i}$ denotes user defined heat flux to the wall or window surface, $\dot{q}_{s,i}$ is the conduction heat flux from the wall at the inside surface, $\dot{q}_{s,o}$ is Into the wall at the outside surface, $\dot{q}_{c,s,i}$ is convection heat flux from the inside surface to the zone air, $\dot{q}_{c,s,o}$ is convection heat flux to the outside surface from the boundary/ambient, $T_{s,i}$ is inside surface temperature and $T_{s,o}$ is outside surface temperature.

3.6.2 Baseline model

The baseline model consists of chiller, cooling tower, circulating pumps, collectors, FCUs, AHUs as well as internal heat gains such as occupants, computers and etc. Figure 3.24 shows the schematic drawing of the base line model.

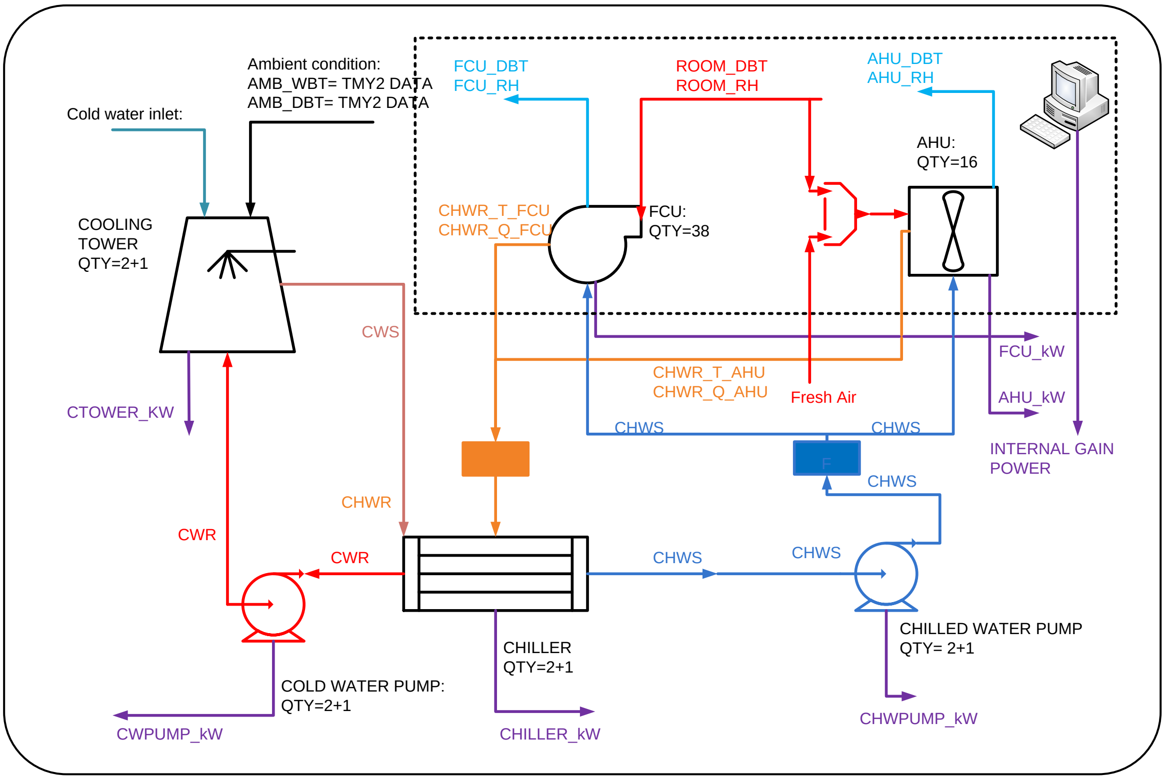


Figure 3.24: The schematic drawing of the base line model.

The chilled water produced in chiller is distributed to the FCUs and AHUs via chilled water pump, the chilled water absorbs the heat from the return air from the room. The required fresh air is supplied and mixed with the room's return air in the AHUs. The chilled water return, directs back to the chiller to complete the chiller cycle. The required cooling water is supplied by the cooling tower units located in the rooftop. The TRNSYS model of the baseline configuration is built based on the as built M&E drawings of the building. The TRNSYS model is demonstrated in Figure 3.25.

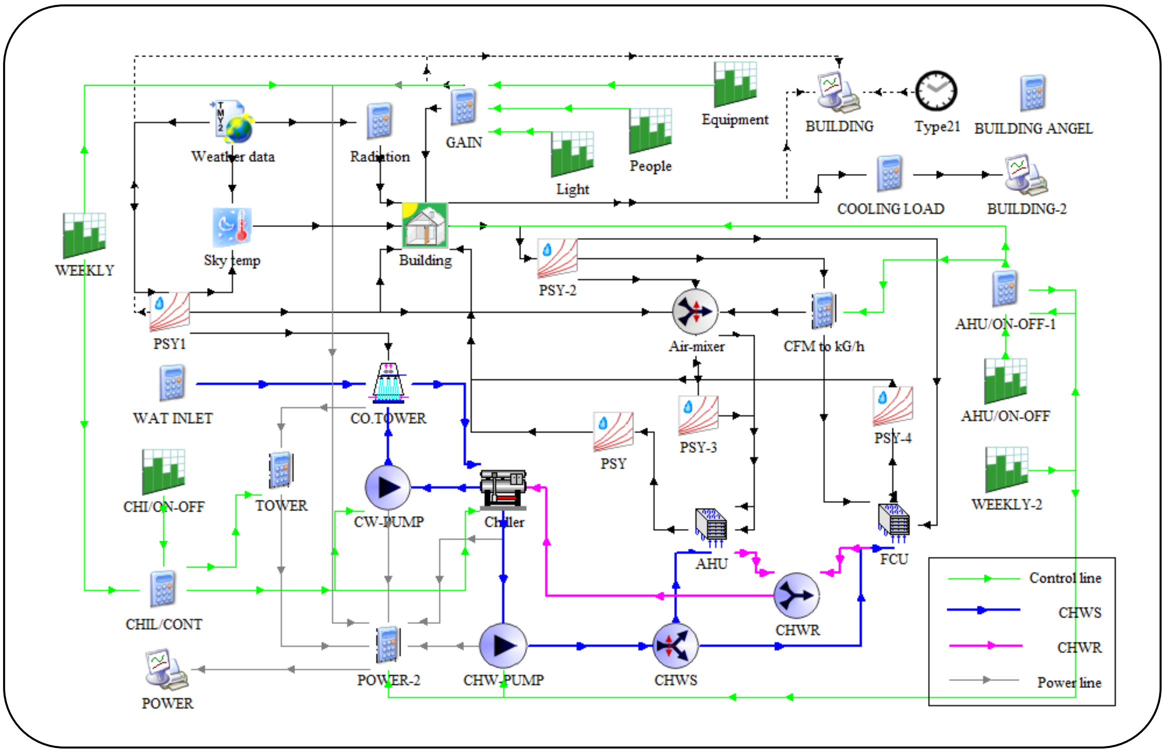


Figure 3.25: TRNSYS simulation of the base line model.

From the Figure 3.25, two water cycles for chilled water and cooling water can be recognized. The produced chilled water in the chiller is distributed to the AHUs and FCUs through chilled water pump and chilled water distributers. The returned water from the building will directed back to the chiller. The cooling water cycle is between the chiller and the cooling tower. The ambient condition is provided as TMY2 data as an input file. The ambient temperature, humidity and solar condition are used as input data for calculating heat transfer via conduction, convection and also solar heat gain for the building. The ambient temperature and humidity is also used as input data to calculate the system behaviour in the cooling tower to calculate the cooling water return temperature during the day. Several control cards are used to simulate the schedule of various internal heat gains such as, occupants, computers and lights. The Psychrometric chart was used when was needed to drive the DBT, WBT and RH from known values. The results output is plotted and at the same time saved in an excel files for post processing. The softcopy of TRNSYS simulation is available in Appendix C. Several TRNSYS components that are used in simulating the baseline model are presented in Appendix D. The TRNSYS deck for the baseline model is presented in Appendix E.

3.6.3 Ice storage tank – Type 221

One of the TRNSYS's major strengths is the ease with which users may write new components to expand upon the capabilities of the program. At the most fundamental level, a component (referred to as a Type) in TRNSYS is merely a black box. The TRNSYS kernel feeds inputs to the black box and in return, the black box produces outputs. TRNSYS makes a distinction between inputs that change with time such as temperature and humidity and inputs that do not change with time such as area or a rated capacity. The time dependent inputs are called "INPUTS" and the time independent ones are called "PARAMETERS". At each iteration and at each time step, the OUTPUTS calculated based on current values of the INPUTS and PARAMETERS.

To simulate the ice storage tank, a FORTRAN subroutine was developed based on the tank configuration and its corresponding performance curve. The Calmac icebank performance curves are presented in Appendix F. The model for an ice-on-coil tank is based on the Calmac 1190 ice -storage tank. The tank is cylindrical with axially tube coils that are stacked vertically. A header system that allows counter flow between two adjacent coils is provided in the tank. The brine that flows through the coils consists of 25% - 75% mixture of ethylene glycol and water. During charging, the brine is pumped into the tubes and gradually built the ice around the coils. During discharge, the ice melts to cool the warm brine being pumped through the coils. The ice melts radially outward leading to a water formation diameter. Figure 3.26 shows the Calmac ice Bank model.

Figure 3.26: Calmac ice Bank® model.

One of the characterizing quantities of an ice storage tank is its effectiveness (ε) that is expressed as the ratio of the actual heat flow to the maximum heat flow.

$$\varepsilon = \frac{T_{ret}-T_{sup}}{T_{ret}-T_{sup,ideal}} \qquad 0 \leq \varepsilon \leq 1 \tag{3.79}$$

Stewart and Gute (1995) showed that while discharging a dynamic ice storage tank the leaving water temperature stays relatively constant for a long time and only towards the end this temperature will start to approach the water inlet temperature ($\varepsilon \rightarrow 1$). Especially for an ice storage system, the tank size strongly depends on the tank performance curve. By having the effectiveness, the rate of heat transfer ($\dot{Q}$) from the brine solution to the ice during charging / discharging can be calculated as follow:

$$\dot{Q} = \varepsilon \dot{m} C_p (T_{in} - T_{ice}) \tag{3.80}$$

The effectiveness by itself, is depending on the overall heat transfer conductance between the brine and the ice in the tank during discharging. The conductance decreases as the ice melts and the layer of water builds up on the surface of the tubes. The brine flow rate also has a direct effect on the effectiveness, by increasing the flow rates, the outlet temperature increased and the effectiveness drops. As the discharging progresses and the ice portion reduced, the tank's effectiveness decreases as well. In Figure 3.27 and Figure 3.28 the Calmac tank effectiveness during charging and discharging process has been plotted for various brine flow rates (Stewart and Gute, 1995). As the flow rate increase, the tank effectiveness decreases.

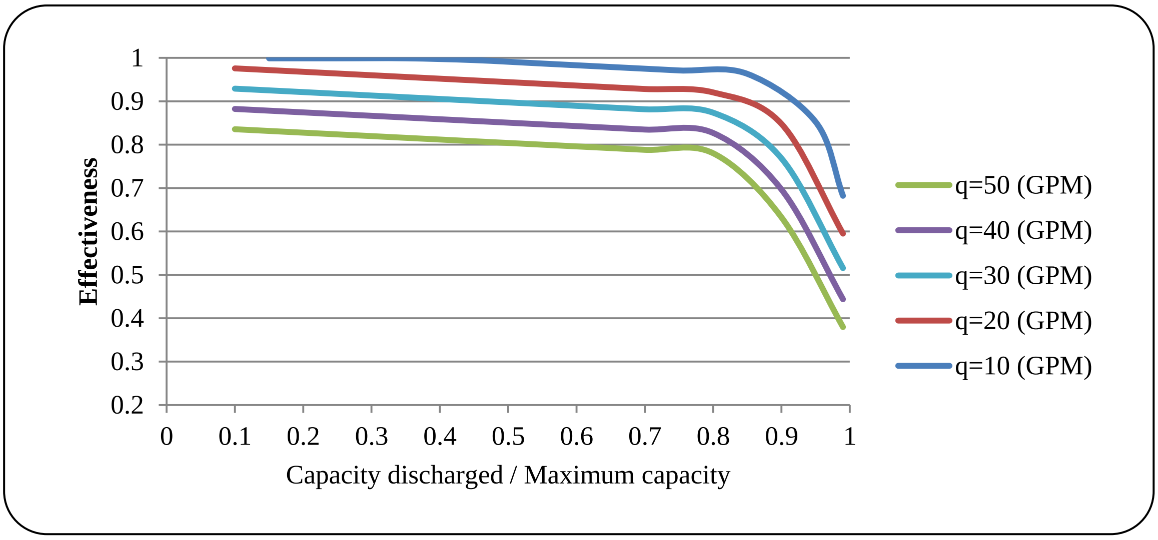


Figure 3.27: Calmac effectiveness profile during discharging process.

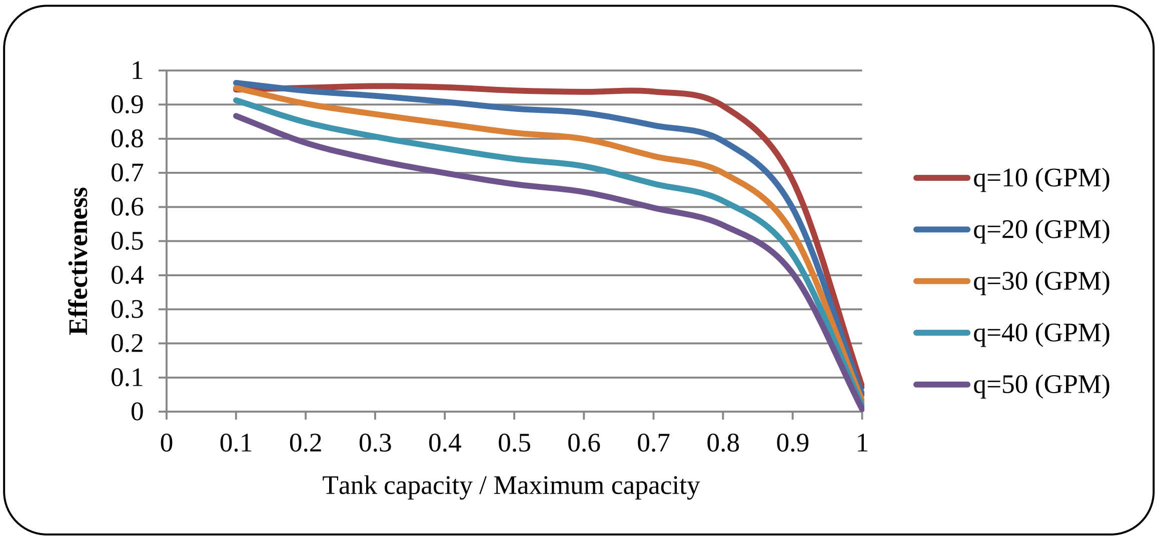


Figure 3.28: Calmac effectiveness profile during charging process.

Where, q represents the flow rate through the ice storage tank. The regression of effectiveness curves is presented in Appendix G. Using the effectiveness curves, a simplified performance model was constructed for use with TRNSYS, the corresponding Fortran source code is presented in Appendix H. The effectiveness was regressed with respect to the volumetric flow rate and the fraction of the capacity discharged.

The tank's maximum capacity is a function of the mass of ice and the inlet brine temperature of the flow, and consists of the latent heat of fusion and sensible heat. By knowing the inlet brine temperature, the fraction of energy discharged and the flow rate, the effectiveness can be found.

$$\text{Maximum tank capacity} = \mathrm{m_i}\left(\mathrm{h_{fg}} + C_P(\mathrm{T_{in}} - \mathrm{T_{ice}})\right) \tag{3.81}$$

By having the effectiveness term, the outlet chilled water temperature can be calculated:

$$\mathrm{T_{out}} = \mathrm{T_{in}} - \varepsilon(\mathrm{T_{in}} - \mathrm{T_{ice}}) \tag{3.82}$$

The charging/discharging capacity is added to the total tank capacity at each time step. At each time step the load, the inlet brine temperature, and the flow rate are required.

3.6.4 Simplification and assumptions

The building is simulated as single zone space filled with air, assuming no interior walls, furniture, etc. It is assumed to have thermal and humidity storage only due to the air that is filling its volume. The model gives only a rough estimate (compared to a "real" building) of the state of the air in the building, since many important real world impacts are neglected. However, it responds to a stream of cold supply air in a similar way as a real room, which is why the model is useful for this simulation.

3.6.5 CTES model

In the CTES model, the chilled water from the chiller will go directly inside the storage tank. The storage tank acts like a heat exchanger and transfer the heat from the tank to the chilled water flow. The returned chilled water will flow through the tank to the chiller to complete its cycle. A second chiller is also provided that can supply part of the required cooling directly to the building (only for partial storage strategy). Figure 3.29 shows a schematic diagram of the proposed system for the ITS storage strategy with full storage strategy. Where, chiller provides all of the required cooling during night-time. In the proposed system, chiller and storage tank are in series configuration where chiller is located at upstream in which, chiller operates at a very high capacity and efficiency. This configuration provides simplified control and piping but the net usable storage is decreased slightly.

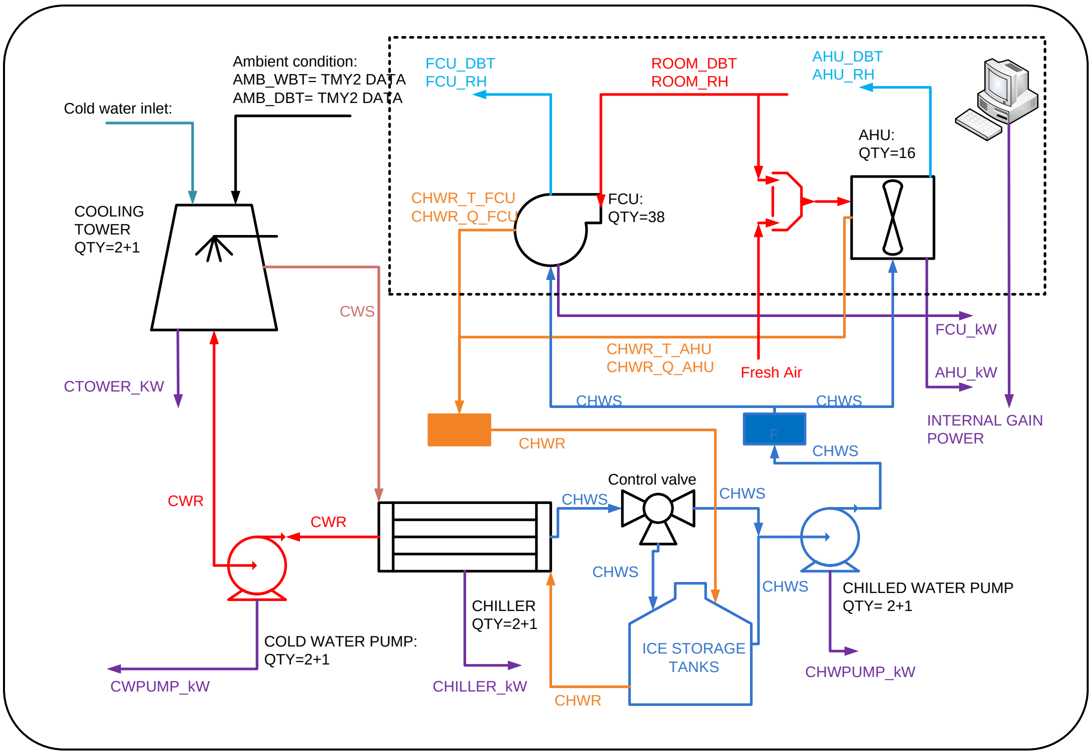


Figure 3.29: The schematic drawing of the ITS model (Full storage).

The corresponding TRNSYS model has been designed for the CTES system configuration as illustrated in Figure 3.30.

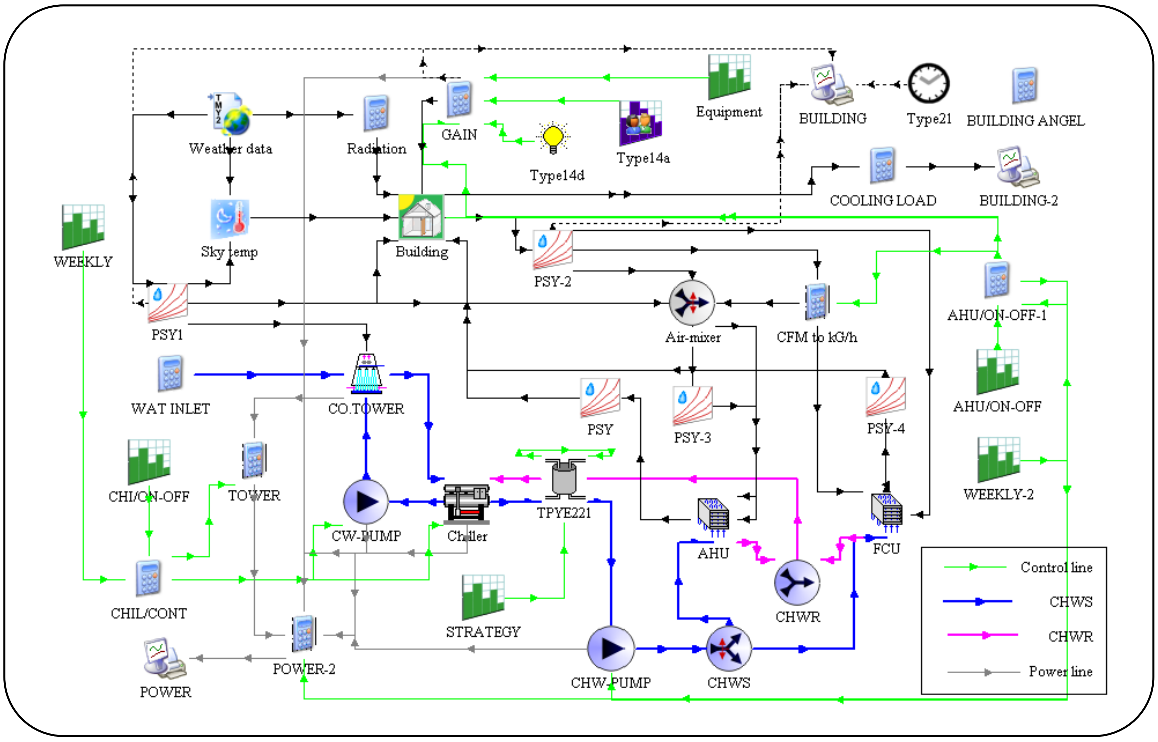


Figure 3.30: TRNSYS simulation of the ITS model.

The Calmac Icebank component, type 221, is generated and has been added to the baseline simulation model in order to simulate the effect of peak shaving on total electricity consumption. Details of the additional TRNSYS component are described in Table 3.14.

The effects of two different storage strategies were studied on the simulated model. The first one is full storage strategy in which the chiller works only during off peak hours. The control card used to force the chiller and the storage tank to operate for the full storage strategy is illustrated in Figure 3.31. The function value of 1 represents the charging period and value 3 represents the discharging hours. The charging hours start at 9:00 and finishes at 21:00.

Table 3.14: Additional TRNSYS components for modelling storage tanks.

Type	Input / Output	
	Calmac Icebank model 1190	
	**Input:**	
TPYE221	T_CHWS_CH	(Temperature, C)
	Q_CHWS_CH	(Flow Rate, kg/hr)
	T_CHWR_LOAD input	(Temperature, C)
	Q_CHWR_LOAD	(Flow Rate, kg/hr)
	CHECK	(dimensionless)
	CHILLER_CAPACITY	(Energy, kWh)
	Output:	
	T_CHWS_TANK	(Temperature, C)
	Q_CHWS_TANK	(Flow Rate, kg/hr)
	T_CHWR_TANK	(Temperature, C)
	Q_CHWR_TANK	(Flow Rate, kg/hr)
	MODE	(dimensionless)
	TANK_CAPACITY	(Energy, kWh)
	E	(dimensionless)
	B	(dimensionless)
	Parameter:	
	T_STORAGE	(Temperature , C
	T_CHARGING	(Temperature , C
	T_DISCHARGING	(Temperature , C
	TANK_MAX_C	(Energy, kWh)
	CP_CHW	(Specific Heat, kJ/kg.K)
	CP_BRINE	(Specific Heat, kJ/kg.K)
	CP_ICE	(Specific Heat, kJ/kg.K)
	TANK_SIZE	(dimensionless)
	CHE_DENSITIY	(Density, kg/m3)
	BRINE_DENSITY	(Density, kg/m3)
	LATENTHEAT_CHW	(Specific Energy, kJ/kg)

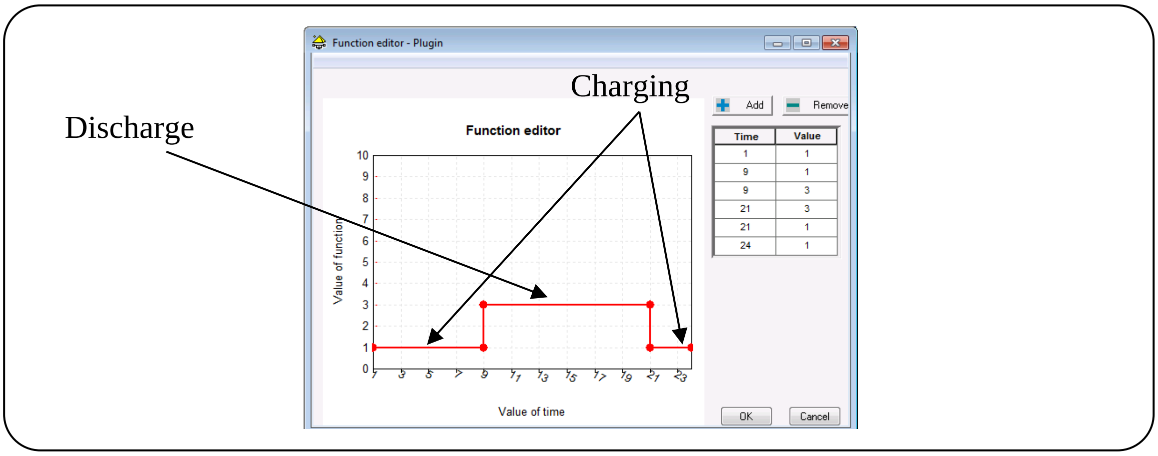


Figure 3.31: Control card for full storage strategy.

For full storage strategy, the chiller only works during the off-peak hours, however, for the partial storage load-levelling strategy, the chiller works continuously for 24 hours a day.

3.7 Chapter summary

The essential theoretical background for the design capacity of CTES systems in the humid tropical climates of Malaysia is presented in detail. The procedure can be used as a general guideline for investigating different CTES system configurations and storage strategies. Due to the simplifications and approximations employed, the results of this methodology contain a certain margin of error. This procedure considers a range of different storage strategies, from full load storage to partial load-levelling storage. These strategies constitute the upper and lower boundaries of the system design, meaning that all possible systems must fall within this range. The procedure contains the detail step-by-step method for cooling load calculation, fieldwork survey, thermodynamic assessment, economic analysis and computer simulation.

Chapter 4. Results and Discussion

In this chapter, the results obtained from this study are presented in sequences. First, the measuring results obtained from the fieldwork study are presented and analysed in detailed. The thermodynamic assessment of an AC system utilizing CTES system based on first and second laws of thermodynamic is presented in the next section. The economic effect and environmental impact of utilizing CTES systems for an office building is investigated and the results are brought in a separate section. The cost benefits of retrofitting conventional AC systems with the CTES systems are evaluated and the long-term effects are presented. Last but not least, the results obtained from a simulation modelling is presented and the potential energy demand reduction is investigated.

4.1 Electricity consumption analysis results of the fieldwork survey

The fieldwork study was conducted continuously from Friday February 24th, 2012, 5:15 PM and continued for almost half a year until Sunday August 12th, 2012 8:00 AM (170 days). All the required data to conduct a complete energy analysis were recorded with high accuracy. The results obtained from the field survey is then used to calculate and sizing the proper chiller and storage tank for the building, also they have been used to validate the computer simulation model.

4.1.1 Total power usage

The power usage of the building was recorded using a power analyser installed in the main distribution cabinet inside the electrical room. Figure 4.1 shows the total power usage fluctuations during the fieldwork period.

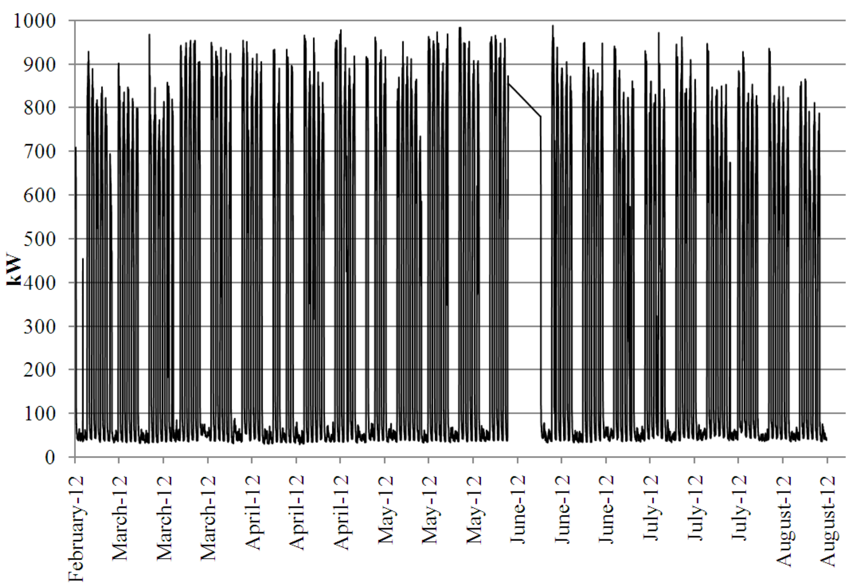


Figure 4.1: Total electricity usage of the building during the monitoring period.

In order to be able to compare the electricity usage pattern between different days of the week, data were analysed and categorized based on the days of the week. The result is presented in Figure 4.2. The maximum and minimum recording values during the fieldwork period are also presented in the figure. To increase the accuracy of the results, the data related to some specific dates were not considered due to their high variability with the normal condition. For instance, the results related to Wednesday April 11th, Wednesday April 25th, Friday March 16th, Tuesday May 1st and Wednesday 28th February are withdrawn due to the unusual operation pattern. The unusual operation happened due to unscheduled holidays during the week, special functions during weekends or during unoccupied hours or due partial chiller usage under maintenance.

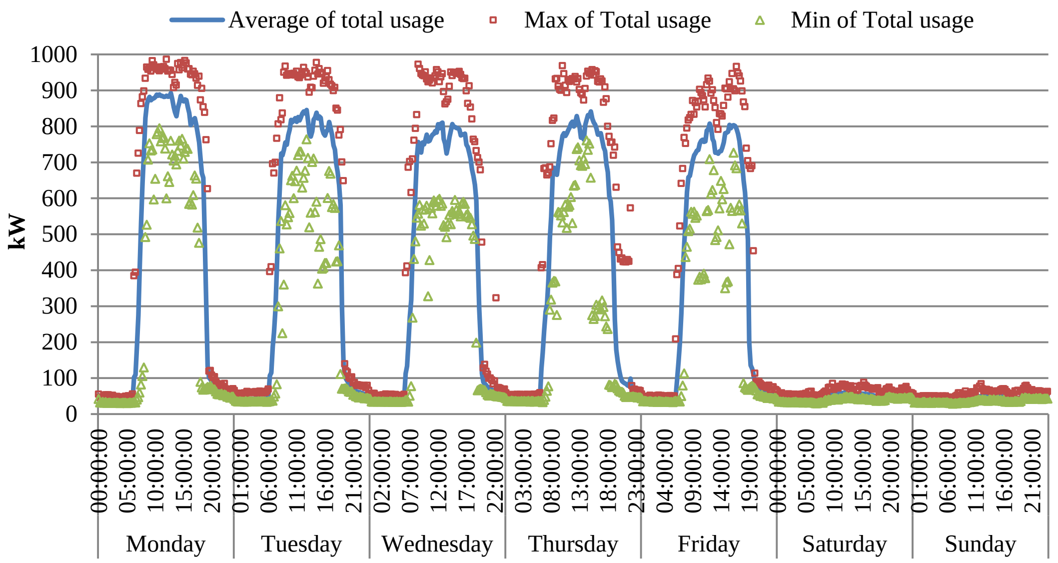


Figure 4.2: The categorised data based on different days of the week.

The share of chiller plant room (consisting of chiller and pumps), is around 60% while the rest is consumed by the building (Figure 4.3). The building energy consumption includes lighting, AHU, FCU, mechanical cooling, lifts, computers, printers, security, data centre and other small electrical appliances. Therefore, the total share of the cooling system is around 65% of the total energy used by the building. However, the only part of electricity consumption that can be shifted to the night-time is the chiller part.

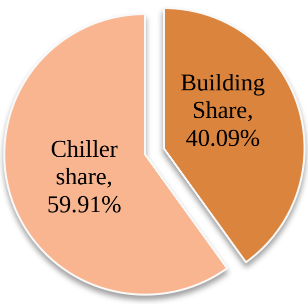


Figure 4.3: The overall electricity usage share of chiller and building.

The average recording data for electricity usage of the building and chiller plant room for different days of the week is presented in Figure 4.4.

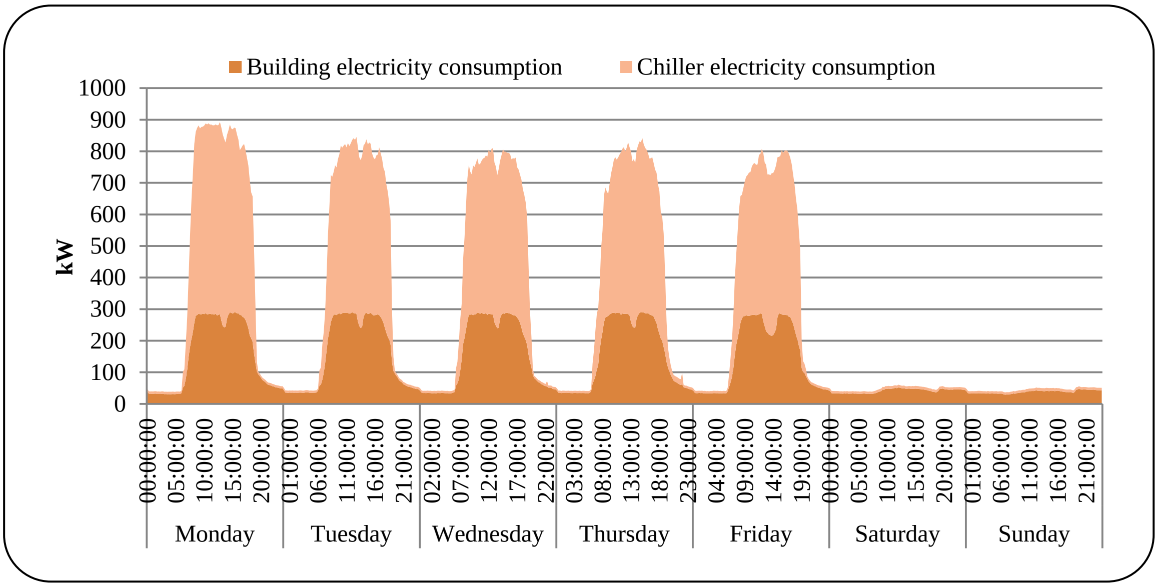


Figure 4.4: The electricity usage share of chiller and building.

Data collection was continued for almost six months, starting from February until end of August, the result reveals that due to the same climate of Malaysia, there is no significant change on the electricity consumption pattern through the year as shown in Figure 4.5.

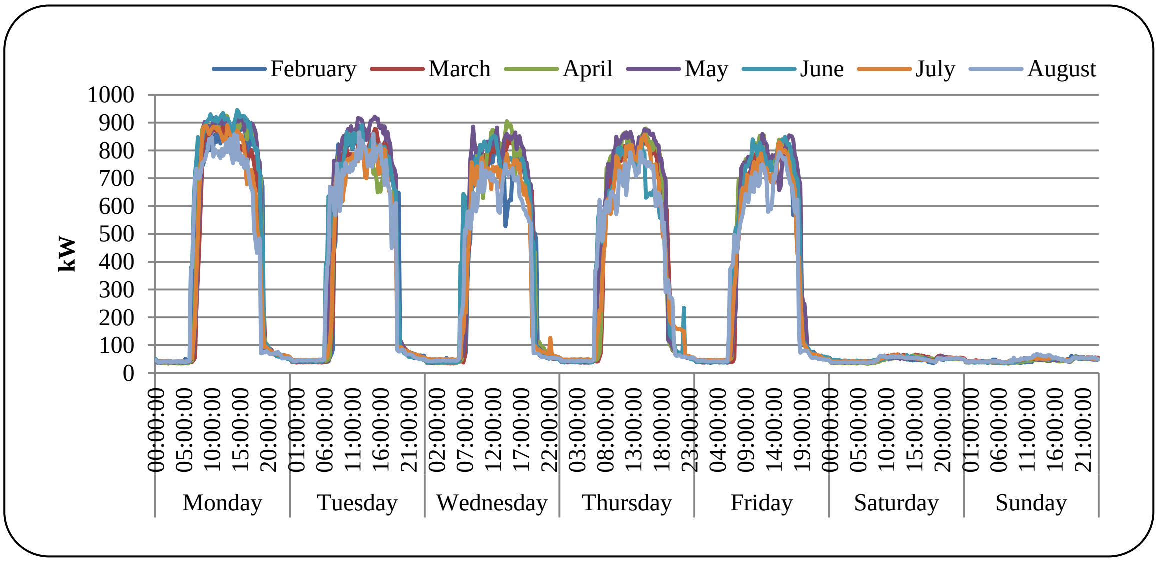


Figure 4.5: The overall electricity consumption of the building in 7 month of the year.

4.1.2 Chiller electricity consumption

The span of the chiller recorded data is presented in Figure 4.6. This figure contains all the recorded data during the fieldwork period. However, due to different circumstances, several unusual chiller working behaviours were detected from the results.

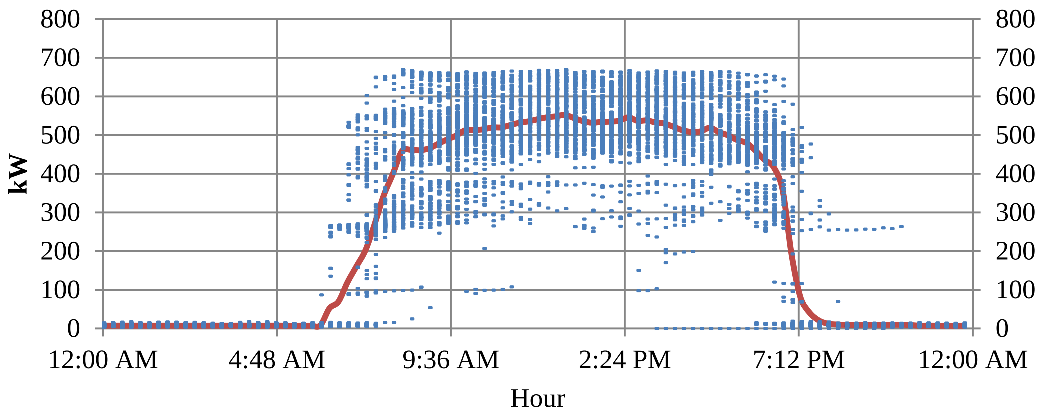


Figure 4.6: The span of all of the recorded data for chiller electricity consumption during weekdays (10,150 points).

By filtering those unclear data from the list, a more stable curve is obtained as is shown in Figure 4.9.

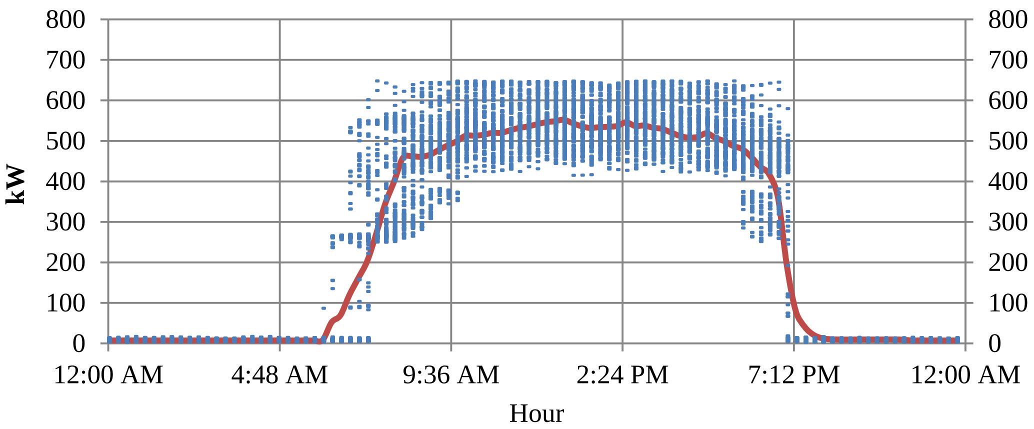


Figure 4.7: The span of the recorded data for chiller electricity consumption during weekdays after filtering the unwanted data (9748 points).

The chiller's electricity consumption pattern during the fieldwork is shown in Figure 4.8. The minimum, maximum and average electricity consumption of the chiller are shown separately for different days of the week. Since the building is an office building, there is generally no cooling load during weekends, except some special days due to special functions and events. However, the data for weekends with special function are withdrawn from the analysis to improve the accuracy.

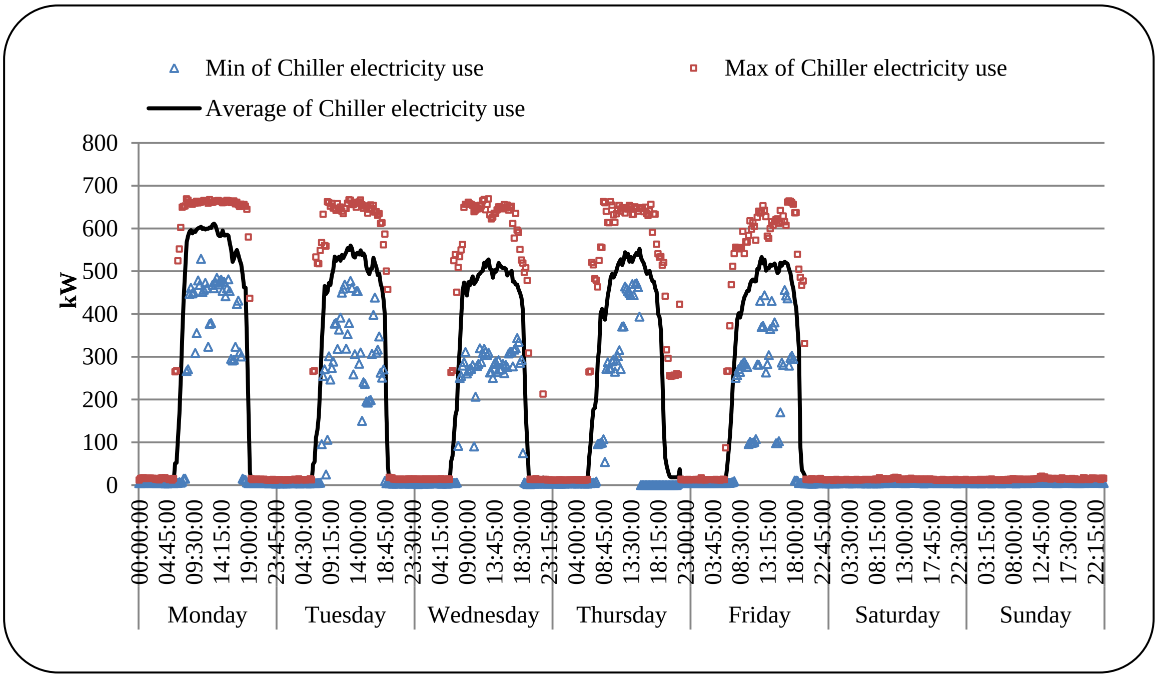


Figure 4.8: Power consumption monitoring results during monitoring period.

The obtained results from different days of the week were compared together and the findings are presented in Figure 4.9. The graph shows that the average building load on Mondays is comparatively higher than other days of the week. That is mainly due to the fact that during weekends the AC system is not operating and consequently the building store the heat during Saturday and Sunday, therefore, it needs more power on the first day of the week to overcome the building "pull-down" load. The same trend happened every day but on a smaller scale. In the first morning hours, the chiller must run in full load to overcome the daily pull-down load.

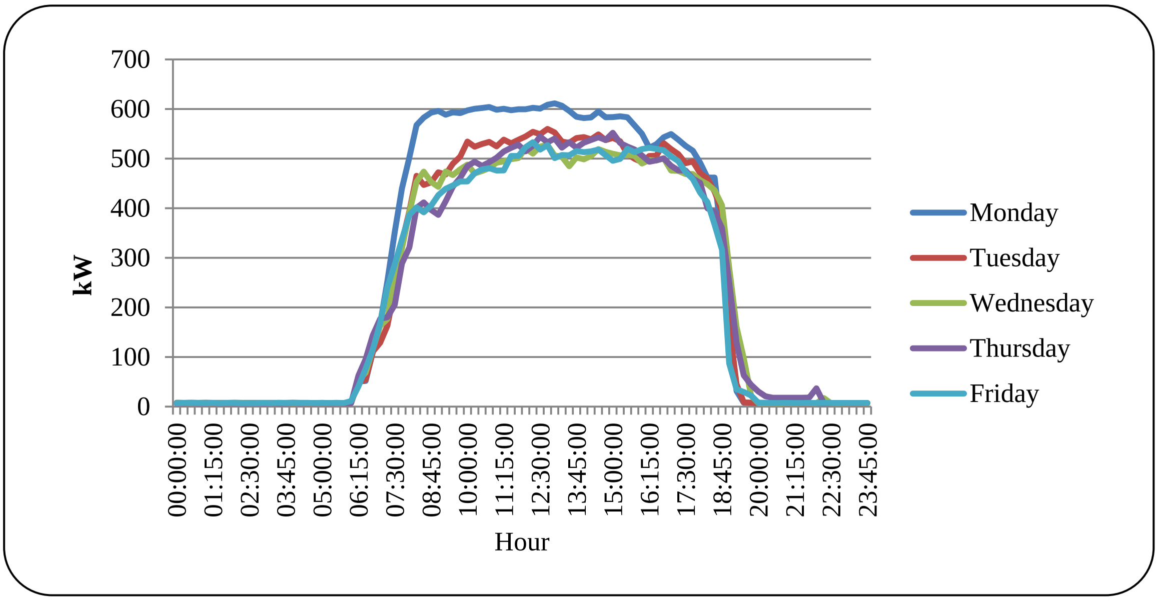


Figure 4.9: Average chiller electricity usage pattern in different days of the week.

The chiller staring time is between 6:45 to 7:00 am every day and the operation ends between 7:15 to 7:30 pm every evening. On Mondays, the pull down load is clearly visible as the highest during the week. Although the chiller is not operating during night-time or early morning hours, there is still a considerable reading shown in the results. The average electricity usage during night-time is presented in Figure 4.10.

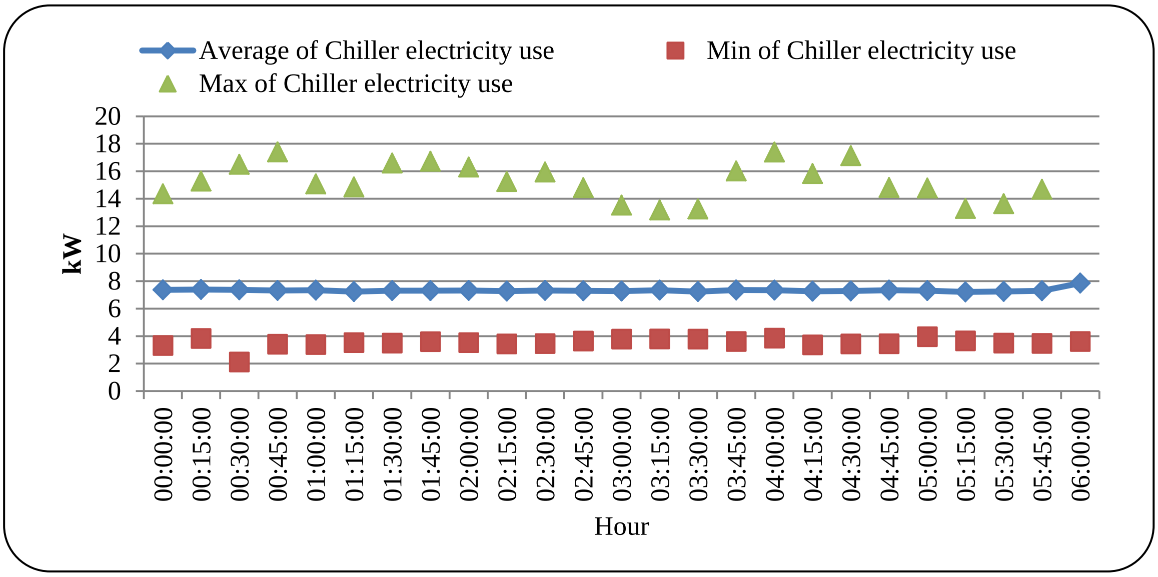


Figure 4.10: The electricity consumption of the chiller during nigh-time hours.

The uncertainty analysis shows that the accuracy of the results varies between 3.5% to 4.1%. The error bars are calculated based on a confidence level of 95%, Figure 4.11. A rough estimation show that around 7.2kW of electricity is used by chiller and its components during the night-times, which are mainly consumed by the security lights, system control, computers and printers inside the mechanical room.

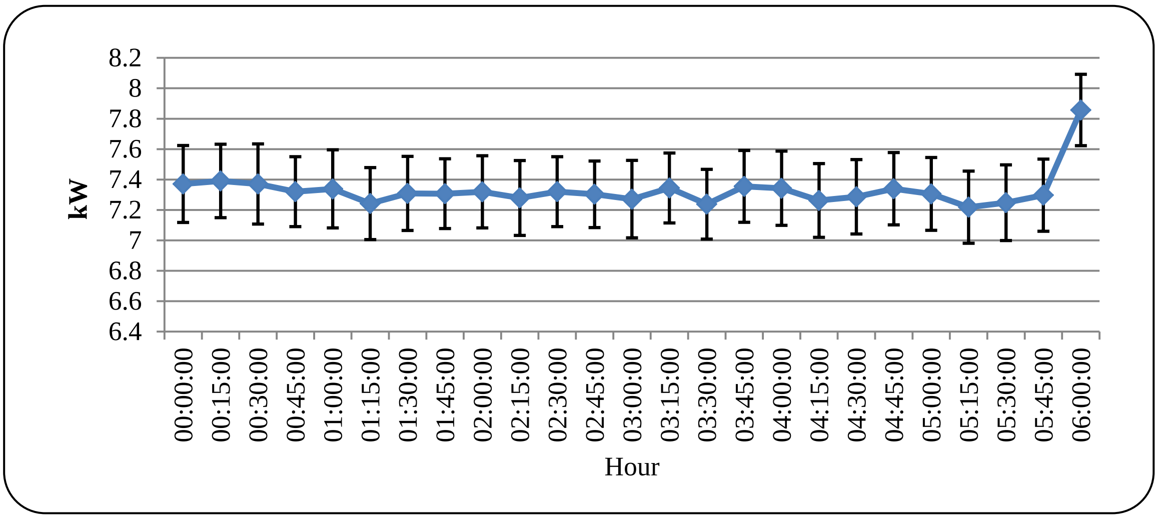


Figure 4.11: The electricity usage of the chiller during nigh-time hours, results from uncertainty analysis.

4.1.3 Building electricity consumption

The categorized data for building electricity usage is presented in Figure 4.12 for different days of the week. The most interesting part of the results is the lunchtime electricity consumption reduction. Normally the occupant leaves their working station between 1:00 to 1:30 pm for lunch hours and return back to work between 2:00 to 2:30 pm. They usually turn off their computers and lights when they are not at their working station. This small energy saving tip can reduce the normal electricity usage by almost 50kW for around 2 hours. This saving is much more on Friday since the lunch hour and pray time is comparatively longer. By means of this small energy saving tip, around 33MWh of electricity usage is saved every year.

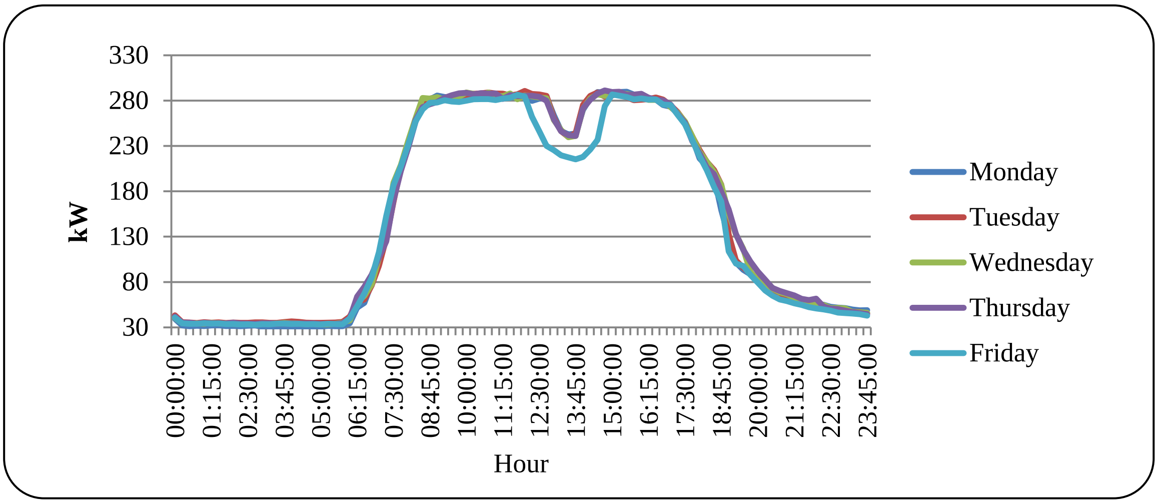


Figure 4.12: Average electricity consumption (kW) of the Building in different days of the week during monitoring period.

Although the building is considered to be totally empty during night-time, but still a considerable amount of electricity is being used during the late night hours, Figure 4.13. The main electricity consumers inside the building are the security system, the data centre, two standby lifts and the security lights. However, the recorded amount of energy usage is considerably higher and it is believed that this amount can be significantly reduced via more restrict rules and regulation to control electricity consumption.

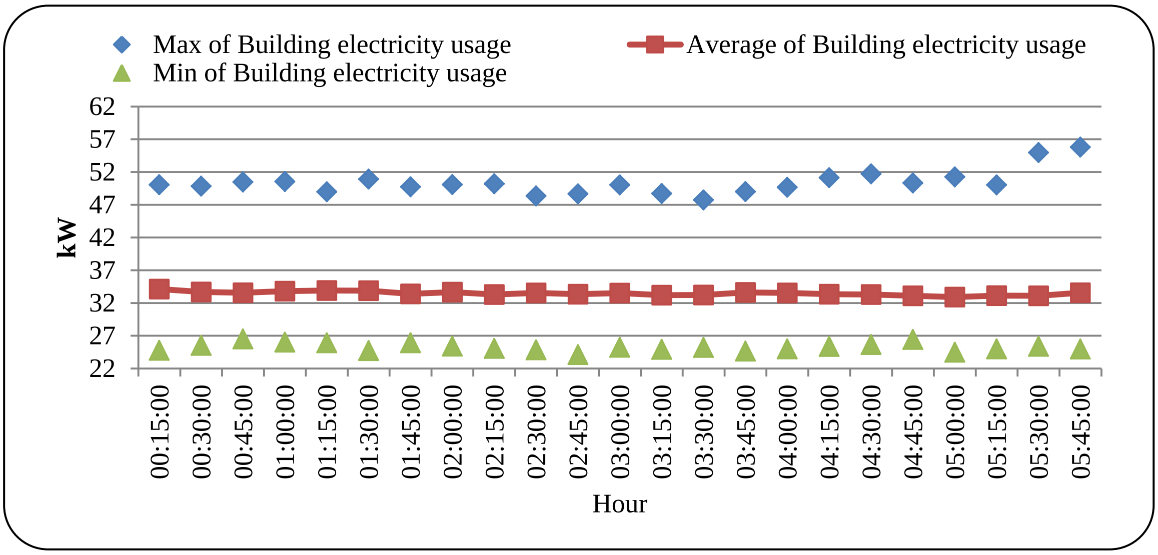


Figure 4.13: The building electricity usage during night-times.

The uncertainty analysis is conducted and it shows that the results accuracy varies between 0.7% to 0.8%, as shown in Figure 4.13.

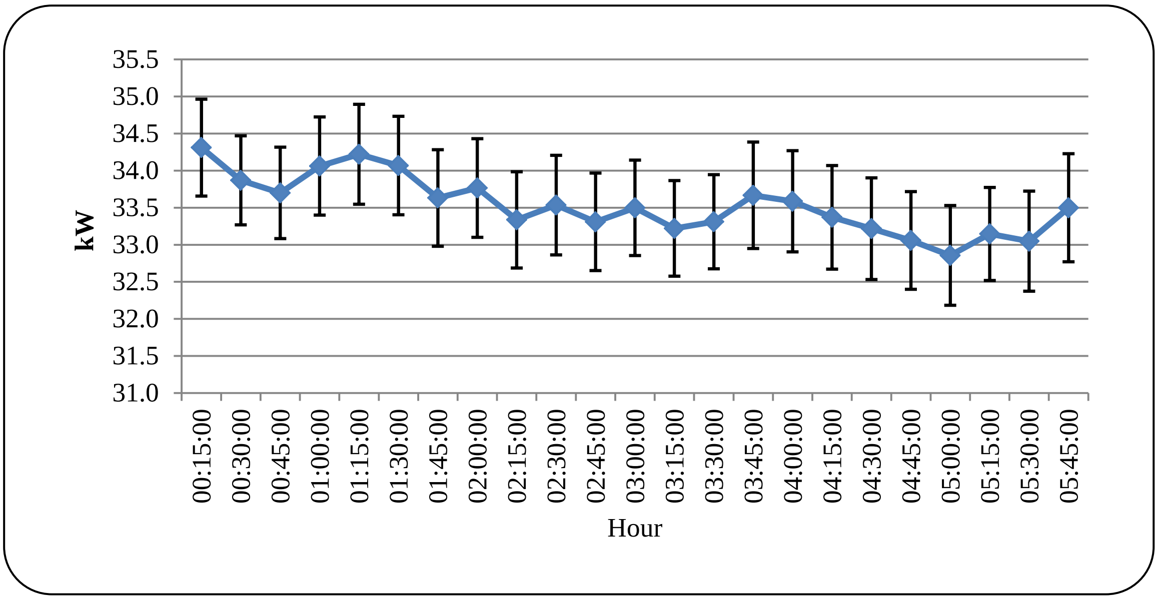


Figure 4.14: The building electricity usage during night-times, results from uncertainty analysis.

4.1.4 The electricity usage break down

The overall electricity consumption without doubt depends on various parameters and factors. One of the main parts of the building's electricity consumption is the lighting. The lighting power consumption varies with level of brightness, sunshine duration, and etc. By analysing the total energy consumption of the building, it was observed that around 40% of the total electricity consumption is used for lighting purpose, 26% is used by AHUs, FCUs, ACSUs, 18% is used for security, safety, around 12% is consumed by computers and printers and 4% is used for lifts.

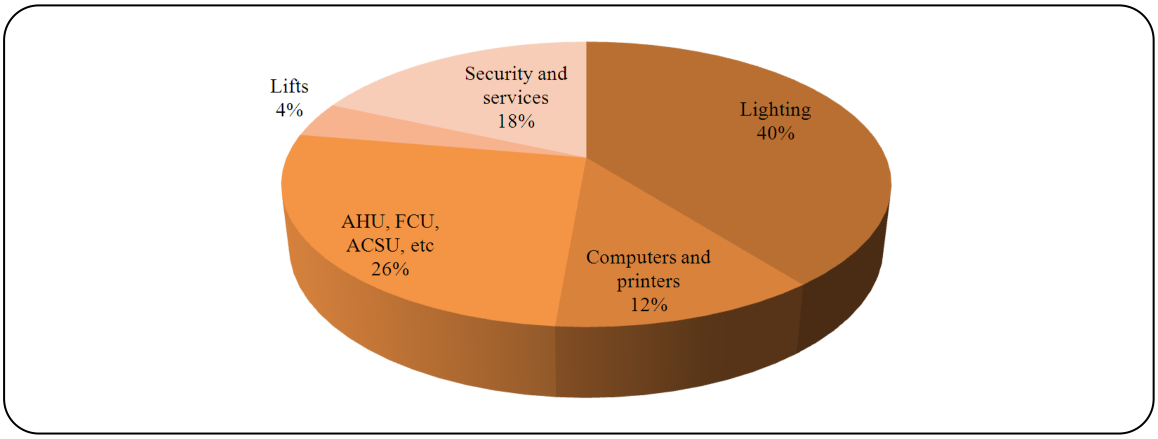


Figure 4.15: Pie chart indicating different shares of electricity consumption.

4.1.5 Temperature and humidity fluctuations

The temperature and relative humidity of ambient was recorded continuously during the fieldwork period. The results are presented in Figure 4.16. The maximum recorded temperature was 34.1ºC occurred on March 22nd at 4:59 PM and the minimum temperature was 26.8ºC occurred on May 3rd at 8:04 AM. The maximum and minimum relative humidity was 84% and 40.6% on April 16th at 11:23 AM and March 6th at 3:12 PM, respectively.

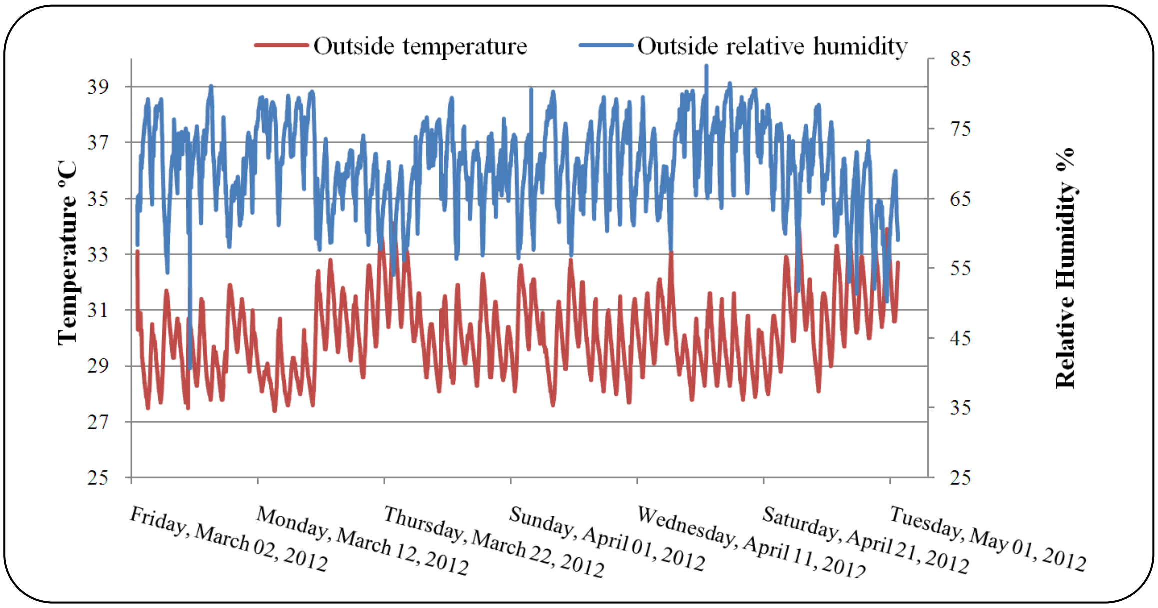


Figure 4.16: Temperature and relative humidity fluctuations of outside the building.

The average temperature fluctuation during a day can be assumed to follow the pattern shown in Figure 4.17.

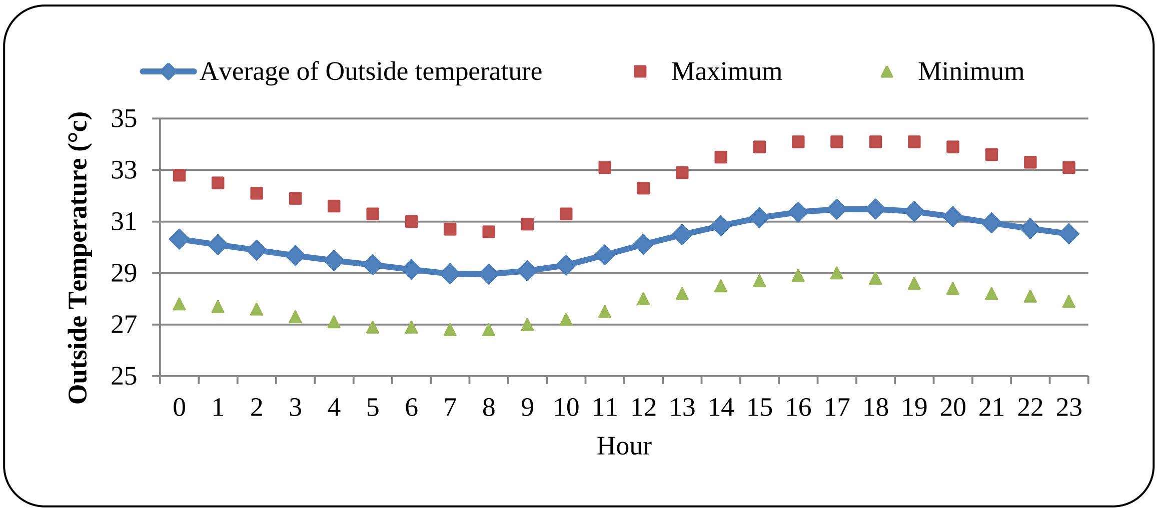


Figure 4.17: The average temperature fluctuation during the data collection with the maximum and minimum records.

The inside temperature fluctuation is analysed and categorized based on different days of the week to show the average temperature fluctuation pattern of the building. The temperature fluctuation of level 2, level 8 and the lobby is presented in Figure 4.18

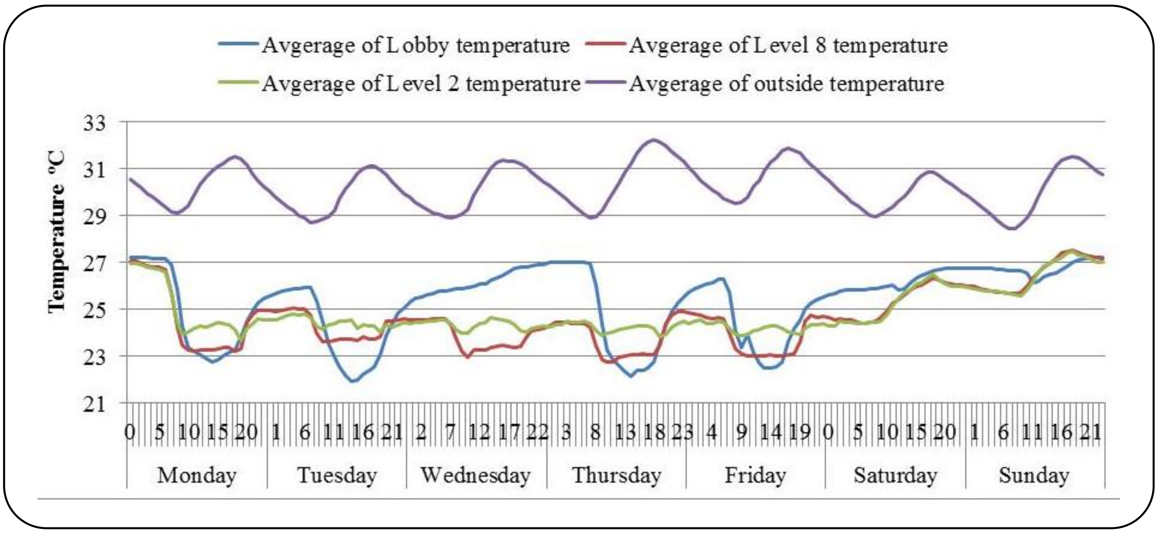


Figure 4.18: The temperature fluctuations of three selected zone inside the building.

4.1.6 Indoor air quality

The good and suitable IAQ in different kind of buildings not only satisfied the occupants and people but also can increase their work's efficiency. Thermal comfort and adaptation to the environment are the significant parts in building construction that can prepare a good situation for occupants and reduce the energy consumption. Behavioural adapting and adjusting clothing insulation can affect occupant thermal comfort. Achieving a good IAQ needs a careful controlling of indoor air parameters such as the dry bulb temperature, the amount of common contaminants and the humidity ratio in the building. The contaminants include such things as CO_2, CO, other gases and vapours, allergens and suspended particulate matter. Allergic reactions including symptoms such as headaches, nausea and the irritations of the eyes or nose may be a clue that IAQ in a building is poor. The comfort zone for summer season stipulated by ASHRAE 2004, determine the DB temperature from 22°C to 27°C and RH between 30% to 60%.

In order to evaluate the present condition of the building, the indoor thermal comfort related measurements were additionally recorded during a sample day. Base on the ASHRAE procedure, the Indoor temperature, RH, CO and CO_2 data were collected from four different heights at each specified sampling point (0.1m, 0.6m, 1.1m and 1.6m from the ground).

A feedback about the general thermal comfort level of occupants was collected during a random interview from approximately 20 occupants. The considered questions are presented in Table 4.1. Overall, it was observed that the temperature in almost all levels is near to the lowest comfort level. Considering the occupant's dress code and activity level, it can be concluded that the HVAC system is over design or is working with more than required load.

Table 4.1: The questions that were asked from the occupants during interview.

Gender	Male	Female
Occupant location:		
Do you often experience the following symptoms?		
	Dry eyes	
	Watering eye	
	Runny nose	
	Dry or irritated throat	
	Headaches	
	Dry skin	
	Rash or irritated skin	
	Flu	
Occupant's Clothing		
Occupant Activity Level		
	Reclining	
	Seated quite	
	Standing relax	
	Light activity, standing	
	Medium activity, standing	
	High activity	
How would you describe your typical level of thermal comfort?		
	Hot	
	Warm	
	Slightly warm	
	Neutral	
	Slightly cold	
	Cold	
How would you describe the indoor Lighting in this area?		
	Too dark	
	Dark	
	Bright	
	Too bright	

Figure 4.19 shows the temperature fluctuation during 16th May, 2012. It can be observed that in this particular day, temperature at levels 1, 2 and 7 is lower than the

minimum, Level 4 has the highest recorded temperature that is well situated between the limited boundaries.

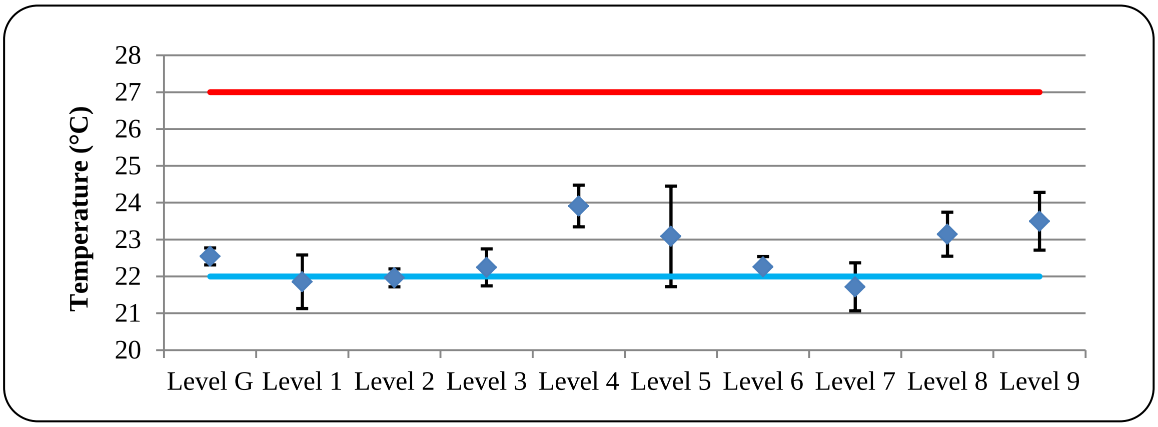


Figure 4.19: Temperature fluctuation during IAQ data collection on 16th May, 2012.

Figure 4.20 shows the RH fluctuations during that particular day of IAQ analysis. It can be observed that unlike temperature, RH in almost all of the levels exceeds the highest comfort level. That is mainly due to the lack of dehumidifier system.

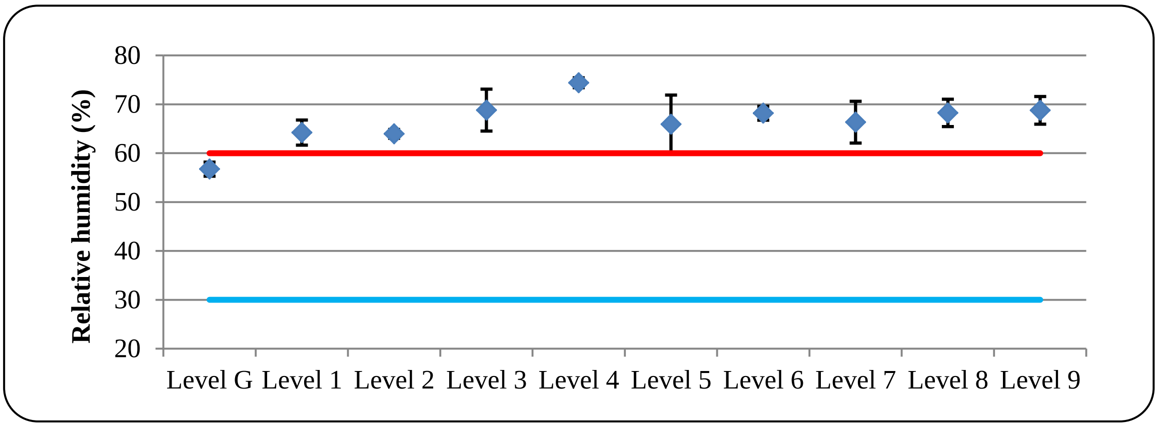


Figure 4.20: Relative humidity fluctuation during IAQ data collection on 16th May, 2012.

According to the ASHREA standard, there are some restrictions for the amount of contaminants to have an acceptable IAQ and a safe environment for occupants. The threshold limits for CO_2 and CO are below 1000ppm and 15ppm, respectively. Typically, when one exposed to excessive CO_2 in long hours the symptom called “Hypercapnia” could happen and for light case drowsiness, dizziness, and headache would present. The CO_2 level is demonstrated as an indicator of the effectiveness of ventilation of the building. As it is shown in Figure 4.21 the CO_2 concentration is well below its maximum limit, also the same results are shown for CO concentration in Figure 4.22. Fluctuation between the results is mainly due to the unpredicted localized activities. All the ridings were conducted in areas without occupants or present of any plants. However, due to ununiformed ventilation channels, the results show a small level of uncertainty. Especially for level 7, despite it has high level of occupancy, the CO_2 concentrations is lower than other levels with the same or even lower occupancy density. It can be concluded that the air change rate and ventilation system are working well and the air circulation is well designed. Indeed, it can be even proposed that the air circulation is more than enough and the level of fresh air from outside is more than standard condition. By decreasing the air change rate, less amount of fresh air from outside will be required and the system can work with a bit lower cooling load.

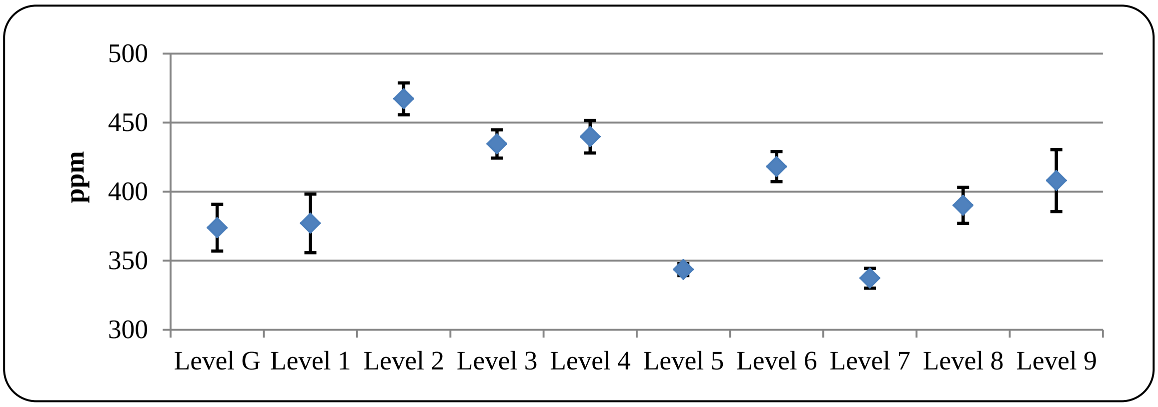


Figure 4.21: CO_2 fluctuation during IAQ data collection on 16th May, 2012.

The CO concentration as well as CO_2 is well below the maximum limit stated by the standard. The highest CO level is recorded at level 9, which is still in the acceptable range.

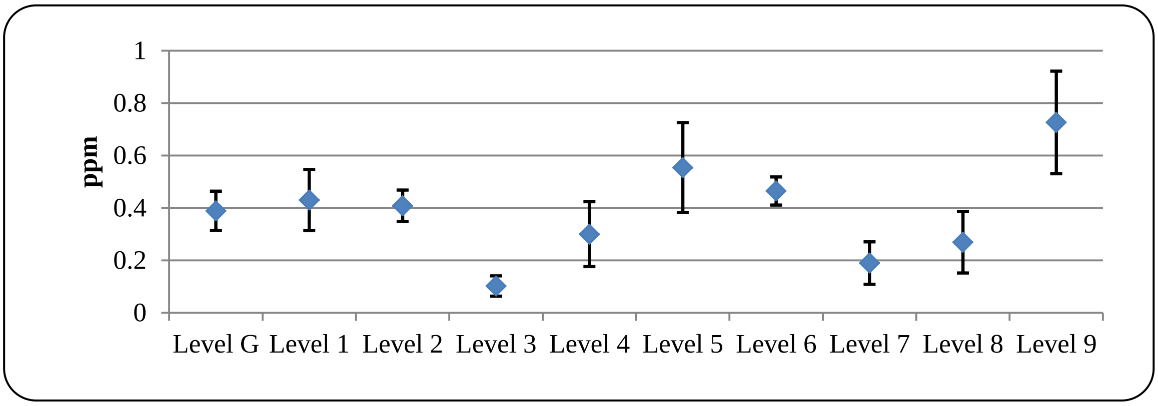


Figure 4.22: CO fluctuation during IAQ data collection on 16th May, 2012.

The result of the indoor air quality shows that the overall condition of the studied building during the survey was over cooled and most of the occupants were not satisfied with the condition. It was found that by upgrading the thermostats and by improving the occupant's awareness about the energy saving methods, the overall energy usage could be decreased and consequently the indoor temperature could be maintained in the comfort range. It should be mentioned that installing dehumidifier can significantly improve the thermal comfort level by reducing the overall humidity of the conditioned space.

4.2 Chiller and storage tank sizing

By using the recorded power consumption of the AC system and applying the mentioned methodology the suitable chiller and storage tank were calculated. The designed parameter is based on five commonly used ITS systems with an average derating factor of 70% during ice making hours.

The total chiller capacity for the full storage strategy is 975kW and the corresponding storage capacity is 8185kWh. However, the maximum required cooling load of a conventional system in a design day is 625kW, which is approximately 47% lower than that of the full storage strategy. Therefore, in full storage strategy the chiller can also switch to non-storage system operation as a contingency strategy in the situations where the storage package is not performing efficiently or in case of special functions. As the number of daytime chiller operating hour increase, the chiller capacity and the corresponding storage capacity decrease in a non-linear trend. Figure 4.23, shows the reduction in required chiller capacity size by increasing the daytime chiller operating hours.

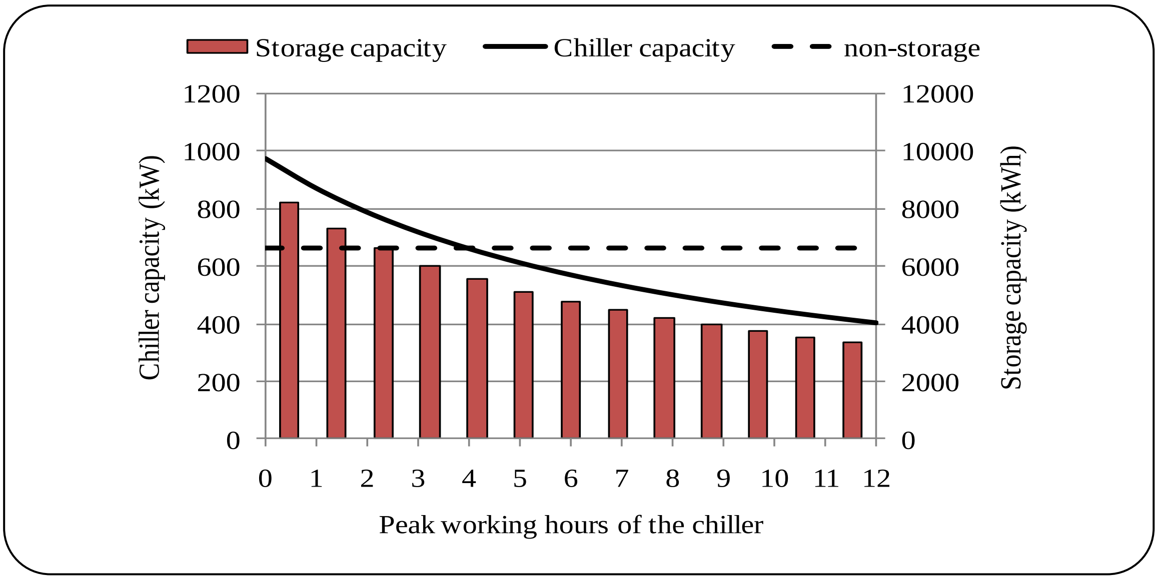


Figure 4.23: Reduction in chiller size by increasing the daytime operating hours

The graph shows that the lowest chiller capacity is achieved when the chiller operates continuously for 24 hours (partial storage-load levelling). The chiller capacity and corresponding storage capacity for the load-levelling strategy are 400kW and 3370kWh respectively, which is almost 40% lower than non-storage and 60% lower than full storage. The full storage and the load-levelling storage strategies are considered as the upper and lower boundaries for the system design thus all other possible systems must fall within this range. Figure 4.24 compares the differences between full load, non-storage and load-levelling storage strategies for the present case study.

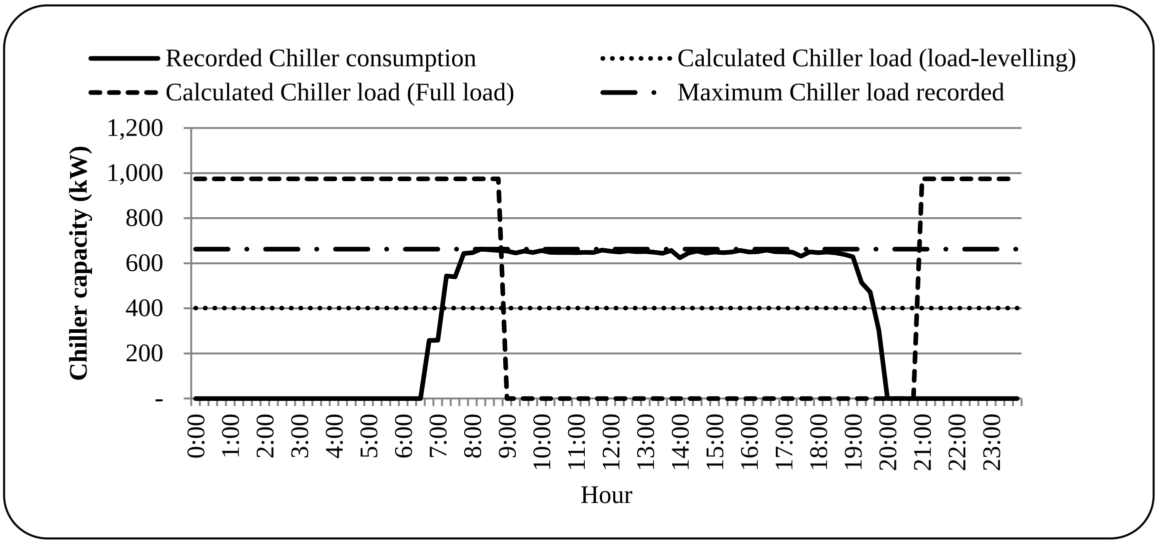


Figure 4.24: Graphical depiction of the differences between the full load, non-storage and load-levelling strategies for the office building.

The full storage strategy requires the largest chiller size and the load-levelling partial storage strategy requires the smallest chiller size. The optimum selection is mainly depends on the localized parameters, such as installation cost, electricity tariff rate and operating costs. The short term and long term economic benefits and environmental effects of utilizing CTES systems for office buildings in Malaysia will be presented in the following sections. Furthermore, thermodynamic analysis through energetic and exergetic evaluation will provide better picture for selecting the most environmentally-friendly system.

4.3 Thermodynamic assessment results

4.3.1 Energetic evaluation

The energetic evaluation is conducted based on the mentioned methodology and the recorded data. The results are presented for five different commonly used ITS system.

Table 4.2, illustrates the charging, storage and discharging energy efficiencies for full storage and load levelling storage strategy.

Table 4.2: The results of energy analysis (%).

Process	Ice on coil (internal)	Ice on coil (external)	Ice slurry	Encapsulated ice	Ice harvesting
			Full storage		
Charging	98.5	98.4	98.7	98.7	98.3
Storage	99.6	99.5	99.5	99.5	99.5
Discharging	99.6	99.6	99.6	99.6	99.6
			Load levelling		
Charging	95.9	95.6	96.6	96.4	95.4
Storage	98.8	98.7	98.6	98.8	98.6
Discharging	99.5	99.5	99.4	99.5	99.4

Overall, the energetic efficiency of all processes is considerably high, with the minimum of 95.4% during charging of ice harvesting technique. It shows that all the systems and processes are energetically well efficient. The storage efficiencies show slight drop by shifting from full storage to load-levelling storage strategy, due to the longer storing hours that lead to more heat loss during storage. The overall efficiencies of all five techniques are compared and showed in Figure 4.25. The highest overall energy efficiency is for the encapsulated ice and ice slurry techniques and the lowest efficiency is for the ice harvesting method.

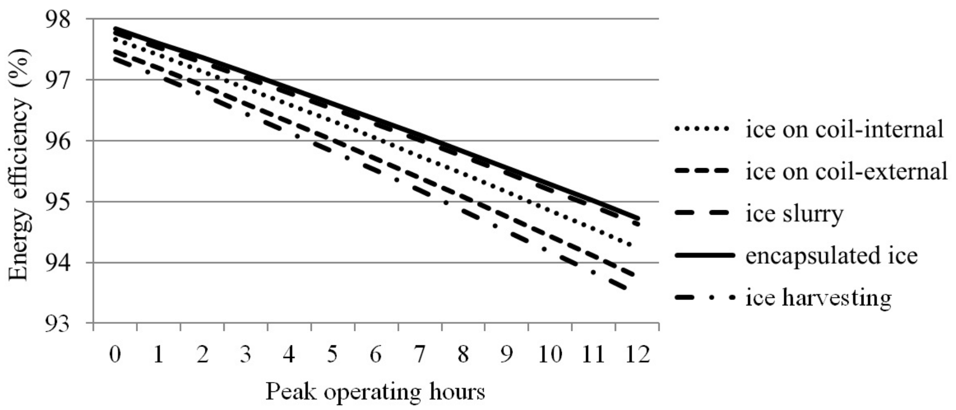


Figure 4.25: Energy efficiency changes by increasing chiller operating hours.

One of the important and effective parameters in energy and exergy efficiency is the ambient temperature, by increasing the ambient temperature the temperature gradient between the stored ice and its surrounding increased that has a direct impact on the heat loss rate. The effect can be observed from Figure 4.26, the figure shows the effect of ambient temperature fluctuations on charging, storage and discharging energy efficiency of an internal ice on coil technique. It shows that the change in ambient temperature has significantly more impact on the charging process than charging and discharging.

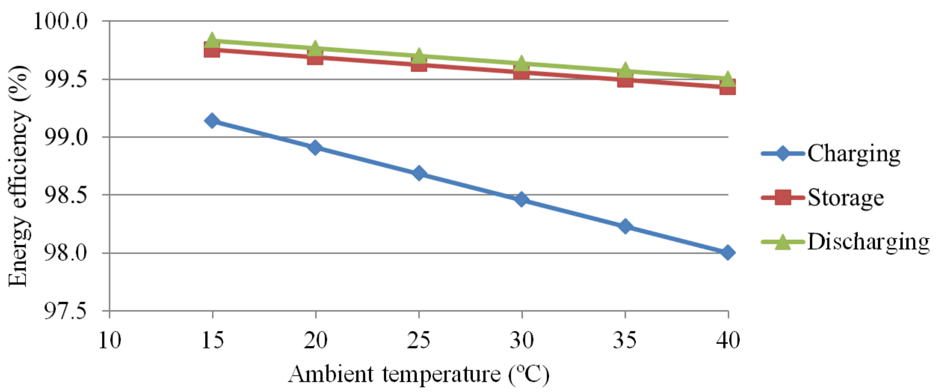


Figure 4.26: Ambient temperature effect on charging, storage and discharging energy efficiency of the ice on coil-internal system.

Generally, by increasing the ambient temperature the overall energy efficiency drops. Figure 4.27 presents the overall energy efficiency changes caused by ambient temperature fluctuation.

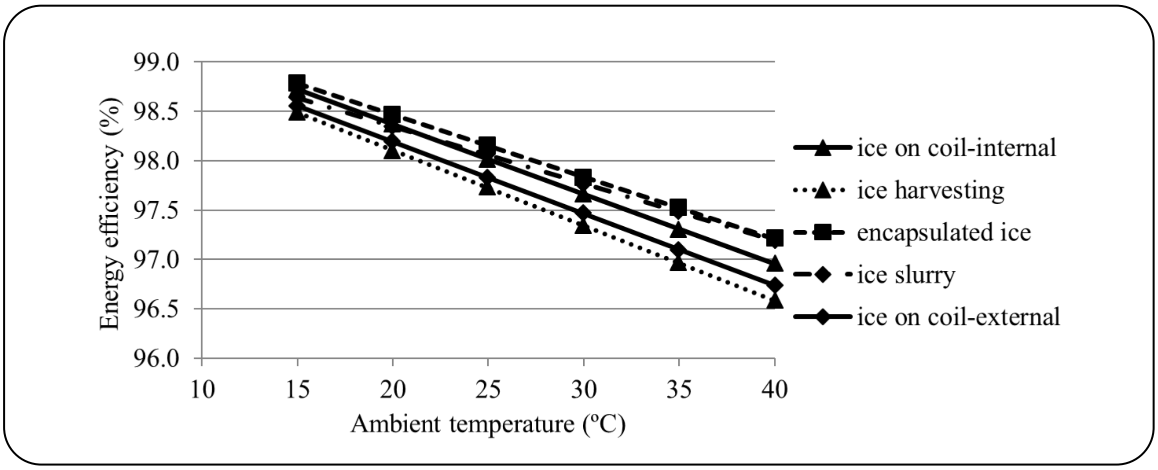


Figure 4.27: Overall impact of ambient temperature changes on energy efficiencies.

4.3.2 Exergetic evaluation

The exergy efficiency results for charging, storage and discharging process are calculated. Overall, the exergy efficiencies are far less than energy efficiencies. This shows that the energy evaluation is not a suitable technique to present the system behaviour. Unlike energy, in exergy analysis the storage process has the highest efficiency and the only loss is due to the exergy destruction by heat loss. The value for exergy efficiencies for charging, storage and discharging process are presented in Table 4.3.

Table 4.3: The results for exergy analysis (%).

Process	Ice on coil (internal)	Ice on coil (external)	Ice slurry	Encapsulated ice	Ice harvesting
			Full storage		
Charging	37.3	35.3	24.9	30.9	34.2
Storage	95.9	95.3	94.9	95.7	95.1
Discharging	49.6	48.8	49.5	49.3	48.4
			Load levelling		
Charging	37.3	35.3	24.9	30.9	34.2
Storage	88.9	87.5	86.4	88.5	86.7
Discharging	42.9	41.6	41.8	42.5	40.9

As the number of storing hours increased, the total exergy destruction increased and consequently the heat leakage and irreversibility term (I) increases. Therefore, the overall exergy efficiency drops as the number of chiller working hours increased. The summarized results of different ITS technologies are presented in Figure 4.28.

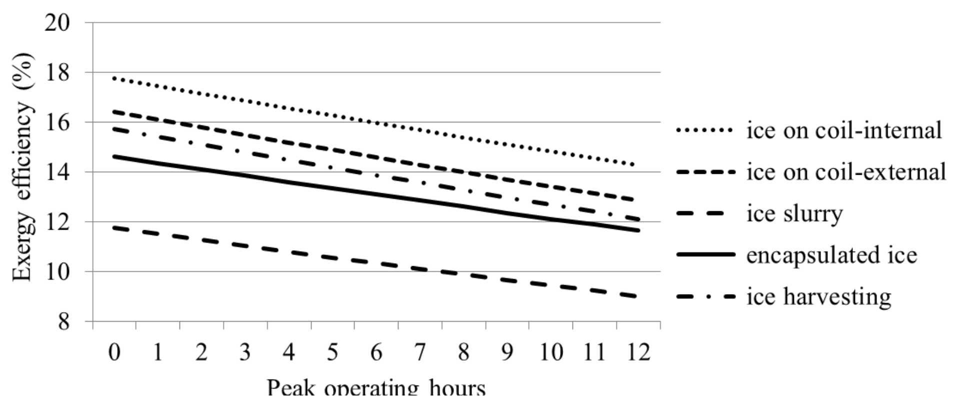


Figure 4.28: Charging, storage, discharging and overall energy efficiency of the ice on coil-internal system.

The impact of ambient temperature fluctuation on exergy analysis shows different pattern than the energy efficiency analysis. The main impact is in storage and discharging process. By increasing the ambient temperature, the temperature gradient between stored ice and its surrounding increased. This shows that the stored cold energy has a higher storing quality. Figure 4.29 shows the impact of increasing ambient temperature on exergy efficiency. The overall results show that the ice on coil (internal) has the highest exergy efficiency.

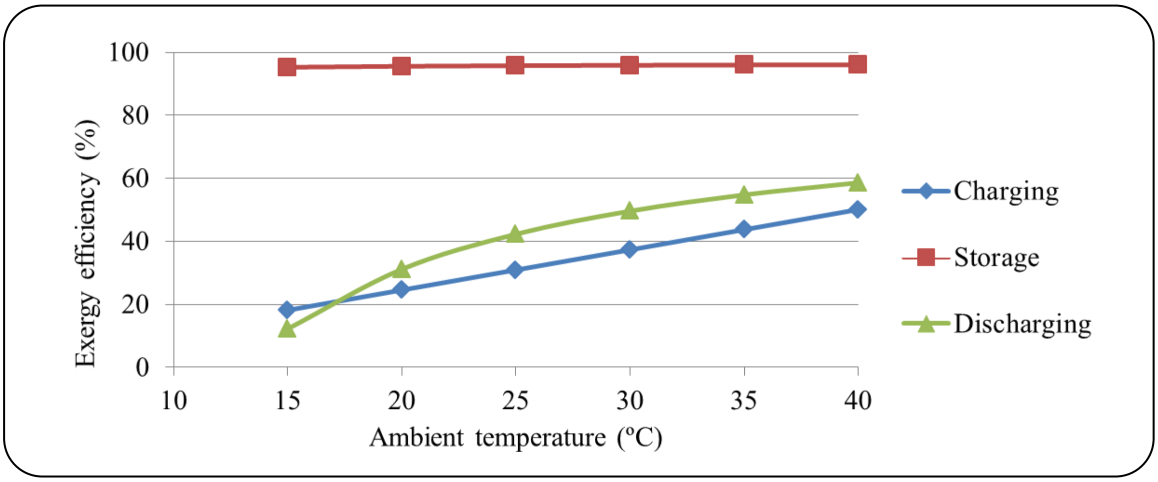


Figure 4.29: Ambient temperature effect on Charging, storage and discharging exergy efficiency of the ice on coil-internal system.

The fluctuation of room set point temperature is also investigated in this work. The results from Figure 4.30, show that by increasing room set point temperature the overall exergy efficiency will significantly reduce.

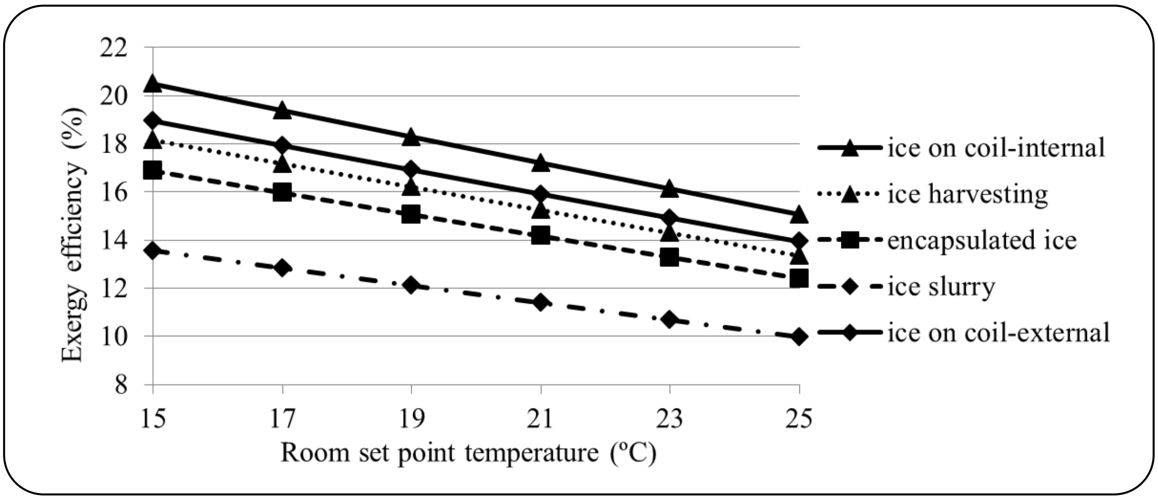


Figure 4.30: Room temperature set point on exergy efficiency.

For an ice on coil (internal) the exergy efficiency changes from over 20% to less than 15% by increasing the set point temperature from 15 to 25ºC. The changing trend is in contrariwise with changing ambient temperature. However, the justification principle is the same. By increasing the room temperature set point, the temperature gradient between inlet and outlet glycol increased, showing that the exergy of the chilled water stream distributing cold inside the building is on low quality. On the other hand, as the temperature gradient between inlet and outlet glycol decreased, the exergy efficiency increased, showing that the discharging process is on better quality.

4.4 Economic and environmental benefits of utilizing the ITS systems

There is always uncertainty about future energy prices and demand charges as well as other economic parameters. In this section, the results of a macroscopic analysis on the energy and economic benefits of using an ITS system for office building applications in Malaysia is presented. First, a normalized cooling load profile for office buildings located in Malaysia has been calculated. The economic evaluation is made based on the calculated load profile for the Malaysian climate. Finally, the potential energy saving is presented.

4.4.1 Cooling load profile, chiller and storage tank sizing

The building cooling load is calculated based on the CLTD method for every hour of the design and the resultant profile over 24 hours is presented in Figure 4.31. The load profile is designed to have its peak at 16:00. Hence, for normalizing the profile, the maximum cooling load is considered at hour 16 and the minimum is considered as zero for the unoccupied hours. A conventional AC system rarely works at full load during the entire daily cooling cycle and the peak normally occurs between 14:00 to 16:00. It can be clearly observed from Figure 4.31 that full chiller capacity is only required for around two hours (from 15:00 to 17:00) and less chiller capacity is required during the rest of the day.

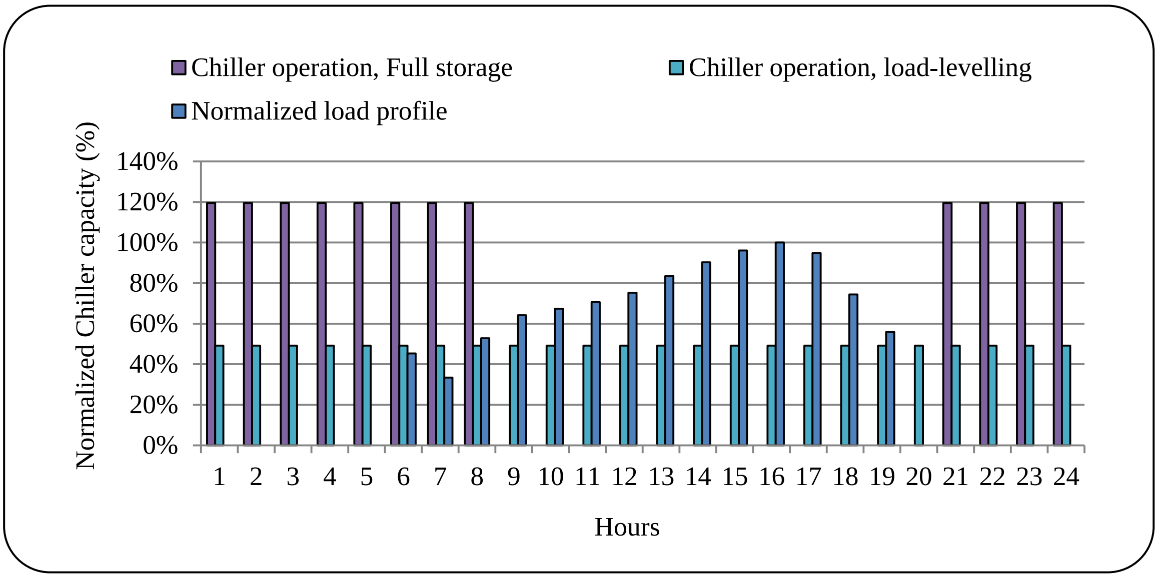


Figure 4.31: Graphical demonstration of differences between conventional system, ITS system (full storage) and ITS system (load-levelling storage) strategies.

By using the cooling load profile, the chiller size for the conventional AC system, full storage and load levelling storage strategy can be calculated. The chiller size for the conventional system is considered as the baseline.

The comparison study between the results shows that the chiller size for full storage strategy is around 1.19 times more than the conventional AC system. However, the chiller size for the load levelling strategy is significantly lower than the chiller size for the conventional AC system being around 51% lower. Table 4.4 shows the chiller sizing results.

Table 4.4: Summary of sizing calculations.

Description	Chiller size (kW)	Difference compare to the non-storage system
Non-storage	a	---
Full storage	1.19a	+19%
Load-levelling	0.49a	-51%

The differences between the chiller size and chiller operation hours of the conventional AC system, full storage and load-levelling storage strategies can also be observed in Figure 4.31. The chiller size for the full storage strategy is considerably more than the chiller size for the conventional system. For the full storage strategy, the chiller only works during the off-peak hours, while for the load levelling strategy the chiller must work on its full capacity for 24 hours a day. The chiller size for the design hour is considered as the base line. The results show that the chiller size for the full storage strategy is around 20% more than the required chiller size for the conventional AC system.

Generally, in the Malaysian market, the total system capacities are 1,000TR and above. Hence, by using the normalized correlation, the required chiller size for three different system designs has been calculated for the various ranges of system capacities, as presented in Figure 4.32. It is assumed that the chiller size increases linearly as the total system capacity of the design day increases.

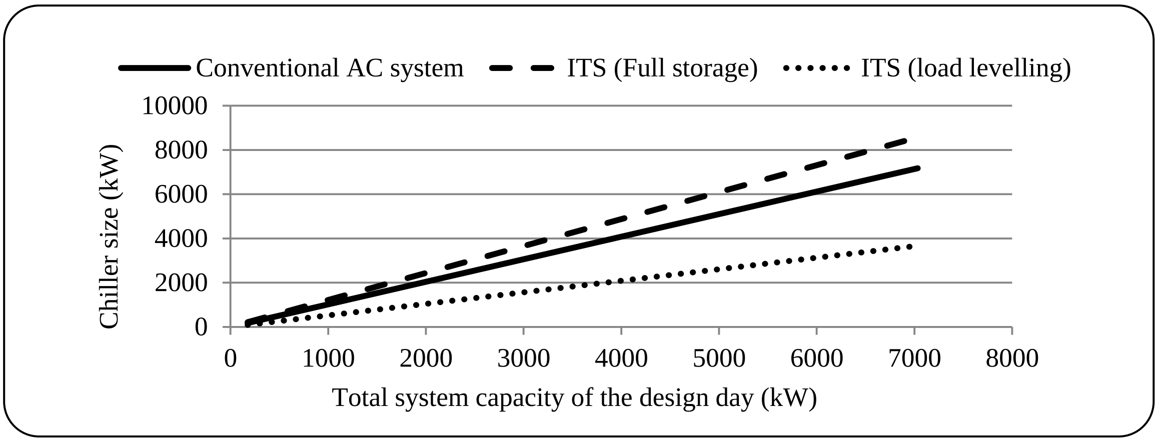


Figure 4.32: Chiller size for conventional, full load (ITS) and load levelling (ITS) systems.

4.4.2 Economic evaluation

The total installation cost for three different system designs over the range of different system capacities has been calculated based on the mentioned rule of thumb. The total installation cost of the full storage strategy is significantly higher than the conventional AC system. However, the total installation cost of the load-levelling strategy is in the same range as the conventional AC system. The results are only valid for a new system design and they cannot be expanded for retrofit projects.

The maintenance cost for different system capacities is calculated and the results show that the maintenance cost for the ITS system with full storage strategy is the most expensive one due to its large chiller size. The total electricity cost comprises two main parts – the maximum demand charge and the on-going charges. The maximum demand charge is calculated based on the maximum required load during the peak period. It was found that the conventional AC system has the highest demand charge due to its large electricity consumption during the peak hours. The demand charge of the load levelling storage strategy is slightly lower than the conventional system. Although the chiller size in the load-levelling strategy is lower than the conventional system, the daily usage of this strategy would raise the demand charge. The demand charge for the full storage strategy is at the lowest possible level owing to the off-peak chiller usage. In this strategy, the only daily electricity usage is for the circulation system and the chiller will not work during the day. The annual on-going charge is then calculated based on the national electricity tariff structure. The results show that the annual on-going costs for the conventional AC system and load levelling storage strategy are nearly similar and the prices for full storage strategy are slightly lower. By adding the annual maximum demand cost to the annual on-going charges the total annual electricity costs of the AC system are calculated and the result is presented in Figure 4.33. The results illustrate that the conventional AC system has the highest annual costs and the full storage strategy has the lowest costs.

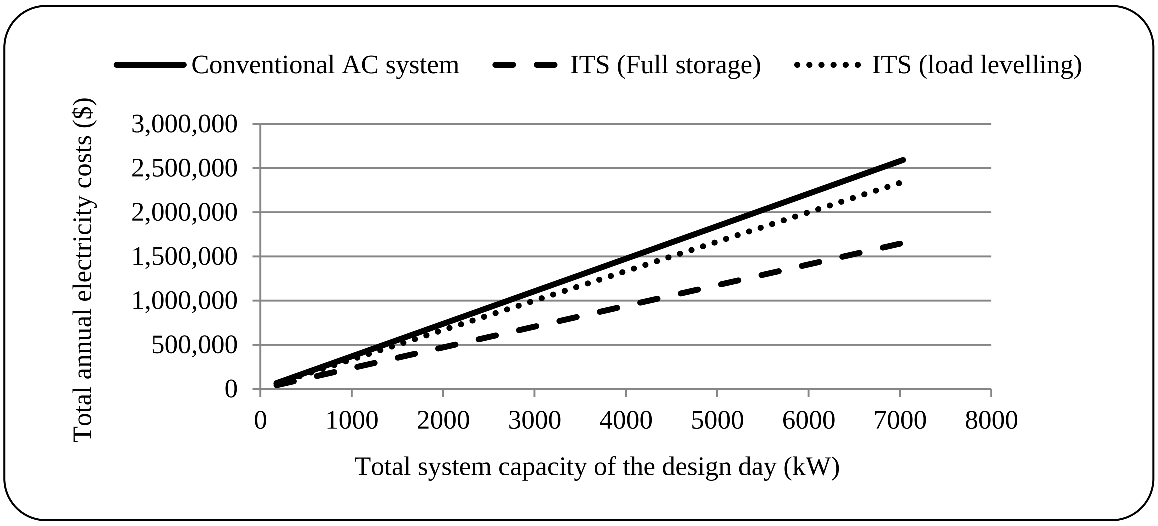


Figure 4.33: Total annual electricity costs for conventional, full load (ITS) and load levelling (ITS) systems.

By deducting the total annual electricity costs of the full storage and load levelling storage strategy from the total annual electricity charges of the conventional AC system, the annual cost saving for each storage strategy can be calculated and the result is presented in Figure 4.34.

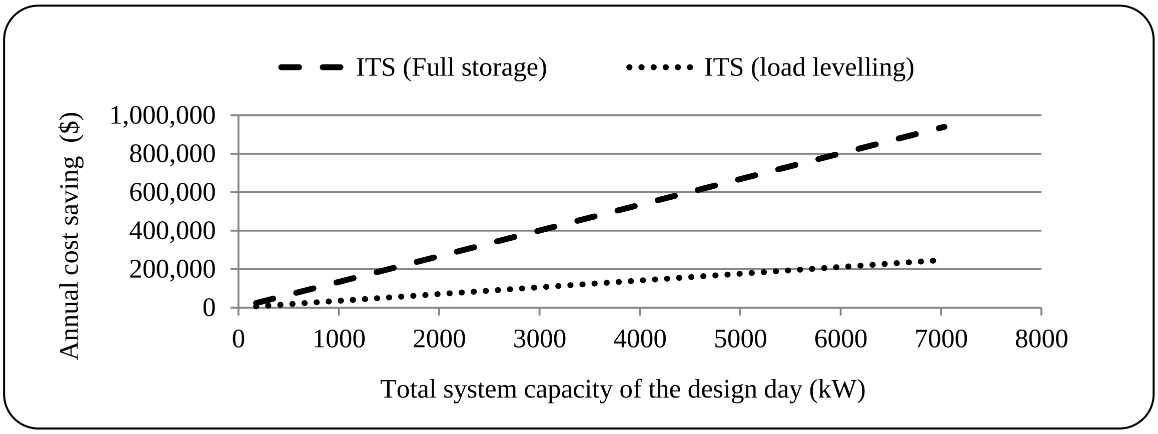


Figure 4.34: Annual cost saving for full load and load levelling ITS systems.

The payback period can now be calculated according to the annual cost saving level, using Equation (3.72). The results show that the PB period of the full storage system varies between 5 to 6 years for system capacities less than 3500kW and for capacities more than that the PB period is around 3 to 4 years, as given in Figure 4.35. On the other hand, the PB period of the load-levelling strategy is considerably lower than the full storage strategy and it varies mostly from 1 to 3 years for system capacities of less than 3500 kW and less than 2 years for system capacities of more than that.

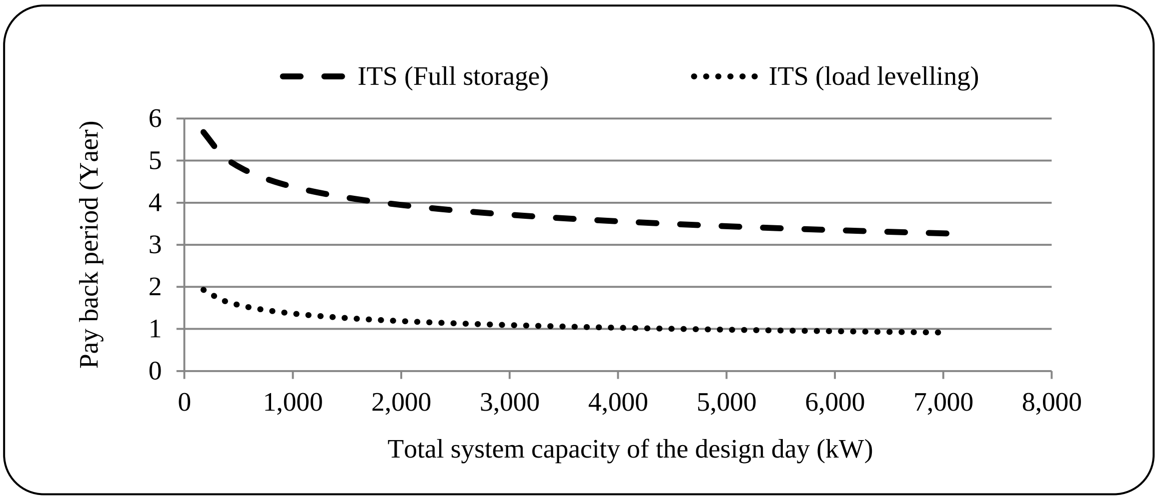


Figure 4.35: Payback period for full load and load levelling ITS systems.

4.4.3 Energy saving

In most of the energy efficient systems the energy consumption is reduced, but the energy usage pattern does not change. Therefore, for a proper energy saving evaluation of a TES system, both energy used in the building and energy used by the power generator must be considered. Generally, for the CTES system, the site energy saving is highly dependent on the system characteristics and there is no guarantee, however, by shifting the energy consumption to the nights, source energy savings almost always occur.

The energy evaluation has been conducted for the full storage and load levelling strategies to investigate the system characteristics. The results for the full storage strategy show that this system configuration consumes significantly more energy than the conventional AC system, which is mainly due to its considerably larger chiller. Considering the load levelling strategy, although the chiller size is significantly smaller than the conventional system, but the long operating hours will consume significant electricity. Therefore, the results of the present study show that the overall energy consumption of the load levelling strategy is 3.7% less than the conventional systems. However, the cumulative energy saving over the year shows that considerable amount of energy can be saved. The cumulative energy saving of the load levelling strategy is presented in Table 4.5.

Table 4.5: The cumulative energy saving of the load levelling strategy.

System capacity (TR)	System capacity (kW)	Total annual energy consumption of conventional system (kWh)	Total annual energy consumption load levelling strategy (kWh)	Total annual energy saving load levelling strategy (kWh)
100	352	1,165,565	1,161,133	41,413
500	1,758	5,827,824	5,805,667	207,067
1000	3517	11,655,648	11,611,333	414,134
1500	5275	17,483,472	17,417,000	621,201
2000	7034	23,311,295	23,222,667	828,268

4.4.4 Environmental effect

The obvious reason for using the TES system is to reduce the energy costs. Besides, energy saving, improving indoor air quality and emission reduction are the other important goals that can be achieved with a proper system design. In Malaysia, around 60% of daily electricity is generated by natural gas in gas turbine power plants. It is known that the ambient conditions under which a gas turbine operates have a noticeable effect on both the power output and efficiency. On the other hand, the operating load has a direct effect on the fuel consumption and consequently on the emission production level of the primary pollutants of CO_2, CO, and VOCs. Generally, the power diminishes in higher ambient temperatures due to lower air density and airflow mass rate. This would lead to reduce the total efficiency because the compressor requires more power to compress air at higher temperature. Conversely, during the night-times when the ambient temperature is lower the power and efficiency will boost up. For a typical gas turbine, at inlet ambient temperatures of near 37°C that occurs normally during the day in Malaysia, power output can drop to as low as 90% compared to the standard condition of sea level and 15°C (Energy and Environmental Analysis, 2008). By having the daily temperature range of an average day in Malaysia, the annual fuel consumption reduction due to shifting load to the night-times can be predicted for the electricity source. The potential of the natural gas to produce CO_2 based on Malaysian data is around 0.53kg/kWh (Shekarchian et al., 2011b; International Energy agency, 2012). By having the annual energy saving on site (in the building) and the annual fuel consumption reduction on source (on the power plant) due to the energy consumption shift, the annual emission reduction potential can be estimated. The result of the site emission reduction of the load levelling strategy is tabulated in Table 4.6.

Table 4.6: The estimated emission reduction due to the electricity consumption shift.

System capacity (TR)	System capacity (kW)	Total annual on site CO_2 emission reduction (kg)
100	352	3000
500	1,758	15,100
1000	3517	30,300
1500	5275	45,500
2000	7034	60,600

It can be observed that the ITS system can noticeably reduce the CO_2 emission production level. It is achievable by reducing the total energy consumption of the building by changing the electricity consumption pattern to overcome the disparity between energy generation and energy demand times. It is believed that in the near future these systems can play a vital role to manage the consumption of the limited natural resources in a more efficient, economical and environmentally benign way.

4.5 Long term cost-benefit analysis of retrofitting ITS systems

The main goal in this section is to predict the economic effects of retrofitting ITS systems with existing conventional AC systems over the next 20 years. In this regard, the total energy consumption of AC systems is calculated based on the data available on (Shekarchian et al., 2011a). Since the ITS systems can only be used for the central AC systems and most of the big office buildings have a central AC system, this work will focus on this part. The total electricity consumption of the AC systems of office buildings in the year 2011 is calculated based on the electricity consumption share of the big office buildings.

The economic effect of retrofitting ITS system is calculated for three different scenarios, the first one is to retrofit 10% of the existing conventional AC systems. The second one is to conduct the work for 25% retrofit and the third scenario will target 50% of the operating AC systems. The capital cost of retrofitting new system configuration is calculated for all three scenarios based on the rule of thumb described earlier in the methodology part. The utility and maintenance expenses are also predicted for the next 20 years. It was assumed that Malaysia will experience a steady and constant interest rate of 7% over the next 20.

The total electricity cost is the sum of the on-going electricity costs computed from the electricity tariff rate and the monthly maximum demand charge. The annual Maximum demand charge is also calculated for the whole year (240 days). The maintenance cost is calculated based on the procedure described in the methodology section. The results for total annual costs of retrofitting 50% of the available systems with ITS system are presented in Figure 4.36. It can be observed that the conventional system has the highest costs followed by the load levelling strategy that has slightly lower costs. The figure also shows that the full storage strategy has considerably lower costs.

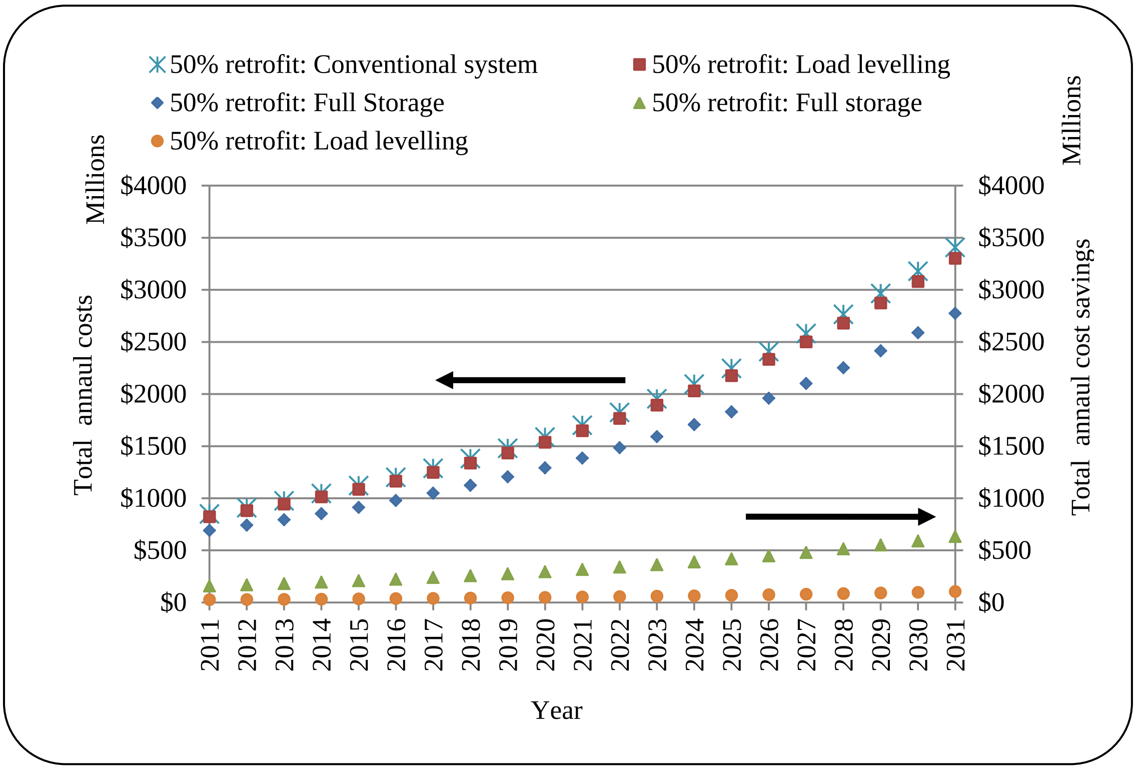


Figure 4.36: Total annual costs and total annual cost savings of retrofitting 50% of the conventional AC systems with ITS system.

By subtracting the total annual costs of each system configuration from the total annual cost of the conventional system the total annual cost savings can be determined. The results for the total annual cost saving by retrofitting 50% of the available systems are shown on the right hand side of Figure 4.36. It can be observed that the total cost saving can reach up to 14% in the best condition. The result of cost savings for three strategies is presented in Figure 4.37.

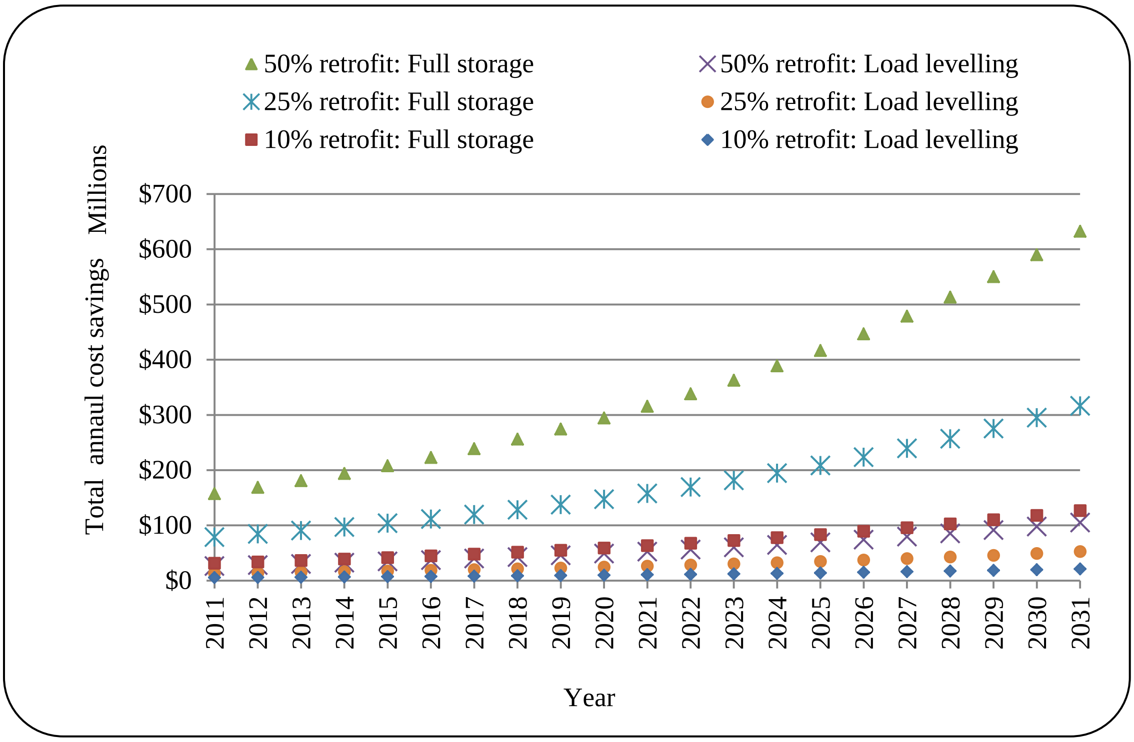


Figure 4.37: Total annual costs savings of retrofitting 10%, 25% and 50% of the conventional AC systems with ITS system.

Obviously, as the retrofitting percentage increases, the total cost savings enhances. The results also indicate that the cost saving of the load levelling strategy is significantly lower than the full storage strategy. The graph shows that even by retrofitting only 10% of the available conventional systems by ITS system, a huge amount of money can be saved over the next 20 years. This would have a direct benefit for customers and also can have significant advantages for the society. The summary of the results is presented in Table 4.7. By comparing the installation, maintenance and electricity costs of the conventional system with the ITS system, it was found that the payback period of the full storage is equal 3 to 6 years For the load levelling strategy this period is varied between 1 to 3 years.

Although the cost savings of CTES systems are significantly higher than the energy savings, but electricity production and distribution during the night hours is significantly more efficient and can save considerable amount of fossil fuels in the power plants that can assist in conserving fossil fuels and decrease harmful emissions.

Table 4.7: Summary of the results.

	Installation cost (M$)			**Total costs (M$ over 20 Years)**			**Total cost saving (M$ over 20 Years)**	
	Conventional system	Full storage	Load levelling	Conventional system	Full storage	Load levelling	Full storage	Load levelling
50%	661	1755	723	38,941	31,716	37,743	7226	1199
25%	331	877	361	19,471	5858	18,871	3613	599
10%	132	351	145	7788	6343	7549	1445	240

4.6 Computer modelling results

Building characteristics and weather data were added to the software to predict the electricity usage pattern throughout the year. The simulation has been conducted in two steps, in the first step the building's baseline model was developed based on its present condition. The results of the baseline model were compared with the actual data recorded from the fieldwork to validate the accuracy of the simulation results. Once the simulation results reach an acceptable accuracy, the proposed CTES systems were added to the model to predict the behaviour of the AC system based on Malaysian climate.

4.6.1 Baseline simulation results validation

After developing the baseline model in TRNSYS simulation software, the results of the existing AC system were obtained for a simulation period of one year (8760 hours) based on Kuala Lumpur weather data. Figure 4.38 shows the simulation plotting window in which, the ambient DBT is shown in red and the zone DBT is shown in pink colour. The output results were saved in an external file in order to perform the post processing analysis.

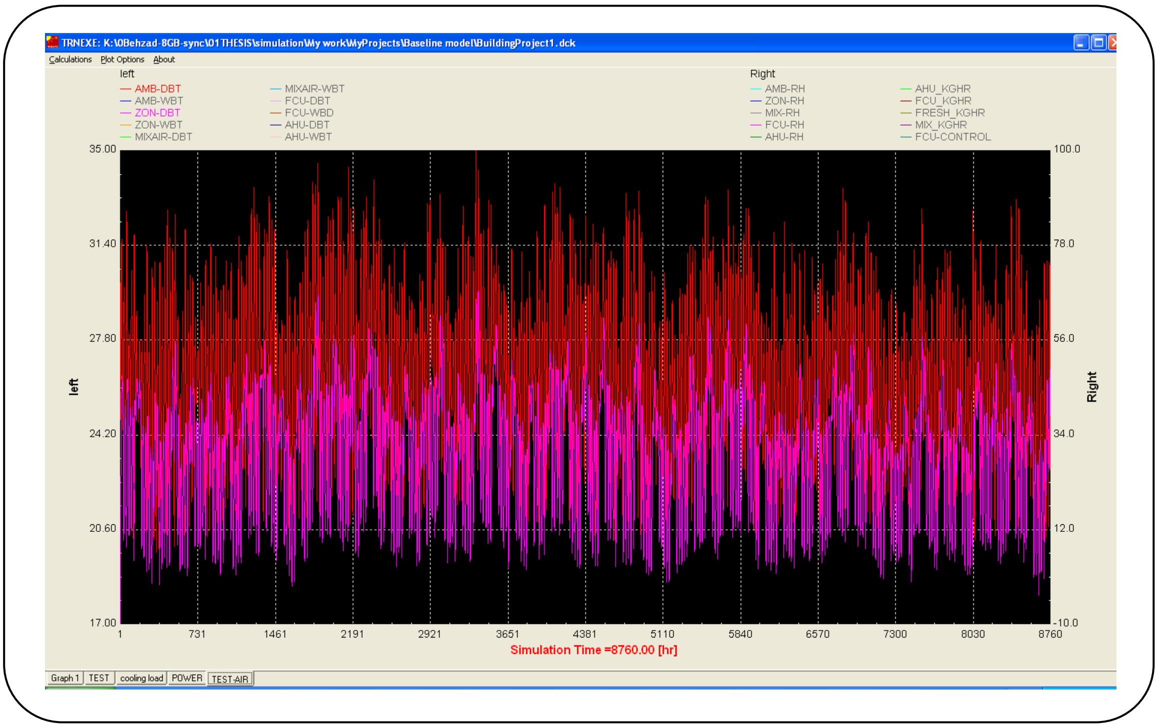


Figure 4.38: The building temperature fluctuations.

Figure 4.39 shows clearly the temperature fluctuations of inside the conditioned zone and its surrounding ambient. The figure shows the average simulated results during the simulation period as well as the minimum and maximum bound for all possible happening conditions during that period. The blue strip is dedicated to the ambient temperature fluctuation and the pink one is for the zone temperature gradients. The thickness of the strips indicates the diversity of the results, as the strip get thinner, the probability of repeating the same outputs increase. As it is shown, the thickness pink strip has the highest thickness during the first day of the week. This indicates the highest temperature fluctuation on this particular day of the week, which is mainly due to the high uncertainty level of the weekends. During weekends, the system is not operating and the building temperature strongly can be changed based on its surrounding condition.

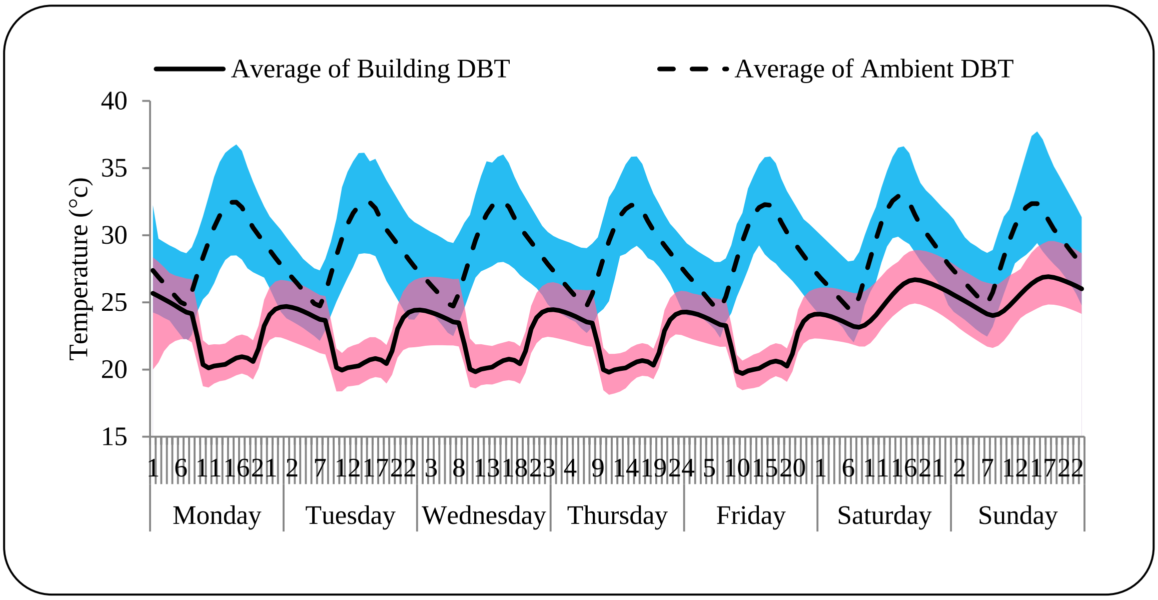


Figure 4.39: Temperature fluctuations of inside the building and surrounding ambient.

The result of the building power consumption during the simulation period and its average trend is presented in Figure 4.40. It is assumed that the chiller has no electricity usage during the night-time. However, this result is slightly different from recording data. Inside the chiller plant room, there are lamps, computers and control system that are working continuously every day. In top of that, the chiller itself is on standby mode and is not completely turned off. Therefore, an overall electricity consumption of around 7kW is consumed per hour during the night-time.

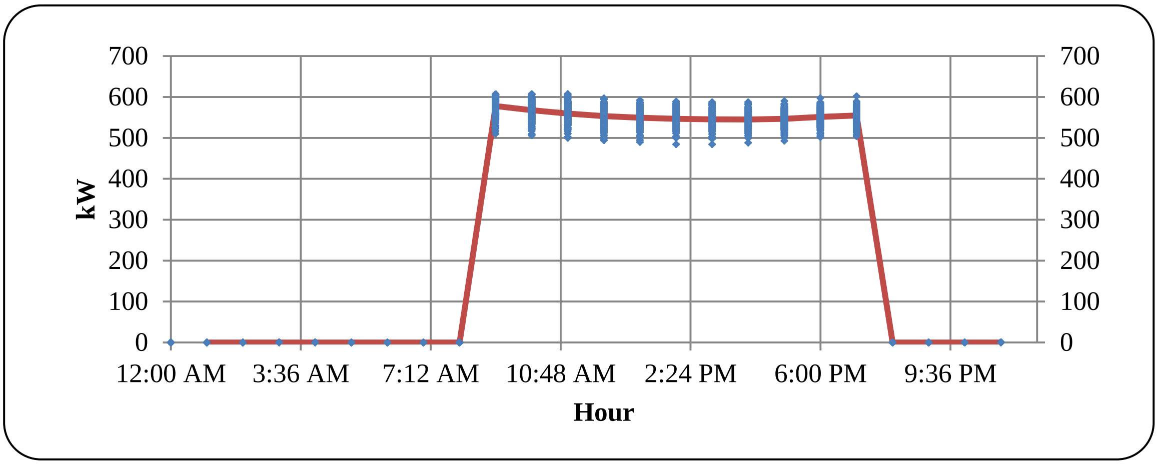


Figure 4.40: The building power consumption span during the simulation period and its average trend.

The results obtained from simulation are plotted against the data collected from fieldwork. The comparison results are presented in Figure 4.41. It should be noted that there are normally considerable deviations between real situations and design conditions. The comparison shows acceptable match, except for the beginning of the day and the last working hour. The deviation is mainly due to the some unscheduled chiller operation, the overruling of the chiller control system and the start-up period. However, these effects were not simulated in the building model due to their unpredictable behaviour.

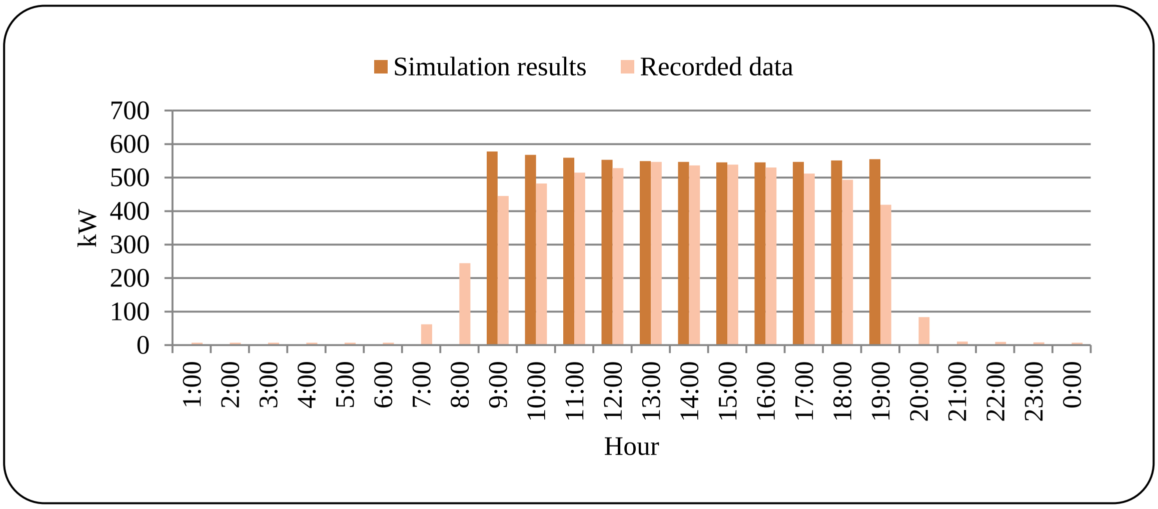


Figure 4.41: Comparison between simulation results and fieldwork data.

The comparison results show that the baseline model has almost the same behaviour as the real building. Therefore, the simulation can be used as a baseline for evaluating the effect of adding a CTES system. The results for two storage strategies of full storage and load levelling storage strategy are presented in the following section.

4.6.2 Full storage strategy

The simulation for full storage strategy was performed for 8760 hours, which represents one year. The temperature fluctuation of inside the conditioned zone was compared with the ambient condition as it is shown in Figure 4.42. The graph shows that the proposed system can perform satisfactory and can supply the required cooling for the building. The temperature fluctuation indicates acceptable indoor temperature and RH that can satisfy occupants in terms of IAQ requirements.

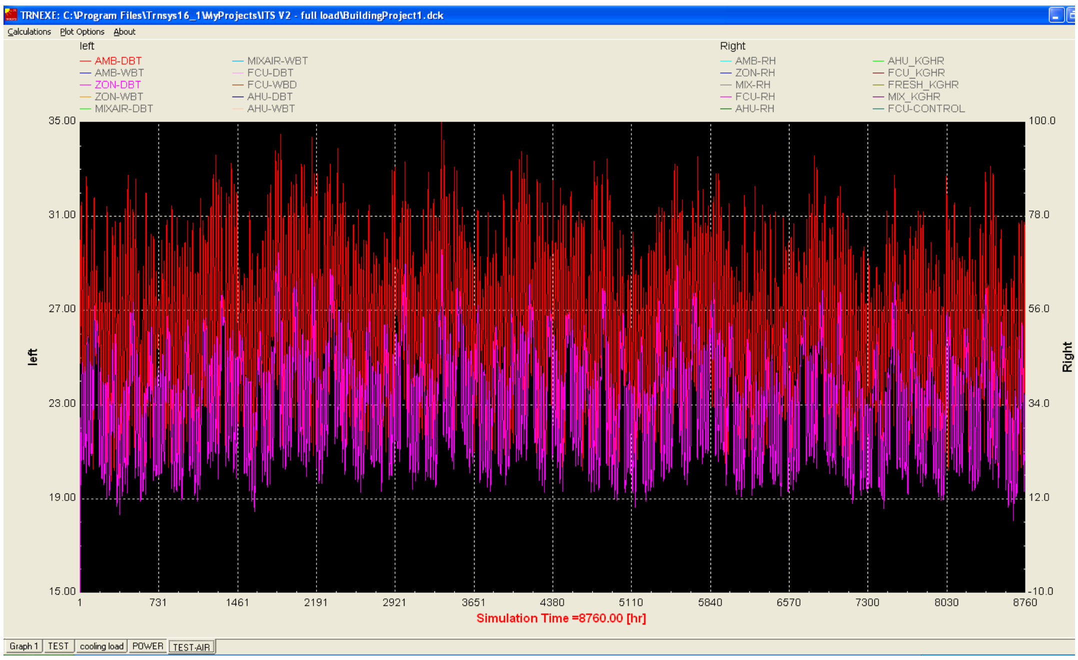


Figure 4.42: Comparison between inside and outside dry bulb temperatures during one year.

The average weekly electricity consumption of the building and chiller are plotted in Figure 4.34. It was assumed that Saturday and Sunday are totally off-days and even the technicians are not working, hence, the chiller is not planned to operate during the night-times at weekends. Although by considering this two nights as operating hours the total chiller capacity could be reduced, but at the same time the operation and control system would be more complicated. As the graph shows the chiller works with its full load during the nights and there is only a slight fluctuation which is mainly due to the ambient temperature variation. The total weekly building electricity consumption is around 35% of the total weekly energy demand. This share contains the electricity consumed by AHUs, FCUs, lighting, computers and other electrical appliances. This graph shows that although chillers are working during the off-peak hours, but still a considerable share of energy is required to cool down the building during the day by AHUs, FCUs and other mechanical cooling devices.

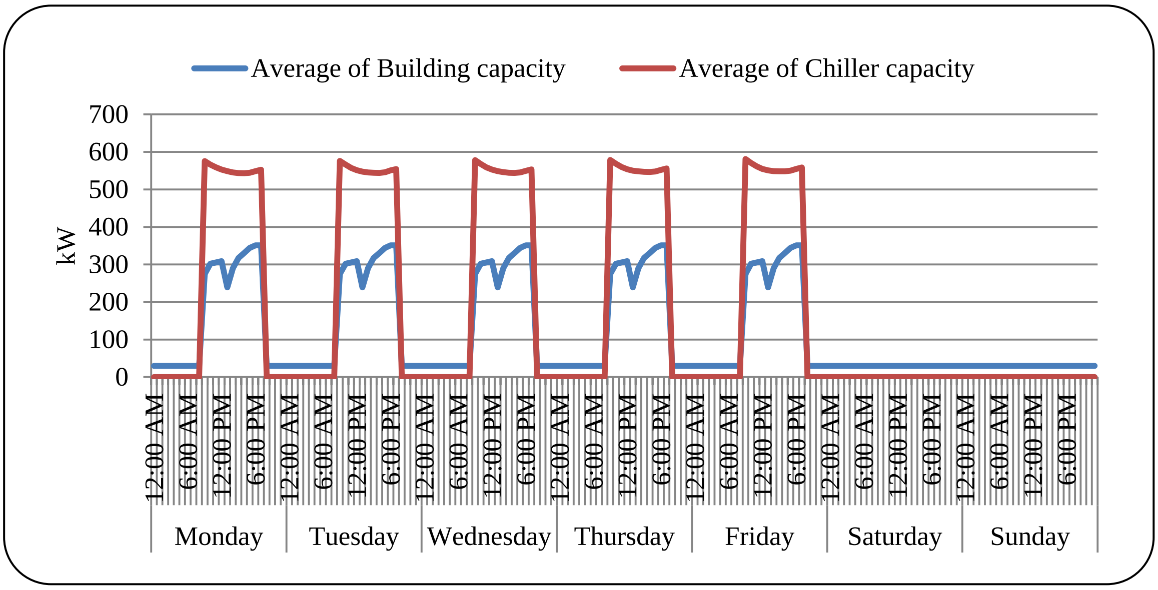


Figure 4.43: The average building and chiller electricity consumption.

The average electricity consumption of the chiller in the full storage strategy is plotted in Figure 4.44. All the data is accumulated in a small band of 15% tolerance during the whole year, which is mainly due to the low temperature fluctuations of the region.

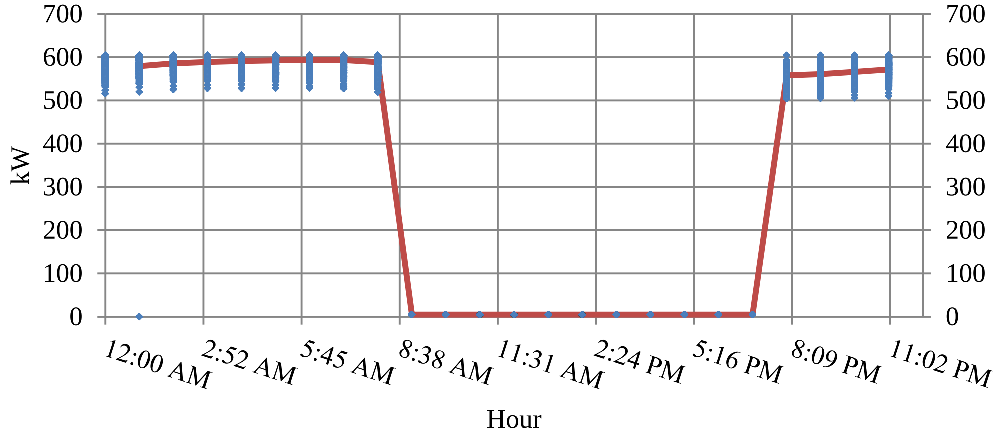


Figure 4.44: The span of the chiller energy consumption and it average pattern.

The chiller operation pattern for the full storage strategy is presented in Figure 4.45.

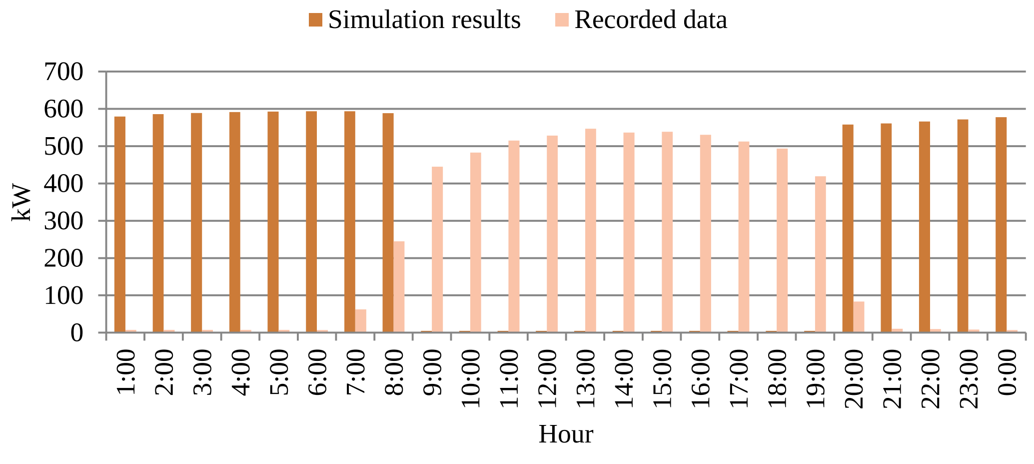


Figure 4.45: The average chiller operation pattern.

The chiller is working in almost its full load during the night times until 9:00 AM. However, the cooling is started two hours earlier at 7:00 AM daily. The required cooling load during the first two hours is provided directly by the chiller. The discharging process starts daily at 9:00 AM and ends at 8:00 PM. The small portion of cooling required during the last working hours, is provided by chiller directly.

4.6.3 Load levelling storage strategy

The partial storage strategy was also simulated based on the validated baseline model. Again, it was assumed that during weekends, no operation allows for the HVAC system, therefore, the chiller starts working on Monday 12:00 AM until Friday 11:59PM. Although the night-time hours during the weekends are ideal for storing ice, but in order to simplify the model and its operation, these hours are considered as non-operating hours. The comparison between the results obtained from full storage and load levelling storage strategies are plotted in Figure 4.46.

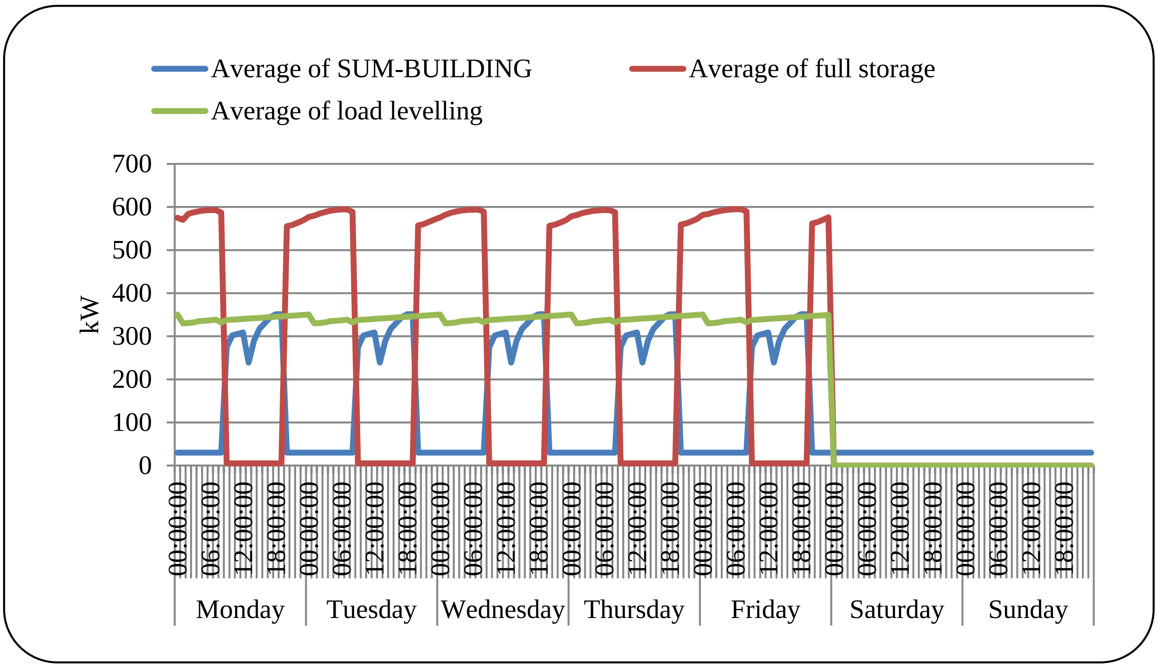


Figure 4.46: The comparison between full storage and load levelling storage strategies.

The overall energy used by the load levelling storage strategy is 4% lower than the total energy used by the non-storage system. This result shows that employing ITS system does not have a significant effect on reducing the total energy usage by the building.

However, the main benefits are cost reduction, bringing balance in the grid system, reducing the overall fuel consumption in the power plants and consequently reducing to total carbon footprint.

Chapter 5. Conclusion and recommendations

This chapter summarizes general conclusions that can be drawn from the results of this project and suggests areas where additional research or refinement is needed.

5.1 Conclusions

i. The review between various available cold thermal energy storage systems and technologies reveals the advantages and disadvantages of different types of the CTES techniques and the storage strategies. Among all, it was concluded that the ITS system has the advantages of larger storage volume capability, but it has a comparatively lower COP than other available techniques.

ii. The fieldwork recording shows that the ambient temperature and humidity nearby the building vary between 27.4ºC to 34.1ºC and from 40.6% to 81.1%, respectively, which is close to the range reported by the meteorological data. Based on the Malaysian statistical data, this fluctuation would be repeated during the year without significant deviation. Hence, the recorded data were used for design purposes with high confidence.

iii. The building's energy consumption trend was recorded and monitored during the fieldwork study. The result shows that on average the chiller and pumps used around 59% of the total building energy demand. However, the total energy used for cooling the building by considering the work of AHUs, FCUs, and other mechanical cooling appliances, is around 65%.

iv. The building power usage pattern, shows that in the first day of the week (Monday) there is around 15% more electricity demand than the last day of the week (Friday). This happens due to the pull-down load effect occurred in the weekends. The high level of diversity factor ensures the significant benefits of utilizing CTES system.

v. The comparison study between the results shows that the chiller size for full storage strategy is around 1.19 times more than the conventional AC system. However, the chiller size for the load levelling strategy is significantly lower than the chiller size for the conventional AC system being around 51% lower.

vi. The thermodynamic analysis shows that all ITS systems are generally highly efficient in terms of energy evaluation. The minimum of energy efficiency was obtained for ice harvesting with 93% and the maximum of 98% belongs to encapsulated technique. However, the exergetic evaluation provides a more realistic picture for the process with far less values. The maximum exergy efficiency was obtained for ice on coil (internal) technique with value of 18%.

vii. A parametric study shows that by changing the room temperature set point, the discharging exergy efficiency changes remarkably. 5ºC increase of the room set point temperature can decrease the exergy efficiency by 4%.

viii. The economic evaluation based on building’s load profile and climate conditions shows that considering the special off-peak tariff rate of \$0.06/kWh, the annual cost saving for full storage strategy varies from \$230,000 to \$700,000 for full storage and from \$65,000 to \$190,000 for load levelling strategy for the total system capacities of 500 TR and 1500 TR (1758kW and 5275kW), respectively. It was found that the full storage strategy can reduce the annual costs of the AC system by up to 35% while this reduction is limited to around 8% for a load levelling strategy.

ix. By comparing the installation, maintenance and electricity costs of the conventional system with the ITS system, it was found that for the full storage strategy it will take 3 to 6 years for the benefits of the investment to be equal with the investment and for the load levelling strategy this period reduced to 1 to 3 years.

x. The comparison results between the conventional AC system and the ITS system indicate that a proper design could lead to lower energy consumption due to better utilization of the equipment. It shows that the load levelling strategy uses almost 4 % less energy than the conventional AC systems.

xi. By having the annual energy saving, the emission reduction potential of utilizing ITS system was estimated based on the potential of the natural gas to produce CO_2 emission. The results show that the annual CO_2 emission reduction for load levelling strategy varies from 3000 to 60,000 kg for the total system capacities of 100 and 2000 TR, respectively.

xii. On the next step, three different scenarios were considered to predict the cost saving potential of retrofitting ITS systems with the conventional AC over the next 20 years. The results show that the annual cost saving for full storage strategy is around 4 times more than the load levelling strategy.

xiii. In the final step, the building was simulated by a computer simulation program. The baseline-model test run shows the same characteristics as the building through the fieldwork period. By trimming the model to match the desired behaviour, the model was used to predict the impact of utilizing ITS system.

xiv. It was shown that the overall energy used by the full load storage strategy is considerably more than the conventional system, however, for the load levelling storage strategy the overall energy usage is slightly lower (less than 4%) than the total energy used by the non-storage system.

xv. These findings suggest that in general using ITS system does not always guarantee lower energy demand, but there are several outstanding benefits that make this technique a unique solution for our today's world, such as cost reduction, bringing balance in the grid system, reducing the overall fuel consumption in the power plants and consequently reducing to total carbon footprint.

5.2 Recommendations for future work

The significant recommendations for future work involving the modelling, design, control, and simulation of CTES system for office buildings and increasing the overall system performance are summarized as follows:

- The effect of night-time ventilation for the CTES system can be investigated by either computer simulation or experimental test. The pre-cooling of the building can significantly reduce the pull-down load. However, using the chiller during the nigh-time for pre-cooling will need more complicated control system to distribute the chilled water between the CTES tank and building in the most effective way.
- The potential effects of global warming and climate change needs to be considered in future modelling, as these changes are predicted to cause greater temperature variations and more severe heat waves.

- Simulate the performance of the ice-storage system under actual control strategies used in practice, and compare the results with those obtained by simulating the system under near-optimal control strategies.
- Investigate the effect of combining of various energy saving techniques on CTES system such as; controlling the light level via movement detector controls, installing manually control ceiling fans to increase the comfort zone from 25 ºC to 29ºC that will consequently affect all the sizing parameters.

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Appendices

Appendix A : List of Publications

The present thesis is based on the work contained in the following papers:

Paper I: Y.H. Yau, **Behzad Rismanchi**, A review on cool thermal storage technologies and operating strategies, Renewable and Sustainable Energy Reviews 16 (2012) 787– 797.

Paper II: **B. Rismanchi**, R. Saidur, H.H. Masjuki, T.M.I. Mahlia, Thermodynamic Evaluation of Utilizing Different Ice Thermal Energy Storage Systems for Cooling Application in Office Buildings in Malaysia, Energy and Buildings, 53, 2012, 17–126

Paper III: **B. Rismanchi,** R. Saidur, H.H. Masjuki, T.M.I. Mahlia, Energetic, economic and environmental benefits of utilizing the ice thermal storage systems for office building applications, Energy and Buildings, 50, 2012, 347–354.

Paper IV: **B. Rismanchi**, R. Saidur, H.H. Masjuki, T.M.I. Mahlia, Cost-benefit analysis of using cold thermal energy storage systems in building applications, Energy Procedia 14 (2012) 493 – 498.

Paper V: **B. Rismanchi**, R. Saidur, H.H. Masjuki, T.M.I. Mahlia, Modeling and Simulation to Determine the Potential Energy Savings by Implementing Cold Thermal Energy Storage System in Office Buildings, Energy Conversion and Management.

Appendix B : Tariff rate structure defined by TNB.

	TARIFF CATEGORY	UNIT	RATES
1	Tariff A - Domestic Tariff		
	For the first 200 kWh (1 - 200 kWh) per month	sen/kWh	21.8
	For the next 100 kWh (201 - 300 kWh) per month	sen/kWh	33.4
	For the next 100 kWh (301 - 400 kWh) per month	sen/kWh	40.0
	For the first 100kWh (401 - 500 kWh) per month	sen/kWh	40.2
	For the next 100 kWh (501 - 600 kWh) per month	sen/kWh	41.6
	For the next 100 kWh (601 - 700 kWh) per month	sen/kWh	42.6
	For the next 100 kWh (701 - 800 kWh) per month	sen/kWh	43.7
	For the next 100 kWh (801 - 900 kWh) per month	sen/kWh	45.3
	For the next kWh (901 kWh onwards) per month	sen/kWh	45.4
	The minimum monthly charge is RM3.00		
2	Tariff B - Low Voltage Commercial Tariff		
	For Overall Monthly Consumption Between 0-200 kWh/month		
	For all kWh	sen/kWh	39.3
	The minimum monthly charge is RM7.20		
	For Overall Monthly Consumption More Than 200 kWh/month		
	For all kWh (From 1kWh onwards)	sen/kWh	43.0
	The minimum monthly charge is RM7.20		
3	Tariff C1 - Medium Voltage General Commercial Tariff		
	For each kilowatt of maximum demand per month	RM/kW	25.9
	For all kWh	sen/kWh	31.2
	The minimum monthly charge is RM600.00		
4	Tariff C2 - Medium Voltage Peak/Off-Peak Commercial Tariff		
	For each kilowatt of maximum demand per month during the peak period	RM/kW	38.60
	For all kWh during the peak period	sen/kWh	31.2
	For all kWh during the off-peak period	sen/kWh	19.2
	The minimum monthly charge is RM600.00		

Appendix C : TRNSYS simulation model

Available in CD ROM

File name:

APPENDIX B-BASELINE MODEL

APPENDIX B-CTES MODEL

Appendix D : TRNSYS components of the baseline model.

Type / symbol	**Description** **Input / Output**
Type 109 	This component serves the main purpose of reading weather data at regular time intervals from a data file, converting it to a desired system of units and processing the solar radiation data to obtain tilted surface radiation and angle of incidence for an arbitrary number of surfaces. In this mode, Type 109 reads a weather data file in the standard TMY2 format. The TMY2 format is used by the National Solar Radiation Data Base (USA). The Kuala Lumpur Airport data is used in this simulation for the year 2006. **Input:** **1)**Building angel **Output:** **1)** Ambient Temperature, Relative humidity (to PSY-1) **2)** solar zenith angle, solar azimuth angle, total radiation on horizontal, beam radiation on horitonzal, sky diffuse radiation on horizontal, angle of incidence on horizontal surface, total radiation on tilted surface, angle of incidence for tilted surface, beam radiation on tilted surface (to Radiation) **3)** sky diffuse radiation on horizontal (To sky Temp)
Type56a 	This component models the thermal behaviour of a building. The building description is read by this component from a set of external files. This instance of Type56 generates its own set of monthly and hourly summary output files. **Input:** **1)** Fictive sky temperature (From Sky Temp) **2)** Heat Gain from Lights, People and Equipment (From GAIN) **3)** Dry bulb temperature (from PSY-1) **4)** Supply Dry bulb temperature and RH from AHU (from PSY) **5)** Supply Dry bulb temperature and RH from FCU (from PSY-4) **6)** Control signal for building AHU and FCU system operation (from AHU/ON-OFF-1) **Output:** **1)** Zone dry bulb temperature and RH (to PSY-2) **2)** SQINF, SQGCONV, SQLATG, SQSOLT, SQABSI, SQCSURF, QSENS_ZONE_A1, SQCOOL (to Cooling Load calculator)

Type 107

Water cooled Chiller

Input:

1) Cooling water return temperature and flow rate (from cooling tower)

2) Chilled water return temperature and flow rate (from CHWR)

3) Control signal (from CHIL/CONT)

Output:

1) Chilled water supply temperature and flow rate (to CHW-PUMP)

2) Cooling water supply temperature and flow rate (to CW-PUMP)

3) Chiller power consumption (to POWER-2)

Type 51

In a cooling tower, a hot water stream is in direct contact with an air stream and cooled as a result of sensible heat transfer due to temperature differences with the air and mass transfer resulting from evaporation to the air. Ambient air is drawn upward through the falling water. Each cooling tower composed of two tower cells that are in parallel and share a common sump. Water loss from the tower cells is replaced with make-up water to the sump.

Input:

1) Ambient dry bulb and wet bulb temperature (from PSY-1)

2) Cooling water supply temperature and flow rate (from CW-PUMP)

3) Make-up water temperature (from WAT INLET)

Output:

1) Cooling water return temperature and flow rate (to Chiller)

2) Cooling tower power consumption (to Power-2)

Type 32

This component models the performance of a chilled water cooling coil. Its purpose is to separate the cooling input into sensible (temperature) and latent (humidity) effects.

Input:

1) Chilled water supply temperature and flow rate (from CHWS)

2) Zone dry bulb and wet bulb temperature (from PSY-3)

Output:

1) Chilled water return temperature and flow rate (to CHWR)

2) Dry bulb and wet bulb temperature of the supply cold air to the zone (to PSY)

Type 114

It models a single speed pump that is able to maintain a constant fluid outlet mass flow rate.

Type 65

The online graphics component is used to display selected system variables while the simulation is progressing. The selected variables will be displayed in a separate plot window on the screen.

Type 14 	The pattern of the forcing function is established by a set of discrete data points indicating the value of the function at various times throughout one cycle. Linear interpolation is provided in order to generate a continuous forcing function from the discrete data. The cycle will repeat every N hours where N is the last value of time specified.
Type 11 	The use of pipe or duct tee-pieces, mixers, and diverters, which are subject to external control, is necessary in thermal systems. This instance of the Type11 model fluids, such as moist air, with two important properties, such as temperature and humidity to model a controlled flow mixer in which two inlet air streams are mixed together according to an internally calculated control function so as to maintain the mixed outlet temperature at or below a user specified value.
Type 33 	This component takes as input the dry bulb temperature and relative humidity of moist air and calls the TRNSYS Psychrometrics routine, returning the following corresponding moist air properties: dry bulb temperature, dew point temperature, wet bulb temperature, etc.

Appendix E : TRNSYS deck for baseline model

The TRNSYS deck for the baseline model is presented below. It is slightly modified to increase readability. This deck was used with TRNSYS 16 and might not be immediately compatible under other TRNSYS implementations. One would have to remove all non-standard components with predefined types or regenerate them through the software. The order of units and equations should not be changed, since variables are often linked.

```
VERSION 16.1
*******************************************************************************
*** TRNSYS input file (deck) generated by TrnsysStudio
*** on Saturday, August 25, 2012 at 13:39
***
*** If you edit this file, use the File/Import TRNSYS Input File function in
*** TrnsysStudio to update the project.
***
*** If you have problems, questions or suggestions please contact your local
*** TRNSYS distributor or mailto:software@cstb.fr
*******************************************************************************
*** Units
*******************************************************************************
*******************************************************************************
*** Control cards
*******************************************************************************
* START, STOP and STEP
CONSTANTS 3
START=1
STOP=720
STEP=1
* User defined CONSTANTS
SIMULATION     START  STOP    STEP    ! Start time    End time Time step
TOLERANCES 0.001 0.001       ! Integration   Convergence
LIMITS 50 50 50              ! Max iterations    Max warnings      Trace limit
DFQ 1                        ! TRNSYS numerical integration solver method
WIDTH 72                     ! TRNSYS output file width, number of characters
LIST                         ! NOLIST statement
                             ! MAP statement
SOLVER 0 1 1                 !Solver statement Minimum relaxation factor Maximum relaxation factor
NAN_CHECK 0                  ! Nan DEBUG statement
OVERWRITE_CHECK 0            ! Overwrite DEBUG statement
TIME_REPORT 0                ! disable time report
EQSOLVER 0                   ! EQUATION SOLVER statement
```

```
* Model "Weather data" (Type 109)
*
UNIT 109 TYPE 109    Weather data
*$UNIT_NAME Weather data
*$MODEL .\Weather Data Reading and Processing\Standard Format\TMY2\Type109-TMY2.tmf
*$POSITION 188 87
*$LAYER Main #
*$# type1 109
PARAMETERS 4
2           ! 1 Data Reader Mode
30          ! 2 Logical unit
4           ! 3 Sky model for diffuse radiation
1           ! 4 Tracking mode
INPUTS 9
*** INITIAL INPUT VALUES
0.2 90 AA_N 90 AA_S 90 AA_E 90 AA_W
*** External files
ASSIGN "D:\0Behzad-8GB-sync\01THESIS\simulation\My work\weather data\MY-Kuala-Lumpur-Airp-486470.tm2" 30
*|? Weather data file |1000
*------------------------------------------------------------------------------
* Model "People" (Type 14)
UNIT 12 TYPE 14       People
*$UNIT_NAME People
*$MODEL .\Utility\Forcing Functions\General\TYPE14h.tmf
*$POSITION 548 95
*$LAYER Outputs # Main #
PARAMETERS 40
1           ! 1 Initial value of time
0           ! 2 Initial value of function
7           ! 3 Time at point-1
0           ! 4 Value at point -1
7           ! 5 Time at point-2
50          ! 6 Value at point -2
8           ! 7 Time at point-3
150         ! 8 Value at point -3
9           ! 9 Time at point-4
300         ! 10 Value at point -4
10          ! 11 Time at point-5
400         ! 12 Value at point -5
11          ! 13 Time at point-6
550         ! 14 Value at point -6
12          ! 15 Time at point-7
550         ! 16 Value at point -7
13          ! 17 Time at point-8
550         ! 18 Value at point -8
14          ! 19 Time at point-9
500         ! 20 Value at point -9
15          ! 21 Time at point-10
500         ! 22 Value at point -10
16          ! 23 Time at point-11
550         ! 24 Value at point -11
17          ! 25 Time at point-12
400         ! 26 Value at point -12
18          ! 27 Time at point-13
150         ! 28 Value at point -13
19          ! 29 Time at point-14
100         ! 30 Value at point -14
20          ! 31 Time at point-15
```

```
100       ! 32 Value at point -15
21        ! 33 Time at point-16
50        ! 34 Value at point -16
21        ! 35 Time at point-17
0         ! 36 Value at point -17
22        ! 37 Time at point-18
0         ! 38 Value at point -18
24        ! 39 Time at point-19
0         ! 40 Value at point -19
*------------------------------------------------------------------------------
* Model "Equipment" (Type 14)
UNIT 23 TYPE 14     Equipment
*$UNIT_NAME Equipment
*$MODEL .\Utility\Forcing Functions\General\TYPE14h.tmf
*$POSITION 620 55
*$LAYER Main # # Main #
PARAMETERS 12
1         ! 1 Initial value of time
40        ! 2 Initial value of function
7         ! 3 Time at point-1
40        ! 4 Value at point -1
7         ! 5 Time at point-2
100       ! 6 Value at point -2
21        ! 7 Time at point-3
100       ! 8 Value at point -3
21        ! 9 Time at point-4
40        ! 10 Value at point -4
24        ! 11 Time at point-5
40        ! 12 Value at point -5
*------------------------------------------------------------------------------
* Model "Light" (Type 14)
UNIT 26 TYPE 14     Light
*$UNIT_NAME Light
*$MODEL .\Utility\Forcing Functions\General\TYPE14h.tmf
*$POSITION 483 115
*$LAYER Outputs # Main #
PARAMETERS 18
1         ! 1 Initial value of time
5         ! 2 Initial value of function
7         ! 3 Time at point-1
5         ! 4 Value at point -1
9         ! 5 Time at point-2
40        ! 6 Value at point -2
14        ! 7 Time at point-3
40        ! 8 Value at point -3
17        ! 9 Time at point-4
80        ! 10 Value at point -4
19        ! 11 Time at point-5
80        ! 12 Value at point -5
20        ! 13 Time at point-6
40        ! 14 Value at point -6
21        ! 15 Time at point-7
5         ! 16 Value at point -7
24        ! 17 Time at point-8
5         ! 18 Value at point -8
*------------------------------------------------------------------------------
* EQUATIONS "BUILDING ANGEL"*
EQUATIONS 5
TURN = 0
```

```
AA_N = 180 + TURN
AA_S = TURN
AA_E = -90 + TURN
AA_W = 90 + TURN
*$UNIT_NAME BUILDING ANGEL
*$LAYER Main
*$POSITION 876 63
*------------------------------------------------------------------------------
* Model "Type21" (Type 21)*
UNIT 19 TYPE 21	Type21
*$UNIT_NAME Type21
*$MODEL .\Utility\Time Values\Type21.tmf
*$POSITION 793 61
*$LAYER Main #
PARAMETERS 2
1	! 1 Mode
0	! 2 Relative time?
*------------------------------------------------------------------------------
* Model "WEEKLY" (Type 14)*
UNIT 25 TYPE 14	WEEKLY
*$UNIT_NAME WEEKLY
*$MODEL .\Utility\Forcing Functions\General\TYPE14h.tmf
*$POSITION 61 185
*$LAYER Main # # Main #
PARAMETERS 12
0	! 1 Initial value of time
0	! 2 Initial value of function
24	! 3 Time at point-1
0	! 4 Value at point -1
24	! 5 Time at point-2
1	! 6 Value at point -2
144	! 7 Time at point-3
1	! 8 Value at point -3
144	! 9 Time at point-4
0	! 10 Value at point -4
168	! 11 Time at point-5
0	! 12 Value at point -5
*------------------------------------------------------------------------------
* Model "CHI/ON-OFF" (Type 14)*
UNIT 33 TYPE 14	CHI/ON-OFF
*$UNIT_NAME CHI/ON-OFF
*$MODEL .\Utility\Forcing Functions\General\TYPE14h.tmf
*$POSITION 129 388
*$LAYER Outputs # Main #
PARAMETERS 12
1	! 1 Initial value of time
0	! 2 Initial value of function
8	! 3 Time at point-1
0	! 4 Value at point -1
8	! 5 Time at point-2
1	! 6 Value at point -2
17	! 7 Time at point-3
1	! 8 Value at point -3
17	! 9 Time at point-4
0	! 10 Value at point -4
24	! 11 Time at point-5
0	! 12 Value at point -5
*------------------------------------------------------------------------------
```

```
* EQUATIONS "WAT INLET"*
EQUATIONS 2
COLDW_T = 22 !C
COLDW_Q = 0 !kg/h
*$UNIT_NAME WAT INLET
*$LAYER Water LoopMain
*$POSITION 137 312
*------------------------------------------------------------------------------
* Model "WEEKLY-2" (Type 14)*
UNIT 48 TYPE 14      WEEKLY-2
*$UNIT_NAME WEEKLY-2
*$MODEL .\Utility\Forcing Functions\General\TYPE14h.tmf
*$POSITION 853 386
*$LAYER Water Loop # Main #
PARAMETERS 12
0         ! 1 Initial value of time
0         ! 2 Initial value of function
24        ! 3 Time at point-1
0         ! 4 Value at point -1
24        ! 5 Time at point-2
1         ! 6 Value at point -2
144       ! 7 Time at point-3
1         ! 8 Value at point -3
144       ! 9 Time at point-4
0         ! 10 Value at point -4
168       ! 11 Time at point-5
0         ! 12 Value at point -5
*------------------------------------------------------------------------------
* Model "AHU/ON-OFF" (Type 14)*
UNIT 49 TYPE 14      AHU/ON-OFF
*$UNIT_NAME AHU/ON-OFF
*$MODEL .\Utility\Forcing Functions\General\TYPE14h.tmf
*$POSITION 852 310
*$LAYER Main #
PARAMETERS 12
1         ! 1 Initial value of time
0         ! 2 Initial value of function
8         ! 3 Time at point-1
0         ! 4 Value at point -1
8         ! 5 Time at point-2
1         ! 6 Value at point -2
17        ! 7 Time at point-3
1         ! 8 Value at point -3
17        ! 9 Time at point-4
0         ! 10 Value at point -4
24        ! 11 Time at point-5
0         ! 12 Value at point -5
*------------------------------------------------------------------------------
* Model "PSY1" (Type 33)*
UNIT 331 TYPE 33     PSY1
*$UNIT_NAME PSY1
*$MODEL .\Physical Phenomena\Thermodynamic Properties\Psychrometrics\Dry Bulb and Relative Humidity Known\Type33e.tmf
*$POSITION 136 250
*$LAYER Main #
PARAMETERS 3
2            ! 1 Psychrometrics mode
1            ! 2 Wet bulb mode
1            ! 3 Error mode
```

```
INPUTS 3
109,1            ! Weather data:Ambient temperature ->Dry bulb temp.
109,2            ! Weather data:relative humidity ->Percent relative humidity
*** INITIAL INPUT VALUES
30 80 1
*------------------------------------------------------------------------------
* Model "Sky temp" (Type 69)*
UNIT 69 TYPE 69       Sky temp
*$UNIT_NAME Sky temp
*$MODEL .\Physical Phenomena\Sky Temperature\calculate cloudiness factor\Type69b.tmf
*$POSITION 188 176
*$LAYER Outputs # Main #
PARAMETERS 2
0                ! 1 mode for cloudiness factor
0                ! 2 height over sea level
INPUTS 4
331,7            ! PSY1:Dry bulb temperature ->Ambient temperature
331,8            ! PSY1:Dew point temperature. ->Dew point temperature at ambient conditions
109,13           ! Weather data:beam radiation on horitonzal ->Beam radiation on the horizontal
109,14           ! Weather data:sky diffuse radiation on horizontal ->Diffuse radiation on the horizontal
*** INITIAL INPUT VALUES
0 0 0 0
*------------------------------------------------------------------------------
* EQUATIONS "Radiation"*
EQUATIONS 19
TRUN_RAD = 0
AISA =  [109,11] * TRUN_RAD
AISZ =  [109,10] * TRUN_RAD
IT_H =  Max([109,12],0) * TRUN_RAD
IB_H =  Max([109,13],0) * TRUN_RAD
ID_H =  [109,14] * TRUN_RAD
AI_H =  [109,16] * TRUN_RAD
IT_N =  [109,18] * TRUN_RAD
AI_N =  [109,22] * TRUN_RAD
IB_N =  [109,19] * LT(AI_N,90)  * TRUN_RAD
IT_S =  [109,24] * TRUN_RAD
IB_S =  [109,25] * TRUN_RAD
AI_S =  [109,28] * TRUN_RAD
IT_E =  [109,30] * TRUN_RAD
IB_E =  [109,31] * TRUN_RAD
AI_E =  [109,34] * TRUN_RAD
IT_W =  [109,36] * TRUN_RAD
IB_W =  [109,37] * TRUN_RAD
AI_W =  [109,40] * TRUN_RAD
*$UNIT_NAME Radiation
*$LAYER Main
*$POSITION 315 87
*------------------------------------------------------------------------------
* EQUATIONS "GAIN"*
EQUATIONS 5
GAINPEOPLE = AHU_CONTROL*[12,1] !number
GAINEQUIPMENT = ([23,1]/100) * AHU_CONTROL * 20 * 3600  !kJ/h
GAINLIGHT = ([26,1]/100) * AHU_CONTROL * 204  * 3600        ! kJ/h
LIGHT_POWER = ([26,1] /100 ) * AHU_CONTROL * 204            !KW
EQIPMENT_POWER = ([23,1] / 100) * AHU_CONTROL * 20          !KW
*$UNIT_NAME GAIN
*$LAYER Weather - Data FilesMain
*$POSITION 389 75
*------------------------------------------------------------------------------
```

```
* Model "BUILDING" (Type 65)*
UNIT 20 TYPE 65       BUILDING
*$UNIT_NAME BUILDING
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 709 61
*$LAYER Outputs # Main #
PARAMETERS 12
10          ! 1 Nb. of left-axis variables
10          ! 2 Nb. of right-axis variables
-10         ! 3 Left axis minimum
50          ! 4 Left axis maximum
0.0         ! 5 Right axis minimum
200         ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
61          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 20
331,7                  ! PSY1:Dry bulb temperature ->Left axis variable-1
331,2                  ! PSY1:Wet bulb temperature ->Left axis variable-2
56,1                   ! Building: 1- TAIR_ZONE_A1 ->Left axis variable-3
56,2                   ! Building: 2- RELHUM_ZONE_A1 ->Left axis variable-4
GAINPEOPLE             ! GAIN:GAINPEOPLE ->Right axis variable-1
19,7                   ! Type21:Day of the week ->Right axis variable-2
19,5                   ! Type21:Day of the year ->Right axis variable-3
19,2                   ! Type21:Simulation month ->Right axis variable-4
331,6                  ! PSY1:Percent relative humidity  ->Right axis variable-5
19,6                   ! Type21:Day of the month ->Right axis variable-7
GAINEQUIPMENT          ! GAIN:GAINEQUIPMENT ->Right axis variable-8
GAINLIGHT              ! GAIN:GAINLIGHT ->Right axis variable-9
*** INITIAL INPUT VALUES
AMB_DBT AMB-WBT BUILDING-DBT BUILDING_RH GAIN_PEOPLE
DAY-WEEK DAY-YEAR MONTH-YEAR AMB-RH BUILDING-RH DAY-MONTH GAIN-
EQUIPMENT GAIN-LIGHT
LABELS  3
left
right
"Graph 1"
*** External files
ASSIGN "result\result-building.txt" 61
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------
* EQUATIONS "CHIL/CONT"*
EQUATIONS 1
ONOFFCONTROL = [33,1]*[25,1]
*$UNIT_NAME CHIL/CONT
*$LAYER Main
*$POSITION 129 489
*------------------------------------------------------------------------------
* Model "CO.TOWER" (Type 51)*
UNIT 36 TYPE 51      CO.TOWER
*$UNIT_NAME CO.TOWER
*$MODEL .\HVAC\Cooling Towers\User-Supplied Coefficients\Type51b.tmf
*$POSITION 322 312
*$LAYER Water Loop # Main #
PARAMETERS 11
1               ! 1 Calculation mode
```

```
1               ! 2 Flow geometry
2               ! 3 Number of tower cells
40              ! 4 Maximum cell flow rate
11              ! 5 Fan power at maximum flow
10              ! 6 Minimum cell flow rate
-1              ! 7 Sump volume
28              ! 8 Initial sump temperature
2.3             ! 9 Mass transfer constant
-0.72           ! 10 Mass transfer exponent
1               ! 11 Print performance results?
INPUTS 7
37,1            ! CW-PUMP:Outlet fluid temperature ->Water inlet temperature
37,2            ! CW-PUMP:Outlet flow rate ->Inlet water flow rate
331,7           ! PSY1:Dry bulb temperature ->Dry bulb temperature
331,2           ! PSY1:Wet bulb temperature ->Wet bulb temperature
COLDW_T   ! WAT INLET:COLDW_T ->Sump make-up temperature
*** INITIAL INPUT VALUES
0 0 0 0 0 0.85 0.85
*------------------------------------------------------------------------------
* EQUATIONS "AHU/ON-OFF-1"*
EQUATIONS 1
AHU_CONTROL = [49,1] * [48,1]
*$UNIT_NAME AHU/ON-OFF-1
*$LAYER Main
*$POSITION 852 231
*------------------------------------------------------------------------------
* Model "Building" (Type 56)*
UNIT 56 TYPE 56       Building
*$UNIT_NAME Building
*$MODEL .\Loads and Structures\Multi-Zone Building\With Standard Output Files\Type56a.tmf
*$POSITION 354 176
*$LAYER Main #
*$#
PARAMETERS 6
31                    ! 1 Logical unit for building description file (.bui)
1                     ! 2 Star network calculation switch
0.5                   ! 3 Weighting factor for operative temperature
32                    ! 4 Logical unit for monthly summary
33                    ! 5 Logical unit for hourly temperatures
34                    ! 6 Logical unit for hourly loads
INPUTS 33
331,7                       ! PSY1:Dry bulb temperature -> 1- TAMB
331,6                       ! PSY1:Percent relative humidity  -> 2- RELHUMAMB
69,1                        ! Sky temp:Fictive sky temperature -> 3- TSKY
IT_N                        ! Radiation:IT_N -> 4- IT_NORTH
IT_S                        ! Radiation:IT_S -> 5- IT_SOUTH
IT_E                        ! Radiation:IT_E -> 6- IT_EAST
IT_W                        ! Radiation:IT_W -> 7- IT_WEST
IT_H                        ! Radiation:IT_H -> 8- IT_HORIZONTAL
IB_N                        ! Radiation:IB_N -> 9- IB_NORTH
IB_S                        ! Radiation:IB_S -> 10- IB_SOUTH
IB_E                        ! Radiation:IB_E -> 11- IB_EAST
IB_W                        ! Radiation:IB_W -> 12- IB_WEST
IB_H                        ! Radiation:IB_H -> 13- IB_HORIZONTAL
AI_N                        ! Radiation:AI_N -> 14- AI_NORTH
AI_S                        ! Radiation:AI_S -> 15- AI_SOUTH
AI_E                        ! Radiation:AI_E -> 16- AI_EAST
AI_W                        ! Radiation:AI_W -> 17- AI_WEST
AI_H                        ! Radiation:AI_H -> 18- AI_HORIZONTAL
```

```
GAINLIGHT            ! GAIN:GAINLIGHT -> 25- LIGHT
GAINPEOPLE           ! GAIN:GAINPEOPLE -> 26- PEOPLE
GAINEQUIPMENT        ! GAIN:GAINEQUIPMENT -> 27- EQUIPMENT
46,7                 ! PSY:Dry bulb temperature -> 29- TS_AHU
46,6                 ! PSY:Percent relative humidity  -> 30- RHS_AHU
45,7                 ! PSY-4:Dry bulb temperature -> 31- TS_FCU
45,6                 ! PSY-4:Percent relative humidity  -> 32- RHS_FCU
AHU_CONTROL          ! AHU/ON-OFF-1:AHU_CONTROL -> 33- ON_OFF
*** INITIAL INPUT VALUES
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
*** External files
ASSIGN "BuildingProject024.bui" 31
*|? Building description file (*.bui) |1000
ASSIGN "T56_std-Output.sum" 32
*|? Monthly Summary File |1000
ASSIGN "T56_std-temp.prn" 33
*|? Hourly Temperatures |1000
ASSIGN "T56_std-q.prn" 34
*|? Hourly Loads |1000
*------------------------------------------------------------------------------
* EQUATIONS "TOWER"*
EQUATIONS 1
COL_TOWER_POWER = [36,3]*ONOFFCONTROL     !kW
*$UNIT_NAME TOWER
*$LAYER Main
*$POSITION 230 387
*------------------------------------------------------------------------------
* Model "Chiller" (Type 107)*
UNIT 27 TYPE 107      Chiller
*$UNIT_NAME Chiller
*$MODEL .\HVAC\Absorption Chiller (Hot-Water Fired, Single Effect)\Type107.tmf
*$POSITION 423 401
*$LAYER Main # # Main #
PARAMETERS 11
4557859.581696         ! 1 Rated capacity
3          ! 2 Rated C.O.P.
66         ! 3 Logical unit for S1 data file
5          ! 4 Number of HW temperatures in S1 data file
3          ! 5 Number of CW steps in S1 data file
7          ! 6 Number of CHW set points in S1 data file
11         ! 7 Number of load fractions in S1 data file
4.190      ! 8 HW fluid specific heat
4.190      ! 9 CHW fluid specific heat
4.190      ! 10 CW fluid specific heat
35999.997336                ! 11 Auxiliary electrical power
INPUTS 8
44,2                        ! CHWR:Outlet flow rate ->Chilled water flow rate
36,1                        ! CO.TOWER:Sump temperature ->Cooling water inlet temperature
ONOFFCONTROL                ! CHIL/CONT:ONOFFCONTROL ->Chiller control signal
*** INITIAL INPUT VALUES
12.2 0 0 1000 142.0 58000.0 6.667 1.0
*** External files
ASSIGN "inputs\HotwaterAdsorbtionchiller.txt" 66
*|? File with fraction of design energy input data |1000
*------------------------------------------------------------------------------
* Model "CW-PUMP" (Type 114)*
UNIT 37 TYPE 114      CW-PUMP
*$UNIT_NAME CW-PUMP
*$MODEL .\Hydronics\Pumps\Single Speed\Type114.tmf
```

```
*$POSITION 322 401
*$LAYER Water Loop # Main #
*$# SINGLE-SPEED PUMP
PARAMETERS 4
100                 ! 1 Rated flow rate
4.19                ! 2 Fluid specific heat
17999.998668        ! 3 Rated power
0.0                 ! 4 Motor heat loss fraction
INPUTS 5
27,3                ! Chiller:Cooling water temperature ->Inlet fluid temperature
27,4                ! Chiller:Cooling water flow rate ->Inlet fluid flow rate
ONOFFCONTROL        ! CHIL/CONT:ONOFFCONTROL ->Control signal
*** INITIAL INPUT VALUES
0 0 1.0 0.9 0.9
*------------------------------------------------------------------------------
* Model "TEST-FLUID" (Type 65)*
UNIT 47 TYPE 65       TEST-FLUID
*$UNIT_NAME TEST-FLUID
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 77 718
*$LAYER Controls #
PARAMETERS 12
10          ! 1 Nb. of left-axis variables
10          ! 2 Nb. of right-axis variables
-10         ! 3 Left axis minimum
40          ! 4 Left axis maximum
-10         ! 5 Right axis minimum
100         ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
67          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 20
27,1        ! Chiller:Chilled water temperature ->Left axis variable-1
41,1        ! CHW-PUMP:Outlet fluid temperature ->Left axis variable-2
34,1        ! FCU:Outlet dry bulb temperature ->Left axis variable-3
43,1        ! AHU:Outlet dry bulb temperature ->Left axis variable-4
34,4        ! FCU:Outlet water temperature ->Left axis variable-5
43,4        ! AHU:Outlet water temperature ->Left axis variable-6
44,1        ! CHWR:Outlet temperature ->Left axis variable-7
27,3        ! Chiller:Cooling water temperature ->Left axis variable-8
36,1        ! CO.TOWER:Sump temperature ->Left axis variable-9
58,3        ! CHWS:Temperature at outlet 2 ->Left axis variable-10
27,2        ! Chiller:Chilled water flow rate ->Right axis variable-1
41,2        ! CHW-PUMP:Outlet flow rate ->Right axis variable-2
34,5        ! FCU:Water flow rate ->Right axis variable-3
43,5        ! AHU:Water flow rate ->Right axis variable-4
44,2        ! CHWR:Outlet flow rate ->Right axis variable-5
27,4        ! Chiller:Cooling water flow rate ->Right axis variable-6
36,2        ! CO.TOWER:Sump flow rate ->Right axis variable-7
58,4        ! CHWS:Flow rate at outlet 2 ->Right axis variable-8
58,2        ! CHWS:Flow rate at outlet 1 ->Right axis variable-9
*** INITIAL INPUT VALUES
CHWS-T CHWS-T-PUMP FCU-DBT AHU-DBT CHWR-T-FCU CHWR-T-AHU CHWR-T CWR-T
CWS-T CHWS-T-AHU CHWS-Q CHWS-Q-PUMP CHWR-Q-FCU CHWR-Q-AHU CHWR-Q CWR-Q
CWS-Q CHWS-Q-AHU CHWS-Q-FCU
LABELS  3
```

```
left
ight
"TEST"
*** External files
ASSIGN "result\TEST.TXT" 67
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------
* Model "CHW-PUMP" (Type 114)*
UNIT 41 TYPE 114     CHW-PUMP
*$UNIT_NAME CHW-PUMP
*$MODEL .\Hydronics\Pumps\Single Speed\Type114.tmf
*$POSITION 421 537
*$LAYER Main #
*$# SINGLE-SPEED PUMP
PARAMETERS 4
100.0              ! 1 Rated flow rate
4.19               ! 2 Fluid specific heat
17999.998668       ! 3 Rated power
0                  ! 4 Motor heat loss fraction
INPUTS 5
27,1               ! Chiller:Chilled water temperature ->Inlet fluid temperature
27,2               ! Chiller:Chilled water flow rate ->Inlet fluid flow rate
AHU_CONTROL ! AHU/ON-OFF-1:AHU_CONTROL ->Control signal
*** INITIAL INPUT VALUES
0 0 1.0 0.9 0.9
*------------------------------------------------------------------------------
* Model "PSY-2" (Type 33)*
UNIT 42 TYPE 33      PSY-2
*$UNIT_NAME PSY-2
*$MODEL .\Physical Phenomena\Thermodynamic Properties\Psychrometrics\Dry Bulb and Relative Humidity Known\Type33e.tmf
*$POSITION 468 204
*$LAYER Main #
PARAMETERS 3
2                  ! 1 Psychrometrics mode
1                  ! 2 Wet bulb mode
1                  ! 3 Error mode
INPUTS 3
56,1               ! Building: 1- TAIR_ZONE_A1 ->Dry bulb temp.
56,2               ! Building: 2- RELHUM_ZONE_A1 ->Percent relative humidity
*** INITIAL INPUT VALUES
0 0 1
*------------------------------------------------------------------------------
* EQUATIONS "COOLING LOAD"*
EQUATIONS 9
COOLING_LOAD = ([56,3]+[56,4]+[56,5]+[56,6]+[56,7]+[56,8])/1000
INTER_CONV = [56,4]/1000
LATENT_VENT_INFIL = [56,5]/1000
SOLAR_RADIATION = [56,6]/1000
TOTAL_RAD_INSIDE = [56,7]/1000
SURFACE_CONVECTIVE = [56,8]/1000
SENSIB_INFILTRATION = [56,3]/1000
SENS_ENERGY = [56,9]
SENS_COOLING = [56,10]
*$UNIT_NAME COOLING LOAD
*$LAYER ControlsMain
*$POSITION 753 132
*------------------------------------------------------------------------------
```

```
* EQUATIONS "POWER-2"*
EQUATIONS 10
CHW_PUMP_KW = [41,3] / 3600  !kj/h  --> kW
CW_PUMP_KW = [37,3] / 3600       !kj/h --> kW
COOLINGTOWER_KW = COL_TOWER_POWER   !kW
CHILLER_KW = [27,11] * 2 * 211  !FRACTION * NOCHILLER * MAXCAPACITY  kW
FCU_KW = 38 *AHU_CONTROL  !kW
AHU_KW = 160.5 * AHU_CONTROL  !kW
LIGHT_KW = LIGHT_POWER  !kW
EQIPMENT_KW = EQIPMENT_POWER  !kW
SUM_BUILDING = EQIPMENT_POWER + LIGHT_POWER   !+ AHU + FCU
SUM_CHILLER = CHILLER_KW + COOLINGTOWER_KW + CHW_PUMP_KW + CW_PUMP_KW
*$UNIT_NAME POWER-2
*$LAYER Weather - Data FilesMain
*$POSITION 322 537
*------------------------------------------------------------------------------
* Model "FCU" (Type 32)*
UNIT 34 TYPE 32       FCU
*$UNIT_NAME FCU
*$MODEL .\HVAC\Cooling Coils\Simplified\Type32.tmf
*$POSITION 760 433
*$LAYER Main #
PARAMETERS 4
7                  ! 1 Number of rows
4                  ! 2 Number of coil circuits
1.0                ! 3 Coil face area
0.02               ! 4 Inside tube diameter
INPUTS 5
42,7               ! PSY-2:Dry bulb temperature ->Inlet dry-bulb temperature
42,2               ! PSY-2:Wet bulb temperature ->Inlet wet bulb temperature
FCU_KGHR           ! CFM to kG/h:FCU_KGHR ->Flow rate of air
58,1               ! CHWS:Temperature at outlet 1 ->Inlet water temperature
58,2               ! CHWS:Flow rate at outlet 1 ->Flow rate of water
*** INITIAL INPUT VALUES
0 0 0 6.6 0
*------------------------------------------------------------------------------
* Model "AHU" (Type 32)*
UNIT 43 TYPE 32       AHU
*$UNIT_NAME AHU
*$MODEL .\HVAC\Cooling Coils\Simplified\Type32.tmf
*$POSITION 602 437
*$LAYER Main #
PARAMETERS 4
7            ! 1 Number of rows
4            ! 2 Number of coil circuits
1.0          ! 3 Coil face area
0.02         ! 4 Inside tube diameter
INPUTS 5
57,7         ! PSY-3:Dry bulb temperature ->Inlet dry-bulb temperature
57,2         ! PSY-3:Wet bulb temperature ->Inlet wet bulb temperature
54,3         ! Air-mixer:Outlet flow rate ->Flow rate of air
58,3         ! CHWS:Temperature at outlet 2 ->Inlet water temperature
58,4         ! CHWS:Flow rate at outlet 2 ->Flow rate of water
*** INITIAL INPUT VALUES
0 0 0 6.6 0
*------------------------------------------------------------------------------
* Model "BUILDING-2" (Type 65)*
UNIT 52 TYPE 65       BUILDING-2
```

```
*$UNIT_NAME BUILDING-2
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 870 132
*$LAYER Main # # Main #
PARAMETERS 12
10          ! 1 Nb. of left-axis variables
10          ! 2 Nb. of right-axis variables
-500        ! 3 Left axis minimum
2000        ! 4 Left axis maximum
0.0         ! 5 Right axis minimum
200         ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
68          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 20
SENSIB_INFILTRATION      ! COOLING LOAD:SENSIB_INFILTRATION ->Left axis variable-1
INTER_CONV               ! COOLING LOAD:INTER_CONV ->Left axis variable-2
LATENT_VENT_INFIL        ! COOLING LOAD:LATENT_VENT_INFIL ->Left axis variable-3
SOLAR_RADIATION          ! COOLING LOAD:SOLAR_RADIATION ->Left axis variable-4
TOTAL_RAD_INSIDE         ! COOLING LOAD:TOTAL_RAD_INSIDE ->Left axis variable-5
SURFACE_CONVECTIVE       ! COOLING LOAD:SURFACE_CONVECTIVE ->Left axis variable-6
COOLING_LOAD             ! COOLING LOAD:COOLING_LOAD ->Left axis variable-7
SENS_ENERGY              ! COOLING LOAD:SENS_ENERGY ->Left axis variable-8
SENS_COOLING             ! COOLING LOAD:SENS_COOLING ->Left axis variable-9
*** INITIAL INPUT VALUES
SENS_INFLIT INTER_CONV LAT_VENT_INF SOLAR-RAD TOTAL_RAD_INS SURFAC_CONV
COOLINGLOAD SENS_ENERGY SENS-COOLING

LABELS  3
left
right
"cooling load"
*** External files
ASSIGN "result\COLING LOAD.txt" 68
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------
* Model "POWER" (Type 65)*
UNIT 38 TYPE 65       POWER
*$UNIT_NAME POWER
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 132 557
*$LAYER Main #
PARAMETERS 12
10          ! 1 Nb. of left-axis variables
10          ! 2 Nb. of right-axis variables
-10         ! 3 Left axis minimum
600         ! 4 Left axis maximum
-10         ! 5 Right axis minimum
600         ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
65          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 20
```

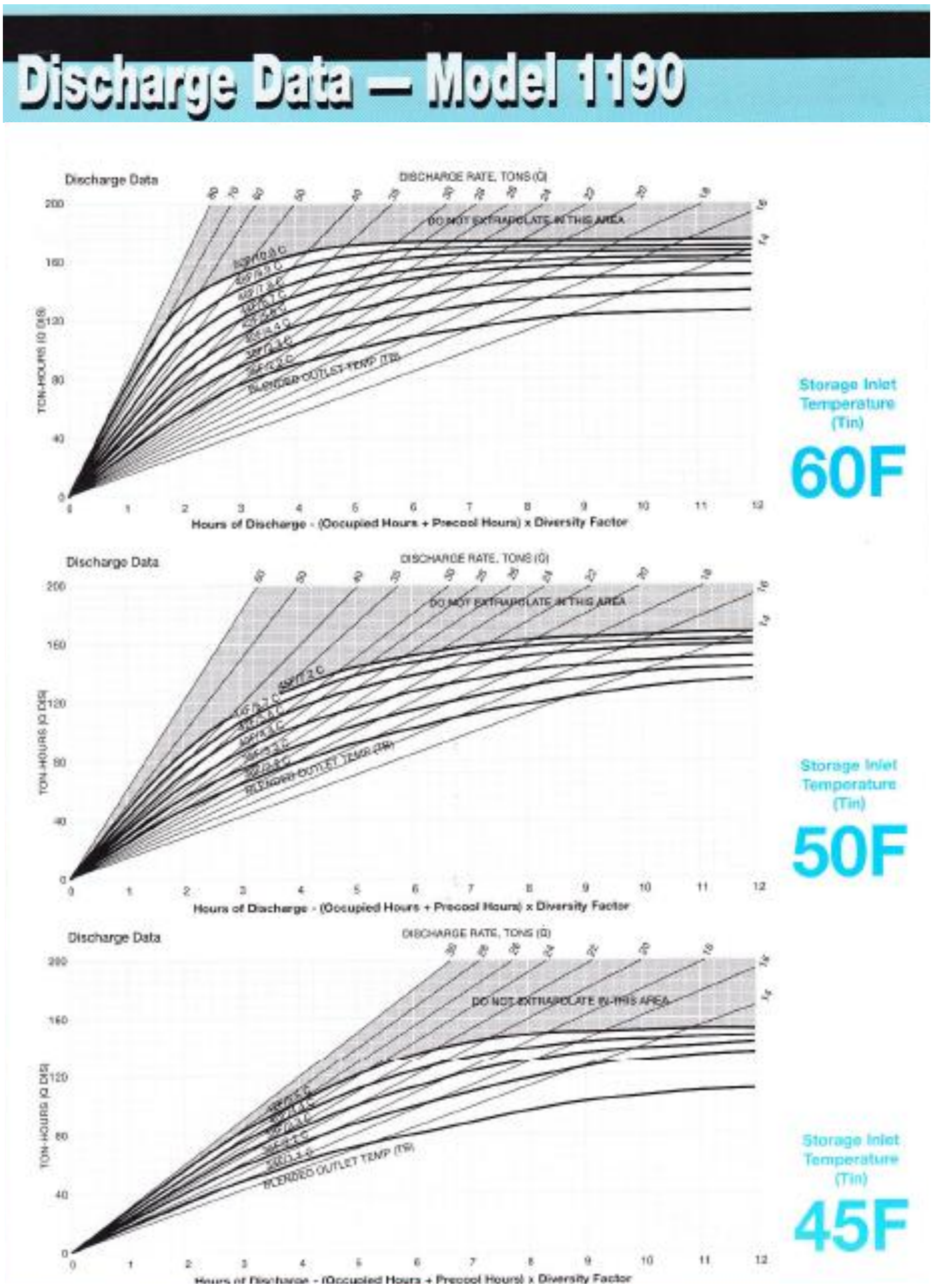
```
AHU_KW                  ! POWER-2:AHU_KW ->Left axis variable-2
FCU_KW                  ! POWER-2:FCU_KW ->Left axis variable-3
COOLINGTOWER_KW         ! POWER-2:COOLINGTOWER_KW ->Left axis variable-4
CHILLER_KW              ! POWER-2:CHILLER_KW ->Left axis variable-5
CW_PUMP_KW              ! POWER-2:CW_PUMP_KW ->Left axis variable-6
CHW_PUMP_KW             ! POWER-2:CHW_PUMP_KW ->Left axis variable-7
LIGHT_KW                ! POWER-2:LIGHT_KW ->Left axis variable-8
EQIPMENT_KW             ! POWER-2:EQIPMENT_KW ->Left axis variable-9
SUM_BUILDING            ! POWER-2:SUM_BUILDING ->Right axis variable-1
SUM_CHILLER             ! POWER-2:SUM_CHILLER ->Right axis variable-2
*** INITIAL INPUT VALUES
AHU-KW FCU-KW COO-TOWER-KW CHILLER-KW CW-PUMP-KW CHW-PUMP-KW
LIGHTING-KW
EQUIPMENT-KW SUM-BUILDING SUM-CHILLER
LABELS  3
left
right
"POWER"
*** External files
ASSIGN "result\KWH" 65
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------
* Model "PSY-4" (Type 33)*
UNIT 45 TYPE 33     PSY-4
*$UNIT_NAME PSY-4
*$MODEL .\Physical Phenomena\Thermodynamic Properties\Psychrometrics\Dry Bulb and Wet Bulb
Known\Type33f.tmf
*$POSITION 756 331
*$LAYER Air Loop # Main #
PARAMETERS 3
1       ! 1 Psychrometrics mode
1       ! 2 Wet bulb mode
2       ! 3 Error mode
INPUTS 3
34,1    ! FCU:Outlet dry bulb temperature ->Dry bulb temp.
34,2    ! FCU:Outlet wet bulb temperature ->Wet bulb temp.
*** INITIAL INPUT VALUES
0 0 1
*------------------------------------------------------------------------------
* Model "CHWR" (Type 11)*
UNIT 44 TYPE 11     CHWR
*$UNIT_NAME CHWR
*$MODEL .\Hydronics\Tee-Piece\Other Fluids\Type11h.tmf
*$POSITION 674 494
*$LAYER Main #
*$# type 11h
*$#
PARAMETERS 1
1       ! 1 Tee piece mode
INPUTS 4
34,4        ! FCU:Outlet water temperature ->Temperature at inlet 1
34,5        ! FCU:Water flow rate ->Flow rate at inlet 1
43,4        ! AHU:Outlet water temperature ->Temperature at inlet 2
43,5        ! AHU:Water flow rate ->Flow rate at inlet 2
*** INITIAL INPUT VALUES
0 0 0 0
*------------------------------------------------------------------------------
* Model "PSY" (Type 33)*
UNIT 46 TYPE 33     PSY
```

```
*$UNIT_NAME PSY
*$MODEL .\Physical Phenomena\Thermodynamic Properties\Psychrometrics\Dry Bulb and Wet Bulb Known\Type33f.tmf
*$POSITION 519 353
*$LAYER Main #
PARAMETERS 3
1        ! 1 Psychrometrics mode
1        ! 2 Wet bulb mode
2        ! 3 Error mode
INPUTS 3
43,1         ! AHU:Outlet dry bulb temperature ->Dry bulb temp.
43,2         ! AHU:Outlet wet bulb temperature ->Wet bulb temp.
*** INITIAL INPUT VALUES
0 0 1
*------------------------------------------------------------------------------
* Model "Air-mixer" (Type 11)*
UNIT 54 TYPE 11     Air-mixer
*$UNIT_NAME Air-mixer
*$MODEL .\Hydronics\Flow Mixer\Moist Air\Type11c.tmf
*$POSITION 586 250
*$LAYER Main #
*$# type 11c
*$#
*$# 1) fresh air
*$# 2) zone T
PARAMETERS 1
8        ! 1 Controlled flow mixer mode
INPUTS 7
331,7            ! PSY1:Dry bulb temperature ->Temperature at inlet 1
331,6            ! PSY1:Percent relative humidity  ->Humidity ratio at inlet 1
CFM_FRESH        ! CFM to kG/h:CFM_FRESH ->Flow rate at inlet 1
42,7             ! PSY-2:Dry bulb temperature ->Temperature at inlet 2
42,6             ! PSY-2:Percent relative humidity  ->Humidity ratio at inlet 2
AHU_KGHR         ! CFM to kG/h:AHU_KGHR ->Flow rate at inlet 2
*** INITIAL INPUT VALUES
0 0 0 0 0 0 1
*------------------------------------------------------------------------------
* Model "TEST-AIR" (Type 65)*
UNIT 55 TYPE 65     TEST-AIR
*$UNIT_NAME TEST-AIR
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 859 729
*$LAYER Controls #
PARAMETERS 12
10       ! 1 Nb. of left-axis variables
10       ! 2 Nb. of right-axis variables
-10      ! 3 Left axis minimum
35       ! 4 Left axis maximum
-10      ! 5 Right axis minimum
100      ! 6 Right axis maximum
1        ! 7 Number of plots per simulation
12       ! 8 X-axis gridpoints
0        ! 9 Shut off Online w/o removing
69       ! 10 Logical Unit for output file
0        ! 11 Output file units
0        ! 12 Output file delimiter
INPUTS 20
331,7        ! PSY1:Dry bulb temperature ->Left axis variable-1
331,2        ! PSY1:Wet bulb temperature ->Left axis variable-2
```

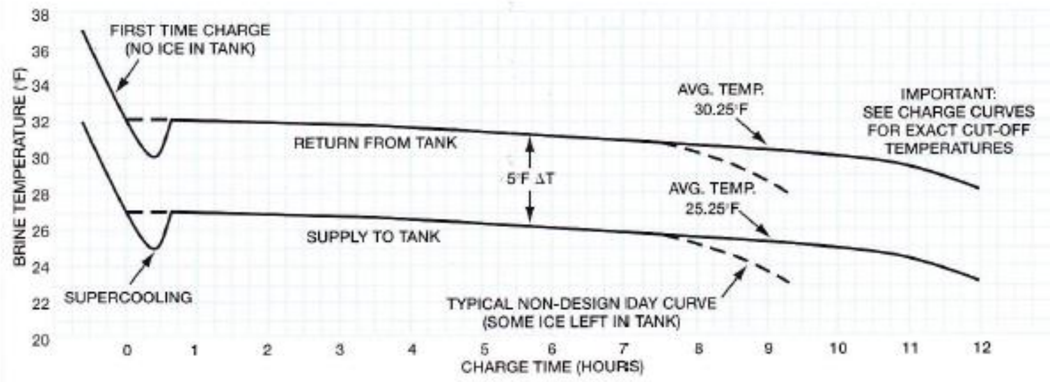
```
42,7		! PSY-2:Dry bulb temperature ->Left axis variable-3
42,2		! PSY-2:Wet bulb temperature ->Left axis variable-4
57,7		! PSY-3:Dry bulb temperature ->Left axis variable-5
57,2		! PSY-3:Wet bulb temperature ->Left axis variable-6
45,7		! PSY-4:Dry bulb temperature ->Left axis variable-7
45,2		! PSY-4:Wet bulb temperature ->Left axis variable-8
46,7		! PSY:Dry bulb temperature ->Left axis variable-9
46,2		! PSY:Wet bulb temperature ->Left axis variable-10
331,6		! PSY1:Percent relative humidity  ->Right axis variable-1
42,6		! PSY-2:Percent relative humidity  ->Right axis variable-2
57,6		! PSY-3:Percent relative humidity  ->Right axis variable-3
45,6		! PSY-4:Percent relative humidity  ->Right axis variable-4
46,6		! PSY:Percent relative humidity  ->Right axis variable-5
AHU_KGHR		! CFM to kG/h:AHU_KGHR ->Right axis variable-6
FCU_KGHR		! CFM to kG/h:FCU_KGHR ->Right axis variable-7
FRESH_KGHR		! CFM to kG/h:FRESH_KGHR ->Right axis variable-8
54,3			! Air-mixer:Outlet flow rate ->Right axis variable-9
AHU_CONTROL		! AHU/ON-OFF-1:AHU_CONTROL ->Right axis variable-10
*** INITIAL INPUT VALUES
AMB-DBT AMB-WBT ZON-DBT ZON-WBT MIXAIR-DBT MIXAIR-WBT FCU-DBT FCU-WBD
AHU-DBT AHU-WBT AMB-RH ZON-RH MIX-RH FCU-RH AHU-RH AHU_KGHR FCU_KGHR
FRESH_KGHR MIX_KGHR FCU-CONTROL
LABELS  3
left
Right
"TEST-AIR"
*** External files
ASSIGN "result\TEST-AIR.txt" 69
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------
* Model "PSY-3" (Type 33)*
UNIT 57 TYPE 33	 PSY-3
*$UNIT_NAME PSY-3
*$MODEL .\Physical Phenomena\Thermodynamic Properties\Psychrometrics\Dry Bulb and Relative
Humidity Known\Type33e.tmf
*$POSITION 589 339
*$LAYER Main #
PARAMETERS 3
2		! 1 Psychrometrics mode
1		! 2 Wet bulb mode
1		! 3 Error mode
INPUTS 3
54,1		! Air-mixer:Outlet temperature ->Dry bulb temp.
54,2		! Air-mixer:Outlet humidity ratio ->Percent relative humidity
*** INITIAL INPUT VALUES
0 0 1
*------------------------------------------------------------------------------
* Model "CHWS" (Type 11)*
UNIT 58 TYPE 11	 CHWS
*$UNIT_NAME CHWS
*$MODEL .\Hydronics\Flow Diverter\Other Fluids\Type11f.tmf
*$POSITION 570 537
*$LAYER Main #
*$# type 11f
PARAMETERS 1
2		! 1 Controlled flow diverter mode
INPUTS 3
41,1		! CHW-PUMP:Outlet fluid temperature ->Inlet temperature
41,2		! CHW-PUMP:Outlet flow rate ->Inlet flow rate
```

```
*** INITIAL INPUT VALUES
0 0 1
*------------------------------------------------------------------------------
* EQUATIONS "CFM to kG/h"*
EQUATIONS 6
CFM_AHU = 2000  !217060   !CFM AHU
CFM_FCU = 10000     !15371 !CFM FCU
CFM_FRESH = 0.1 * CFM_AHU                        !10% IS FRESH AIR
AHU_KGHR = CFM_AHU * 1.6992 * [42,4]             !KG/HR AHU
FCU_KGHR = CFM_FCU * 1.6992 * [42,4]             !KG/HR FCU
FRESH_KGHR = CFM_FRESH * 1.6992 * [42,4]         !KG/HR FRESH
*$UNIT_NAME CFM to kG/h
*$LAYER OutputsMain
*$POSITION 696 250
*------------------------------------------------------------------------------
END
```

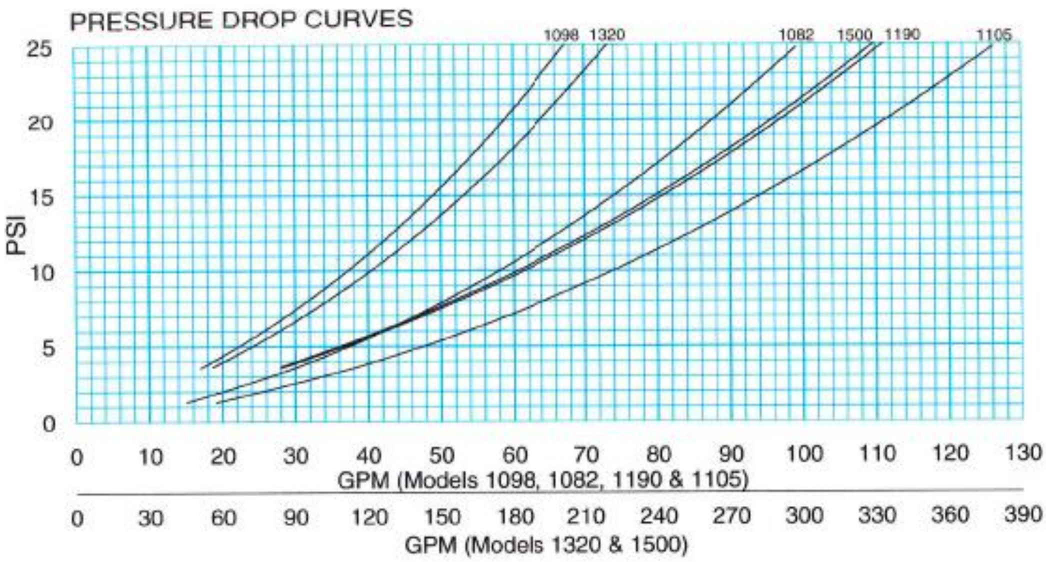
Appendix F : Calmac performance curves



Typical Charge Characteristics



Pressure Drop Curves



Appendix G : Ice bank storage tank characteristics

Regression of effectiveness curves

$\varepsilon = C_0+C_1+C_2+C_3+C_4+C_5+C_6+C_7+C_8+C_9+C_{10}+C_{11}+C_{12}+C_{13}+C_{14}+C_{15}$

$$B = \frac{\text{Tank Capacity}}{\text{Maximum Capacity}}$$

q = Flow Rate through Ice-Storage Tank (GPM)

For Discharging:

If B< 0.66 then:	**If B ≥ 0.66 then:**
$C_0 = 0.84119769$	$C_0 = 25.62156701$
$C_1 = 0.200276759 \times B$	$C_1 = - 110.463303 \times B$
$C_2 = 1.636547199 \times B^2$	$C_2 = 176.6331532 \times B^2$
$C_3 = - 5.204433828 \times B^3$	$C_3 = - 114.555632 \times B^3$
$C_4 = 4.196217689 \times B^4$	$C_4 = 22.86186786 \times B^4$
$C_5 = 0.015118414 \times q$	$C_5 = - 0.01026212 \times q$
$C_6 = - 0.000390064 \times q^2$	$C_6 = - 0.0004725 \times q^2$
$C_7 = 3.64763\times10^{-6} \times q^3$	$C_7 = 5.03616\times10^{-7} \times q^3$
$C_8 = - 1.24338\times10^{-8} \times q^4$	$C_8 = - 2.1181\times10^{-9} \times q^4$
$C_9 = - 0.053871746 \times B \times q$	$C_9 = 0.105010295 \times B \times q$
$C_{10} = 0.064822502 \times B^2\times q$	$C_{10} = - 0.27724386 \times B^2 \times q$
$C_{11} = 0.000354565 \times B \times q^2$	$C_{11} = 0.001260003 \times B \times q^2$
$C_{12} = - 0.034354947 \times B^3 \times q$	$C_{12} = 0.179974285 \times B^3 \times q$
$C_{13} = - 0.000142311 \times B^2 \times q^2$	$C_{13} = - 0.00078403 \times B^2 \times q^2$
$C_{14} = -9.15865\times10^{-7} \times B \times q^3$	$C_{14} = - 1.8073\times10^{-7} \times B \times q^3$
$C_{15} = 0.0$	$C_{15} = 0.0$

For Charging:	
If B 0≤ .755 then:	If B> 0.755 then:
$C_0 = 1.077255269$	$C_0 = 1.511144226$
$C_1 = -\ 0.079156996 \times B$	$C_1 = 0.22757868 \times \log_{10}(-B+1.0)$
$C_2 = -\ 0.0046742 \times q$	$C_2 = -\ 0.009864783 \times q$
$C_3 = 0.0$	$C_3 = 3.83656{\times}10^{-5} \times q^2$
$C_4 = 0.0$	$C_4 = -\ 0.281804303 \times B$
$C_5 = 0.0$	$C_5 = 0.0$
$C_6 = 0.0$	$C_6 = 0.0$
$C_7 = 0.0$	$C_7 = 0.0$
$C_8 = 0.0$	$C_8 = 0.0$
$C_9 = 0.0$	$C_9 = 0.0$
$C_{10} = 0.0$	$C_{10} = 0.0$
$C_{11} = 0.0$	$C_{11} = 0.0$
$C_{12} = 0.0$	$C_{12} = 0.0$
$C_{13} = 0.0$	$C_{13} = 0.0$
$C_{14} = 0.0$	$C_{14} = 0.0$
$C_{15} = 0.0$	$C_{15} = 0.0$

Appendix H : Fortran code (Type 221)

Subroutines for Calmac ice storage tank model

This section contains only the source codes for Types 221 (Storage tank). The complete set of types can be found on the disk accompanying this thesis.

```
      SUBROUTINE TYPE221 (TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C***********************************************************************
C Object: CALMAC ICE BANK
C Simulation Studio Model: TPYE221
C
C Author: BEHZAD RISMANCHI
C Editor: BEHZAD RISMANCHI
C Date:    September 13, 2012 last modified: September 13, 2012
C
C ***
C *** Model Parameters
C ***
C       T_STORAGE          C         [-Inf;+Inf]
C       T_CHARGING         C         [-Inf;+Inf]
C       T_DISCHARGING      C         [-Inf;+Inf]
C       TANK_MAX_C         kWh       [-Inf;+Inf]
C       CP_CHW             kJ/kg.K   [-Inf;+Inf]
C       CP_BRINE           kJ/kg.K   [-Inf;+Inf]
C       CP_ICE             kJ/kg.K   [-Inf;+Inf]
C       TANK_SIZE          -         [-Inf;+Inf]
C       CHE_DENSITIY       kg/m^3    [-Inf;+Inf]
C       BRINE_DENSITY      kg/m^3    [-Inf;+Inf]
C       LATENTHEAT_CHW     kJ/kg     [-Inf;+Inf]
C ***
C *** Model Inputs
C ***
C       T_CHWS_CH          C         [-Inf;+Inf]
C       Q_CHWS_CH          kg/hr     [-Inf;+Inf]
C       T_CHWR_LOAD        C         [-Inf;+Inf]
C       Q_CHWR_LOAD        kg/hr     [-Inf;+Inf]
C       CHECK              -         [-Inf;+Inf]
C       CHILLER_CAPACITY   kWh       [-Inf;+Inf]
C ***
C *** Model Outputs
C ***
C       T_CHWS_TANK        C         [-Inf;+Inf]
C       Q_CHWS_TANK        kg/hr     [-Inf;+Inf]
C       T_CHWR_TANK        C         [-Inf;+Inf]
C       Q_CHWR_TANK        kg/hr     [-Inf;+Inf]
C       MODE               -         [-Inf;+Inf]
C       TANK_CAPACITY      kWh       [-Inf;+Inf]
```

```
C               E                              -          [-Inf;+Inf]
C               B                              -          [-Inf;+Inf]
C ***
C *** Model Derivatives
C ***
C (Comments and routine interface generated by TRNSYS Studio)
C************************************************************************

C   TRNSYS acess functions (allow to acess TIME etc.)
    USE TrnsysConstants
    USE TrnsysFunctions

C-----------------------------------------------------------------------------------------------------------------------
C   REQUIRED BY THE MULTI-DLL VERSION OF TRNSYS
    !DEC$ATTRIBUTES DLLEXPORT :: TYPE221                   !SET THE CORRECT TYPE
                                                            NUMBER HERE
C-----------------------------------------------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------------------------------------------
C   TRNSYS DECLARATIONS
    IMPLICIT NONE                      !REQUIRES THE USER TO DEFINE ALL VARIABLES
                                       BEFORE USING THEM
     DOUBLE PRECISION XIN              !THE ARRAY FROM WHICH THE INPUTS TO THIS
                                       TYPE WILL BE RETRIEVED
     DOUBLE PRECISION OUT              !THE ARRAY WHICH WILL BE USED TO STORE
                                       THE OUTPUTS FROM THIS TYPE
     DOUBLE PRECISION TIME             !THE CURRENT SIMULATION TIME - YOU MAY
                                       USE THIS VARIABLE BUT DO NOT SET IT!
     DOUBLE PRECISION PAR              !THE ARRAY FROM WHICH THE PARAMETERS
                                       FOR THIS TYPE WILL BE RETRIEVED
     DOUBLE PRECISION STORED           !THE STORAGE ARRAY FOR HOLDING VARIABLES
                                       FROM TIMESTEP TO TIMESTEP
     DOUBLE PRECISION T                !AN ARRAY CONTAINING THE RESULTS FROM
                                       THE DIFFERENTIAL EQUATION SOLVER
     DOUBLE PRECISION DTDT             !AN ARRAY CONTAINING THE DERIVATIVES TO
                                       BE PASSED TO THE DIFF.EQ. SOLVER
     INTEGER*4 INFO(15)                !THE INFO ARRAY STORES AND PASSES
                                       VALUABLE INFORMATION TO AND FROM THIS
                                       TYPE
     INTEGER*4 NP,NI,NOUT,ND           !VARIABLES FOR THE MAXIMUM NUMBER OF
                                       PARAMETERS,INPUTS,OUTPUTSAND DERIVATIVES
     INTEGER*4 NPAR,NIN,NDER           !VARIABLES FOR THE CORRECT NUMBER OF
                                       PARAMETERS,INPUTS,OUTPUTS AND DERIVATIVES
     INTEGER*4 IUNIT,ITYPE             !THE UNIT NUMBER AND TYPE NUMBER FOR THIS
                                       COMPONENT
     INTEGER*4 ICNTRL                  !AN ARRAY FOR HOLDING VALUES OF CONTROL
                                       FUNCTIONS WITH THE NEW SOLVER
     INTEGER*4 NSTORED                 !THE NUMBER OF VARIABLES THAT WILL BE PASSED
                                       INTO AND OUT OF STORAGE
     CHARACTER*3 OCHECK                !AN ARRAY TO BE FILLED WITH THE CORRECT
                                       VARIABLE TYPES FOR THE OUTPUTS
     CHARACTER*3 YCHECK                !AN ARRAY TO BE FILLED WITH THE CORRECT
                                       VARIABLE TYPES FOR THE INPUTS
C-----------------------------------------------------------------------------------------------------------------------

C-----------------------------------------------------------------------------------------------------------------------
C    USER DECLARATIONS - SET THE MAXIMUM NUMBER OF PARAMETERS (NP), INPUTS
C    (NI),
C    OUTPUTS (NOUT), AND DERIVATIVES (ND) THAT MAY BE SUPPLIED FOR THIS TYPE
C    PARAMETER (NP=11,NI=6,NOUT=8,ND=0,NSTORED=0)
```

```
C------------------------------------------------------------------------------------------------------------------

C------------------------------------------------------------------------------------------------------------------
C    REQUIRED TRNSYS DIMENSIONS
      DIMENSION XIN(NI),OUT(NOUT),PAR(NP),YCHECK(NI),OCHECK(NOUT),
       1   STORED(NSTORED),T(ND),DTDT(ND)
      INTEGER NITEMS
C------------------------------------------------------------------------------------------------------------------
C------------------------------------------------------------------------------------------------------------------
C    ADD DECLARATIONS AND DEFINITIONS FOR THE USER-VARIABLES HERE

C    PARAMETERS
      DOUBLE PRECISION       T_STORAGE
      DOUBLE PRECISION       T_CHARGING
      DOUBLE PRECISION       T_DISCHARGING
      DOUBLE PRECISION       TANK_MAX_C
      DOUBLE PRECISION       CP_CHW
      DOUBLE PRECISION       CP_BRINE
      DOUBLE PRECISION       CP_ICE
      DOUBLE PRECISION       TANK_SIZE
      DOUBLE PRECISION       CHE_DENSITIY
      DOUBLE PRECISION       BRINE_DENSITY
      DOUBLE PRECISION       LATENTHEAT_CHW

C    INPUTS
      DOUBLE PRECISION       T_CHWS_CH
      DOUBLE PRECISION       Q_CHWS_CH
      DOUBLE PRECISION       T_CHWR_LOAD
      DOUBLE PRECISION       Q_CHWR_LOAD
      DOUBLE PRECISION       CHECK
      DOUBLE PRECISION       CHILLER_CAPACITY

C     OUTPUT
       DOUBLE PRECISION      T_CHWS_TANK
       DOUBLE PRECISION      Q_CHWS_TANK
       DOUBLE PRECISION      T_CHWR_TANK
       DOUBLE PRECISION      Q_CHWR_TANK
       DOUBLE PRECISION      MODE
       DOUBLE PRECISION      TANK_CAPACITY
       DOUBLE PRECISION      E1, E
       DOUBLE PRECISION      B

C     PARAMETERS
       DOUBLE PRECISION      C0,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15
       DOUBLE PRECISION      STORE
       DOUBLE PRECISION      Q_I
       DOUBLE PRECISION      Q

C------------------------------------------------------------------------------------------------------------------
C       READ IN THE VALUES OF THE PARAMETERS IN SEQUENTIAL ORDER
      T_STORAGE             =PAR(1)
      T_CHARGING            =PAR(2)
      T_DISCHARGING         =PAR(3)
      TANK_MAX_C            =PAR(4)
      CP_CHW                =PAR(5)
      CP_BRINE              =PAR(6)
      CP_ICE                =PAR(7)
      TANK_SIZE             =PAR(8)
      CHE_DENSITIY          =PAR(9)
```

```
      BRINE_DENSITY       =PAR(10)
      LATENTHEAT_CHW =PAR(11)

C-----------------------------------------------------------------------------------------------------------------------
C    RETRIEVE THE CURRENT VALUES OF THE INPUTS TO THIS MODEL FROM THE XIN
C    ARRAY IN SEQUENTIAL ORDER

     T_CHWS_CH           =XIN(1)
     Q_CHWS_CH           =XIN(2)
     T_CHWR_LOAD       =XIN(3)
     Q_CHWR_LOAD       =XIN(4)
     CHECK                    =XIN(5)
     CHILLER_CAPACITY=XIN(6)

     IUNIT                     =INFO(1)
     ITYPE                     =INFO(2)
C-----------------------------------------------------------------------------------------------------------------------
C    SET THE VERSION INFORMATION FOR TRNSYS
     IF(INFO(7).EQ.-2) THEN
          INFO(12)=16
          RETURN 1
     ENDIF
C-----------------------------------------------------------------------------------------------------------------------

C-----------------------------------------------------------------------------------------------------------------------
C    DO ALL THE VERY LAST CALL OF THE SIMULATION MANIPULATIONS HERE
     IF (INFO(8).EQ.-1) THEN
          RETURN 1
     ENDIF
C-----------------------------------------------------------------------------------------------------------------------

C-----------------------------------------------------------------------------------------------------------------------
C    PERFORM ANY 'AFTER-ITERATION' MANIPULATIONS THAT ARE REQUIRED HERE
C    e.g. save variables to storage array for the next timestep
     IF (INFO(13).GT.0) THEN
          NITEMS=0
C         STORED(1)=... (if NITEMS > 0)
C         CALL setStorageVars(STORED,NITEMS,INFO)
          RETURN 1
     ENDIF
C-----------------------------------------------------------------------------------------------------------------------

C-----------------------------------------------------------------------------------------------------------------------
C    DO ALL THE VERY FIRST CALL OF THE SIMULATION MANIPULATIONS HERE
     IF (INFO(7).EQ.-1) THEN

C    SET SOME INFO ARRAY VARIABLES TO TELL THE TRNSYS ENGINE HOW THIS TYPE
C    IS TO WORK
     INFO(6)=NOUT
     INFO(9)=1
     INFO(10)=0  !STORAGE FOR VERSION 16 HAS BEEN CHANGED

C    SET THE REQUIRED NUMBER OF INPUTS, PARAMETERS AND DERIVATIVES THAT
C    THE USER SHOULD SUPPLY IN THE INPUT FILE
C    IN SOME CASES, THE NUMBER OF VARIABLES MAY DEPEND ON THE VALUE OF
C    PARAMETERS TO THIS MODEL....
          NIN=NI
          NPAR=NP
          NDER=ND
```

```
C    CALL THE TYPE CHECK SUBROUTINE TO COMPARE WHAT THIS COMPONENT
C    REQUIRES TO WHAT IS SUPPLIED IN
C    THE TRNSYS INPUT FILE
           CALL TYPECK(1,INFO,NIN,NPAR,NDER)
C    SET THE NUMBER OF STORAGE SPOTS NEEDED FOR THIS COMPONENT
     NITEMS=0
C    CALL setStorageSize(NITEMS,INFO)

C          RETURN TO THE CALLING PROGRAM
           RETURN 1

    ENDIF
C-----------------------------------------------------------------------------------------------------------------------

C-----------------------------------------------------------------------------------------------------------------------
C    DO ALL OF THE INITIAL TIMESTEP MANIPULATIONS HERE - THERE ARE NO
C    ITERATIONS AT THE INTIAL TIME
     IF (TIME .LT. (getSimulationStartTime() +  . getSimulationTimeStep()/2.D0)) THEN

C    SET THE UNIT NUMBER FOR FUTURE CALLS
     IUNIT=INFO(1)
     ITYPE=INFO(2)

C    CHECK THE PARAMETERS FOR PROBLEMS AND RETURN FROM THE SUBROUTINE
C    IF AN ERROR IS FOUND
C    IF(...) CALL TYPECK(-4,INFO,0,"BAD PARAMETER #",0)

C    PERFORM ANY REQUIRED CALCULATIONS TO SET THE INITIAL VALUES OF THE
C    OUTPUTS HERE
C          T_CHWS_TANK
                OUT(1)=0
C          Q_CHWS_TANK
                OUT(2)=0
C          T_CHWR_TANK
                OUT(3)=0
C          Q_CHWR_TANK
                OUT(4)=0
C          MODE
                OUT(5)=0
C          TANK_CAPACITY
                OUT(6)=0
C          E
                OUT(7)=0
C          B
                OUT(8)=0

C    PERFORM ANY REQUIRED CALCULATIONS TO SET THE INITIAL STORAGE
C    VARIABLES HERE
     NITEMS=0
C    STORED(1)=...

C    PUT THE STORED ARRAY IN THE GLOBAL STORED ARRAY
C    CALL setStorageVars(STORED,NITEMS,INFO)

C    RETURN TO THE CALLING PROGRAM
     RETURN 1

     ENDIF
C-----------------------------------------------------------------------------------------------------------------------
```

```
C-----------------------------------------------------------------------------------------------------------------------
C    *** ITS AN ITERATIVE CALL TO THIS COMPONENT ***
C-----------------------------------------------------------------------------------------------------------------------


C-----------------------------------------------------------------------------------------------------------------------
C     RETRIEVE THE VALUES IN THE STORAGE ARRAY FOR THIS ITERATION
C     NITEMS=
C     CALL getStorageVars(STORED,NITEMS,INFO)
C     STORED(1)=
C-----------------------------------------------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------------------------------------------
C     CHECK THE INPUTS FOR PROBLEMS
C     IF(...) CALL TYPECK(-3,INFO,'BAD INPUT #',0,0)
C     IF(IERROR.GT.0) RETURN 1
C-----------------------------------------------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------------------------------------------
C    *** PERFORM ALL THE CALCULATION HERE FOR THIS MODEL. ***
C-----------------------------------------------------------------------------------------------------------------------
C     ADD YOUR COMPONENT EQUATIONS HERE; BASICALLY THE EQUATIONS THAT WILL
C     CALCULATE THE OUTPUTS BASED ON THE PARAMETERS AND THE INPUTS.REFER TO
C     CHAPTER 3 OF THE TRNSYS VOLUME 1 MANUAL FOR DETAILED INFORMATION ON
C     WRITING TRNSYS COMPONENTS.
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C     ICE STORAGE TANK MODEL USING A REGRESSION OF EFFECTIVENESS CURVES
C     CALMAC 190 Ton Hour Tank
C     BEHZAD RISMANCHI
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C                                    -----------------
C     T_CHWS_CH      ---> |                   | ----> T_CHWS_TANK
C     Q_CHWS_CH      ---> |                   | ----> Q_CHWS_TANK
C                                    | STORAGE  |
C     T_CHWR_TANK <--  |                   | <--- T_CHWR_LOAD
C     Q_CHWR_TANK <--  |                   | <--- Q_CHWR_LOAD
C                                    -----------------
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C     ***INITIAL VALUE FOR TANK_CAPACITY***
C     ***IF NORMAL TIME STEP INFO(7)=0 IS THE FIRST CALL
C     ***IF ITERATION STEP INFO(7)=1,2,3,...

      TANK_CAPACITY = CHILLER_CAPACITY

      IF (TIME.EQ.1) THEN
            TANK_CAPACITY =  TANK_MAX_C/2
      ENDIF
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C     ***STORAGE STRATEGY***
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C     ***CHARGING***
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
      IF          (CHECK.EQ.1) THEN
C           **** SET B VALUE ***
            B= TANK_CAPACITY / TANK_MAX_C
            IF (B.GE.1.0) B=1.0
C           ***SET Q ***
            Q = Q_CHWS_CH * 7.481/(BRINE_DENSITY *60.0) !CONVERT FROM KG/H TO GPM
C           ***SET E***
            IF(B .LE. 0.755) THEN
                  C0=1.077255269D0
```

```
          C1=-0.079156996D0*B
          C2=-0.0046742D0      *Q
          C3=0.0
          C4=0.0
          C5=0.0
          C6=0.0
          C7=0.0
          C8=0.0
          C9=0.0
          C10=0.0
          C11=0.0
          C12=0.0
          C13=0.0
          C14=0.0
          C15=0.0
      ELSE
          C0= 1.511144226D0
          C1= 0.22757868D0*DLOG10(-B+1.0D0)
          C2=-0.009864783D0*Q
          C3= 3.83656D-5*Q**2
          C4=-0.281804303D0*B
          C5=0.0
          C6=0.0
          C7=0.0
          C8=0.0
          C9=0.0
          C10=0.0
          C11=0.0
          C12=0.0
          C13=0.0
          C14=0.0
          C15=0.0
      END IF
      E=C0+C1+C2+C3+C4+C5+C6+C7+C8+C9+C10+C11+C12+C13+C14+C15
      E1= E
C
C     E = (T_OUT - T_IDEAL) / (T_OUT - T_IN)
C
      IF (E .GE. 1.0) E=.99
      IF (E .EQ. 1.0) E=.99
      IF (E .LE. 0.0) E=0.0
      IF (B .GE. 1.0) E=0.0

      T_CHWR_TANK = T_CHWS_CH - E * (T_CHWS_CH - T_CHARGING)
      Q_CHWR_TANK = Q_CHWS_CH

      T_CHWS_TANK = 0.0
      Q_CHWS_TANK = 0.0

      IF (INFO(7).EQ.0) THEN
          TANK_CAPACITY = TANK_CAPACITY +
   &      Q_CHWS_CH * CP_CHW * ABS(T_CHWR_TANK - T_CHWS_CH)

          IF(TANK_CAPACITY.GE.TANK_MAX_C) TANK_CAPACITY = TANK_MAX_C
          IF(TANK_CAPACITY.LE.0.0)      TANK_CAPACITY = 0.0
      ENDIF

C   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C   ***STORAGE***
```

```
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

      ELSEIF  (CHECK.EQ.2) THEN

            T_CHWS_TANK = T_STORAGE
            Q_CHWS_TANK = 0.0
            T_CHWR_TANK = T_STORAGE
            Q_CHWR_TANK = 0.0
            TANK_CAPACITY = TANK_CAPACITY

C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C     ***DISCHARGE***
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
      ELSE

C           **** SET B VALUE ***
            B= 1. - TANK_CAPACITY / TANK_MAX_C
            IF (B.GE.1.) B=1
C           ***SET VB ***
            Q = Q_CHWR_LOAD * 7.481/(BRINE_DENSITY *60.0)        ! KG/H TO GPM
C           ***SET E***
            IF(B .LT. 0.66) THEN
                  C0   =0.84119769D0
                  C1   = 0.200276759D0*B
                  C2   = 1.636547199D0*B**2
                  C3   = -5.204433828D0*B**3
                  C4   = 4.196217689D0*B**4
                  C5   = 0.015118414D0*Q
                  C6   = -0.000390064D0*Q**2
                  C7   = 3.64763D-6*Q**3
                  C8   = -1.24338D-8*Q**4
                  C9   = -0.053871746D0*B*Q
                  C10 = 0.064822502D0*B**2*Q
                  C11 = 0.000354565D0*B*Q**2
                  C12 =-0.034354947D0*B**3*Q
                  C13 =-0.000142311D0*B**2*Q**2
                  C14 =-9.15865D-7*B*Q**3
                  C15 = 0.0
            ELSE
                  C0   = 25.62156701D0
                  C1   =-110.463303D0*B
                  C2   = 176.6331532D0*B**2
                  C3   =-114.555632D0*B**3
                  C4   = 22.86186786D0*B**4
                  C5   = -0.01026212D0*Q
                  C6   = -0.0004725D0*Q**2
                  C7   = 5.03616D-7*Q**3
                  C8   = -2.1181D-9*Q**4
                  C9   = 0.105010295D0*B*Q
                  C10 = -0.27724386D0*B**2*Q
                  C11 = 0.001260003D0*B*Q**2
                  C12 = 0.179974285D0*B**3*Q
                  C13 = -0.00078403D0*B**2*Q**2
                  C14 = -1.8073D-7*B*Q**3
                  C15 = 0.0
            END IF

            E=C0+C1+C2+C3+C4+C5+C6+C7+C8+C9+C10+C11+C12+C13+C14+C15
            E1= E
```

```
          IF (E .GE. 1.0) E=1.0
          IF (E .LE. 0.0) E=0.0
          IF (B .GE. 1.0) E=0.0

          T_CHWS_TANK = T_CHWR_LOAD - E * (T_CHWR_LOAD - T_DISCHARGING)
          Q_CHWS_TANK = Q_CHWR_LOAD

          T_CHWR_TANK = 0
          Q_CHWR_TANK = 0

          IF (INFO(7).EQ.0) THEN

             TANK_CAPACITY = TANK_CAPACITY -
     &       Q_CHWS_TANK * CP_CHW * ABS(T_CHWR_LOAD-T_CHWS_TANK)
             IF(TANK_CAPACITY.GE.TANK_MAX_C) TANK_CAPACITY = TANK_MAX_C
             IF(TANK_CAPACITY.LE.0.0)        TANK_CAPACITY = 0.0

          ENDIF
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
      ENDIF
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
C     ***LAST STEP***
C     ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
      MODE = CHECK

      OPEN (5,file='CALMAC.dat')
      IF (TIME.EQ.1) WRITE (5,200)
      WRITE (5,100) TIME, CHECK, B, Q, E1, E,
     &       T_CHWS_CH  , Q_CHWS_CH  , T_CHWR_TANK, Q_CHWS_TANK,
     &       T_CHWS_TANK, Q_CHWS_TANK, T_CHWR_LOAD, Q_CHWR_LOAD,
     &       TANK_CAPACITY

100   FORMAT (162(E12.4,2x))
200   FORMAT (  2X,  'TIME',            10X,    'CHECK',
     &          9X,  'B',               13X,    'Q',
     &          13X,'E1',               12X,    'E',
     &          12X,'T_CHWS_CH',        6X,     'Q_CHWS_CH',
     &          5X,  'T_CHWR_TANK',     3X,     'Q_CHWS_TANK',
     &          3X,  'T_CHWS_TANK',     3X,     'Q_CHWS_TANK',
     &          3X,  'T_CHWR_LOAD',     3X,     'Q_CHWR_LOAD',
     &          3X,  'TANK_CAPACITY')
C-----------------------------------------------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------------------------------------------
C    SET THE STORAGE ARRAY AT THE END OF THIS ITERATION IF NECESSARY
C      NITEMS=
C      STORED(1)=
C     CALL setStorageVars(STORED,NITEMS,INFO)
C-----------------------------------------------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------------------------------------------
C    REPORT ANY PROBLEMS THAT HAVE BEEN FOUND USING CALLS LIKE THIS:
C      CALL MESSAGES(-1,'put your message here','MESSAGE',IUNIT,ITYPE)
C      CALL MESSAGES(-1,'put your message here','WARNING',IUNIT,ITYPE)
C      CALL MESSAGES(-1,'put your message here','SEVERE',IUNIT,ITYPE)
C      CALL MESSAGES(-1,'put your message here','FATAL',IUNIT,ITYPE)
C-----------------------------------------------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------------------------------------------
C    SET THE OUTPUTS FROM THIS MODEL IN SEQUENTIAL ORDER AND GET OUT
```

```
C          T_CHWS_TANK
           OUT(1)=     T_CHWS_TANK
C          Q_CHWS_TANK
           OUT(2)=     Q_CHWS_TANK
C          T_CHWR_TANK
           OUT(3)=     T_CHWR_TANK
C          Q_CHWR_TANK
           OUT(4)=     Q_CHWR_TANK
C          MODE
           OUT(5)=     MODE
C          TANK_CAPACITY
           OUT(6)=     TANK_CAPACITY
C          E
           OUT(7)=     E
C          B
           OUT(8)=     B
C---------------------------------------------------------------------------------------------------------------------
C    EVERYTHING IS DONE - RETURN FROM THIS SUBROUTINE AND MOVE ON
     RETURN 1
     END
C---------------------------------------------------------------------------------------------------------------------
```

Appendix I : Terms and definitions

Air Handling Unit	Consisting of a blower(s), heat exchanger and filters with refrigerant, chilled water or brine on the tube side to perform one or more of the functions of circulating, cooling, cleaning, humidifying, dehumidifying and mixing of air.
Charging	Storing cooling capacity by removing heat from a cool storage device.
Chiller priority	Control strategy for partial storage systems that uses the chiller to directly meet as much of the load as possible, normally by operating at full capacity most of the time. Thermal storage is used to supplement chiller operation only when the load exceeds the chiller capacity.
Coefficient of Performance (COP)	The ratio of Net Refrigerating Effect divided by Compressor Shaft Power or Thermal Power Input.
Compressors	Machines in which compression of refrigerant vapour is effected by the positive action of linear motion of pistons, rotating elements (screws, vanes, scrolls etc.) or conversion of velocity energy to pressure in a centrifugal device.
Condenser	The heat exchanger, which utilizes refrigerant to water/air heat transfer, causing the refrigerant to condense and the water/air to be heated.
Cool storage	As used in this thesis, storage of cooling capacity in a storage medium at temperatures below the nominal temperature of the space or process.
Demand limiting	A partial storage operating strategy that limits capacity of refrigeration equipment during the peak period.
Design load profile	Calculated or measured hourly cooling loads over a complete cooling cycle that are considered to be the desired total cooling load that must be met by mechanical refrigeration and capacity from a cool thermal storage system.
Discharge capacity	The maximum rate at which cooling can be supplied from a cool storage device.

Evaporator	The heat exchanger wherein the refrigerant evaporates and cools another fluid.
Fully charged condition	State of a cool thermal storage system at which, according to design, no more heat is to be removed from the storage device.
Fully discharged condition	State of a cool thermal storage system at which no more usable cooling capacity can be delivered from the storage device.
Nominal storage capacity	A theoretical capacity of the thermal storage device. In many cases, this may be greater than the usable storage capacity.
Pull down load	Unmet cooling or heating load that accumulates during a period when a cooling or heating system has not operated and which must be met on system start-up before comfort conditions can be achieved.
Storage cycle	A period in which a complete charge and discharge of a thermal storage device has occurred, beginning and ending at the same state.
System capacity	Maximum amount of cooling that can be supplied by the entire cooling system, which may include chillers and thermal storage.
Temperature, dry bulb	The temperature indicated by any temperature sensing element in air.
Temperature, wet bulb	It is the dynamic equilibrium temperature attained by a liquid surface when the rate of heat transfer to the surface by convection equals the rate of mass transfer away from the surface.
Thermal storage capacity	A value indicating the maximum amount of cooling that can be achieved by the stored medium in the thermal storage device.
Thermal storage device	A container plus all its contents used for storing cooling energy. The heat transfer fluid and accessories, such as heat exchangers, agitators, circulating pumps, flow-switching devices, valves and baffles that are integral with the container, are considered a part of the thermal storage device.
Tons of refrigeration (TR)	One ton of refrigeration is the amount of cooling obtained by one ton of ice melting in one day: 3024 kCal/h, 12,000 Btu/h or 3.516 thermal kW.