INDOOR AIR QUALITY AND CLIMATE CHANGE IMPACTS ON AIR-CONDITIONING AND MECHANICAL VENTILATION (ACMV) SYSTEMS IN COMMERCIAL BUILDINGS IN THE TROPICS

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Title of Project Paper/Research Report/Dissertation/Thesis ("this Work"):

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ABSTRACT

Climate change will imply new condition for building industry and sufficient information on the possible implications will be crucial in years to come to mitigate the potential impacts. Numerous studies have been conducted to assess building's energy consumption in the future; however, some of the studies do not take into account climatic variability and occupant's reaction towards the temperature shift.

For the indoor air quality study, case studies were done at the green building which employed the radiant slab cooling and commercial non-green building with conventional cooling system. The field measurement was carried out at the Energy Commission building in Putrajaya, Malaysian Green Technology Corporation building in Bangi and Construction Research Institute of Malaysia in Cheras. Standard procedure given by the ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) was employed during the field work measurement. For objective measurement, parameters such as the room temperature, relative humidity, air velocity and the concentration of indoor pollutants were collected. The results were then compared to the MS1525:2007 and ASHRAE Standard-55 and 62 2010. The results showed that the indoor air quality in the building were within the acceptable standard recommended by the Malaysian Standard (MS 1525:2007) and ASHRAE Standard 55 and 62-2010 except for the relative humidity in the non-green building and air velocity for the green buildings

Case study also has been systematically done for the climate change impacts on the air conditioning system at the Construction Research Institute of Malaysia building taken into consideration the temperature, humidity and cooling load of the building. The

TRNSYS simulation results showed that the total maximum cooling load required in the years of 2000, 2020, 2050 and 2080 are 297000 kJ/hr, 305000 kJ/hr, 321000 kJ/hr and 332000 kJ/hr. The results were then compared with the year 2000 as the reference year. It is observed that the maximum cooling load needed in the year of 2020, 2050 and 2080 increase by 2.96%, 8.08% and 11.7% respectively. As the design cooling load is 211011 kJ/hr, the system is predicted to be unable to provide sufficient cooling load to the office space in the future as the maximum cooling load needed in the year 2080 is 332000 kJ/h.

The air distribution study was also conducted at the same building. The air flow and velocity were measured at selected locations in the office building and compared with the Computational Fluid Dynamics (CFD) simulation. Both results showed that the indoor air flows are mixture of low R and fully turbulent flows.

The incapability of the existing system to meet the cooling load requirement will lead to overheating in the office space and affects occupant health and performance. Regular maintenance and retrofitting are required in order to ensure that the system is able to provide sufficient cooling for the space. This study is undertaken to initiate the environmental awareness among the building designer with the issue that is often ignored.

ABSTRAK

Perubahan iklim telah mengubah kondisi dan membawa cabaran baru kepada sektor bangunan. Kajian dan maklumat lengkap mengenai impak perubahan iklim kepada bangunan hendaklah dijalankan untuk mengenalpasti cara menangani dan mengurangkan potensi impak tersebut dalam kehidupan manusia.

Tiga kajian kes telah dipilih untuk menilai kualiti udara dalaman (IAQ) di bangunan hijau dan komersial, pergerakan udara di dalam bangunan dan impak perubahan iklim kepada beban pendinginan sistem penyaman udara untuk tahun 2000,2020, 2050 dan 2080. Kajian lapangan telah dijalankan di bangunan hijau iaitu Kementerian Tenaga di Putrajaya dan Pusat Tenaga Malaysia di Bangi dan bangunan komersial iaitu di Makmal Kerja Raya di Cheras.

Penilaian kualiti udara dalaman dijalankan mengikut prosedur standard yang telah ditetapkan oleh ASHRAE. Antara parameter yang digunakan untuk pengukuran objektif ialah suhu bilik, kelembapan relatif, halaju udara, dan konsentrasi pencemaran dalaman. Hasil kajian lapangan kemudiannya dibandingkan dengan standard yang telah ditetapkan oleh MS 1525:2007 dan ASHRAE. Hasil kajian menunjukkan kualiti udara dalaman di ketiga-tiga bangunan adalah di dalam tahap yang memuaskan dan menepati standard yang telah ditetapkan kecuali untuk kelembapan relatif bagi bangunan Makmal Kerja Raya dan halaju udara bagi kedua-dua bangunan hijau. Kelembapan udara yang rendah di dalam pejabat sewaktu masa bekerja telah menyebabkan staf pejabat merasakan kondisi pejabat adalah terlalu sejuk walaupun suhu yang di dalam pejabat menepati standard. Di dalam bangunan hijau pula, penggunaan “radiant slab cooling” merupakan punca halaju udara yang rendah di dalam pejabat yang membawa kepada ketidakselesaan staf sewaktu masa

Bagi kajian impak perubahan iklim kepada sistem penyaman udara dan pergerakan udara di dalam bangunan, beban pendinginan di Makmal Kerja Raya telah dianggarkan mengunakan kaedah pengiraan Perbezaan Suhu Beban Pendinginan/Faktor Beban Pendinginan (CLTD/CLF) manakala beban pendinginan untuk tahun 2000,2020,2050 dan 2080 disimulasikan menggunakan simulasi TRNSYS. Pergerakan udara di dalam bangunan pula disimulasikan menggunakan CFD dan hasil simulasi kemudiannya telah dibandingkan dengan hasil kajian lapangan.

Untuk kajian impak perubahan cuaca, hasil simulasi menunjukkan bahawa total beban pendinginan akan meningkat seiring dengan peningkatan suhu. Total maksima beban pendinginan yang diperlukan oleh sistem penyaman udara Makmal Kerja Raya pada tahun 2000,2020,2050 dan 2080 adalah 297000kJ/jam, 305000 kJ/jam, 321000 kJ/jam dan 332000 kJ/jam. Jika dibandingkan dengan tahun 2000, peningkatan beban pendinginan adalah sebanyak 2.96% untuk tahun 2020, 8.08% untuk tahun 2050 dan 11.7% untuk tahun 2080. Sistem penyaman udara sedia ada mungkin tidak dapat membekalkan pendinginan yang diperlukan memandangkan limit beban pendinginan sistem sedia ada adalah 211011 kJ/jam. Bagi kajian pergerakan udara, hasil simulasi dari CFD menunjukkan bahawa halaju udara di dalam pejabat adalah sangat rendah dan di sesetengah lokasi, tiada pergerakan udara. Ini mengakibatkan ketidakselesaan kepada staf memandangkan rakyat Malaysia telah biasa dengan pergerakan udara yang sederhana lajunya untuk meningkatkan keselesaan.

Ketidakupayaan sistem yang sedia ada untuk membekalkan pendinginan yang diperlukan pada masa hadapan akan mengakibatkan ketidakselesaan di dalam pejabat dan mengganggu kesihatan dan prestasi staf. Pengubahsuaian sistem yang sedia ada perlu dilaksanakan untuk memastikan sistem penyaman udara sedia ada mampu membekalkan pendinginan dan memastikan keselesaan para staf walaupun berlaku peningkatan suhu akibat perubahan iklim.

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NOMENCLATURE

ACMV	Air-Conditioning and Mechanical Ventilation
AHU	Air-Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	Computational Fluid Dynamic
CO	Carbon dioxide
CO_2	Carbon monoxide
DBT	Dry Bulb Temperature
DOSH	Department of Occupational, Safety and Health
EPA	Environmental Protection Agency
HCOH	Formaldehyde
HVAC	Heating, Ventilating and Air-conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
ISO	International Organization for Standardization
PM	Particulate-matter
RH	Relative Humidity (%)
T	Indoor temperature
TVOC	Total Volatile Organic Compound
VOCs	Volatile Organic Compound

CHAPTER 1: INTRODUCTION

1.0 Research background

In recent years, we have experienced hotter summer, wetter winter and other erratic weather events such as frequent flood, drought, tsunami and heat waves. Most of our daily activities contributing to the increase in the greenhouse gases in the atmosphere which in turn intensify the climate change effects on us. Based on all of the strong indications of global warming trends, which affect the average air temperature and greenhouse gases composition, various studies have been carried out by researchers all over the world to study its impacts on politics, economy, energy, health and agriculture. The Intergovernmental Panel of Climate Change (IPCC) Third Assessment Report stated that *"The basis of research evidence is very limited for human settlement, energy and industry. Energy has been regarded mainly as an issue for Working Group III, related more to the causes of climate change than to impacts.Impacts of climate change on human settlement are hard to forecast, at least partly because the ability to project climate change at an urban or smaller scale has been so limited. As a result, more research is needed on impacts and adaptations in human settlement."*

Building industry is one of the industries that appeared to be vulnerable to the climate change impacts. The erratic weather patterns such as summer heat waves, frequent flood, drought and winter storm imposed various challenges for buildings. Global warming in terms of dramatic temperature rise is predicted to strongly affect the future energy usage in buildings, particularly due to overheating. Currently, many of us resort to air-conditioning as a mean to improve comfort and ignoring the fact that its usage would contribute to carbon emission, thus increasing the climate change effects even more.

The climate change impacts on building could be summarized as "*increase in electric demand and reduced energy supply reliability*". Various studies have been undertaken to estimate the building energy requirement in the future. Most of these studies indicated that the possible climate change impacts on buildings are on the building heating and cooling requirement, energy use and peak demands, building sustainability, longevity and emissions. Nevertheless, most of these studies do not include the effects of temperature change on the building energy usage due to global warming. In fact, changes in climate condition are predicted to have a direct impact on building energy requirement as the demand for energy usage for cooling and heating are closely associated with temperature variations and conditions. Existing weather data used for building design are commonly derived from the last half century (1961-1990) which does not manifest the recent and future climate pattern. Therefore, the impacts of climate change need to be studied regionally, as different climate change impacts are expected in different seasons, periods and countries.

Due to the climate change impacts, building designed based on the current standard may increase the operating and maintenance cost of the building in the next few years. To adapt to the changes in temperature, level of precipitation and relative humidity, buildings now are fully equipped with air-conditioning to increase the occupant comfort and well-being. Other than providing comfort, the air-conditioning also provides good indoor air quality to the space as occupants spent almost 90% of their time indoor. Poor indoor air quality commonly related to the air-conditioning and ventilation problems which would lead to the "Sick Building Syndrome" (SBS). Nuisance odors, cold, warm, draught and stuffy environment are general factors that contributing to the occupant discomfort and loss in productivity. Therefore, legislations on indoor air quality proposed by the Department of Safety and Health, Malaysia, MS 1525:2007 and ASHRAE are to ensure that the indoor air quality in the building is at an acceptable standard.

Therefore, this research will focus on the indoor air quality, and the climate change impacts on commercial buildings, including the green buildings in the tropics. Recently, climate change impacts on building energy demand and consumption have been discussed widely all around the world. However, only several studies have focused on the impacts regionally especially in the tropics. The findings of this study are hoped to serve as an assessment and evaluation in terms of indoor air quality and climate change impacts for future building design in the tropics.

1.1 Research objectives

The main objectives of this research are:

i. To investigate the current **indoor air quality** of the green and non-green building in the tropics through physical measurements and compares it with standard requirements.

ii. To evaluate the **current cooling load** of the existing air-conditioning system and compare it with design cooling capacity.

iii. To estimate the **future cooling load** needed for green and non-green building in the tropics in the year 2020, 2050 and 2080.

iv. To assess the **air distribution** in the office space in the building.

1.2 Research case studies

The purpose of case studies is to assess the indoor air quality and climate change impacts on the air-conditioning and mechanical ventilation (ACMV) systems of green and non-green building in the tropics. Recently, the effects of erratic weather events on building energy consumption and indoor air quality have been widely discussed internationally. However, only few studies have focused on the regional impacts, especially in the tropics and up to now; studies on the indoor air quality in the green building are hardly found.

Three case studies have been selected to perform the study on the air-conditioning and mechanical ventilation (ACMV) system. The case studies include the non-green building (Construction Research Institute of Malaysia (CREAM) building in Cheras), high-rise green building (Energy Commission building in Putrajaya) and low-rise green building (Malaysia Green Technology Corporation (MGTC) building in Bangi).

1.3 The importance of research

Numerous over-sizing ACMV design were applied in most of the commercial buildings in the tropics as cooling calculation data and weather files for building design are traditionally based from weather data taken about 40 years ago (1961-1990).Over sizing design incurs high initial cost to set up the plant and also creates problems on their control system as the control systems fail to maintain the indoor condition accordingly. Furthermore, this design promotes the growth of fungus and mold due to the hot and humid climate. In addition, most of the studies that have been conducted to assess building's energy consumptions do not take into account the climatic condition and the current consumer trend towards changes in outdoor temperature. Up to date, there are hardly any studies that have concentrated on the possible effects of climate change on building in the tropics, especially in Malaysia, Singapore and Indonesia.

This research will therefore, focus on the ACMV designs for commercial non-green and green buildings in the tropics taken into account climate change implications. It is important to study the implications of the climate change on buildings regionally as the different climate change phenomenon is expected in different countries, season and periods. The data collected from this research could be used to develop strategies for building improvement, in terms of design and ACMV plant, which will save energy and cost and establish guidelines for building adaptations for different applications in commercial building in the tropical countries that will reduce energy consumption thus reduce the utility bills and carbon emissions in the future.

CHAPTER 2.0 LITERATURE REVIEW

2.1 Indoor air quality in building

2.1.1 Humidity, temperature and air velocity

Humidity in air is the total of moisture in the air; which influences the occupant comfort level. It creates dryness or moisture sensations on our skin. Moisture penetrates and affects buildings through air movement via heating, ventilation and air-conditioning system, bulk or liquid via water leaks in the roof, wood and concrete into the facility, capillary and diffusion. Oversized air-conditioning is insufficient to circulate office air and remove excess moisture, which leads to wet, cold, and humid conditions. In appropriate sized units, the moisture is condensed on the coil and removed through the condensate drain as the indoor coil temperature is lower than the air dew-point temperature.

Humid condition makes people feel the dryness sensations on the skin and promote mold growth. Low humidity condition increased the chances for upper respiratory infections. The dry states also produce electrostatic charge on both office appliances and their users. However, the humidity can be controlled by lowering or increasing its water content in the ventilated air using proper appliances and controls called dehumidifying and humidifying respectively. The humidity control is important to maintain the optimum level of productivity in the office environment.

According to the guideline produced by ASHRAE, 80% of the building occupants feel most comfortable at the temperature between 24.5-28 °C. The ASHRAE Standard 55-2010 addressed in summer, most of the occupants feel comfortable at the temperature between 23 to 26 °C with relative humidity between 20-60%. This standard is similar to the one suggested by the Department of Standard Malaysia [1] and only applicable for typical office activities such as typing and seating with air movement less than 0.2 m/s.

Excessively high or low temperature in the office space contributes to the "Sick Building Syndrome". High temperatures can cause fatigue, irritability headache, reduce in productivity, coordination and alertness [2-5]. Occupant's comfort is normally associated with the indoor temperature and air quality. The thermal comfort needs of an individual depend on their activity level, age and physiology. The occupants might suffer from heat rash, lost focus and fainting in an extreme heat office environment. Likewise, if the environment is too cold, the occupants might lose their flexibility, dexterity and judgment. In both conditions, the occupants are prone to accidents that would lead to a decrease in the work productivity.

In the tropics, the desirable indoor air temperature is in the range of 23- 26°C that is suitable for the sedentary or near sedentary physical activity levels such as typing, resting, and other general office works. Level of thermal comfort highly depends on the air temperature and speed, radiant temperature, humidity, types of physical activities and clothing worn. However, for the indoor design condition; the design key factors include the dry bulb temperature, relative humidity and the air movement. Table 2.1 shows the studies of the recommended design of the thermal comfort zone in air-conditioned offices in Malaysia and in neighboring countries. Most of these studies suggested a higher indoor temperature range for countries in the tropics compared with the one recommended by the ASHRAE Standard 55-2004 as occupants in the tropics are used to much higher environmental temperature and air movement. However, ASHRAE Standard 55-2010 has evaluated the impacts of elevated air movement [6]. Elevated air movement increases the maximum operative temperature; hence the equivalent comfort can be maintained in a wider range of operative temperature. Thus, the use of elevated air speeds to widen the acceptable range of thermal conditions has been adjusted and expanded. The standard has produced a new method to express and selects the air speed limits and alternatives to determine the boundaries of comfort at air movement above 0.15 m/s.

Air movement is important in terms of comfort as it gives the feeling of coolness and freshness to the human body by enhancing the heat transfer between the air and human body and lowered the human skin temperature. Occupant's perception on air movement is associated with several factors such as air velocity and its variations, air temperature and personal factor, which include their overall thermal sensation and activity level [7]. The air movement influenced the heat gain or loss through the building envelope, occupant's comfort and removal of indoor contaminants in the building. Air velocity affects the evaporative and convective heat losses from the human body that determines the thermal comfort conditions [8, 9]. The air movement preference also differs based on personal perception. In the seasonal country, the occupants prefer to have an air-tight building, to reduce the undesirable air movement inside the space. However, Malaysian are used to the high air movement, as the outdoor condition is hot and humid [10]. Thus, they prefer to open window and door to increase the indoor air velocity to achieve comfort. Occupants in the tropics could bare higher indoor temperature when indoor air velocity is increased [11]. According to the MS 1525:2007 and ASHRAE Standard 55-2010, the acceptable air velocity inside a building is between 0.15-0.50 m/s and 0.8m/s. However, excessive air velocity or draft will leads to occupant's discomfort. Therefore, it is recommended that the draft below 0.25 m/s is sufficient enough to dissipate the heat and moisture and replace it with fresh air [12].

Table 2.1: Studies of recommended design of thermal comfort zone in Malaysia and neighboring countries

Study	**Location**	**Comfort zone**		
		Air temperature (˚C)	Relative humidity (%)	Air velocity (m/s)
M. N. Shaharon, 2012 [13]	Malaysia	21.6-23.6	42-54	-
Department of Standard Malaysia MS1525: 2007[14]	Malaysia	22-26	55-70	0.15-0.7
Abdul Rahman, 2006 [10]	Malaysia	24-28	-	-
A. Ahmad, 2004[15]	Malaysia	24.5-28	73	-
ASHRAE Standard 55-2004 & 2010 [16, 17]		23-26	20-60	0.8
K. W. Tham, 2002 [18]	Singapore	23.3-24.4 23-25.2	54-62 60-74	0.1-0.18 0.08-0.15
K. W. Cheong, 2001[19]	Singapore	22.1-22.48	60-62	0.12-0.16
M. R. Ismail, 2001 [20]	Malaysia	24.6	40-80	-
T. H. Karyono, 2000	Indonesia	25-30	-	-
Zain-Ahmed, 1998 [21]	Malaysia	24.5-28	72-74	0.3
A. M. Abdul Shukor, 1993 [22]	Malaysia	28.2	50	0.1
Bush, 1992[23]	Bangkok	22-30.5	50	-

Nevertheless, it was impossible for all of the occupants in a space to be thermally satisfied. Different persons might have a difference view on the agreeable thermal comfort. The different climate conditions affect the view on the acceptable thermal comfort. For instance, occupants who lived near the tropics where the climate was more hot and humid were well adapted to high temperatures and high humidity when compared to those who live in the colder weather. It should be taken into consideration that different person were having different physiological acceptance of thermal comfort conditions [24].

2.1.2 Ventilation

Ventilation is vital in providing good indoor air quality in the building as it replaces the air within a given space to remove airborne particles, odours, heat, smoke and provides fresh air to maintain the thermal comfort in the room. Inadequate exhaust ventilation and uneven air distribution due to the high ventilation rates lead to indoor problems in the office space. The volume of air supply for human depends on the oxygen for respiration and removal of products of exhalation, body odour, unnecessary heat, moisture and contaminants.

Nowadays, most of the office buildings commonly use the air-conditioning to remove the heat from the space to cool the air to the acceptable temperature and controls the humidity level in the building. The efficiency of the air-conditioning strongly depends on the certain factors such as the air supply quality, airborne pollutant level and the thermal condition of the space.

The ventilation in the office space is crucial to dilute contaminants and provides occupants the oxygen for breathing. A good ventilation system can removes the odours arising from human occupation and unwanted heat or the sensible heat, especially in crowded places to maintain the comfort level. However, the findings in the season countries may not be applicable to the buildings in the tropics due to differences in climate and practices for energy conservation, operations and maintenance of building. Therefore, physical measurement and subjective evaluation for indoor environment in the tropics building are required.

Table 2.2: Fresh air supply rate for general work activities in air-conditioned office

Types of work activity	**Minimum fresh air supply rate (m^3/min/person)**
Open-plan office (non-smoking)	0.43
Private office (with moderate smoking)	0.6
Conference rooms or offices (with heavy smoking)	1.0

2.1.3 Location of supply diffuser and return air grilles

The air supply diffusers and return air grilles delivered air evenly to all parts of the office space and removed or diluted the contaminants effectively. An effective air delivery system refers to a system that manage to deliver ventilation air to the occupants rather than the mechanical performance of the ventilation systems [25]. Thus, the relationship of the air delivery system and the air flow patterns that they generate is important in evaluating the efficiency of the air delivery system.

There are several types of air delivery systems such as mixing, displacement and local system. The mixing system is highly used by the open-plan offices. It provides good indoor air quality given that the system is properly design and operated [26]. The location of supply diffuser, panel height and workstation size do not affect the concentration contaminants. High panels usually blocked the acceptable airflow and cause thermal dissatisfaction among the occupants [27].

Compared to the mixing system, the displacement and local system produces better indoor environment if the contaminated air is raised adequately above the head of the occupant. Studies proved that the location of the diffuser has certain effects on the occupant comfort [28, 29] and ventilation efficiency [25]. However, improper control of the displacement system creates drafts and vertical differences in the temperature [28].

2.1.4 Indoor contaminants

Contaminants in the office space come from several sources; either particles of gases such as carbon dioxide, carbon monoxide, formaldehyde that enters the building via ventilation systems, infiltration via walls, building equipments and materials and accumulation of dust and moisture in the ventilation system and office space. Contaminants make the air feel stale, dusty, creates unpleasant odors, which leads to physical symptoms and discomfort.

The main source of carbon dioxide contaminants in the office space is human respiration. The measurement of carbon dioxide concentration is used to evaluate the indoor air quality. Normal adults at rest state required 0.2 and 0.12 liters/s air and only 5% is absorbed as oxygen by the lungs whereas the exhaled breath contains approximately 3 to 4% of carbon dioxide which approximately 0.004 liters/s. The acceptable carbon dioxide concentration level by ASHRAE, World Health Organization (WHO), Malaysian Code of Practice on Indoor Air (DOSH) is 1000 ppm (1.78g/m^3) or 0.5% by volume for an exposure of 8 hours [30-32]. The accumulation of carbon dioxide concentration above 1000 ppm may cause the occupants to suffer physical symptoms and impose serious health risk.

Many organizations in the world had produced their own guidelines regarding the acceptable limit of contaminants in the building. However, in Malaysia, the ASHRAE Standard-55 and Malaysia Code of Practice of Indoor Air Quality were widely used. Both of these guidelines include several contaminants such as carbon monoxide, nitrogen dioxide, radon and sulphur dioxide, formaldehyde, ozone and respirable dust particles (Table 2.3).

Table 2.3: Limit of indoor contaminants

Contaminants	**WHO Standard[31]**	**ASHRAE & DOSH [30, 32, 33]**	**NIOSH [34]**	**Source**
Carbon Dioxide	12000	1000	5000	Human respiration
Carbon Monoxide	5	10	35	Combustion products, Tobacco smoke
Formaldehyde	0.12	0.1	0.016	Furniture, Fittings, Insulation, Paper
Radon	79 Bq/ m³	-		Building material
Sulphur Dioxide	1.35	-		External environment
Ozone	0.08	-		Photocopiers, laser printers,

Carbon monoxide greater than 15ppm can be considered harmful and had serious effects to human health. The presence of carbon monoxide in the building is due to the tobacco smoking and incomplete combustion of hydrocarbon. However, as most of the regulation prohibits smoking in the building, the carbon monoxide concentration in the building is mainly found from the incomplete combustion of the hydrocarbon fuels from the vehicle outside the building. Buildings with internal parking or loading dock are more likely to have high carbon monoxide concentration. For other contaminants such as formaldehyde, it usually enters the building via building products that continue to disperse formaldehyde gas for a long period of time, mostly in its first year. Exposure to formaldehyde may cause irritation to eyes, skin, nose and upper respiratory area.

As far as the respirable dust particles are concerned, the recommended limit given by DOSH is 150 μ g m $^{-3}$ [32]. The size of these particles is determined by the diameter of an assumed spherical particle and range from 0.01 µm to the size of insects and leaves. The maximum allowable number of particles per cubic meter of air is determined by the ISO Classification Air Cleanliness that consists of nine class levels of airborne particulate cleanliness as shown in Table 2.4 below[35].

Table 2.4: Airborne particle concentration limits from ISO/FDIS 14644-1 (ISO 14644-1, 1999)

ISO classification number	**Maximum concentration limits (particles/m^3) for particles equal to and larger than the considered sizes**					
	0.1 µm	0.2 µm	0.3 µm	0.5 µm	1 µm	5 µm
Class 1	10	2				
Class 2	100	24	10	4		
Class 3	1000	237	102	35	8	
Class 4	10000	2370	1020	352	83	
Class 5	100000	23700	10200	3520	832	29
Class 6	1000000	237000	102000	35200	8320	293
Class 7				352000	83200	2930
Class 8				3520000	832000	29300
Class 9				35200000	8320000	293000

2.2 Overview of green buildings in Malaysia

Recently, the awareness of green technology and sustainable development had been increasing in Malaysia, which leads to the launching of the National Green Technology Policy on 24th July 2009 to promote sustainability in the built environment. Furthermore, in the 9th Malaysia Plan, the government plans to increase the energy-efficient incentives in the transportation, industrial, public building and commercial sector. Related to this, building sector has now focused to design an energy-efficient building that employed passive and active devices to achieve optimum use of energy.

For decades, Malaysia had strongly depended on the non-renewable-energy as the non-renewable-energy is heavily subsided by the government compared to the renewable-energy. However, the rising of the urban population and energy price will affect the building energy usage and its operating cost in the future. According to Tony Arnel, the Chairman of World Green Building Council, by using green technology in buildings, the government can reduce the building's operating cost by as high as 9%, increase the building values and return in investment by 7.5% and 6.6 % respectively [36].

Green building by definition is a building, which is energy and resource-saving, use recycle materials, minimise its toxic substance emission throughout its life span, harmonise with local climate, traditions, culture and surroundings, able to uphold and improve the human life quality and at the same time maintain the capacity of the ecosystem locally and globally [36]. Green building often built by recycled-content and non-toxic building materials, conserves natural flora and provides better indoor air quality. Usually, it is equipped with sensor-controlled and compact fluorescent lighting, high-efficiency air-conditioning equipment, building integrated photovoltaic (BIPV) system, solar thermal tube, solar chimneys, on-site cleaning, re-use of wastewater, building orientation, radiant cooling system, salvaged lumber products, recycled concrete aggregates, green roof, waterless urinals and facilities for bicyclists.

The advantages of green buildings are better use of building resources, significant operational savings, efficient use of water and energy conserve natural resources, employed natural lighting and flexible interiors, recycling facilities, easy access to public transportation, increased workplace productivity and recycle construction and demolition waste. On the economic view, green buildings increase the environmental added value through the improvement of productivity, and net income, decreased the repair cost by improvement of durability and the utilities cost by energy savings.

The common assessment methods used for building sustainability is Building Research Establishment Environmental Assessment Method (BREEAM, U.K.), Leadership in Energy and Environmental Design (LEED, US), Building Environmental Performance Assessment Criteria (BEPAC, Canada), Green Building Tool (GBTool, 20 countries), Comprehensive Assessment System for Building Environmental Efficiency (CASBEE, Japan), Life-Cycle Assessment/Life-Cycle Cost (LCA/LCC Tool, Hong Kong), Green Building Evaluation System (EEWH, Taiwan), Green Star (Australia and New Zealand) and Green Mark (Singapore)[37].

In 2001, the "Code of Practice on Energy-Efficient and use of renewable-energy in non-residential buildings" (Malaysian Standard MS 1525) was introduced. The MS 1525:2007 is a code that provides design recommendations for the energy-efficiency of non-residential buildings. It specifies the condition and minimum standards for energy-efficiency in the new building design and methods for determining compliances with these standards. The MS 1525 covers the overall thermal transfer value (OTTV) for building envelopes, designing an efficient lighting system, minimising losses in electrical power distribution equipment, designing an energy-efficient air-conditioning and mechanical ventilation system, a good energy management and recommendations for renewable-energy applications. Based on this guideline, all buildings exceeding 4000 m^2 of air-conditioned space shall be provided with Energy Management System (EMS), the OTTV shall not be exceeded 50 W/m² and RTTV shall not exceed 25 W/m².

Another guideline, which is the Building Energy Index (BEI), is derived by dividing the total kWh or electricity used per year with the building area based on meter square calculations. Most of the buildings in Malaysia are energy-efficient as most of them exceed the benchmark for Energy-Efficient buildings (EEB), which was set at 135kWh per square meter per year. The average BEI of office buildings in Malaysia is around 200-250 and only a few buildings such as Securities Commission HQ (less than 120), LEO Building (100), the PTM's ZEO Building (50) and the Energy Commission HQ (80) has BEI less than 150.

On 29 May 2009, the government has launched another guideline, which is the Green Building Index (GBI) to increase the awareness and use of green technology in the building industry. The GBI is developed specifically for the Malaysia-tropical climate, environmental and development context, cultural and social need. It is Malaysia's own green rating tool for buildings developed to increase awareness among building practitioners and public about environmental and sustainability issues and our responsibility for our future generation. In order to encourage the building practitioner to engage with green technology, the building owners who get the GBI certificates and the buyer who purchase buildings with GBI certificates from the developer will be given income tax exemption by the government.

The GBI rating tools gives a chance for developers and building owners to design and construct green and sustainable buildings that are water and energy-efficient, had better indoor environment and better accessibility to public transport and recycling centre. The GBI is developed to suit our local climate, culture, building codes and practice. However, the development of GBI faces several challenges such as adoption of other Green Tools, capital cost barrier, not in local building codes and lack of local professional in green buildings industry.

2.3 Cooling capacity

2.3.1 Components of cooling load

Cooling load needed for a particular building is equal to the total heat gain inside the building which includes the heat transferred through the building envelopes, occupants, lights and equipments. The total of cooling load inside a building consists of sensible and latent heat, which must be calculated and tabulated separately. The sensible heat gain which affects the dry bulb temperature usually occurs in solar radiation, heat conduction, sensible heat convection and radiation, ventilation from outside air and infiltration air while the latent heat gain which affects the moisture content in the conditioned space is mainly due to the occupants, appliances and lights.

2.3.2 Cooling load calculation method

According to ASHRAE Handbook Fundamental (2001), there are several methods to determine the cooling load for a space which includes the Transfer Function method (TFM), Cooling Load Temperature Difference/Cooling Load Factor (CLTD/CLF) method and Total Equivalent Differential/ Time Averaging (TETD/TA) method.

There are few limitations or advantages of each cooling load calculation method in terms of accuracy and simplicity. The unpredictability of the occupancy, human reaction, outdoor weather changes, differences in heat gain data for electrical equipment and unknown features of the ACMV equipments often contribute to the inaccuracy in predicting the actual cooling load needed.

The CLTD/CLF method was found to be the most practical cooling load calculation method as it produces the cooling load needed according to the peak load values required by the sizing equipment. The results from this method are based on the space features and vary according to the model employed to produce the CLTD/CLF data provided by the table. It should be noted that engineering judgment is needed in the custom table interpretation and suitable correction factors application.

2.3.3 CLTD/CLF method

The current Cooling Load Temperature Difference / cooling load factor (CLTD/CLF) method was developed by Rudoy and Duran (1979) in GRP 158 (ASHRAE 1979). This method engaged the hand calculation method with tabulated CLTD and CLF values. The transfer function method that produces the cooling loads for the standard environmental conditions and zone types were used for the tabulated CLTD and CLF.

This method does not convert the heat gain to the building to cooling load instantaneously. The Cooling Load Temperature Difference (CLTD), the solar cooling load factor (SCL) and the cooling load factor (CLF) are taken into the calculation of cooling load. These factors include the effect of time lag in conductive heat gain via opaque exterior surface and time delay by thermal storage when converting the radiant heat gain to cooling load.

The Cooling Load Temperature Difference (CLTD) is the difference in theoretical temperature that considered the combined effects of inside and outside air temperature difference, daily temperature range, solar radiation and heat storage in the construction or building mass. This factor is influenced by the building's orientation, tilt, month, day, hour and latitude and used to adjust the conductive heat gains from the walls, roof, floor and glass. Meanwhile, the cooling load factor (CLF) taken into account the radiant energy that enters the conditioned space at a particular time which does not turn into a part of cooling load immediately. The CLF values for different surfaces have been derived as functions of solar time and orientation and are presented in the form of table in ASHRAE Handbooks. These factors are used to adjust the heat gains from internal load such as occupants, lightings and electrical equipments. The solar cooling load factor (SCL) is used to adjust the transmission of heat gain from glass; from the window or wall.

2.3.3.1 Sensible heat transfer (conduction via roof, wall and glass)

The sensible cooling load includes the heat transfer by conduction via building walls, window, floor, roof and heat transfer by radiation via fenestration such as windows and skylight. The basic heat gain equation for roof, wall is:

$$Q = UA(\Delta T) \tag{2.1}$$

where Q: heat gain in Btu/hr

U: the thermal transmittance for roof/wall etc

A: the area of roof/ wall in ft², ΔT is the temperature difference in ˚F

The heat gain is then converted to cooling load using the room transfer function (Sol-air temperature) for the rooms with light, medium and heavy thermal characteristics. The equation is then modified as:

$$Q = UA(CLTD) \tag{2.2}$$

where CLTD: Cooling Load Temperature Difference ˚F, (the values are determine from tables in Chapter 28 in ASHRAE Fundamentals Handbook (Table 31(roof), Table 33 (wall), Table 34 (glass))

However, the ASHRAE tables determine the hourly CLTD values for one base case (the outdoor maximum temperature of 95˚F with mean temperature of 85˚F and daily range of 21˚F), the equation is further adjusted by applying the correction factors for conditions other than mentioned base case. The following equation was given to adjust to other latitudes and months and other indoor and outdoor design temperatures:

$$CLTD_{corrected} = (CLTD\ ) + (78-T_R) + (T_o-85) \tag{2.3}$$

where $(78- T_R)$: indoor design temperature correction

(T_o-85): outdoor design temperature correction, T_R: room temperature, °F

T_o: outdoor temperature, °F

Thus, the equation of conduction heat gain for wall, roof is further adjusted by applying the correction factor.

$$Q = UA(CLTD_{corrected}) \tag{2.4}$$

2.3.3.2 Solar heat gain

The solar transmission through glass is determined by the cooling load SCL factor and shading coefficient (SC). The cooling load equation for solar transmission through glass is:

$$Q_{glasssolar} = A(SC)(SCL) \qquad 2.5$$

where Q: solar transmission load through the glass in btu/hr

SC: shading coefficient (ASHRAE 1997, Chapter 27, Table 11)

SCL: solar cooling load factor (ASHRAE 1997, Chapter 28, Table A28-36)

2.3.3.3 Internal heat gain (people, lighting, appliances and infiltration air)

The internal sensible hat gains are due to the occupants, lighting and appliances. The cooling load depends on the magnitude of the heat gain hourly and the thermal responses of the zone. The heat gain by people consists of two components[38]:

$$Q_{sensiblepeople} = N(Q_s)(CLF) \qquad 2.6$$

$$Q_{latentpeople} = N(Q_L) \qquad 2.7$$

where N: number of people in space (ASHRAE 1997, Table 28-3)

Q_s and Q_L : sensible and latent heat gain from occupancy (ASHRAE 1997, Chapter 28, Table 3)

CLF: cooling load factor by hour occupancy (ASHRAE 1997, Chapter 28, Table 37)

Table 2.5 below gives representative rates at which heat and moisture are given off by human beings in different conditions and activities. People generate both sensible and latent heat components according to activity level.

Table 2.5: Heat gain from occupants at various activities (at indoor temperature of 26˚C)[38]

Activity	**Total heat (Btu/hr)**		**Sensible heat (Btu/hr)**	**Latent heat (Btu/hr)**
	Adult (male)	Adjusted		
Seated at rest	400	350	210	140
Seated, very light work, typing	480	420	230	190
Seated, eating	520	580	255	325
Seated, light work, typing	640	510	255	255
Standing, light work or walking slowly	800	640	315	325
Light bench work	880	780	345	435
Light machine work	1040	1040	345	695
Light machine work, walking three mi/hr	1360	1280	405	875
Moderate dancing	1600	1600	565	1035
Heavy work, lifting, athletics	2000	1800	635	1165

The sensible cooling load from lighting could be calculated using following equation [38]:

$$Q_{sensible} = 3.41 x W x F_{UT} x F_{SA} x CLF \qquad 2.8$$

where W: watts input from electrical lighting plan or lighting load data

F_{UT} : lighting use factor

F_{SA} : special ballast allowance factor

CLF: cooling load factor (ASHRAE 1997, Chapter 28, Table 38)

The sensible and latent cooling load from appliances can be calculated using these equations[38, 39]:

$$Q_{latent} = Q_{in} x F_{U} \qquad 2.9$$

$$Q_{sensible} = Q_{in} x F_U x F_R x CLF \qquad 2.10$$

where Q_{in} : rated energy input from appliances (ASHRAE 1997, Chapter 28, Table 5 to 9 or

ASHRAE 2001, Chapter 29, Table 8 to 10)

F_U : usage factor (ASHRAE 1997, Chapter 28, Table 6 and 7)

F_R : radiation factor (ASHRAE 1997, Chapter 28, Table 6 and 7)

CLF: cooling load factor, by hour occupancy (ASHRAE 1997, Chapter 28, Table 37 and 39)

It is impossible to accurately calculate the heat gain or loss due to infiltration. Some of the factors that influenced the inaccuracy of the calculation include the building construction, chimney effects, wind direction and velocity. According to Haines and Wilson (1994), the common example of infiltration that take places inside a building are leaking around frames and gasket on window and door, porous wall, vertical air movement via stairwells, elevator shafts, ducts and numerous construction openings[40]. The cooling load due to infiltration of ventilation is determined using equation below[38]:

$$Q_{sensible} = 1.08 \text{ x CFM x } (T_o - T_i) \qquad 2.11$$

$$Q_{latent} = 4800 \text{ x CFM x } (W_o - W_i) \qquad 2.12$$

where $Q_{sensible}$:sensible heat cooling load, Btu/h

CFM: infiltration flow rate (ASHRAE 1997, Chapter 25)

$(T_o - T_i)$: temperature difference between dry bulb temperature outside and inside ,˚F

Q_{latent} = latent heat cooling load, Btu/h

CFM = air flow rate for cooling, ft^3/min

$(W_o - W_i)$: humidity ratio difference between humidity ratio outside and inside (lb water/lb dry air)

2.4 Climate change

Only about a decade ago, global warming and climate change were just a hypothesis. However, by now the global warming and extreme weather events are being recognized as leading the changes in global climate. In Asia, these events can be seen in increased flooding in Malaysia, tsunami in Indonesia and droughts in Australia, while in Europe, there are events such as increasingly intense summer heat waves, melting glaciers and rising sea levels. At the poles, there is an increased melting of Arctic ice and permafrost. All of these phenomena are potential signs of incremental warming.

Currently, we experienced much warmer summers, colder winters and frequent extreme weather events, which indicate an acceleration of atmospheric warming. Cases of heavy precipitation have become more frequent with the increase in atmospheric vapour. Eighty percent of the additional heat in the climate system has been absorbed by the ocean since 1961 and since then, the ocean temperature has risen down to depths of 3000 m. During 1993-2003, the sea level has risen up to 3.1 mm per year due to the losses from the land-based ice sheets of Antarctica and Greenland[41].

Bader (2003) in his study [42] disclosed that there was a large difference in high summer and low winter temperature, resulting in extremely cold weather in October 2003. In a separate study in the following year, Luterbach et al (2004) [43] concluded that 2003 was the hottest summer and 1709 was the coldest European winter. If we remember, the summer of 2003 caused many fatalities. For instance, there were 15000 deaths recorded in France due to the high temperature during night time. Another study by Schar et al (2004) [44] went a step further and found that the increase in average temperature, were responsible for the summer heat waves in 2003. These studies imply that adaptation to climate change should be planned in advance to prevent further fatalities in the future.

Climate change by definition is a climate shift due to human activities modifying the proportion of natural greenhouse gases in the lower atmosphere. Over the centuries, researchers all around the world have been debating the causes of climate change. Climate change occurs mostly due to the economic development and human actions prior to modern life. Generally, there are three spheres of climate change impacts, the primary (wind speeds, floods, extreme climatic events, temperatures, driving rain), secondary (variations of plants and animals) and tertiary (community, institutional, behavioral) spheres. Naturally, the earth's climate depends on its natural greenhouse gases. The heat radiated from the lower atmosphere is absorbed by these gases, which radiate most of it back towards the atmosphere surface. The earth would be approximately 18℃ colder without the existence of these natural greenhouse gases.

Generally, global warming is due to natural and anthropogenic forces. Simulations based on the historical global climate show that natural forces, such as the tilt of the earth's axis, alone could not produce the warming recorded over the past 40 to 50 years. Eventually, both of these forces have produced the observed climate change phenomenon. The main cause of the anthropogenic force is undoubtedly the rise of greenhouse gases emissions.

The IPCC Second Assessment Report [45] states the possibilities of opposing effects of the human influence on global climate change, such as the increase in carbon emissions into the atmosphere. The proportions of carbon, methane and nitrous dioxide in the atmosphere have been increasing since the Industrial Revolution in the 18th century (Figure 2.1), causing the natural greenhouse effect to intensify and so changing the earth's climate. Carbon dioxide produced by burning of fossil fuel and methane released from agricultural activities are trapping heat in the troposphere zone, hence increasing the warming effects even further. In contrary, aerosols emissions such as sulphates produce cooling effects in the lower atmosphere. In 1992, the proportion of carbon (CO_2) emissions in the atmosphere had significantly increased by 30%, nitrous dioxide (N_2O) by 15% and methane (CH_4) by 14% [46].

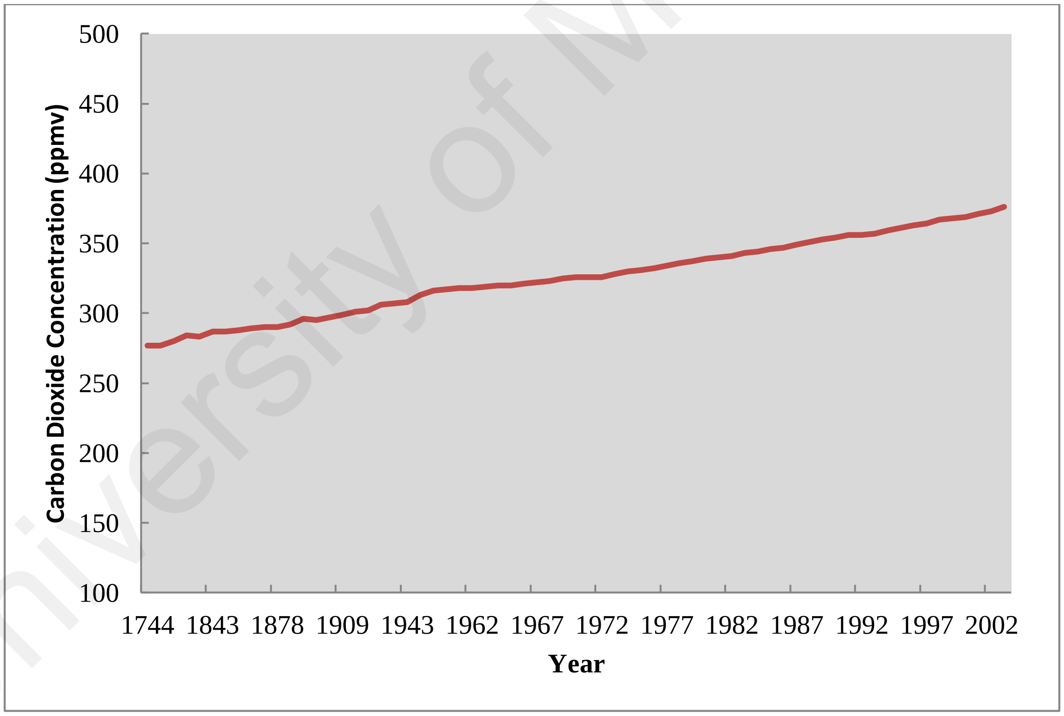

Figure 2.1: Global Carbon Dioxide Concentration (parts per million by volume) [47]

2.4.1 Climate change scenario

Predictions of climate change for the next 100 years are typically associated with the term scenario rather than the term prediction. Several uncertainties must be taken into consideration during the interpretation of future climate prediction, such as the unknown factor of the actual climate system's response to the changes in the atmospheric concentrations, socio-economic advancement and carbon emissions scenarios. On the other hand, for the quantitative evaluation of effects of climate shift on building operations, the regional climate variability must be considered.

For the past 10 years, the Intergovernmental Panel on Climate Change (IPCC) has put substantial efforts into characterising the possible effects of carbon emissions produced by human daily activities. The IPCC focused on developing an *atmosphere-ocean General Circulation Model (GCM)*, which is comparable with the model employed for weather forecasting. In this model, the equations are derived based on the physics of the atmospheric motion, which are solved by advanced computers. A high level of spatial resolution (5x5 degrees longitude and latitude) [41] is anticipated in the GCM. The main GCMs are *CSIRO2 (Australia)*, *HadCM3 (United Kingdom)*, *PCM (US)* and *CGCM2 (Canada)* [48].

The IPCC Work Group (WG) III has developed major storylines, which correspond to the possible variations of diverse social, demographic, environmental, technological and economic progress. Four emissions scenarios from the storylines, which reflect the range of potential climate change effects as defined by the IPCC, are [49]:

i. *A1 scenario family: rapid population and economic development, three groups of alternative energy system change: fossil intensive, non-fossil resources or balance among sources*

ii. *A2 scenario family: continuous population growth but fragmented economic growth*

iii. *B1 scenarios family: population peaks in mid 21st century; economic change towards service and information economy, clean and resource-efficient technologies at global level*

iv. *B2 scenario family: a local solution to economic, social, environmental sustainability; intermediate population and economic development*.

When combined within the GCM, the scenarios represent a range of potential climate impacts resulting in 16 combinations of climate predictions and scenarios.

Due to the increase of carbon emissions, the global average surface temperature has also risen since 1861(Figure 2.2). This is no surprise since the earth has been continuously warming over the last 12000 years since the last major ice age glaciations. The increase in global average temperature is the parameter that obviously indicates incremental warming. In the IPCC Fourth Assessment Report (AR4), the global average temperature has increased up to 0.74^{0}C since the 18th century. Additionally, the Third Assessment Report of the IPCC [48] predicts that over the period of 1990-2100, the global mean surface temperature will increase by 1.4˚C to 5.8˚C, and extreme weather events will become more frequent. There will also be an increase in temperature of up to 3.5^{0}C with the uncertainty of ±0.2^{0}C for different climate settings in the year of 2100 relative to 2000. Based on observations, 1996 was the single warmest year during the 147 years period of recording, and 1995-2007 were among the top 12 warmest years.

In Malaysia, climate change is determined by the mountainous topography and complex land-sea interactions. Since 1961, there has been an increasing temperature trend in Malaysia. According to the data obtained between 1961-1990 and 1998-2006 (Figure 2.3), Peninsular Malaysia has experienced a much higher temperature rise (0.5°C to 1.5°C) compared to East Malaysia (0.5°C to 1.0°C) [50] .

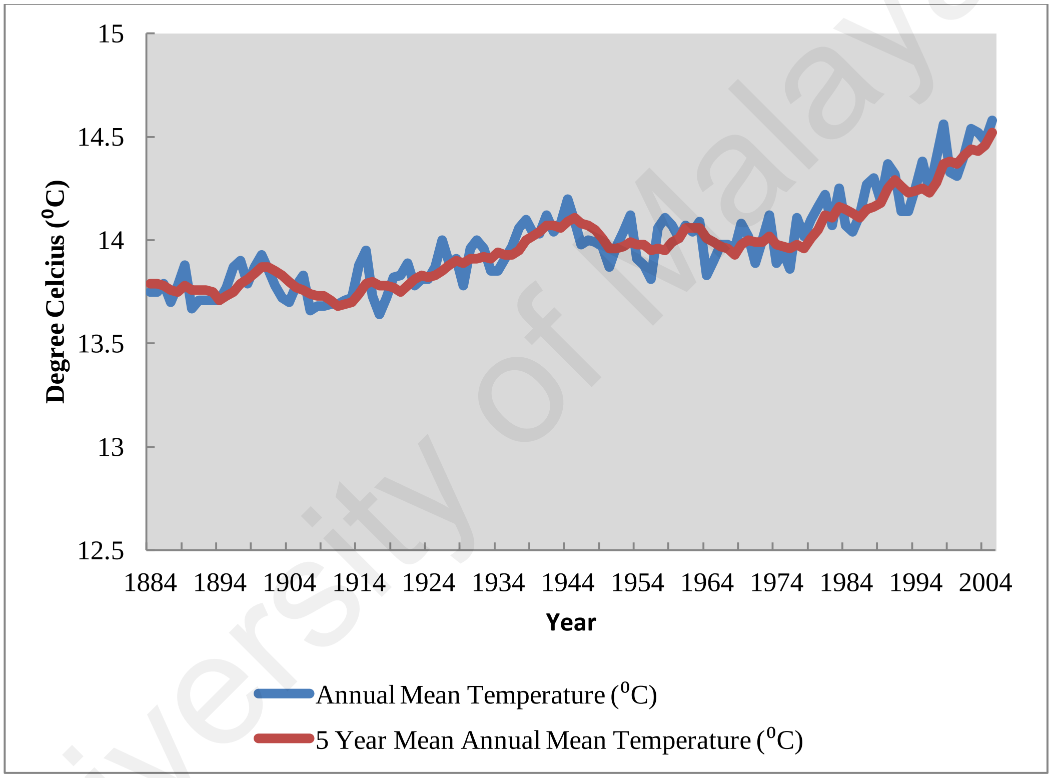

Figure 2.2 : Mean Global Surface Temperature 1880-2005 [47]

According to the Malaysia Meteorological Department, the annual average temperatures are projected to rise in 2028, 2048, 2061 and 2079. The highest temperature rise for Peninsular Malaysia is 3.7°C (December-February), Sabah 4.1 °C (March-May) and Sarawak 3.9°C (March and May) [50]. Based on the simulation of predicted temperatures for three emissions settings (A2, A1B and B2), the highest (obtained in A2 simulation) and lowest values (obtained in B2 simulation) of the annual surface temperature varies between 2.3 °C to 3.6 °C for Peninsular Malaysia and 2.4° C to 3.7° C for East Malaysia.

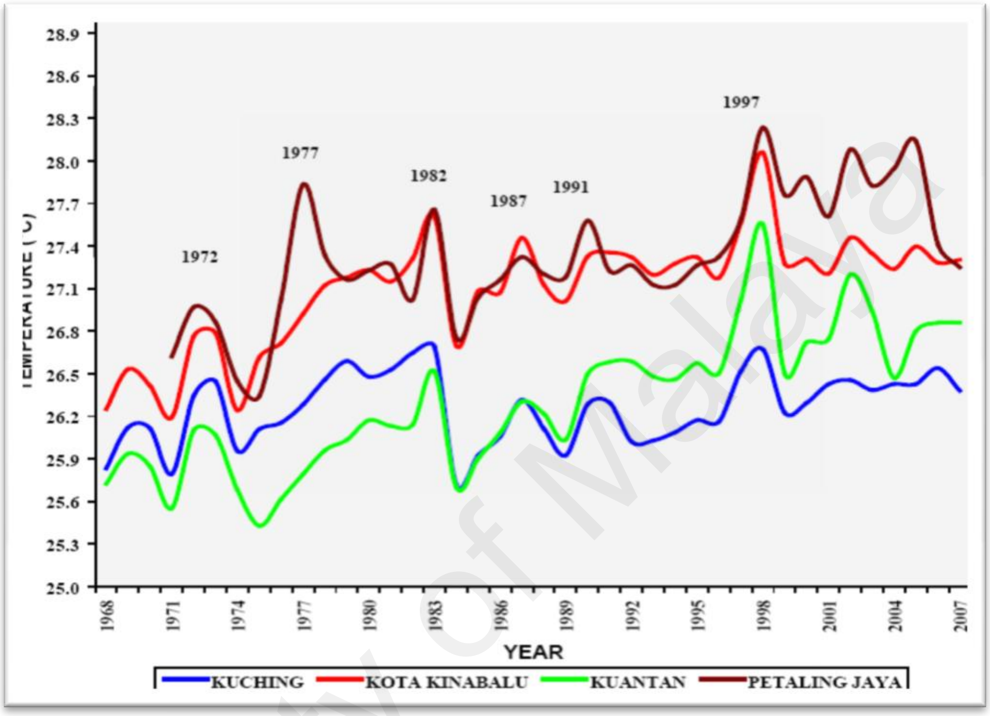

Figure 2.3: Seasonal mean temperatures for Peninsular Malaysia and East Malaysia, respectively [50]

Based on the climate change projections in the U.K., the average warming per decade was expected to rise between 0.1-0.3^{0}C for the low emission setting and 0.3-0.5^{0}C for the high emission setting [51]. Related to this, winters are anticipated to become wetter and summer to become hotter and dryer. By the 2020s, the frequency of wetter winters is likely to rise to 15% and by the 2050s; the frequency will increase to 25%. Meanwhile, by the 2080s, the number of cooling degree-days is predicted to rise by twofold in the south of the U.K. [52]. In the Third Assessment Report, it has been estimated that the area-averaged mean warming over the land regions of Asia will rise by 3^{0}C in the 2050's and by 5^{0}C in the 2080’s [48]. Related to this, the temperature rise would likely be notable across Asia during all seasons.

A research conducted by the Hadley Centre in the U.K. (2004) [53] proposed that the average global temperatures across Europe will rise by up to 2.4 and 5.4°C over the next century due to the high greenhouse gases emissions. Up to 2005, the carbon concentration in the lower atmosphere has risen dramatically from 280 ppm to 380 ppm. During pre-industrial times, the rise of greenhouse gas concentrations due to the increase of temperature was approximately 450 ppm carbon dioxide eq for 2.1°C, 550ppm for 2.9°C, 650 ppm for 3.6°C, 750ppm for 4.3°C, and 1000ppm for 5.5°C. According to the predicted emissions of carbon dioxide based on various emission scenarios, the highest carbon dioxide concentration was obtained in the A2 scenario compared to B2 and A1B. Based on the current practices regarding fuel type usage and socio-economic activities, the carbon concentration in the A1B scenario is expected to increase from 350ppm to 700ppm by the year of 2100.

2.4.2 The contribution of buildings to climate change

The Fourth Assessment Report of the IPCC (AR4) acknowledged that since 1750, the proportion of carbon emitted to the global atmosphere has been rising primarily due to human activities. Nowadays, in developed and developing countries, buildings sector are accountable for almost 40% of world energy consumption and approximately 30% of the overall greenhouse emissions [41]. The most important elements in the emission scenarios considered in the building energy consumption are the carbon emissions and environmental implications. Many commercial buildings are responsible for up to 200 tonnes of carbon emissions per square meter of floor space due to the electricity consumption during the operational phase [41].

In absolute terms, the Fourth Assessment Report of the IPCC (AR4) estimated building related carbon emissions to amount to around 8.6 million metric tons of CO_2 equivalent in 2004 [41]. Carbon emissions by definition describe the carbon dioxide emitted directly or indirectly by an activity. The main source of these emissions are the combustion of fossil fuels for cooling, heating, and lighting purposes, and to power electrical appliances. Apart from that, the buildings sector is also accountable for significant amounts of non-CO_2 greenhouse gases emissions such as halocarbons, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) due to their applications in cooling, refrigeration and, in the case of halocarbons, insulation materials. In 2004, it was estimated that buildings were responsible for approximately one third of global greenhouse gas emissions related to CO_2 and 60% of halocarbon emissions [41].

The emissions and electricity consumption of buildings are anticipated to increase by 2.5% per year for commercial buildings [41]. Buildings are accountable for a substantial proportion of energy-related emissions when emission footprints and life energy cycle use are taken into consideration [54, 55]. The greenhouse emissions can be divided into two categories. The first one are the direct emissions from the on-site combustion of fuels for heating and the second one are the emissions from the electricity used to cool, heat and supply power to the buildings. Some of the factors which affect building related emissions are energy, building design, building envelope, on-site distributed generation, energy end used in buildings, lighting, air-conditioning, space heating and ventilation [56].

Perez Lombard et al (2008) [57] in their review paper believed that buildings should be considered separately and become the third main sector in energy consumption, which can be divided into domestic and non-domestic buildings. Energy consumption in buildings comprises a significant proportion of the services shared with the other main sectors such as transport and industry. The increase in buildings' energy use to the level of transport and industry is due to the enhancement of buildings' technical services, growth in population, increasing demands on comfort levels as well as the rise in time spent inside buildings [58].

Obviously, the buildings' operational phase consumes the largest fraction of their energy use. Mechanical systems such as air-conditioning have enhanced the development of buildings that depends on the high-energy input for their daily operation which is totally different with building in the past. Nowadays, all high-rise buildings depend on mechanical systems such as elevators and pumps to raise the water to the high levels. In addition, artificial lighting, air-conditioning system and ventilation is needed in the offices which are distanced from the façade. Building with shell glass and steel which is not properly insulated faced a hard time to adjust with the inner climates without excessive air-conditioning usage, especially in dry and humid climates [59].

According to studies, the buildings' operation phase produces approximately 80% of carbon emissions to meet several energy requirements for heating, cooling, lighting, ventilation and other electrical appliances [60]. Perez et al (2008) [57] in their review addressed the fact that heating, ventilation and air-conditioning (HVAC) in developed countries are responsible for 50% of energy consumption in buildings and 20% of the final national energy consumption. Additionally, Kwok et al (2010) [54] reported that in the US, nearly 40% of the amount of principal energy needs is consumed by buildings, of which 34.8 % is used for HVAC equipment. The environmental impact of HVAC equipment is caused by the usage of electricity, water, refrigerant and embodied energy.

In the US, space conditioning accounts for 30% of the energy use in commercial sector and almost 14.3% of this energy is used for heating, ventilation, air conditioning and refrigeration (HVACR) and products including the heating, cooling and parasitic equipments. In the commercial building, almost a quarter of the energy is consumed for lighting, 42% for HVACR and the remaining amount is used by the electronics equipments. Overall, the HVACR energy use in the commercial buildings represents over 6% of the total country emissions in the U.S, 4% of approximately 21 Metric tonne (Mt) of the total country emissions in Australia and 1-2% of the total country emissions in India. However, in the case of India, this percentage is increasing extremely fast for electricity demand in commercial buildings [61].

The energy consumption during the operational phase of a building are influenced by several interconnected factors, such as climate and location, level of demand, supply, and source of energy, function and use of the building, building design and construction materials, and the level of income and behavior of its occupants. Climatic conditions and the type of environment in the building affect every aspect of a building's energy consumption over its lifetime. More significantly, the level of greenhouse gas emissions from buildings is directly related to the level of demand, supply and source of energy. In 2009, buildings' operational phases consumed 77% of all the electricity produced at power plants in the US, while in Japan, the average annual energy consumption during the buildings' operational phase was determined to be 1.21 GJ/m² and their average annual carbon emissions were about 87 kg/m² [62]. Beatriz et al (2010) [63] addressed that the carbon emissions due to the electrical consumption are much higher compared to diesel and gas. From observations made from a sample of 31 hotels, 81.6% of the carbon emissions were found to be caused by electricity consumption. The large carbon emissions factor in the electric generation system in the Balearic Islands is accountable for these results.

The generation of electricity itself is the main cause of the production of greenhouse gases. At the global level, it has been estimated that direct combustion of energy from fossil fuels in buildings has discharged approximately 3 Giga tonnes (Gt) of CO_2 in 2004, compared with 8.63 Gt of CO_2 per year from all energy and users [41]. Generally, buildings can be categorised into residential and non-residential buildings. In most countries, the residential sector is accountable for the greatest fraction of total primary energy use. Nevertheless, the energy consumption in commercial buildings such as offices, shopping malls, hospitals and government buildings is also growing drastically.

Currently, US commercial and residential buildings consume approximately 3800 quadrillion Btu of principal energy, including the losses during electricity production, which emits approximately 0.6 Gt carbon [64]. In Canada, the total of energy use in the building sector was 614 TerraWatt hours (TWh) in 1999 and contributed more than 10% of

Canada’s total carbon emissions (approximately 699 Mt CO_2 equivalent greenhouse gas emissions). In 1999, total emissions from this sector were 71.9 Mt; 43 Mt (60%) from the residential sub-sector and 28.9% (40%) from the commercial and institutional sub-sector [65].

In Brazil, the building sector including the commercial, residential and public services is accountable for approximately 20% of total energy use and for about 42% of electricity use. In total, the residential sector consumes 23% of the country’s electricity while the non-residential sector is responsible for 19% of the consumption [66]. In low-income countries such as sub-Saharan Africa, the residential sectors consume as much as 56.2 % while commercial sectors only consume 2.2% of the total energy use [67].

Similarly, buildings in China are liable for 42% of the energy consumption, where the commercial sector covers about 8%, while the residential sector alone covers the remaining [68]. In India, the electricity consumption stood at 587 billion kWh in 2006, where 8% was being used by the commercial sector and 25% in the residential sector. Commercial buildings use 32% of the electricity consumption for air-conditioning, 60% for lighting and 8% for other equipment. Emissions in the commercial sector can be estimated at between 11 to 14 Million Metric tonnes (MMt) due to the implementation of mechanical ventilation [61].

Meanwhile in the ASEAN region, commercial buildings are accountable for 30% of all the electricity use and will demand approximately another 40% of generation capacity in years to come [69]. In 2004, commercial buildings in Malaysia were accountable for 75% of total national energy consumption while the residential buildings accounted for 44%. Typical office buildings in Malaysia use more than 260 kWh/m²of energy per year and are responsible for almost 21% of total national commercial energy consumption [70]. Related to this, the energy consumption of office buildings is estimated to be around 6090 GigaWatt hours (GWh). The main energy users in office buildings are air conditioners (57%), lighting (19%), pumps and lifts (18%) and electrical appliances (6%) [71]. Building energy consumption of different countries and building sectors are summarised in Figure 2.4.

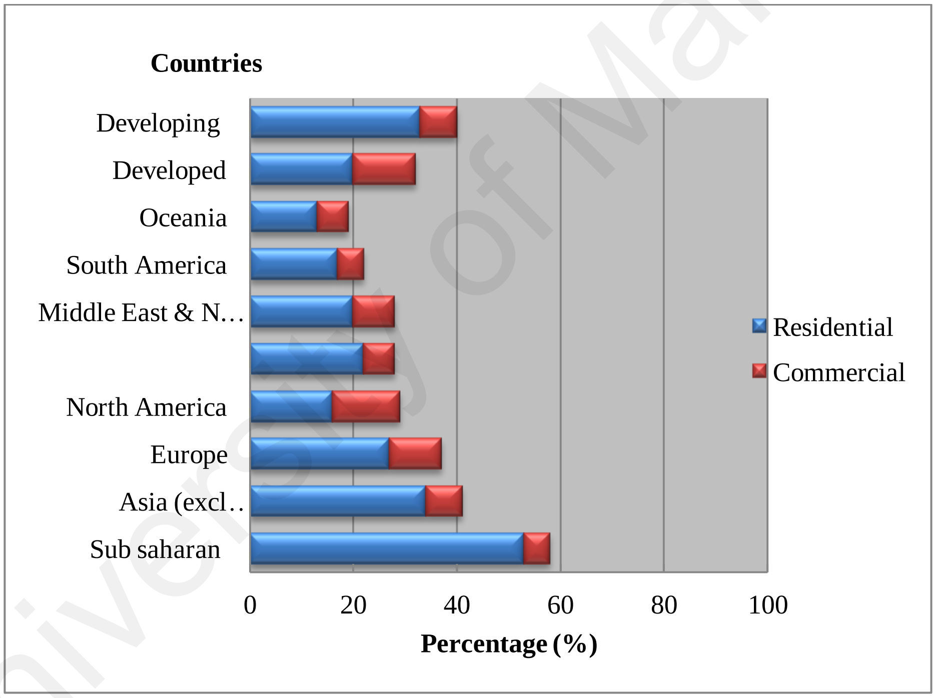

Figure 2.4: Percentage of energy use in commercial and residential building in the world [72]

2.4.3 Climate change impacts on buildings and their technical services

The typical life span of a building is estimated to be from around 60 to more than100 years, thus the implications of different climate change scenarios on buildings should be considered in advance to enable the society to adapt to these changes in the future. Historically, variability in regional climate has significantly affected building performance across the world. Numerous studies have been carried out to estimate the impacts on buildings and their technical services under changing climate. Most of these studies have focused on analysing the climate change effects on energy consumption, electricity and related greenhouse gas emissions. Until now, few studies have concentrated on the potential impacts in tropical regions, especially in Malaysia, Singapore and Indonesia.

2.4.4 Climate change impacts on building sustainability and indoor environmental quality

Undoubtedly, climatic variability has led to physical damage to building structures. For instance, buildings are exposed to faster degradation and damage due to the increase in wind speed, level of precipitation, long exposure to sun and temperature changes [73]. In addition, some parts of the building external envelopes are subject to extensive degradation across Europe due to the long exposure to ultraviolet radiation and increased frequency of frost occurrence. According to K.R. Lisa (2001) [74], during the New Year's Day in 1992, the hurricane in northwestern Norway had caused damages to buildings which cost nearly NOK 1.3 billion, while several buildings had collapsed due to heavy loads of snow throughout Northern Norway during winter of 1999-2000. Additionally, most of the buildings in Eastern and Southern Norway were badly damaged due to heavy rainfall over long periods during autumn.

Another study conducted by Graves et al (2000) [75] addressed the fact that the sustainability of building envelopes was badly affected by the increases in driving rain quantities and the frequency of intense weather events in several parts in England which in turn, increase the buildings' maintenance costs. This study indicates that the cost of repairing damaged buildings due to the increase in wind speeds by 6% adds up to approximately £1-2 billion [76]. Higher wind velocity, increase in precipitation and frequent temperature changes could weaken the buildings' structure, loosen the roofing, and cause damage to the cladding, overhead electric and telephone connections. Wind driven rain in combination with increased in precipitation and wind loads amplified the weathering of high rise buildings [77]. Spence et al (1998) [78] found in their study that an increase in wind speed from 40-45 m/s would increase the number of damage incidents by a factor of five. Typically, older buildings are more vulnerable to wind damage. There are other cases in Denmark which prove that abrupt climate change is responsible for the collapse of old buildings. For instance, in Oslo in 2006, an apartment built in the late 1880's had fallen apart due to the wet weather and frequent temperature changes [79].

A similar study undertaken in Norway [74] noticed that most structural damages in buildings were due to water and moisture. Recently, the undesirable impacts of wet materials on the quality of indoor air and the ensuing health problems have been widely discussed [74]. Dampness and moisture might accumulate in the building's structure through leaks in the roof, windows or piping, or due to the insufficient ventilation or moisture from the ground which penetrates the building's structure by capillary movement. Long exposure to mold can lead to other respiratory problems, while more droughts and wildfires can result in more particulate air pollution such as by dust and smoke.The particulates from the air, which accumulate in the building, could affect the lungs and heart health. The related adverse health effects vary from irritation of the respiratory system and mucous membranes and infections to permanent diseases such as allergies and asthma.

Flooding in Oxford, U.K, back in December 2008, for example, had effects on the building structure and caused health problems due to the increased humidity and mold growth. Increased precipitation and indoor humidity, which leads to mouldy interiors of buildings, has the potential to extensively increase the airborne exposure to fungi, including mycotoxin that produce microbial volatile organic compounds (MVOCs) [80]. Additionally, the release of chemicals and particles from building materials, bacteria, dust mites and other pests was found to increase with dampness, which can be allergenic in the indoor environment of the buildings [81]. In fact, faster growth of micro-organisms at higher germination power rates occurs at higher precipitation and temperature. This affects the species of microorganism growth, which may result in enhancement of more significant aesthetical damage on building materials [82].

Other phenomena such as summer heat waves had led to the increased in usage of air conditioners which produce a cycle of additional energy consumption and contribute to global warming even further. The main climatic variables that determine the amount of energy required for air conditioning are solar radiation, outside air temperature, wind, rain and night sky radiation. The increased usage of air conditioning and fans necessitated by the rise in temperatures mostly leads to higher radon concentrations ensuing from decreased air exchange rates, particularly for tightly sealed buildings. The usage of air conditioning in closed buildings results in higher radon concentrations. The use of forced air by HVAC systems tends to reduce the stratification of radon between floors, thus increasing the radon concentrations on the upper floor where the occupants spend most of their time [83]. In addition, higher internal temperatures will increase the release of solvents and other pollutants from building materials and furnishings into the air. For instance, higher temperatures in the walls and cavities of buildings will increase the release of formaldehyde into the internal building space [84].

Likewise, long exposure to Ultraviolet (UV) radiation will also damage the building materials, such as plastics, paint and coatings such as specific hydrophobic and antigraffiti coatings, rubber products, wood and paper. Moreover, escalating amounts of plastic usage in building construction will also add to the plastic degradation problems [79]. Higher temperatures in combination with longer exposure to UV radiation may also expedite the degradation of roofing materials as roof materials are exposed to wind, rain, snow, hail, sunlight and temperature swings. Besides, higher temperature and annual precipitation influenced the conservation and durability of building materials. At the same time, high precipitation during winter will possibly result in more intense damage of the building materials due to frost [82].

2.4.4 Impacts of climate change on traditional air-conditioning and mechanical ventilation systems in building

At present, most of the buildings in Europe opt to use natural ventilation and do not implement the electricity-using cooling appliances such as central air conditioning units and ventilators as an effort to reduce environmental and cost impacts [85]. However, this is gradually changing. Recently, energy consumption related to heating, ventilation and air conditioning (HVAC) have been increasing throughout Europe [57]. As the temperatures continue to rise, the cooling potential of natural ventilation has decreased. Thereby, the demand for space cooling during summer will rise due to the increase in internal temperature during summer heat waves. One of the energy requirement studies carried out in Athens, Greece indicated that the energy demands by the 2080s will rise by 30% during July and August [86]. Humphreys [87] in his study proved that people's comfort temperature in a free-running building has a strong linear relationship with the average outdoor temperature. This study demonstrated a strong relationship of people's expectation and knowledge about the indoor climate according to the outdoor climate variability. Thus, the increased in temperature will definitely affect the occupant comfort in the future.

Back in 1994, only 10% of the U.K.'s large buildings used air conditioning [88]. Currently, about a quarter of the UK's large buildings are estimated to have air conditioning and by 2020, this percentage is projected to rise up to 40% [89]. However, most of the buildings that were constructed before 1990 are naturally ventilated and has been proven to function poorly during summer heat waves [90]. This has escalated the urgency for the U.K. government to have a proper climate change weather file to assess the building performance. The prevalent trend of using glass facades on 'sealed' buildings has increased the risk of overheating and the reliance on energy intensive mechanical cooling systems in London's buildings. Furthermore, the increase in average summer temperatures of 0.73^0C per decade over the past 30 years in London has also increased the risk of internal overheating [91]. The projected rise in both average and extreme temperatures will make London's buildings more uncomfortable, more expensive to operate due to high cooling energy costs and potentially dangerous to the occupant's health due to the high internal temperatures in poorly ventilated offices. These changes could result in productivity reduction, the need for retrofitting mechanical systems ventilation and depreciation of property values [91]. In addition, climatic variability will also affect the comfort and performance of building technical services due to the inconsistent power outages and quality, prolonged cold and rainy seasons, flooding, intense heat waves and winter storms [12]. Jentsch et al (2008) [92] in their study came to the conclusion that appropriate actions such as usage of thermal mass, external solar shading and well designed ventilation strategies such as night cooling can keep the naturally ventilated buildings more comfortable during hot weather. All of these are required to ensure that naturally ventilated buildings in the U.K. and other countries can perform well during extreme weather events.

In a different study conducted in Iran by Delfani [93], the increased in outdoor dry and wet bulb temperature together with moisture content in the air have caused the greenhouse effects to intensify. In addition, the latent heat gain and humidity content of the outdoor air during the summer season has also risen, thus causing buildings to increase their cooling load. Under these conditions, better HVAC equipment is needed for dehumidification of air in order to achieve acceptable comfort conditions [93]. The rise in humidity level due to the changes in wet bulb temperature has caused the direct evaporative coolers used to cool buildings incapable of achieving the appropriate comfort conditions in the humid climate, thus the implementation of high consumption chillers has become necessary [93].

In the same study, findings showed that the cooling equipment performance depends on the humidity and outdoor temperature. He concluded that the cooling devices' performances in a building are strongly affected by the changes in climate. The wet bulb temperature (WBT) and wet bulb depression (WBD) decrease drastically due to the change in outdoor moisture content as a result of climate change. For 1% rise in outdoor design conditions of hot seasons, the DBT has increased from 36.96 °C in 1967-1976 to 37.23 °C in 1997-2006, while the WBT has increased from 18.66 °C to 21.97 °C, thus affecting the efficiency of cooling devices. Thereby, the cooling demands during this period will likely increase due to the increase of WBT.

In Hong Kong, a study by Lam et al (2004) [94] found a fundamental trend of temperature increase in recent years, particularly in the last ten years. During 1961-1970, the DBT has increased by 0.4°C while the WBT has increased by 0.5°C. Investigations on seasonal factors found that the temperature increases happen during mid season and winter due to warmer winter periods. For instance, the DBT during the 10-year period rose by 0.1, 0.6 and 0.3 °C in summer, winter and seasons between correspondingly. In contrast with Delfani [93], this study indicated that there will be no significant impacts on energy use, particularly in cooling, due to the temperature increase in subtropical Hong Kong. However, this study has not included the global warming effects during the summer period in the subtropical climate, and the existing design should be analyzed using current weather data to evaluate the effects on building energy consumption.

2.4.5 Impacts of climate change in building's heating and cooling energy consumption

The most apparent and significant implications of climatic variability on electricity usage in buildings are the effects on the cooling and heating energy consumption. Numerous studies have been conducted to predict commercial building energy consumption. Currently, increasing demand for appropriate thermal comfort during cold winter and hot summer is leading to the increase in building energy consumption [95, 96]. Previous studies have discovered that there has been an important trend of temperature increase over the past few years resulting in decrease in comfort in winter and further discomfort in hot summer [45,48]. The methodology used to determine the changing patterns in heating and cooling demand is traditionally established on a formal relationship based on changes in degree-days, energy requirement prior to cooling and heating, and expected changes in cooling market penetration. The location of the country strongly affects the number of heating degree-days. Typically, the number of heating degree-days of a country situated far from the equator is greater than its cooling degree-days.

Many studies have predicted climate change effects on energy requirements. A study conducted by Belzer et al (1996) [97] determined the impacts of temperature variability and building features on energy consumption in large buildings using the detailed Commercial Building Energy Consumption Survey (CBECS) data on the United States (US) commercial buildings. The Belzer model projected a decline in yearly energy needs for heating and a rise in annual cooling energy demands. In addition, Sheppard et al (1997) [98, 99] carried out a separate study to analyze the consequence of climate shift on energy consumption in large buildings in the Sydney region. In this study, it was estimated that the energy consumption would increase by 10-17%, mostly due to the increase in carbon emissions to the atmosphere.

In another study conducted in the U.S., Considine et al (1999) [100] found that the climate variability had a strong impact on natural gas and electricity demands. In a follow up study [101], he studied the implications of weather variations on monthly energy requirements among different users and concluded that energy demand in all sectors is vulnerable to variability in degree-days. He also found that the elasticity of heating degree-days have significant effects on energy use and emissions impacts, as the elasticity of heating degree days is greater than the elasticity of cooling degree days. However, his study does not focus on the potential climate change implications on user demand.

Another study carried out by Frank (2001) [102] concluded that office building cooling energy will rise by up to 1050% as the number of cooling days increases. The calculations demonstrated that the building energy demands for space heating in all climate settings are highly affected by the thermal insulation level. Generally, the life span of buildings in Switzerland is approximately a century and historically, engineers and architects have presumed that the outdoor climate would not change according to the statistical data compiled over 30 years ago. He suggested that this particular approach under the Swiss SIA Standards [103] has to be reassessed and the building weather design standards, particularly during hot summers, have to be reevaluated. However, this study was not entirely adequate since only a few building parameters were systematically analyzed.

One of the studies carried out in New Zealand [104] stressed that the climate change risk plans and rating tools are crucial for future revisions and assessment of building codes. Generally, most studies on energy demand to date have applied the cooling and heating degree-day approach [105, 106]. However, only a few studies have employed detailed numerical simulation modeling [107]. Most of these studies predict a drastic increase in the cooling energy requirements, which compensates for the huge decrease in heating energy requirements.

Christenson et al (2006) [108] in their study investigated the effects of climate change on building design specifications to determine the energy required for heating and cooling. They found that in years to come, energy required for heating in Switzerland would drop significantly depending on the magnitude of temperature increase, building location and quality. In addition, the future relative decrease in heating energy use is predicted to outweigh the reduction in heating degree-days in buildings with high internal and solar gains. However, contrary to this, the potential cooling energy demand is expected to increase significantly from 50-170% between 1901 and 2003 based on cooling degree days at the 18.3°C threshold. In the period of 1975 to 2085, the cooling degree-days are estimated to rise by 2100%. Findings from other study concurred that there will be more cooling degree-days compared to heating degree-days [109]. Thus, electricity demand related to heating and cooling will change, as more cooling and less heating is needed. Presently, nearly all countries in the world depend on electricity for space heating and cooling. The generally obvious trends of increases in cooling and declines in heating demand validate the results from earlier studies [97, 106, 110, 111].

De Cian et al (2007) [112] in their empirical study proposed that lower energy use is expected during the winter in colder countries such as Canada and Norway and higher energy use during summer and spring in hot countries such as Mexico. In mild countries such as Italy, the additional energy required during summer is evened out by the decline in demand for gas, oil products and coal in winter and spring. In colder countries, the elasticity of electricity requirements due to winter temperatures is -0.21, while in warmer countries it is 1.17. This implied that the demand for electricity would increase by up to 1.17% in hot countries and decreased by up to 0.21% in colder countries for a 1% increase in summer temperature, which is similar to the conclusions from a previous study by Considine et al (1999) [100]. A very similar study conducted by Eskekand et al (2009) [113], which yielded the same results, concluded that the demand would change by 2kWh per capita due to the variability in heating degree days, and by 8kWh per capita in cooling degree days for a unit increase in temperature.

Meanwhile, Scott et al (2007) [114] in a current review of U.S. energy systems identified that energy consumption is subject to a 5% change for 1°C increased in temperature. The same effects would also be experienced by Australia and New Zealand as reported by the IPCC. For instance, the demand for energy in New Zealand would increase by 3% for 1°C increased in winter temperature. In addition, Mansur et al (2008) [115] found that residential and commercial buildings will consume energy in the form of oil, gas and electricity due to warmer summers and cooler and wetter winters. They concluded that the climate change will decrease the usage of other fuels for heating and would likely raise the electricity consumption for cooling.

Radhi (2009) [116] in his study in UAE identified that there will be significant positive impacts on the heating degree-days and negative impacts on the cooling degree-days. The heating degree-days, particularly under scenario 4, will have a sharp drop, where the decrease reaches 100%, while the cooling degree-days will steadily rise up in the range of between 16% to 27% in 2050 and 22% to 42% in 2100. Related to this, a drastic change is expected in the proportion of energy consumption through air conditioning usage to attain acceptable comfort during the hot summer in Al-Ain city. A different study that reached the same results was conducted by Jaber et al (2003) [117], who found that electricity consumption in commercial buildings is comparatively high due to the usage of air conditioners and ventilation resulting from the hot and dry climate during the summer in Jordan. However, there are no data available related to certain or different types of commercial buildings' energy consumption and performance to date.

Overall, the impacts on heating and cooling requirements are obviously critical under the changing climate and the findings are coherent throughout all studies in different seasons, periods and regions (Table 2.6).

Table 2.6: Climate change impacts on heating and cooling energy consumption

Study: Author(s), Date and Place	Change in energy consumption (%)	Temperature change (°C) and Date for Change
Rosenthal et al **1995, USA**	Cooling: +15% Heating: -16%	1°C (2010)
Belzer et al **1996, USA**	Cooling: + 53.9% or + 9.0-13.8 % Heating : -29.0 to -35%	3.9 °C or 1°C (2030) 1°C (2003)
T. H. Frank **2001, Switzerland**	Cooling: +1050%	4.4°C (1984-2003)
J.C. Lam **2004, Hong Kong**		WBT + 0.5°C (1961-1070) DBT + 0.4°C (1961-1970)
Scott et al **2005,USA**	Cooling: +9.4 -15% Heating: -5% to -24%	1°C (2020) 1.7°C median (2020)
Christenson et al **2006, Switzerland**	Cooling: + 50-170%	At Cooling Degree-Days (CDD) 18.3 °C threshold (1901-2003)
Huang **2006,USA**	Cooling: +17% +36% +53% Heating: -12% -22% -33%	 1.7°C (2020) 3.4°C (2050) 5.3°C (2080) 1.3°C (2020) 2.6°C (2050) 4.1°C (2080)
De Cian et al **2007, Italy**	Electricity demand + 1.17 % (hot country) -0.21% (cold country)	For +1% rise in summer temperature

Radhi 2009,UAE	Cooling degree-days (CDD)	
	+ 16-27%	2050
	+ 22-42%	2100
Delfani 2010,Tehran		For +1% rise in outdoor temperature: WBT + from 18.66°C (1967-1976) to 21.97°C (1997-2006) DBT + from 36.96(1967-1976) to 37.23 °C (1997-2006) WBT +18.66°C from (1967-1976) to 21.97°C (1997-2006)

2.4.6 Impacts of climate change on electrical peak demand and energy consumption in building

Many studies have been conducted regarding the climate change effects on energy consumption and peak demand. Nearly all of the studies estimated the impacts based on the traditional approach by degree-days. All of the studies showed a drastic increase in cooling energy demand and a sharp fall in heating energy demand. Sailor (2001) [118] and Rong et al (2007) [119] in their study on the effects of current and potential climate shifts particularly on cooling and heating requirement in the U.S. demonstrated this clearly. Moreover, the results from Aebischer et al’s (1998) [120] study also confirmed this by showing that the growth of cooling energy demand by 2035 under the changing climate will probably offset the decline in the heating energy demand. However, studies on climate variability in the dry and hot countries in the Middle East and the effects on HVAC systems have not specifically been conducted up to now [93].

According to one of the studies carried out in Australia, the erratic weather patterns are anticipated to have strong impacts on energy consumption, particularly on the electrical peak demand [121]. The cooling energy requirements are predicted to increase due to the warming climate and may subsequently offset the advantage of the heating energy savings [102, 122]. BRANZ in a comprehensive study on the climate change effects on different building types in Australia stated that the ongoing climate change will strongly affect the energy consumption in buildings [123].

During hot summer days, the risk of demand not being met seems to be escalating due to the air conditioner usage in all cities worldwide [124]. Global warming increases the magnitude of peak demands, resulting in the need for additional generating capacity to be installed at considerable cost with uncertain implications on greenhouse emissions. The increase in air conditioner usage has increased the sensitivity of electricity demand to hot summer weather [124]. Mansur et al (2005) [125] in their study disclosed that building electricity consumption would decline by about 3% for 1°C rise in January temperatures. The warmer temperatures would have a strong impact on fuel oil consumption, as the fuel oil demand would increase by 12% per 1°C increase. Warming is predicted to have the greatest impact on the heating degree-days in the countries where fuel oil is most dominant. In fact, most of the energy consumption of older vintage commercial buildings which use fuel oil, is more sensitive to temperature swings.

In a study conducted in Australia, Howden et al (2007) [121] found that the range of response of electricity demand to climate change is similar to that in the U.S.. In the U.S., for 3°C increased in temperature, the average electricity demand will rise by 3.5 to 13% for tropical locations, 2.5 to 7% for temperate locations and decrease the demand by about 5% in cool locations [126]. Findings showed that the frequency and variability of intense weather events such as heat waves would have significant implications on the peak electricity demand for cooling.

Extreme warming is anticipated to raise the energy demand for space cooling in most countries that use electricity. Apparently, in most of the studies, the effect of the climate warming is not necessarily related to the humidity and temperature, given that the amount of the impacts is higher than the temperature shift [126]. Several studies predicted that increases in cooling demands in the long term would outweigh the decreases in heating as the temperature continues to increase [56]. These impacts, however, are not necessarily discovered in studies on the climate change predicted in the U.S. during the 21st century.

Other studies conducted in commercial buildings have demonstrated that commercial buildings are less responsive to temperature changes for space cooling when compared to residential buildings. Related to this, Rosenthal et al (1995) [110] stated that the commercial buildings' cooling increased by 15% while the residential buildings' cooling increased by up to 20% per 1°C increase. The same applies to commercial buildings' cooling requirements in Scott et al's (2005) [127] study: a 15% increase per 1°C change.

Hadley et al (2006) [128] conducted a study using the Degree-Das National Energy Modeling System (DD-NEMS) energy model. This model had provided an overall estimation of energy demand, supply and price response in a market model. However, the drawback of this model is that it only predicted until the year 2025, when the climate changes are about to directly influence the energy requirements. This study suggested that the rise in cooling demand will offset the decline in heating demand. Nevertheless, the rise in cooling demand was predicted to dominate elsewhere in the country.

Huang et al (2006) [129] took their study in a new direction and found that the climate variability effects on energy requirements in large buildings are highly dependent on the building types and climate change scenarios. The simulations illustrated a 9.2% decline per 1 °C change in energy consumed for heating. Huang's study showed that energy demand in colder regions will drastically decline compared to that in temperate regions. In 2020, he predicted a drastic rise in cooling energy consumption, a 10% increase per 1°C change. According to the analysis, the electric energy use is predicted to increase by 10% to 15% in the future. Additionally, based on the econometric study, the usage of electricity will also increase due to the variability in electricity consumption such as lighting and plug loads.

In the same study, Huang et al (2009) [129] addressed that by 2020, the site energy use in U.S. building stock would decrease by 7% due to the 1% decrease in primary energy corresponding to the losses in electricity during generation and transmission. His study estimated that the demand for cooling in commercial building would increase while in contrary, the demand for heating would decline due to less exposure to outdoor conditions and their large internal heat gains. Accordingly, the same trend is expected in other building types such as malls and hotels. However, this study does not consider the socioeconomic factors of climate change adaptation strategies.

It is projected that in 2050 and 2080, newer sealed buildings will need more cooling and less heating compared with older existing buildings due to the impacts of further increases in temperature. The cooling loads are predicted to rise by 85% in 2050, while in contrast the heating load is predicted to decrease by 28% as a result of global warming across all building types and climate change scenarios. Meanwhile, in 2080, the heating requirements have been estimated to decline by about 45% and the cooling requirements to increase by about 165%. Related to this, the ratio of cooling to heating energy consumption in 2080 is approximately 60% in site energy.

Most studies to date on building energy demand for cooling and heating have been based on simplified analyses using the constant rise in annual average temperature or changes in cooling or heating degree-days. Results from these studies appeared to be insufficient and imprecise to illustrate the climate change implications on building energy technologies. For instance, the insufficient information on solar radiation, humidity and diurnal temperature changes makes it hard to evaluate the implications of climate variability on certain types of HVAC system usage, such as evaporative cooling, night cooling, natural ventilation, radiant slab cooling and other equipments.

Xu et al (2009) [130] in their study in California take a step further and develop more detailed hourly weather data and models to investigate the California specific impact of global warming on buildings' energy consumption. This study utilized the archived General Circulation Model (GCM) projections and statistically downscaled these data to the site scale to be used as an input for building heating and cooling simulations. They concluded that electricity consumption for cooling would rise by more than 50% over the next 100 years. The cooling electricity consumption will rise by about 25% for the A2 scenario and between 2 to 8 percent for all three IPCC carbon scenarios analyzed in this study. Generally, cooling energy consumption will rise while the heating energy will decline for all kinds of buildings. However, small buildings are more sensitive to climate change than larger buildings because the percentage of envelope heat gain and heat loss of small buildings is greater compared to the large buildings. In addition, the peak electricity demand will rise in certain types of buildings that are more sensitive to climate change. Nevertheless, this study is a preliminary step of applying future hourly weather data to predict the effects of global warming. A follow up study should be conducted to address the implications of climate change on existing buildings as most of the buildings were built according to weather files in the past.

2.4.7 Impacts of climate change on buildings' carbon emission

As the observed atmospheric carbon dioxide increases, the near surface air temperature is predicted to increase as well. Of all the impacts of warming, the most important and well-studied is the impact of increasing greenhouse gases emissions due to the changing pattern of energy demand, particularly for cooling and heating in buildings. Generally, the climatic variability has strong impacts on energy consumption in commercial buildings. Energy demand and consumption in a building depends on the building activities, total floor space, building shell efficiency and heating and cooling capacity [128].

From the viewpoint of emissions, temperature swing will strongly affect the primary energy losses especially during electricity generation. As more cooling is needed compared to heating, primary energy will change by a different amount compared to the energy demand. The primary energy will differ from the energy demand as electricity is consumed more for space cooling compared to heating. The rise in cooling demand due to the temperature rise would outweigh the decline in heating demand. Thus, the changing pattern in energy use will strongly affect the fossil-fuel carbon emission[131, 132]

In one study conducted by Hadley et al (2006) [128], they predicted that the 1.2°C scenarios would led to a cumulative (2003-2025) energy rise of 1.09 quadrillion Btu for cooling/heating requirements. For a 3.4°C scenario, the decreased heating requirement would produce a cumulative (2003-2025) heating/cooling energy reduction of 0.82 quads due to temperature increases during the winter months. Nevertheless, in both scenarios, the rise in carbon emissions from electricity generation offsets the carbon emission decreases due to the reduced in heating requirements.

Another study by Isaac and van Vuuren (2009) [133] projected the world's energy heating demand will rise until 2030, and later stabilize for the scenario applied. In contrast, the energy required for cooling purposes is predicted to increase dramatically between 2000 and 2100, mostly due to the increase in income. The carbon emissions associated with heating and cooling rise to 0.8 GtC and 2.2 GtC in 2000 and 2100 respectively; which is approximately 12% of the total of carbon emitted into the atmosphere due to energy use. In addition, the global carbon emissions in the reference scenarios will increase in 2100, where the emissions increased to more than 0.3 GtC under the changing climate due to the changing patterns in energy demand. The rise in emissions is due to the fact that the emissions factor for electricity is considerably higher compared to fuels. This will definitely affect India and China due to the increased use of air conditioning as it contributes to global warming even further. Currently in India, total emissions rise steadily with the increased usage of air conditioners. Somewhat in contrast, in China the initial rise was much more drastic, but will stabilize later on due to the earlier implementation of air conditioners in China due to higher incomes and larger prospects of decrease in heating energy demand. In other parts of Asia, the study indicates a clear increase in emissions due to the temperature rise while in the U.S., lower emissions are expected in agreement with the findings of the United States Climate Change Science Programs (USCCSP) (2006).

2.5 TRNSYS simulation

TRNSYS stands for TRaNsient System Simulation is a simulation program with a modular structure. It is a transient thermal energy system simulation program first developed at the University of Wisconsin-Madison. The software identified the system description language based on the system which consists of components that are linked together. Basic components in thermal and electrical energy system, components for weather data input, time-dependent forcing functions and output of simulations are provided in the TRNSYS library. In addition, the modular nature of TRNSYS software provides flexibility to the programme as it could also handle other mathematical models which are not included in the standard TRNSYS library. Detailed analysis of any system that depends on time could be carried out in TRNSYS. This software has been widely use in the solar systems application, low-energy building, HVAC and renewable-energy system.

Simulation Studio (TRNSYS 16) is a complete simulation package containing several tools, from simulation engine programs and graphical connection programs to plotting and spreadsheet software. It is an integrated tool which can be used from the design of a project to its simulation. TRNSYS 16 is user friendly software that provides multiple connection port for complex case and an output window to handle all the output in one central location. In addition, it provides multi-zone building model (Type 56) simulation which is integrated with TRNBuild.

TRNBuild is the visual interface of the multi-zone building model (Type 56). As the multi-zone building (Type 56) is quite complex, the parameters of TYPE 56 like wall, window and roof material properties are not described directly in the TRNSYS input file. Alternatively, two files that contain the information on the building description (*.BLD) and the ASHRAE transfer function for walls (*.TRN) are assigned. TRNBUILD (formerly known as PREBID) has been developed to provide an easy-to-use tool for creating the *.BLD and *.TRN files. Starting with some basic project data, the user describes each thermal zone in turn. Finally, the desired outputs are selected. All data entered are saved in a so-called building file (*.BUI), a readable ASCII text file.

2.5.1 Weather files

Transient simulations of energy consumption in building sector need a consistent engineering weather data to produce reliable results. TRNSYS for instance depends on these weather data file to project the performance of various HVAC systems. Numerous “typical” weather data file such as ASHRAE’s Weather Year for Energy Calculations (WYEC), Typical Meteorological Year Type 2 (TMY2) and the National Research Centre of Canada’s Canadian Weather for Energy Calculations (CWEC) could be use to conduct such assessment [134].

The researcher could chose either to use observational data of long period or to choose certain year to assess the building’s performance as the selection of the suitable weather data file plays an important role in computer simulation. Guan [135] in her research stated that in order to assess the impact of climate change on the building environment, the provision of suitable weather data is crucial. She presented an effective framework and procedure to generate future hourly weather data. This method is proven to solve different levels of available information associated with climate change and maintain the main characters of a typical year data for chosen period[74].

The current Typical Meteorological Year was produced from hourly measurements of solar irradiance (global and diffuse on horizontal surface), ambient temperature, wind speed and direction, and humidity ratio for certain period. The weather data of Kuala Lumpur for 20 years period were provided by the Malaysia Meteorological Department. The weather data provided was used to generate TMY2 weather profile which can be used to predict the future trends of the weather profile. TRNSYS runs through hourly values of several parameters included in a Typical Meteorological Year (TMY) file. Analysis could be done to evaluate the hourly load of building for a year, the annual energy consumption and the maximum load for certain appliances [136].

TMY data is a set of hourly values of solar radiation and meteorological elements for a period of one-year generated from long-term observed data [137]. Study claimed that meteorological variables are highly random for short period of time like days and night and highly deterministic for long periods of time like months and years[138]. However, these data sets correspond to the occurrence and consistency of the weather in all months. The

TMY created a standard hourly data of solar radiation and other meteorological elements that permit corroboration on the performance of different solar energy systems and configurations for various locations..

The generation and assessment of building simulation weather files by Jentsch in U.K. In their research, they stated that recent weather files used for building simulation are not suitable to evaluate the forthcoming climate change effects. This research illustrates the combination of future U.K. climate scenarios into the commonly used Typical Meteorological Year (TMY2) and EnergyPlus/ESp-r Weather (EPW) file formats and reveal the effects of climate change through analysis of a case study [139].

2.6 Computational Fluid Dynamics (CFD) simulation

Back then, experimental measurement is the only method used to determine the contaminant dispersion, air distribution and thermal comfort in a building. However, recently, computer simulation has been used to assess and predict these parameters due to the rapid development of computer technology. The computer simulation such as the Computational Fluid Dynamics (CFD) model has been used to solve Navier-Stokes equations for flow and conservation transport equations for energy and species. The CFD models give virtual 3D information on air, temperature and contaminants distribution in the domain which is impossible to get from the experimental measurement due to time and money-consuming. In several studies, the results computed from the CFD simulations were found to be in close relation with the experimental data [140-142]. Nevertheless, the CFD could not replace the experimental measurement as the most reliable data were obtained from the experiments [143]. Thus, the computed results should be compared with the experimental one to get better results.

2.6.1 Governing equations

There are three conservation principles that govern a CFD simulation. These principles include the principle of mass, momentum and energy conservation. The flow of the fluids is analysed using the *Continuity* equation (which includes the momentum conservation and energy conservation), the *Navier-Stokes equation* and the *energy equation*. The equations involved are as followed:

Conservation of mass:

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial \rho}{\partial x_i}+\frac{\partial}{\partial x_j}[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)]+\rho f_i \qquad 2.13$$

where ρ : density of the fluid

t : denoted as the time,

u_i : velocity vector of the velocity component (*u*, *v*, *w*) in Cartesian coordinate (x, y, z) representing the 3D space and volume.

Conservation of momentum:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_i\right)=0 \qquad 2.14$$

where ρ : density of the fluid

μ : kinematic viscosity

ρf_i : the body force per unit mass acting on the fluid particles or elements in the direction of x, y and z.

Conservation of energy:

$$\frac{\partial}{\partial t}\left(\rho H\right)+\frac{\partial}{\partial x_i}(\rho u_i H)=+\frac{\partial}{\partial x_i}\left(\frac{K}{c_p}\frac{\partial H}{\partial x_i}\right)+S_H \qquad 2.15$$

where H :entalphy

K: the thermal conductivity of the element use

c_p :specific heat and S as a source term[144, 145].

Most of the flow in air-conditioning room is turbulent, thus the standard *k*-epsilon model is used to assess the air distribution[146]. The standard *k*-epsilon model is a semi-empirical model based on model transport equations for the turbulent kinetic energy (*k*) and its dissipation rate (ε). The transport equation for k is computed from the actual equation, while the transport equation for ε is derived using physical reasoning. The turbulent kinetic energy, *k* and its rate of dissipation, ε is attained from the following transport equations:

$$\rho\frac{Dk}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k+G_b-\rho\varepsilon-Y_M \qquad 2.16$$

$$\rho\frac{D\varepsilon}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad 2.17$$

The convective heat and mass transfer modeling in *k*-epsilon models is given by the following equation:

$$\frac{\partial}{\partial t}\left(\rho\varepsilon\right)+\frac{\partial}{\partial x_i}\left[u_i\left(\rho E+p\right)\right]=\frac{\partial}{\partial x_i}\left[k+\left(\frac{c_p+\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial T}{\partial x_i}+u_j\left(\tau_{ij}\right)_{eff}\right]+S_h \qquad 2.18$$

The Newtonian fluid is a fluid that the stress tensor is linearly proportional to the first spatial derivatives of the velocity components [147]. Most of fluid are Newtonian fluids and air is the example of Newtonian fluid that has low viscosity. Other Newtonian fluids are water, oil, sugar solution and other gases. For an incompressible, isotropic, Newtonian fluid, such as low air velocity flow, the viscous stress, τ_{ij} is expressed as:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \qquad 2.19$$

2.7 Conclusion

This chapter presents reviews on the indoor air quality and climate change impacts on building studies conducted by various researchers in the world. The literature reviews give guidance in constructing the research methodology which consists of physical measurement and simulation work.The methodology used in this study will be discussed in further detail in Chapter 3.

CHAPTER 3.0 METHODOLOGY

Basically, the methodology has been designed to meet the research objectives. The methodology has been divided into several parts consist of:

1. Physical measurement on-site for indoor air quality study
2. Cooling load calculation for current cooling load estimation
3. TRNSYS simulation software for future cooling load prediction
4. CFD simulation software for air distribution assessment

3.1 Physical measurements

The indoor air quality study was carried out using the approach established by Cheong and Lau [19] to evaluate the indoor air quality for air-conditioned buildings.

Table 3.1: Indoor Air Quality Study methodology

Pre-measurement planning stage	▪ Understand the background of the building ▪ Review the Mechanical and Electrical drawings ▪ Site visit to the building
Physical measurement stage	▪ Field measurement ▪ Objective measurement (includes physical, particulate and ventilation study)
Evaluation stage	▪ Data analysis ▪ Objective parameters ▪ Comparison with ASHRAE standard and MS 1525:2007 ▪ Determine implication and causes
Recommendation stage	▪ Corrective plans ▪ Strategies to minimise the implication

3.1.1 Pre-measurement planning

ASHRAE Standards and Handbooks, journals and literatures were used as guidelines to plan for the measuring procedures to determine the indoor air quality, comfort level and contaminant distribution.

Before the physical measurements were carried out, meetings with the facility management were conducted to seek permission and background of the building, the ACMV system and the feedback from the occupants. The HVAC system and floor areas of the building were studied from the mechanical and electrical (M&E) drawing provided.

Site visits to the building had also been conducted to get a clearer view of the building's floor areas and the HVAC systems; this includes the location of the air supply and return grille and the air-handling unit. Locations of sampling points were determined, and problem areas were observed during the site visit session. The instruments, parameters, and data table needed for data collection were identified and prepared.

3.1.2 Measurement procedures

Selection of a sampling method use in the indoor air quality study depends on the objectives of the study, the contaminants concern and the required sampling duration. In this case study, the parameters chosen are the room temperature, relative humidity, air velocity and indoor contaminants, which include carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde (HCHO) and total volatile organic compound (TVOC). Based on the ASHRAE method, the sampling probe should be located between 0.75 to 1.2 m from the floor at the middle of the room or an occupied space. If the space is served by different air-handling unit, one sample should be taken from each floor or space. If the floor space is larger than 3000 m², the minimum numbers of sampling points suggested are shown in Table 3.2 below.

Table 3.2: Numbers of sampling points

Area of building (m^2)	Minimum number of sampling points
3,000 – 4,999	8
5,000 – 9,999	12
10,000 – 14,999	15
15,000 – 19,999	18
20,000 – 29,999	21
30,000 or more	25

Respirable particulate matters are particle, which is 10 microns (PM10) or less in diameter. The accumulation of dust particles in large compositions inside the lung is hazardous to the respiratory system. Sampling for respirable particulate is conducted by using an apparatus with a sizing selection device with an average diameter of four micrometers and is based on penetration characterisation below:

Table 3.3: Respirable particulates

Particle aerodynamic diameter (micrometer)	Respirable particulate mass (%)
0	100
1	97
2	97
3	74
4	50
5	30
6	17
7	9
8	5
10	1

3.1.3 Instrumentation

The indoor air condition such as the dry bulb temperature (DBT), relative humidity (% RH), concentration of carbon dioxide (CO2), carbon monoxide (CO) and formaldehyde (TVCOH) and air velocity (v) were measured using instrumentation in APPENDIX A:

3.1.3 (a) PP Monitor Stand Alone System (SAS)

The PP Monitor Stand Alone System (SAS) is used to measure several indoor air quality parameters such as temperature, humidity, air velocity and indoor contaminants, such as carbon dioxide, carbon monoxide, nitrogen dioxide, ozone, sulphur dioxide, total volatile organic compound and formaldehyde. The results, reports and scheduling options could be assessed immediately and several results could be displayed in a visual format on the screen as the device has a graphical user interface (GUI).The sensor range are as follows:

Table 3.4: Sensor range of PP Monitor Stand Alone System (SAS)

Parameter	Range
Temperature (CMOSens technology)	-40 to +128˚C
Humidity (CMOSens Techonology)	0-100 %
VOC's (PID)	0-20 ppm
Formaldehyde (electrochemical)	0-10 ppm
Carbon dioxide (NDIR)	0-5000 ppm
Carbon monoxide (electrochemical)	0-100 ppm
Nitrogen dioxide (electrochemical)	0-20 ppm
Sulphur dioxide (electrochemical)	0-5 ppm
Ozone (electrochemical)	0-1 ppm
Particulates	Respirable size, PM10, PM2.5, PM 1.0 size fractions
Air velocity	Measures low velocities down to 0.05 m/s

3.1.3 (b) TSI AeroTrak Handheld Particle Counter

The particle concentration measured using this handheld device ranges from 0.3 to 10 µm with ±5% accuracy. This unit employed the isokinetic sampling probe with laser diode that acts as the light source. The readings were taken automatically and the data were retrieved using TRAKPro Lite software. Average values from the total air samples was used for data analysis.

3.1.3 (c) TSI DustTrak II Handheld Aerosol Monitor

This handheld device measures aerosol concentrations corresponding to 0.1 to 10µm or respirable size fraction with ±0.1% accuracy in measurement or 0.001 mg/m^3. Different size-selective impactors are used to measure the mass of aerosol in certain size such as 1µm, 2.5µm, 4µm and 10µm.

3.1.3 (d) Velocicalc Multi-Function Ventilation Meter

The Velocicalc Multi-Function Ventilation Meter measures air velocity, airflow, temperature, humidity and pressure. This unit is capable to measure air velocity from 1.27 to 78.7 m/s with ± 1.5 % accuracy in its readings.

3.1.3 (e) Q-Trak Air Quality Monitor

This device measures CO2, CO, temperature and relative humidity simultaneously. The data collected at one-minute log intervals could be saved for 38.9 days. The data logging, analysis and documentation can be done using TRAKPRO software.

3.1.3 (f) Alnor EBT721 Balometer

The Alnor EBT721 Balometer Electronic Balancing Tool is a detachable multi-purpose digital manometer used to measure the off grille supply parameter. The unit is capable to measure the volumetric air flow and temperature by placing the unit under the grille or diffuser.

3.2 Cooling Load calculation

Cooling load temperature difference (CLTD) method has been applied to estimate the cooling load needed for the office space and the calculated value is compared with the design cooling capacity of the office space.

3.3 TRNSYS simulation

The weather data were converted into the Typical Meteorological Year (TMY2) for the simulation purpose. The Typical Meteorological data (TMY2) established by Mark Jentsch in the U.K. for Kuala Lumpur were simulated in TRNSYS Studio for the one-year period for the year of 2000, 2020, 2050 and 2080.

The baseline simulation is created using TRNSYS simulation Studio based on the design specification obtained and site study at the building. Essentially, this simulation requires several settings for certain module. In this case, the building has been modeled in the multi-zone (Type 56a) module. The space geometry, orientation of the building, portion of the window in percentage, material properties of window, wall and roof, heat gain due to occupants, laptop and lighting is defined in Type 56a in the TRNBuild. The equivalent air-conditioning system for the space is created then integrated through the inlet air properties setting through the ventilation system in the Type 56a module. The cooling load rate, dry bulb temperature and relative humidity are plotted using the output plotter module (Type 65b). The maximum cooling load required by the office is predicted from the baseline model using the TRNSYS Studio for 4 different TMY2 years in Kuala Lumpur. The simulations were conducted for the year of 2000, 2020, 2050 and 2080.

3.4 Computation Fluid Dynamics (CFD) software

The assessment on the air distribution in the office space is done on a commercial CFD software package FLUENT Inc. CFD simulations are designed to assess the air distribution in the office space. The simulated results in the form of contours were verified with the empirical results to obtain significant and agreeable match between those two data. The results were analysed and compared between the physical measurement and CFD simulations to have a final discussion upon the air distribution in the building.

CHAPTER 4: FIELD ANALYSIS OF INDOOR AIR QUALITY AND THERMAL COMFORT IN HIGH-RISE AND LOW-RISE GREEN OFFICES WITH THE RADIANT SLAB COOLING SYSTEM IN MALAYSIA

4.0 Abstract

Even the concept of green building concept is fairly new in Malaysia; the development of this industry has been growing in recent years prior to the launch of Malaysia's own standard; the Green Building Index (GBI). One of the criteria assessed in the GBI is the energy-efficiency which takes about 21% of the overall assessment. Considering this, the passive design has been included in the green building concept to reduce the energy usage while still maintaining occupant thermal comfort. This study attempts to assess the passive design effectiveness in terms of indoor air quality and thermal comfort in the tropics. Two green office buildings that incorporated the radiant slab cooling and conventional cooling system have been selected as case studies. A detailed assessment in terms of thermal comfort parameters (temperature and relative humidity), indoor pollutants' concentration (carbon dioxide, carbon monoxide and formaldehyde) and air movement was carried out. The results show that the thermal comfort and indoor air quality parameters fall within the Malaysian Standard (MS1525:2007) and ASHRAE Standard 55 and 62-2010 except for the air movement in both of the buildings.

4.1 Introduction

Green building is building that is designed, built and operated to have minimum negative effects to the environment, both indoor and outdoor. Green building technology is the recent resort to combat climate change as the technology involved contributes to huge reduction in energy usage and carbon emission. In Malaysia, the demand for green buildings have continued to increase due to the environmental conditions, rising energy costs, government initiatives, building code and greater availability of green products [148]. In terms of indoor environment, the green building provides acceptable indoor air quality to the building occupants with minimum energy usage.

Indoor air quality in the office space plays an important role in the occupant's performance and health as the occupants spent almost 10 hours in the office; five days per week. Poor indoor air quality due to the air-conditioning and ventilation problems and airtight building could lead to Sick Building Syndrome (SBS) [91, 149, 150]. Several studies [2, 151-153] shown that common work-related signs of SBS were lethargy, blocked nose, fatigue, dry throat and headache. The SBS resulted by poor indoor air quality could affect the occupant productivity and well-being [154]. Studies proved that 6-10 % of loss in productivity was due to the indoor air quality problem in the building [5, 155].

In a hot-humid tropical region such in Malaysia that receives lots of sunshine throughout the year; the air conditioner has no longer become a luxury item, but a need to provide better thermal comfort for the occupants. The usage of air-conditioner has significantly increased the energy consumption of a building; thus increase its impacts to the environment in terms of carbon emission [71]. In addition, study shows that the occurrence of SBS is highly associated with the type of ventilation system installed in the building, and often occurs in buildings with the mechanical ventilation system compared to the normal ventilation system [3]. However, green building design offered a cost-effective solution to solve this problem. Passive design such as natural ventilation, shading, orientation and spatial organization, and cooling techniques such as radiant cooling or indirect evaporative cooling have been incorporated in the green building design to optimise the occupant thermal comfort, provide better indoor air quality while at the same time, minimising the energy consumption [156]. Studies show that passive ventilation such as radiant slab cooling in conjunction with the conventional cooling system provides better thermal comfort and air quality environment [157-159].

Many studies [4, 19, 160, 161] have been carried out to assess the indoor air quality and thermal comfort in commercial building, but only few studies focus on green building as green building is fairly new in most of the countries around the world, including Malaysia. This study was conducted to assess the indoor air quality and thermal comfort in the green office building in the tropics. Two green buildings that employed a cooling system that consists of radiant slab cooling, and variable air volume (VAV) system were selected as case studies. As radiant slab cooling design is rather new in Malaysia, these case studies could serve as an assessment in terms of indoor air quality for future green building's design in the tropics.

4.2 Building description

4.2.1 Case study 1: High-rise green building (Energy Commission, Putrajaya)

The Energy Commission (EC) building in Putrajaya was designed and built based on the sustainable concept, taking into consideration the fossil fuel reduction, water savings, green building materials, indoor environmental quality, traffic and transport management, construction and demolition plan and waste minimisation. The Building Energy Index (BEI) of this building is projected to be 85 kWh/m^2/ year which is much lower compared to the standard index of 135kWh/m²/ year (MS 1525:2007). The total gross floor area is 14229sqm in a total site area of 4928.11 sqm.

The building was designed in a unique diamond shape as its efficiently avoid infiltration via the advantage of tilted façade. The building slanted façade which is self shading increase the energy-efficiency of the building. Instead striking directly to the façade and infiltrate inside the air-conditioned the building, the wind striking the tilted façade will flow below to help ventilate the parking area at the basement level. The perimeter outer walls are tilted at 65° from horizontal. Due to this, the sun penetration on the west and east façade is strongly reduced while the north and south facades receive no direct sunlight at all. The internal light shelves were incorporated to focus the natural daylight into the office space while low-energy coating is used to coat the glazing to address the heat.

The buildings employed extensive use of glass and modern materials to enhance its exterior design. The atrium of the building is exposed to the intense solar radiation during the day to minimise the thermal impact and solar heat gain and for natural lighting purpose. The reflective panels and automatic roller blind systems were incorporated into the atrium design to optimise the daylight utilisation. In this regards, a 2-meter-wide glare free daylight zone is achieved around the atrium for all floors while on the top floor, the roof lights are employed to bring in daylight for circulation areas.

50% of the office space is day-lit by using the low-e glazing that is reflective on the outside allows daylight into the building and minimises heat gain from the sun. With the integration of daylight sensors, the artificial lighting is to be switched off when sufficient light is provided by daylight to save energy and to reduce the heat gain. In addition, a split window design for all exterior façade together with an internal light shelf helps to redirect natural light into the depths of the working space. To ensure visual and comfort for the occupants, a fixed glare protection blind for the upper daylight window and slightly tinted vision windows are employed in the building.

The building also uses energy-efficient equipment to save energy and reduce cost. For instance, energy-efficient T5 fluorescent tubes are used instead of the conventional T8 fluorescent. Proper distribution of lighting to reduce the power consumption to approximately 50% by special fittings. To ensure adequate fresh air and oxygen is delivered to the occupants, carbon dioxide sensors are installed in the building.

The building also had a Sunken Garden at the northeast side of the ground level which is filled with lush landscape, rich textures of paving materials accentuating the calmness and serenity of the space providing natural day lighting to the basement. Rainwater harvesting is located at the roof where rainwater is collected for the use of toilet flushing and irrigation, which covers more than half of water load required for the building.

4.2.2 Case study 2: Low-rise green building (Malaysia Green Technology Corporation, Bangi)

The Malaysia Green Technology Corporation (MGTC) Building is situated in Bandar Baru Bangi, Selangor and serves as a pilot project of a low-energy office in Malaysia. It employed both active and passive design and generate energy for its own usage. This building does not employ fossil fuels as its electricity is generated its own by solar building integrated photovoltaic (BIPV) systems. Four different solar BIPV using different technologies were implemented in this building. The electricity produced by the BIPV systems is recorded and is directly consumed; therefore there is no battery installed in the system. Currently, the BIPV system produced approximately 103 MWh yearly based on the actual outputs in three months time. The building energy usage was reduced by the implementation of energy-efficient (EE) characteristics in the building. Thus, the total payback time for the system employed is estimated to be less than 22 years according to the technologies' used and subsidised electricity tariff without considering the embodied energy and material cost.

The building utilised the passive technique such as orientation and vegetation, balanced with active techniques such as energy savings lighting system, double-glazed window, floor slab cooling and thermal wall at its west and east façade order to achieve the super energy-efficiency outputs. High performance glazing and sealed double glazing had been implemented and had proven to be effective in harnessing high visible low infra-red and ultra-violet transmittance and preventing unwanted heat radiation into the building.

The building also incorporates floor slab cooling complemented by the conventional cooling system. The embedded tubes were placed within the concrete floor slabs to the room below and above them. The floor slab cooling produced cooling by releasing the stored cooling effects to the room during operating hours. The indoor air quality is conserved through the dehumidification process. The supply hot and humid fresh air is replaced with cooler and drier exhaust air by using the desiccant heat wheel that reduced the energy usage to dehumidify the indoor air quality in the building.

4.2.3 Radiant/chilled slab cooling system in the building

Radiant slab cooling has recently created more demand in Europe [162] as it was viable to create more comfortable thermal environment with lower energy usage [159, 163-167]. However, as it is still new and rare in Malaysia, more studies are needed to evaluate the suitability and performance of the radiant slab cooling in the tropics. As radiant slab cooling is complemented with the conventional air cooling system in the hot and humid climates, the main problem of its application is the condensation of the moisture from air limit cooling capacity on the panels which affects the removing of latent heat load [159, 164]. However, if there is no condensation, the relative humidity in vicinity of the radiant slab is still much higher than it is in the occupied zone which promotes the growth of molds and fungi that could be a contaminant source in the room.

The radiant slab cooling transfers almost half of the heat through radiation [168], thus the volume of supplied air can be reduced and lowered the energy used to transport the air [159] . It increases the heat rejection by radiation and decreases the perspiration compared to the conventional air cooling system[169]. In terms of energy consumption, 80% of savings could be achieved given that the occupants were satisfied with the thermal comfort [163, 164]. A climate chamber test proved that the radiant slab cooling comply with the ISO 7730 standard [170].

In these case studies, the air-conditioning in the building is provided by two separate systems, the conventional cold air supply system and radiant slab cooling system. The radiant cooling panel consists of extruded aluminium panels with metal tube linked to one side of the panel [165]. The basis of the slab cooling design is to acts as a thermal storage and cooled down the heat masses of the building during night time. Direct cooling of the concrete slab with embedded chilled water pipes is found to be the most efficient way to cool the building mass at night and acts as a thermal storage for daytime heat load since the highest heat capacity of the building rest in the concrete mass. This operation does not only bring down the daytime maximum demand, but also provides the most efficient way to cool the largest portion of heat capacity in a building by direct mean, instead of through cooling by the air-handling unit (AHU). In the EC building, the variable volume (VAV) air system is employed. The VAV system provides cooling to the space by increasing the airflow proportionally based on the cooling load. This approach altered the air delivered to the space whilst maintain the temperature. The VAV system acts as a backup in case where there is a breakdown of the radiant slab cooling.

The AHU operation and slab cooling charging cannot run simultaneously. During operation of the AHU in the daytime, the motorized valves isolating the slab cooling to chilled water-supply system will be closed. The slab cooling can only be charged during night time. The time for full charging of the slab differs from time to time depends on the weather conditions. The dew-point of the slab surface in the tropics' condition is 18˚C. The surface of the chilled floor slab temperature is predicted to be approximately 20-23˚C to prevent condensation occurs on the slabs. Study indicates that the supply cooling water temperature is limited to 24-25.8˚C to avoid condensation of the air moisture in the panels [164]. The slab cooling taken away almost 30% of the sensible heat; thus, the supply airflow can be relatively lower. More often than not, these design features lower the air movement and increase the relative humidity due to low dehumidification. The implementation of radiant slab cooling is advantageous as the conventional air conditioner in the building can be downsized to save energy whilst the usage of water and pump reduce the energy used to transport the cooling around the building. The downsized AHU prevents condensation on the chilled slab and provides adequate fresh air to the occupants. The system also improved the acoustics comfort by reducing the air ventilation rate and noise caused by the ducts.

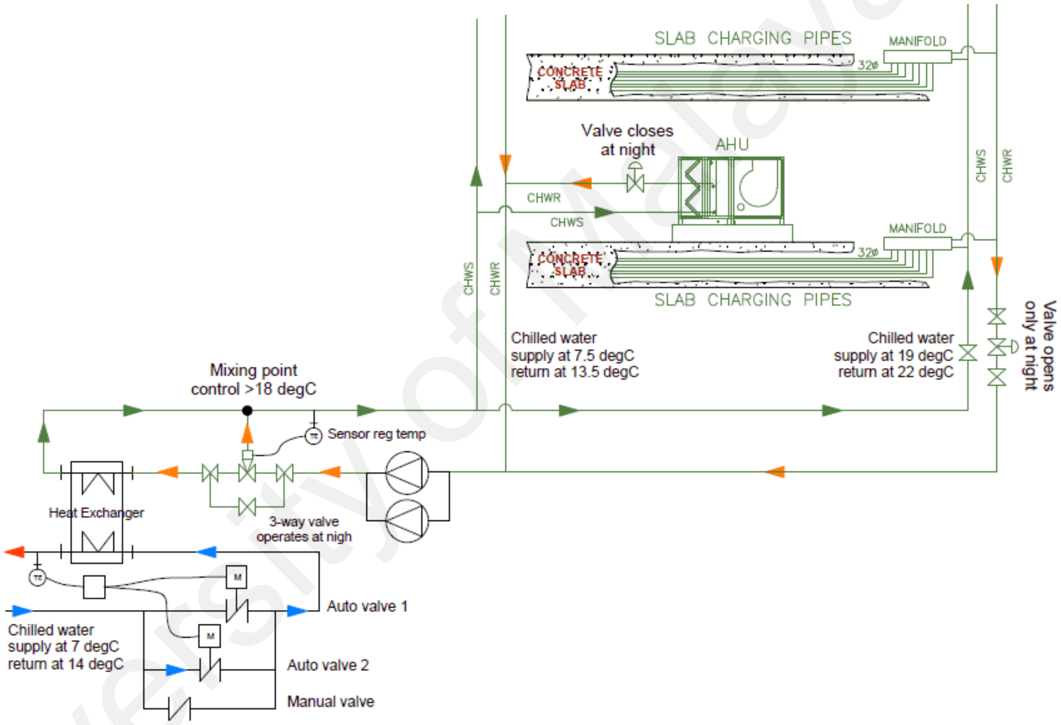

Figure 4.1: Chilled Slab Cooling system installed in Case Study 1

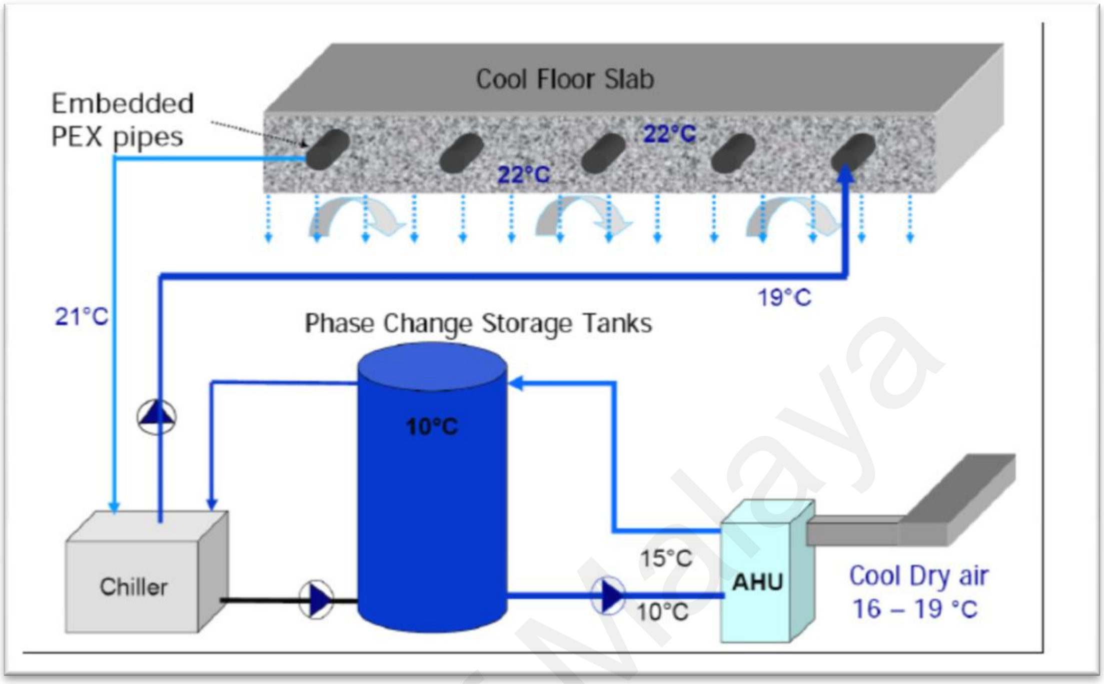

Figure 4.2: Air-Conditioning system installed in Case Study 2

4.3 Methodology

Field measurements were carried out to measure the indoor air quality and thermal comfort parameters such as temperature, relative humidity, contaminants, particle concentration and air velocity. PP Monitor Stand Alone System (SAS), TSI AeroTrak Handheld Particle Counter, TSI DustTrakII Handheld Aerosol Monitor and Velocicalc Multi-Function Ventilation Meter were used for the field measurement. The measurement was conducted at several locations in the office space in the building at 1 m above the floor level. The field measurement for the EC building was conducted for a week while for the MGTC building for two weeks.

4.4 Sampling points

4.4.1 Case Study 1

Several sampling points were determined before conducting the measurements. The building consists of seven floors. On each floor, the main sampling point was at the return off grille and additional sampling points were chosen based on the occupancy (shown in APPENDIX B1). Since there is only one air-handling unit (AHU) for each floor, the return air grille was chosen as the main sampling point as it could represents the average indoor air quality of the whole floor. Additional sampling points are shown in the floor plan. The indoor air quality study was not carried out at the 1st floor as it only has been occupied occasionally. The readings were logged for one week from 8.30 am to 5.30 pm while for the air velocity; the readings were taken at the interval of two hours. The sampling times were at 8.30 am, 10.30 am, 12.30 pm, 2.30 pm and 4.30 pm.

4.4.2 Case study 2

The sampling point was located inside the office in the 1st and 2nd floor of the building (shown in APPENDIX B2). The data were logged for a week at the 1st (17-24th February 2012) and 2nd floor (9-16th February 2012) in the building.

4.5 Results and discussion

4.5.1 Evaluation of thermal comfort

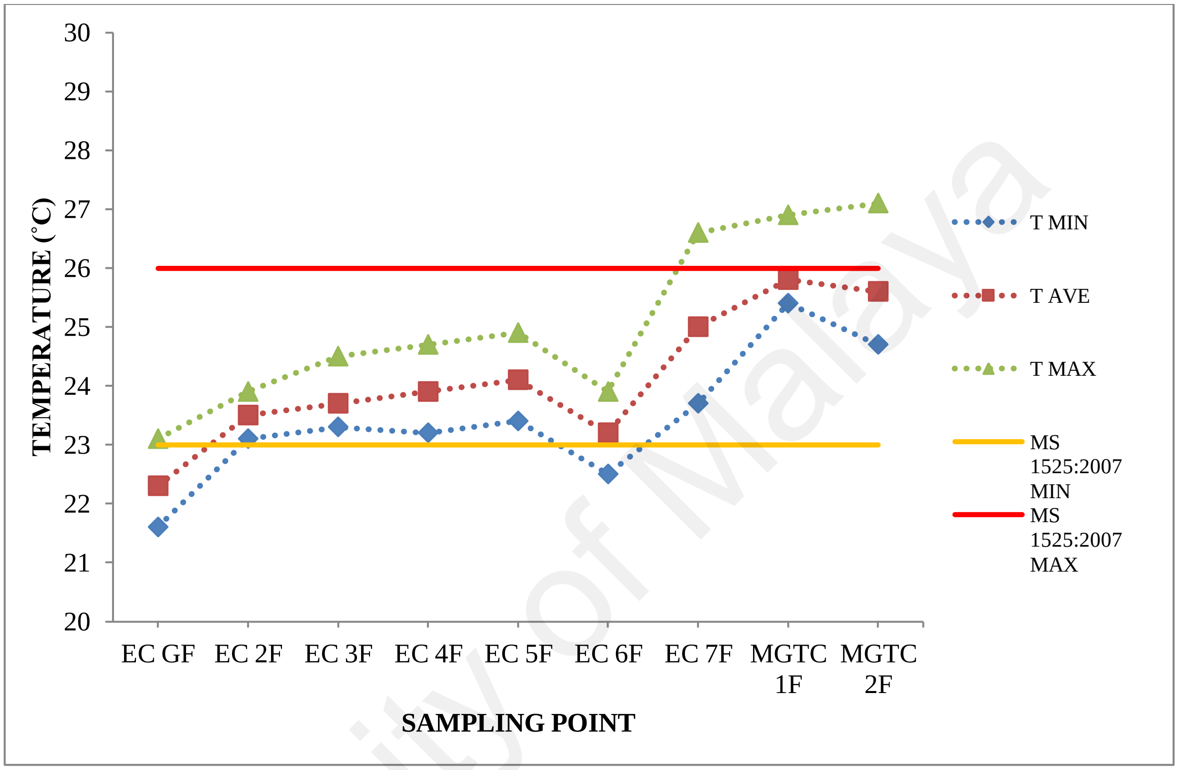

Figure 4.3: Indoor Temperature

The indoor air quality and thermal comfort assessment is crucial to the health and productivity of the occupants. According to the Malaysian 1525:2007 and ASHRAE standard [33, 171] the acceptable dry bulb temperature for office building is within the range of 23-26 ºC. The results showed that the average temperatures in EC building were within the range of design temperature recommended by both standards. This is mainly due to the design of the chilled slab that helps to maintain the dry bulb temperature below 24ºC during working hours. It is also observed that the indoor condition is still cool enough even the temperature rise after sunrise at few additional sampling points. In MGTC building, the indoor air temperature in the 1st floor ranged between 25.4 to 26.9˚C and in

2nd floor between 24.7 to 27.1˚C. Even the maximum temperature was slightly higher than both standards; the value still falls within the recommended limit according to studies [10, 21] that stated the thermal comfort in Malaysia varies from 24-28˚C. It is noted that the occupants near the façade feel slightly uncomfortable for certain time of the day due to the radiant heat from the sun.

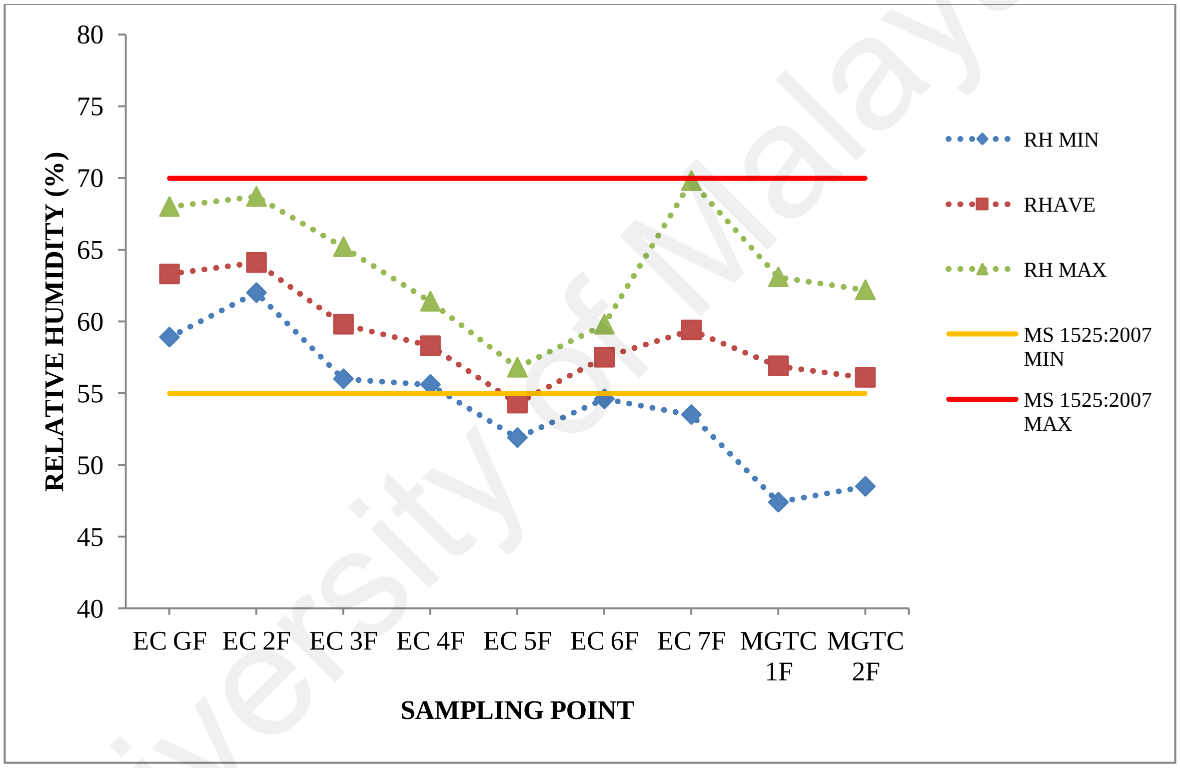

Figure 4.4: Relative Humidity

Average relative humidity at each floor in the building in the EC building varies between 52.4 to 68% which were within the design standard given by the MS 1525:2007 except at the 5th and 7th floor. The relative humidity in both levels were slightly lower from the minimum standard suggested, however the values were still in the acceptable range according to ASHRAE Standard 55-2010 (20-70%). In the MGTC building, the relative humidity in the 1st floor ranged between 47.4 to 63.3% while in the 2nd floor ranged between 48.5 to 62.2 %. An averaged reading recorded was 56% which is within the recommended standard. This proves that the installation of the chilled slab thermal storage system in both buildings managed to clamp the maximum peak heat load of the building while at the same time maintaining the thermal comfort to the occupants. The chilled slab design complemented with the conventional air-conditioner managed to keep the relative humidity in both of the buildings between 50-70%.

4.6.2 Evaluation of indoor air contaminants concentration

The Code of Practice of Indoor Air Quality by Ministry of Human Resource Malaysia recommends that the allowable average airborne concentration of carbon dioxide in the building is 1000 parts per million (ppm), for the carbon monoxide is 3ppm, and for the formaldehyde is 0.1ppm.

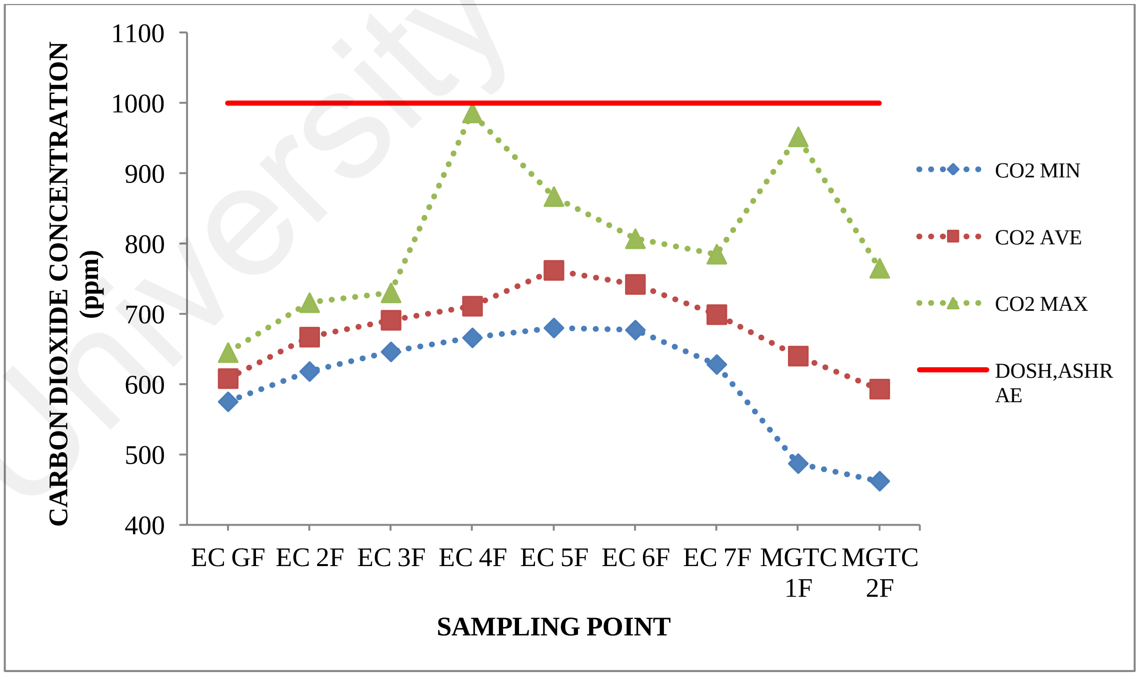

Figure 4.5: Carbon Dioxide concentration

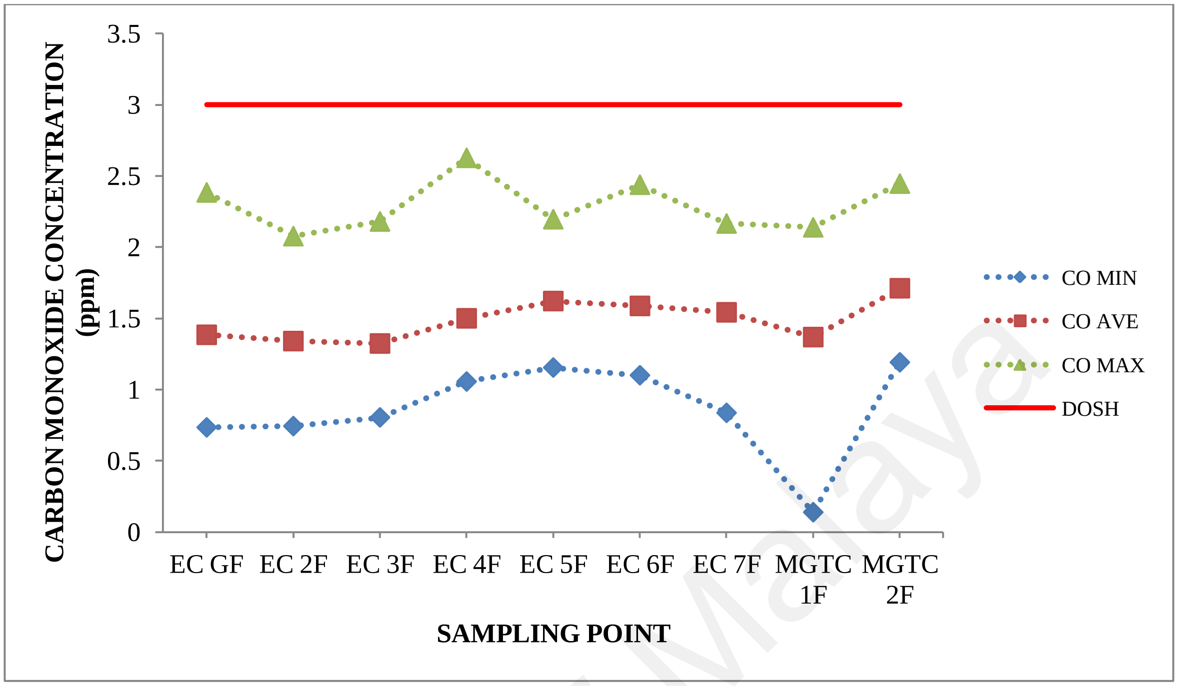

Figure 4.6: Carbon Monoxide concentration

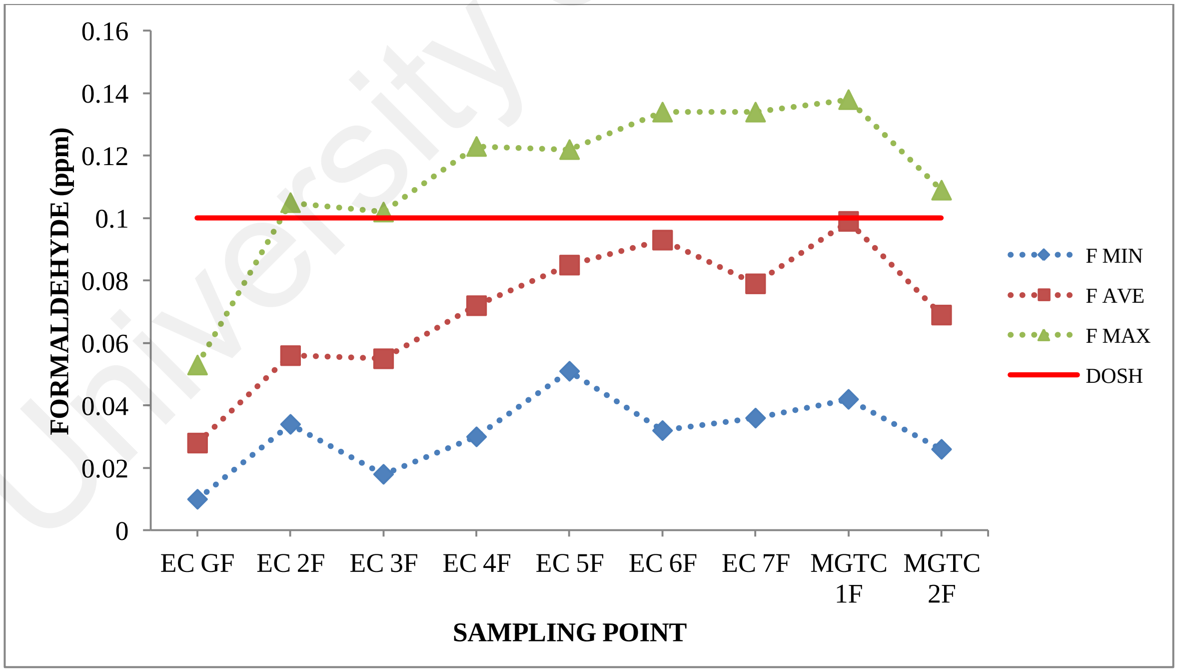

Figure 4.7: Formaldehyde concentration

In the EC building, the averaged reading recorded for carbon dioxide, carbon monoxide and formaldehyde were 700ppm, 1.3ppm and 0.043ppm respectively. It is observed that the concentrations of these contaminants in the EC building were within the allowable limit recommended by the Malaysia Code of Practice on Indoor Air Quality and ASHRAE Standard 62-2010. However, the concentration of the formaldehyde in 2nd, 4th and 7th floor is slightly higher than 0.1 ppm in the morning and decreased throughout the day due to the air flushing system in the building.

In the MGTC building, the average carbon dioxide concentration for the 1st floor was 649 ppm while in the 2nd floor was 593 ppm. In terms of carbon monoxide and formaldehyde, the averaged values recorded were 1.368ppm and 0.069 ppm for the 1st floor and 1.771ppm and 0.099 ppm for the 2nd floor. It can be seen that the concentration of carbon dioxide went up to 952 ppm during office hours and decrease to 462 ppm after office hours. The increase in the carbon dioxide concentration is due to the occupant's density as more people were in the building during office hours.

As both buildings are airtight, excessive concentration of carbon dioxide could cause irritation to the respiratory system and allergies [33]. The carbon dioxide sensor had been installed in this building to monitor the levels of carbon dioxide in these buildings to ensure delivery of minimum outside air requirements. It is noted that the readings of the carbon dioxide concentration are around 500-600 ppm as the set point is set around 550ppm. The level of carbon dioxide in both buildings is very low compared with the average office buildings in Malaysia, which normally have the carbon dioxide concentration between 850 – 1000 ppm. The installation of fresh air controller and the carbon monitoring system manage to maintain the carbon dioxide level in the office. The fresh air intake in the floor space is regulated by the carbon dioxide level which is also a proxy indication of the activity within the floor space. The AHU will pump in more fresh air with the increase of the number of people in the floor space. Otherwise the fresh air supply will be reduced depends upon the demand.

In terms of carbon monoxide, the location of the building itself explained the existence of this contaminant in the office space. Carbon monoxide enters the building through incomplete oxidation of carbon from vehicles outside the buildings as the buildings are located at the traffic area and parking zone. However, the recorded readings were relatively low compared to the recommended limit.

Formaldehyde usually enters the building through building products. These products continue to out-gas formaldehyde for long periods of time, mostly during the first year. The building products in these buildings are selected with the lowest material of formaldehyde and other volatile organic compound. Thus, results show that the reading of this contaminant is very low. In EC building, it is also observed the level of formaldehyde in the ground floor in is lower compared with other floors due to the more effective dissipation of the contaminants through the openable window, door and passage way. In addition, the outward draft from the door due to the buoyancy also contributes to minimise the contaminant concentration in the ground floor.

Overall, the concentrations of indoor contaminants inside both of the buildings are acceptable, and within the limit recommended.

4.6.3 Evaluation of particle contaminants

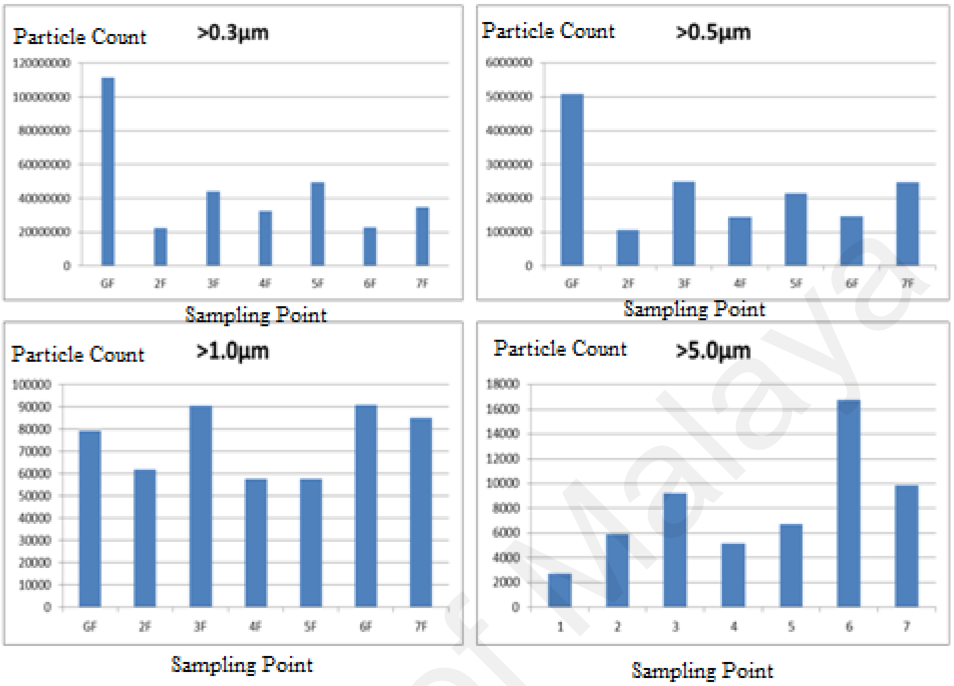

Figure 4.8: Particle counts in the EC building

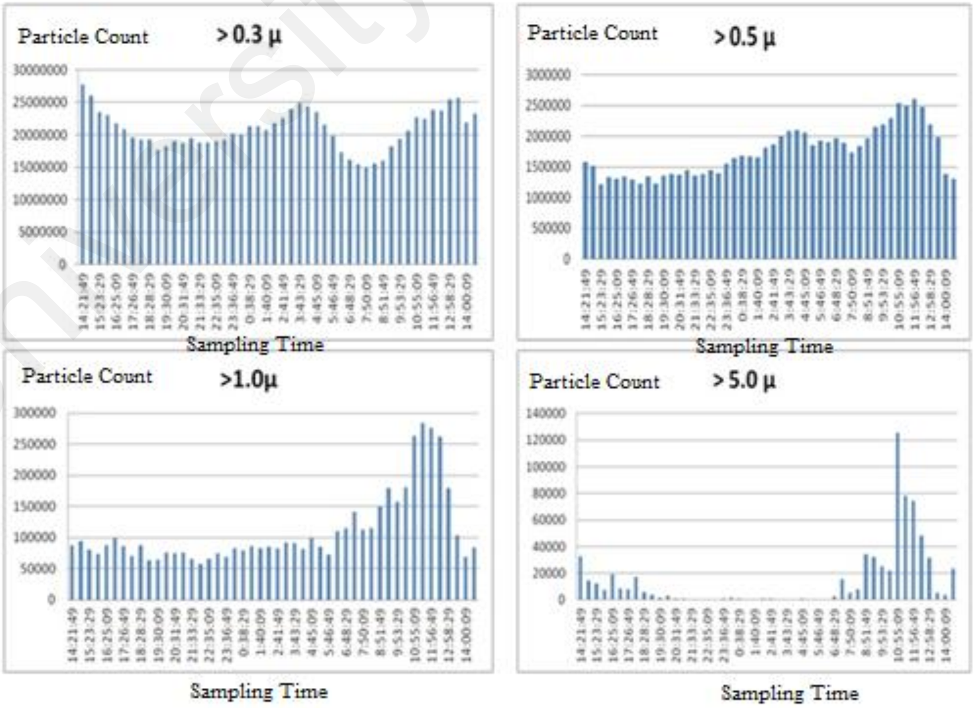

Figure 4.9a: Particle counts in MGTC building (1st floor)

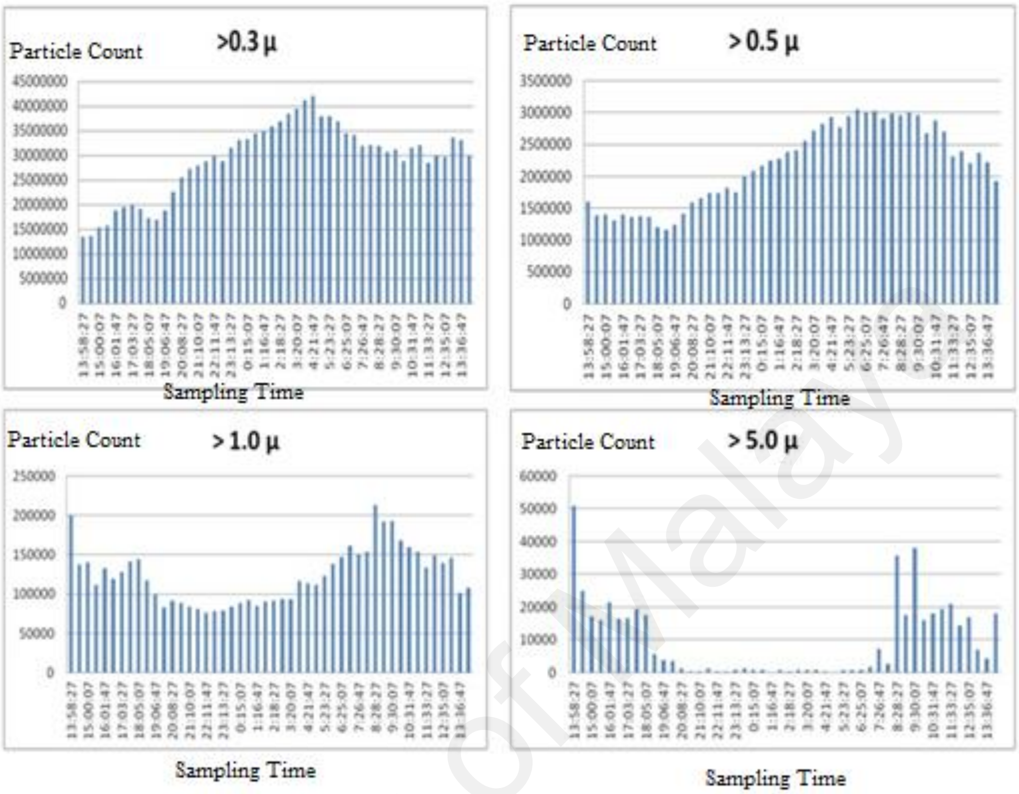

Figure 4.9b: Particle counts in MGTC building (2nd floor)

The ISO 146441 Clean room Classification is classified by the number and size of the particles permitted per volume of air. The results showed that the highest particle count for both building in terms of particle size of PM0.3,PM 0.5, PM 1.0 and PM 5.0 were 110000000, 5000000, 280000 and 130000 respectively. Measurement illustrated that the numbers of particle levels in both buildings were well below the maximum range recommended by the ISO 14644-1, CLASS 9 which has the highest allowable level of contaminants. According to this classification, the limit of particle count for particle size of PM0.5, PM1.0 and PM5.0 is 35200000, 8320000 and 293000 correspondingly. All in all, the results reflect that the indoor air quality in both buildings were generally good. The particulate-matter in the occupied zone is reduced below the minimum with the installation of the electronic filter. These filters charge suspended fine particles in the air with high voltage and precipitate them through electrical discharge at arresting wires.

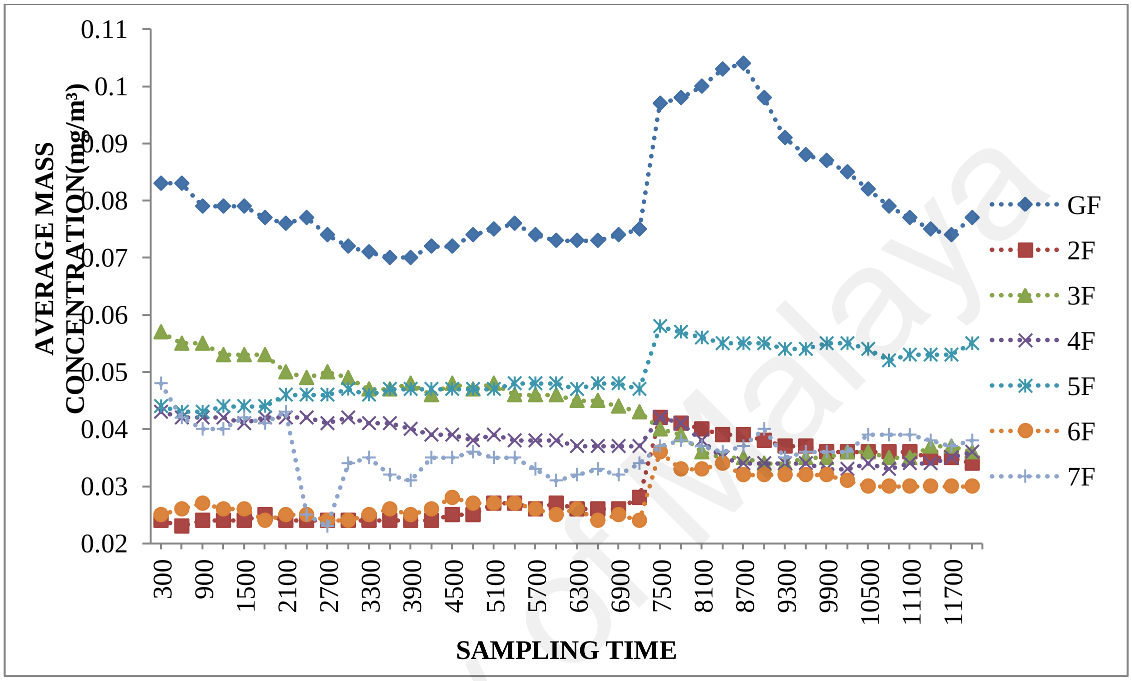

Figure 4.10: Average mass concentration in EC building

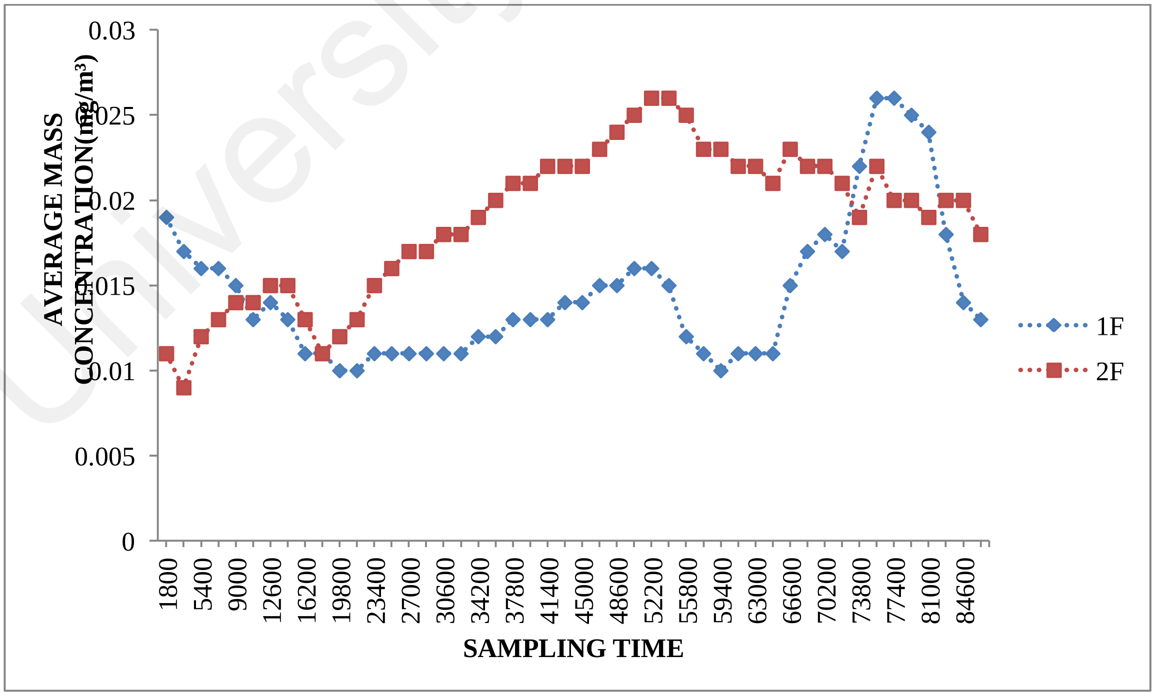

Figure 4.11: Average mass concentration in MGTC building

The Code of Practice of Indoor Air Quality by Ministry of Human Resources, Malaysia stated that the particulates concentration must not exceed 0.15mg/m³. The results from the field measurement indicate that the average weight of dust particle in the EC building was within the range of 0.025-0.086 mg/m³ while in the MGTC building was within 0.009 to 0.026 mg/m ³. The dust particle in the ground floor in EC building was slightly higher compared to other floors due to the frequent opening of the door. Overall it can be said that the average weight of dust particle in the building are all far below the criteria recommended in Malaysia Standard. This reflects that the indoor environment in the office is clean and healthy due to the installation of the advanced air filtration system (APPENDIX B5).

4.6.4 Evaluation of air movement

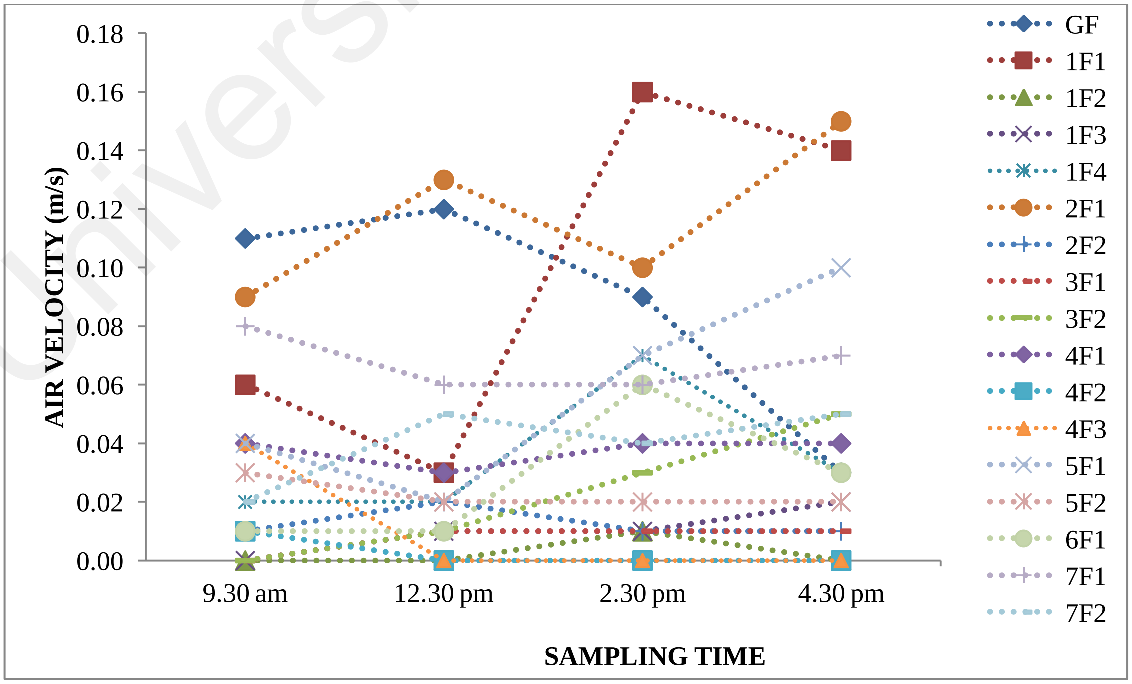

Figure 4.12: Air velocity in EC building

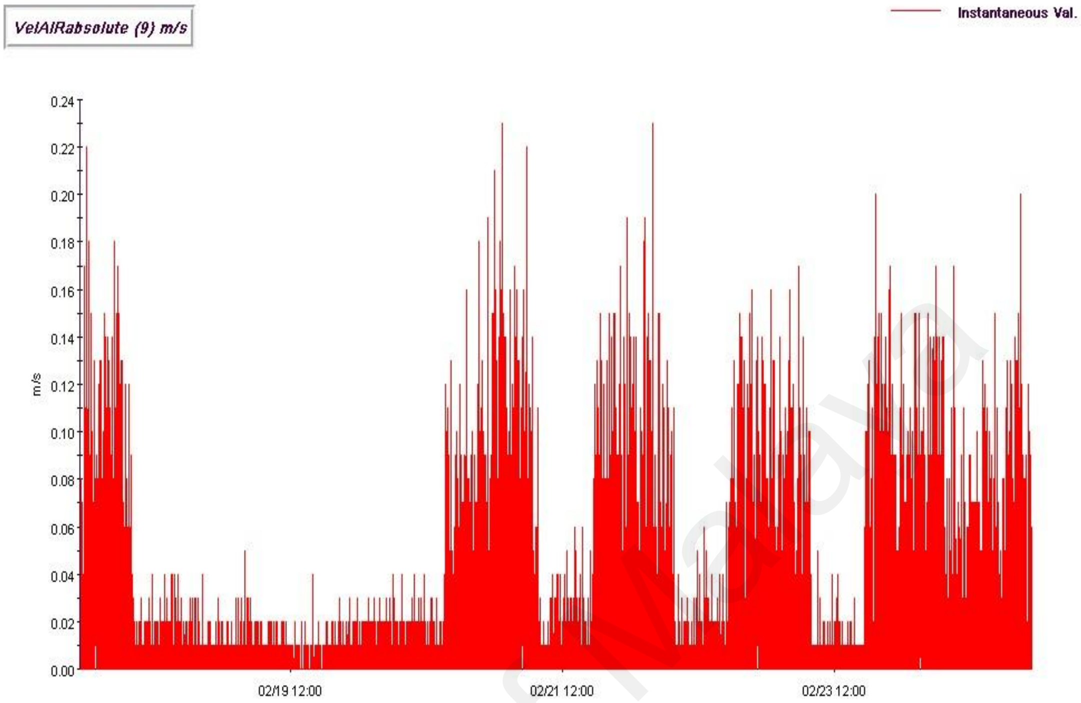

Figure 4.13a: Air velocity in MGTC building (1st floor)

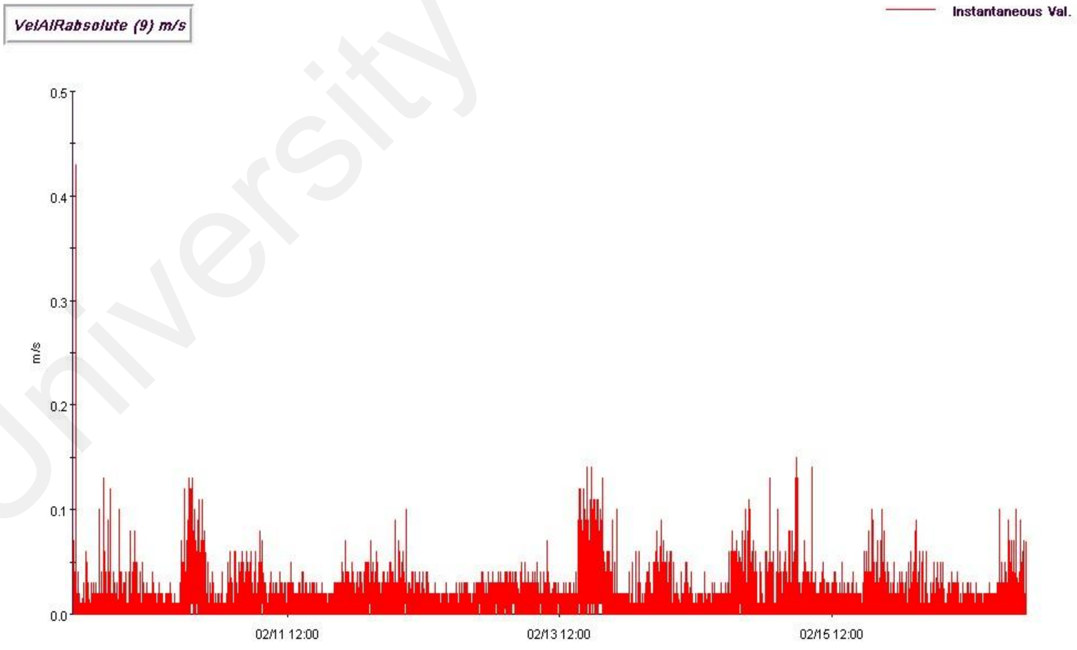

Figure 4.13b: Air velocity in MGTC building (2nd floor)

The recorded air velocity ranged between 0.0 to 0.16 m/s with a mean value of 0.03 m/s in the EC building while in the MGTC building, the air velocity in the 1st floor ranged from 0.0 to 0.22 m/s with a mean value of 0.015m/s and in the 2nd floor, the air velocity was between 0.0 to 0.43 m/s with a mean value of 0.011 m/s.

From the results, it can be observed that the mean air velocity inside both buildings fall extremely below the Malaysian Standard (MS 1525:2007) of 0.15 m/s. It was also found that, there was no air movement at all at some location. During the walkthrough, some of the occupants said that they prefer to have desk fan to increase the air movement during office hour. This signifies that some of the occupants were not satisfied with the level of air movement in the office space as in a hot-humid country as in Malaysia, the occupants are used to have ample air movement to cool the space [10].

In the EC building, the air-handling unit (AHU) system was based on fan power variable air volume (VAV) system that complements the chilled slab design. To effectively reduce the sensible heat, the AHU selected for chilled slab design have less primary airflow, thus the secondary airflow was induced by the fan power VAV box at the user terminal. According to study [172], the implementation of VAV system decreased the total primary flow rate during the part-load condition when the thermal load is reduced.

The chilled slab design usually increased the relative humidity as it taken away the heat load profile in the building. With the absent of enhanced localised air movement, occupants may feel warm even the temperature was within the recommended standard. In addition, the radiant slab cooling and airtight building provide less draught rate that reduced the discomfort of feeling cold [159]. While this is advantageous in the season countries, this is not applicable in Malaysia as the occupants in Malaysia were found to be more comfortable with ample air movement even if the temperature in the office is above 26˚C [10].

4.6 Conclusion and recommendation

The study assessed the indoor air quality inside two of the green office in Malaysia. Field measurement showed that the thermal comfort and indoor contaminants concentration were within the standard recommended by the MS 1527:2007 and ASHRAE Standard 55-2010 except for the air movement which was extremely below the given limit. The air-tight building design and less draught might be beneficial in seasonal countries, especially during winter, but not in a hot-humid country like Malaysia as occupants prefer to have ample air movement with cool surrounding to meet their comfort expectation [10]. The implementation of the radiant slab cooling had contributed to the low air movement in the building due to the downsized AHU system. However, in this case, the occupants may improve their comfort level by using a mini laptop fan to increase personal comfort. A mini laptop fan could provide a refreshing movement of the air on the upper body which makes the occupants feel cooler. Additionally, air curtain or wall mount fan coil units could be installed to increase the air movement.

This study concluded that the radiant cooling system which was employed in both buildings managed to provide better indoor air quality and thermal comfort with low-energy consumption except for the air movement. While the implementation of the radiant cooling system is still new in Malaysia, improvement could be made in designing buildings with such cooling system. In the future, the occupant’s relation with the indoor thermal comfort of green building in the tropics should be taken into consideration during the designing stage to ensure that the passive strategies meet their purpose in providing better comfort and energy-efficiency.

The indoor air quality assessment in air-conditioned office in the tropics will be discussed in Chapter 5.

CHAPTER 5: INDOOR AIR QUALITY ASSESSMENT IN AIR-CONDITIONED OFFICE IN THE TROPICS

5.0 Abstract

This study aimed to assess the indoor air quality in the air-conditioned office in Malaysia. The experimental study has been carried out at the Construction Research Institute of Malaysia (CREAM) building located in Kuala Lumpur, Malaysia. The indoor temperature, relative humidity and indoor contaminants were measured for a week. Results from the physical measurement reflect that the indoor air quality and thermal comfort parameter were within the acceptable limit recommended by MS1525:2007 and ASHRAE standard except for the relative humidity in the office space. The oversized air-conditioning system has led to this condition, thus the occupants tend to feel cold and need to wear extra clothes during working hours even the temperature is within the desired limit. Consequently, it is strongly recommended that a humidifier be installed in the office space to increase the humidity level and comfort.

5.1 Introduction

The indoor air quality has become a very significant environmental issue. Many studies associated with indoor air quality and thermal comfort in office buildings have been carried out in different climate [4, 173-182]. In Malaysia, almost all the buildings are air-conditioned due to the hot-humid climate. Even the installation of air-conditioning in the building aims to provide comfort to the occupants, more often than it imposed other problems in terms of comfort and health.

As people spend almost 30% of their time in the office, the air-conditioning system has to be able provide comfort and efficiently removes odours and contaminants. However, in recent years, the number of complaints related to the indoor air quality level in the office has increased as it is closely associated with the health and well-being of the occupants. Several symptoms experienced by the occupants inside the office space includes headaches, dry eyes and throat, sneezing, stuffy and blocked nose and dry or irritated skin [183-185] which is commonly known as the “Sick Building Syndrome (SBS)”. All these symptoms have led to absentee, loss in productivity and economy. Studies have been taken to investigate the factors contributing to SBS. Some of the factors include indoor pollutants[185-187], ventilation rate [188-190], human activity, work-related [191] , gender, temperature rise [192, 193] and moisture[194-196]. However, studies showed that better indoor air quality would lead to increase in work performance and productivity [197-199]. Therefore, the indoor air quality assessment is important to ensure that the occupants inside the office are thermally satisfied and are in good condition to work. This present study aims to evaluate the indoor air quality in air-conditioned office in the tropics taken into account the heat island effects.

5.2 Building description

The Construction Research Institute of Malaysia (CREAM) building owned by the Construction Industry Development Board (CIDB) was chosen as a case study. This government research building is located in the Kuala Lumpur, which experiences hot and humid climates throughout the year. The location of the building itself; which is at the congested city centre explained the heat island effects which surround the building. The building consists of two floors; where the ground floor locates the laboratories, and the first floor is mainly offices. Multiple units of normal split, constant air volume and air-cooled type air-conditioning systems whereby each zone is conditioned under the corresponding split unit with individual controls were used to condition this building. In this study, the office space which is installed with the split type ducting air-conditioning system (Air-Cooled Ducted Blower) was chosen as the sampling location. The total floor area is 324 m² and accommodates around 20 people during office hours. The CREAM building is operating from 8.30 am to 5.30 pm. The detailed building's M & E drawing is attached in APPENDIX B.

Figure 5.1: CREAM building, Kuala Lumpur

5.3 Methodology

The indoor air quality assessment in this study follows this approach [19]:

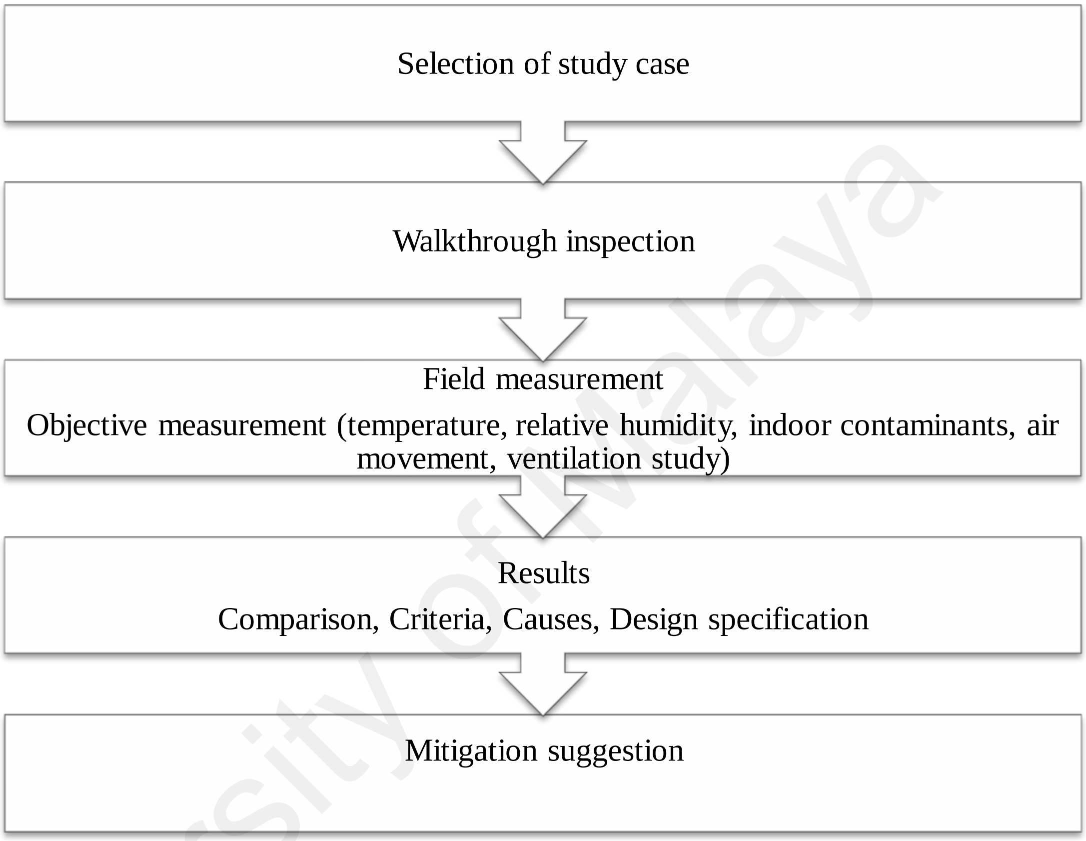

Figure 5.2: Indoor Air Quality assessment method

After the selection of the case study, a preliminary walkthrough has been carried out to assess the air-conditioning system operation, room area and volume, occupants, contaminants source and air supply and diffuser location. The mechanical and electrical (M&E) drawings were obtained from the office staff. The field measurement was then conducted to evaluate the indoor air quality and thermal comfort parameters in the office space. Sampling point was determined and as per instructed in ASHRAE method, the room conditions were measured by locations about 1 meter level below the diffusers and 1 meter above the floor. Only one main sampling point was chosen at the return air grille as it could represent the average indoor air quality and thermal comfort inside the office space. PP Monitor SAS was used to measure the dry bulb temperature (DBT), relative humidity (%RH) and the concentration of carbon dioxide (ppm), carbon monoxide (ppm) ,formaldehyde (ppm) and total volatile organic compound (ppm). The sampling point was shown in Figure 5.3 below. These data were logged from 9.00 am to 5.00 pm for a week and the time step for each interval of data logging was set to be 30 seconds.

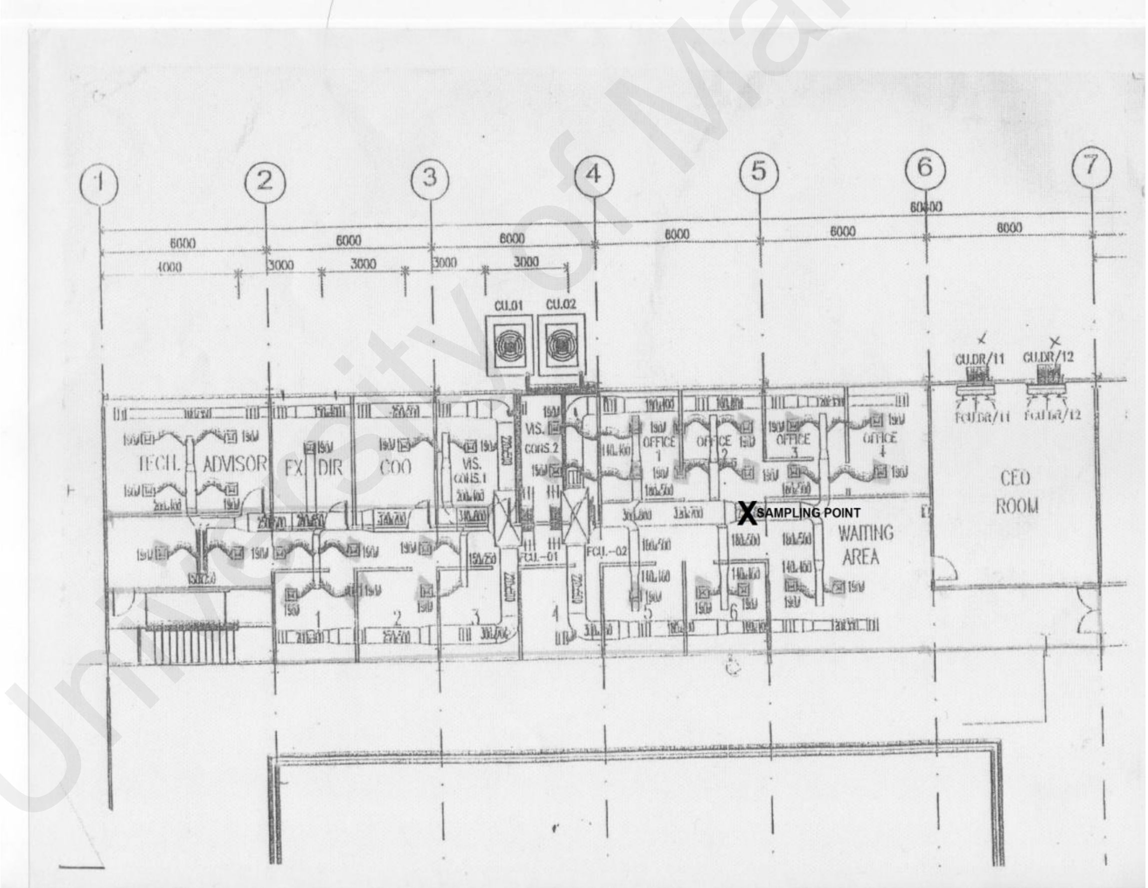

Figure 5.3: Sampling point location

5.4 Results and discussion

The aim of this case study is to assess the indoor air quality in the air-conditioned office in the tropics. Field measurement has been carried out for a week and the evaluation on the indoor temperature, relative humidity and air contaminants had been conducted.

5.4.1 Evaluation of indoor temperature

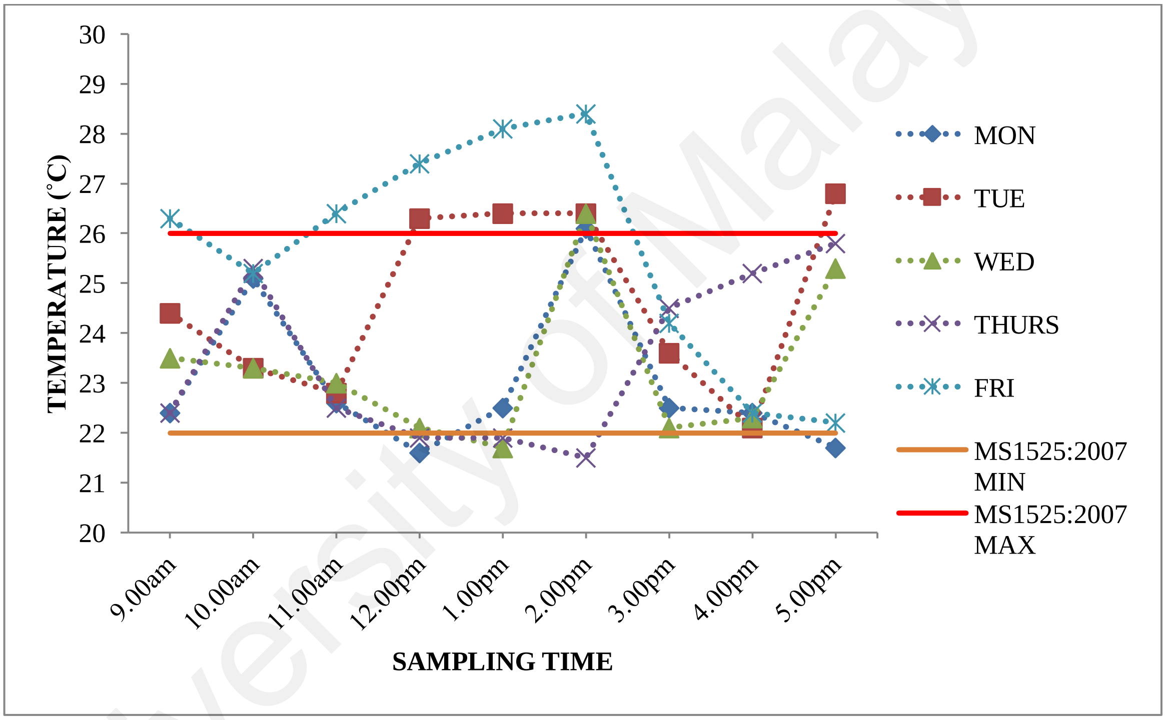

Figure 5.4: Indoor Temperature

According to several studies conducted in Malaysia [10, 21, 200], the ideal indoor temperature in air-conditioned space fluctuates from 24-28˚C, while the recommended indoor temperature according to MS1525:2007 and ASHRAE Standard 55-2010 ranged between 22 to 26˚C[33, 171]. In this case, measurements show that the temperature in the building varied throughout the day. The temperature during the working hours (9.00am to 1.00pm and 2.00pm to 5.00pm) is within the acceptable limit in the MS 1525:2007.

However, the temperature got slightly higher from the given standard during lunch hour (1.00-2.00pm) as the air-conditioning is switched off to reduce energy usage as most of the occupants were not in the office during that time.

5.4.2 Evaluation of indoor relative humidity

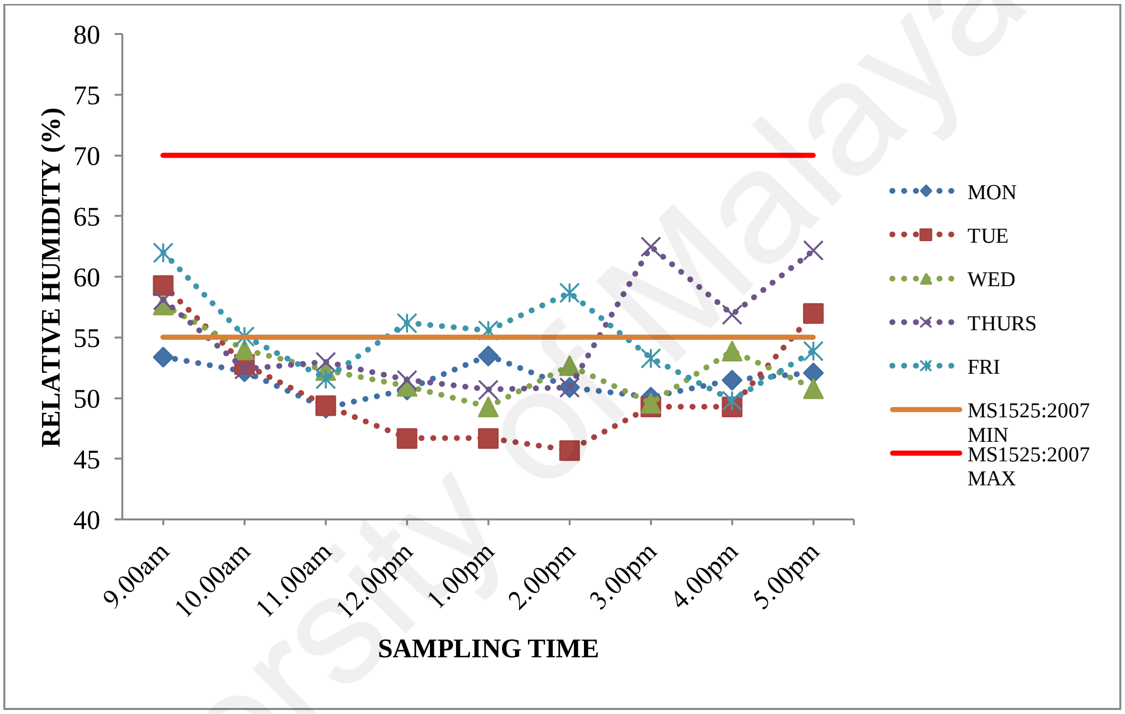

Figure 5.5: Indoor Relative Humidity

The acceptable relative humidity recommended by the MS1525:2007 is between 55 to 70% while ASHRAE Standard 55-2010 is in the range of 30-60 % [33, 171]. Figure 5.5 shows that the relative humidity (45.7-62.5%) is lower than the standard given by MS 1525:2007. This is mainly due to the excessive air-conditioning. Basically, the air conditioners remove moisture from the air to a certain degree. As the air conditioners in the building are oversized, they greatly reduced the moisture level in the office area, which makes the air feel dry. Low humidity makes the occupants feel as if the air temperature is lower than it actually is. This explained why the occupants feel cold and need to wear extra clothing during working hours even the temperature is within the acceptable range. In addition, low humidity could cause thermal distress and affects the occupant’s health. To overcome this problem, humidifier that introduces water vapours to the air can be used in the office space to keep the occupants comfortable during working hours. In addition, the temperature of the room could be increase to save energy and improve this condition.

5.4.3 Evaluation of carbon dioxide concentration

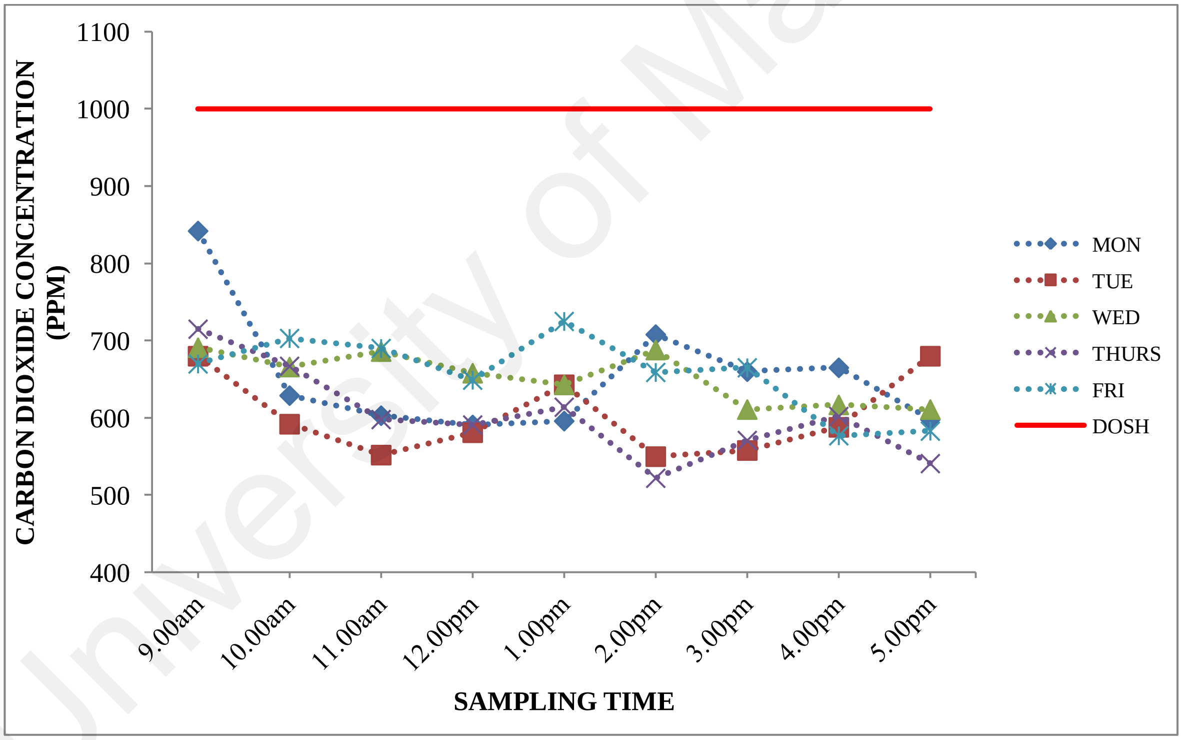

Figure 5.6: Carbon Dioxide concentration

The indoor contaminants assessed include the carbon dioxide, carbon monoxide, formaldehyde and total volatile organic compounds. The carbon dioxide concentration in the office space depends on the level of occupancy and physical activities. Carbon dioxide concentration in the office space is the main indicator of the indoor air quality. High concentration of carbon dioxide could lead to “Sick Building Syndrome.”Almost 50% of the studies related to carbon dioxide concentration indoor proved that by reducing the carbon dioxide concentration to below 800 ppm, the risk of Sick Building Syndrome is also reduced significantly [201]. In Figure 5.6, it can be observed that the carbon dioxide concentration is fluctuating from 552 to 750 ppm throughout the week. However, the concentration was within the maximum limit given by the Malaysian Code of Practice on Indoor Air Quality, ASHRAE and WHO (World Health Organization) standard which is below 1000 ppm. The carbon dioxide concentration inside the office space tends to increase throughout the operating hour and highly depends on the level of occupancy, location and time. The concentration of carbon dioxide was at its highest during Monday morning as the office space was fully occupied compared to other days in the week. In this case, the level of carbon dioxide in the office can be considered low due to the low occupant density in the office space.

5.4.4 Evaluation of carbon monoxide concentration

The main source of carbon monoxide inside a building is from the incomplete combustion of vehicle emission [202] and tobacco [203]. However, as most of the buildings in Malaysia prohibited smoking in buildings, the combustion of tobacco could be excluded. Long exposure to this gas is hazardous as it combines with haemoglobin in the blood and decreases the oxygen supply to the body. The common symptoms of carbon monoxide poisoning include headaches, rapid breathing, nausea and dizziness [204].

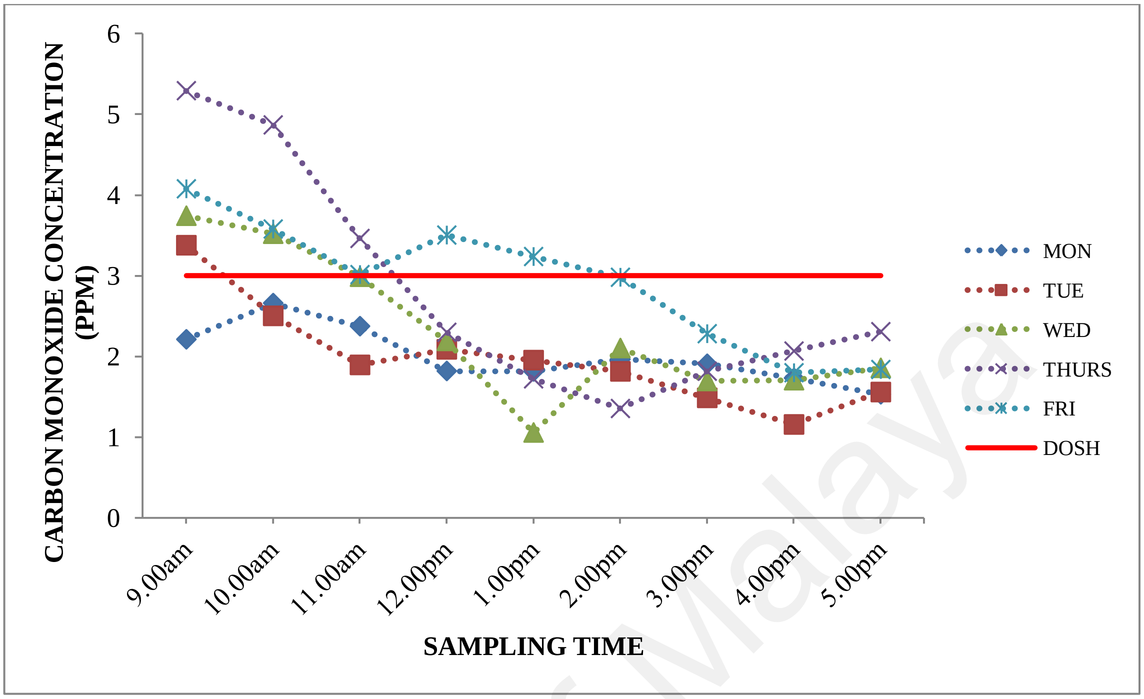

Figure 5.7: Carbon Monoxide concentration

From Figure 5.7, the carbon monoxide readings ranged between 1.156 to 5.195 ppm throughout the week. The carbon monoxide concentration slightly exceeds the allowable limits which 3 ppm according to the Malaysian Code of Practice of Indoor Air Quality. However, the ASHRAE Standard 62-1989 indicated that the maximum limit for 8-hour average exposure to carbon monoxide must not exceed 9 ppm. Nonetheless, level greater than 5 ppm implies the existence of unpleasant combustion contaminants. In this case, the carbon monoxide concentration is at its highest at early morning as the office building is in close proximity with the heavy traffic and parking area.

5.4.5 Evaluation of formaldehyde concentration

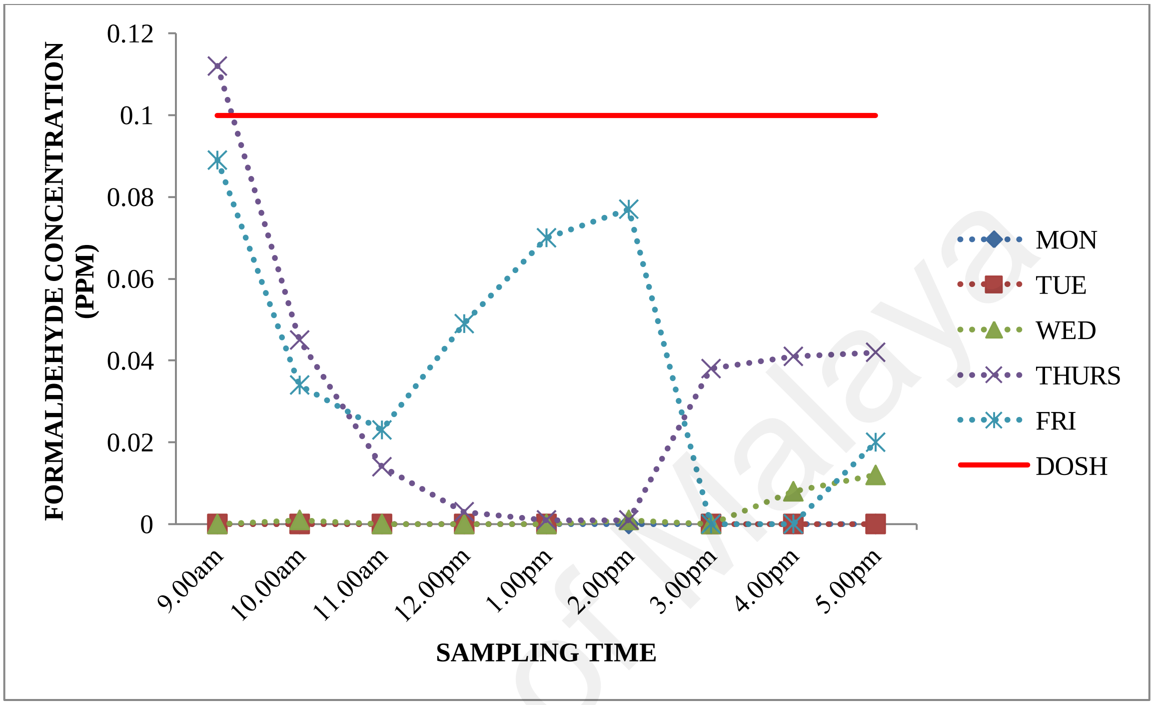

Figure 5.8: Formaldehyde concentration

Formaldehyde is a colourless gas with a pungent smell that is known to cause irritation to the nose, eyes, throat, and lower respiratory system [183] if the concentration level is above 0.1 ppm. Formaldehyde concentration below 0.05 ppm is unlikely to cause severe irritant symptoms, however, could increase the risk for allergen sensitivities, chronic irritation and cancer [183].Readings in Figure 5.8 show that the formaldehyde concentration in the office space is within the below the tolerated limit which is 0.1 ppm except on Thursday morning. The main source of formaldehyde in the office space is the air freshener dispenser located near the PP monitor.

5.4.6 Evaluation of total volatile organic compound (TVOC) concentration

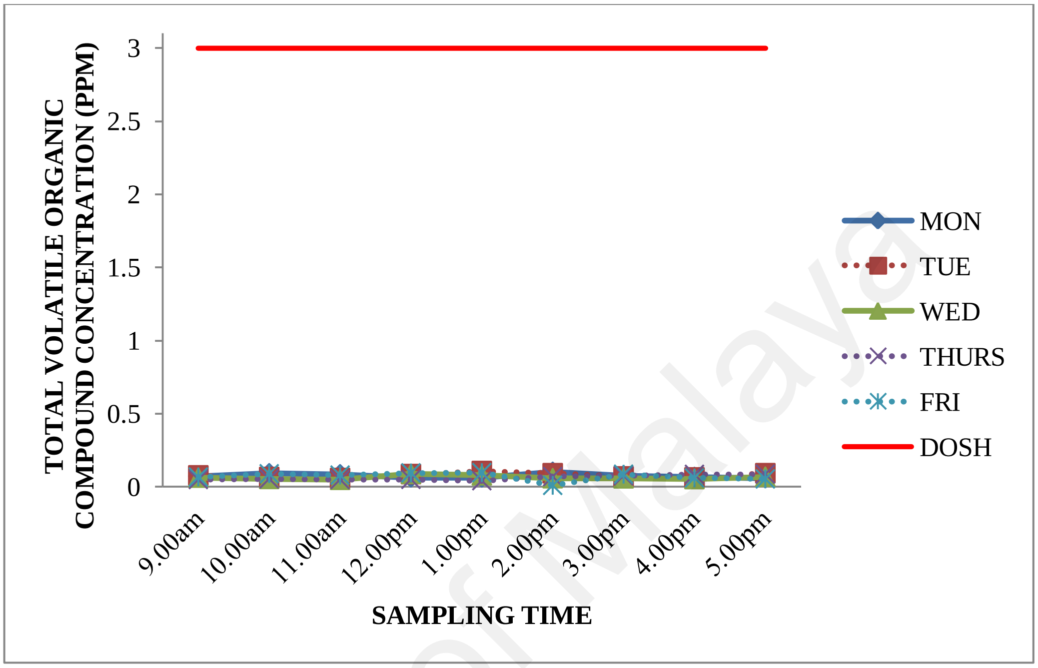

Figure 5.9: Total Volatile Organic Compound (TVOC) concentration

The total volatile organic compound (TVOC) refers to gases produce by carbon-containing chemical at room temperature. Building materials, air freshener, office equipments, paints and people are some of the sources of TVOCs emission [205]. The TVOC is often related on how the occupants perceived the odours and had undesirable impacts to health, which could irritate the eyes, nose and throats [206]. The severity of these effects depends on the order of the magnitude. According to studies [207, 208], irritation to eyes is normally due to the TVOCs emission from cleaning products, water-based paint and photocopier. In this case, the readings for TVOC lie far below the threshold limit specified by the DOSH [32], which is 3 ppm.

5.4.7 Evaluation of particle contaminants

The indoor air quality inside the office space is highly affected by the outdoor and indoor condition. The particles found inside the office space are mainly originated from the outdoor air [209-211]. Several factors that affect the particle distribution in a ventilated room includes indoor particle source, infiltration of outdoor particles via ventilation and building envelopes, filtration, deposition onto building surfaces and particle removal via ventilation [212]. In the office space, the ratio of indoor and outdoor particles in the accumulation mode (0.1 to 0.5µm) increase as the air change rates increased [211]. Accumulation of dust inside the ventilation system promotes a habitat for microbial contaminants, which leads to severity health problems [213, 214]. The particulate-matter behaves differently from the indoor gas pollutants [215], thus as far as the health is concerned, the particulate-matter measured in the office space was smaller than 10µm or smaller than 2.5 µm [216].

According to the Code of Practice of Indoor Air Quality by Ministry of Human Resources, Malaysia, the concentration of particles inside a building must not exceed 0.15 mg/m^3 to ensure good indoor air quality. The results from Figure 5.10 indicate that the average weight of dust particle inside the office space range from 0.013 to 0.06 mg/m^3 which lie far below the recommended limit. Figure 5.11 shows the particles count in the office, as a function of size. Overall, the particle counts in the office indicate that there is no cause to concern. This proves that the filter in the air-handling unit works efficiently to remove the particles in the air. The dust particles on Thursday was slightly higher compared to other days in the week due to the frequent opening of the door due to maintenance work that is going on during that day.

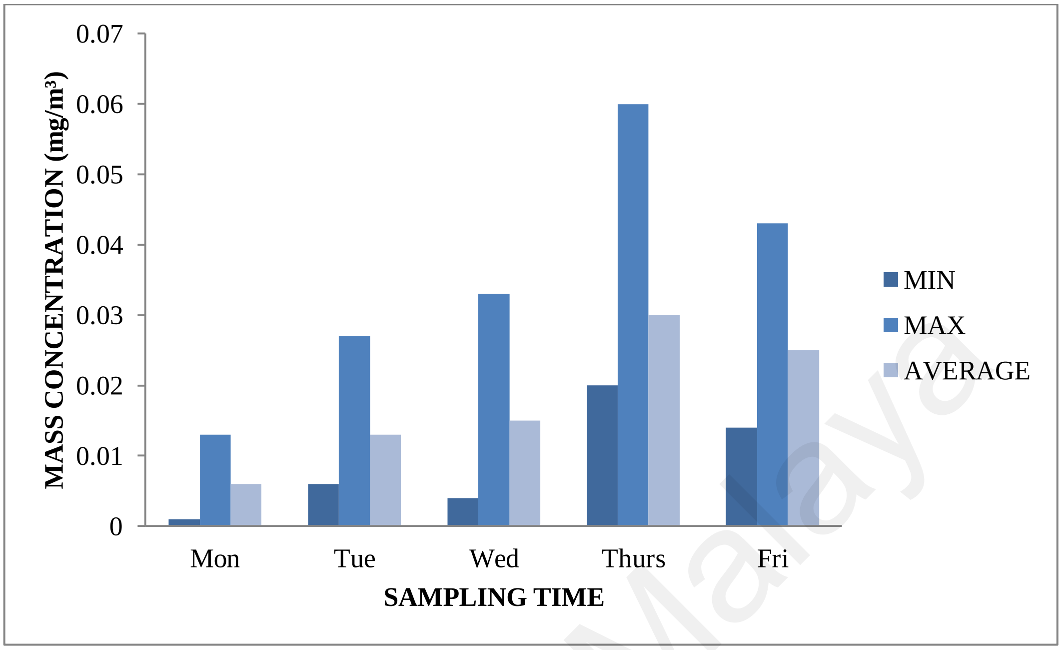

Figure 5.10: Average mass concentration in the office space

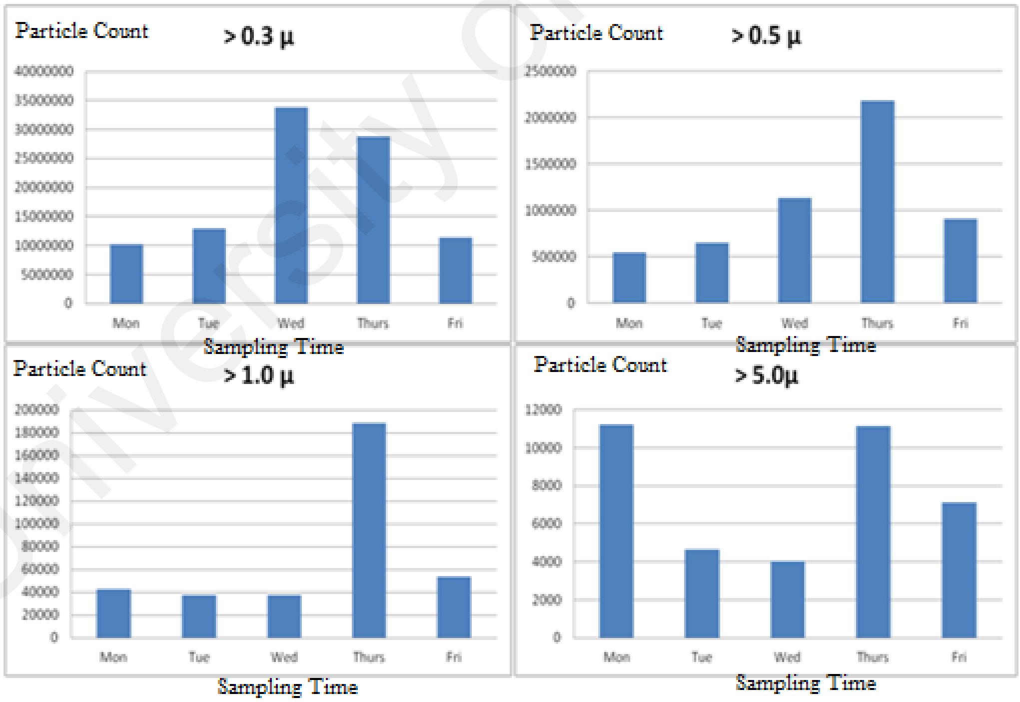

Figure 5.11: Particle counts in the office space

5.5 Conclusion and recommendation

An indoor air quality assessment in the air-conditioned office in Malaysia is presented. The thermal comfort and indoor air quality parameters were measured for a week. The measurement aimed to evaluate the indoor air quality and occupant comfort in the office space. From the results, the indoor temperature inside the office space was in the range of 20-28˚C and the indoor relative humidity was between 45.7- 62.2% which is relatively lower than the standard. The oversized air-conditioning system installed inside the office space has led to this condition. Therefore, the occupants tend to wear extra clothing during working hours as they feel cold even the temperature was within the desired limit. Other parameters such as the indoor pollutants concentration were found to be within the recommended limit suggested by the MS 1525:2007, ASHRAE and WHO standard. As far as the relative humidity is concerned, humidifier could be installed in the office space to increase the occupant comfort. There are several types of humidifier that could be installed inside the office space such as the electronic humidifier, steam humidifier, impeller or ultrasonic humidifier. However, taken into consideration the cost and size of the office space, a steam humidifier is the best solution which is least expensive, hygienic and able to conditions the space accordingly. Generally, the humidification systems manifolds can be retrofitted to the existing air handling units (AHU) or the air ducts (in-ducts). Additionally, the portable steam humidifier could also be used to improve the condition.

The climate change impacts on the cooling load in the office building in Malaysia will be discussed in detailed in Chapter 6.

CHAPTER 6: CLIMATE CHANGE IMPACTS ON COOLING LOAD IN THE OFFICE BUILDING IN MALAYSIA

6.0 Abstract

Building industry is accountable for almost a third of the global energy-related carbon emission and 60% of the halocarbon emissions. The emissions originated from the combustion of fuels for electricity used for cooling, heating and electrical equipments. The building's carbon emissions intensify the climate change impacts on us and one of the most obvious impacts is the rise in the global average temperature. Rising in global average temperature influence the comfort and well-being of us as most of our time are spent indoor. Many of us resort to air-conditioning as a medium to increase our comfort without realising that its usage will contribute to the carbon emission and increase the effects of climate change even further. Numerous studies have been conducted to assess the climate change impacts in terms of energy consumption of a building; however, only few studies were carried out in the tropical region. This study aimed to project future cooling load needed in the year of 2000, 2020, 2050 and 2080 in the tropics using TRNSYS simulation. From the simulation results, the total cooling load increases as the temperature change. The total maximum cooling load required in the year of 2000, 2020, 2050 and 2080 are 297000 kJ/hr, 305000 kJ/hr, 321000 kJ/hr and 332000 kJ/hr. If compared with the year 2000, the maximum cooling load needed in the years of 2020, 2050 and 2080 increases by 2.96%, 8.08% and 11.7% respectively.

6.1 Introduction

Based on all the strong evidence of global warming trends affecting average air temperatures and composition of greenhouse gases, a vast number of studies on climate change impacts on diverse aspects of human life, such as economy, health, energy, water resources, politics and agriculture, have been conducted. The Third Assessment Report Work Group (WG) II [41]acknowledged that "*The basis of research evidence is very limited for human settlement, energy and industry. Energy has been regarded mainly as an issue for Working Group III, related more to causes of climate change than to impacts. Impacts of climate change on human settlement are hard to forecast, at least partly because the ability to project climate change at an urban or smaller scale has been so limited. As a result, more research is needed on impacts and adaptations in human settlement*".

Climate change by definition is the climate shift due to human activities that modify the proportion of natural GHG in the lower atmosphere .Some of the impacts of climate change can be seen in terms of frequent extreme weather events, increased variability in climatic conditions and rise in temperature. Bader in his study disclosed that there was an abrupt difference in temperature from hot summer to cold winter, resulting in extremely cold weather in October 2003 [42]. In a separate study in the following year, Luterbach et al concluded that 2003 was the hottest summer and 1709 was the coldest European winter [43]. If we remember, the summer of 2003 caused many fatalities. For instance, France alone recorded nearly 15000 deaths above average for the season and these were directly related to nights during which the temperature did not drop below 29 °C. Another study by Schar et al went a step further and found that the increase in average temperature, were responsible for the summer heat waves in 2003 [44]. These studies imply that adaptation to climate change should be planned in advance to prevent further fatalities in the future.

As one of the largest sources of greenhouse gases emission that caused climate change, building sector also appears to be vulnerable to challenges from climate change, especially global warming. The potential implications of increasingly extreme weather patterns such as winter storms, droughts, flooding, earthquakes and storms introduce various challenges for building sustainability. Global warming is anticipated to have strong implications on future energy demand of buildings, in particular with regard to the overheating aspect.

The Fourth Assessment Report of IPCC (AR4) acknowledged that since 1750, the proportion of carbon emitted to the global atmosphere has been rising primarily due to the human activities [41]. Nowadays, in developed and developing countries, buildings are accountable for more than 40% of global energy consumption and approximately 30% of global greenhouse emissions [54, 55, 71].Due to the energy consumption in the buildings, the most important elements in the emission scenarios considered are the carbon emissions and environmental implications. Many commercial buildings are responsible for up to 200 tonnes of carbon emissions per square meter of floor space annual and mostly due to the electricity consumption during operational phase [46].

In the ASEAN region, the commercial buildings are accountable for 30% of all the electricity use and will demand approximately another 40% of generation capacity in years to come [69]. In 2004, buildings in Malaysia are accountable for 75% of total national energy consumption including the residential buildings which consume almost 44% from it. Typical office buildings in Malaysia use more than 260 kWh/m²of energy per year and are responsible for almost 21% of total national commercial energy consumption [70]. Related to this, office buildings energy consumption is estimated to be around 6090 GWh. The main energy users in the office buildings are air conditioners (57%), lighting (19%), pump and lifts (18%) and electrical appliances (6%)[71].

The Fourth Assessment Report of the IPCC (AR4) estimated building related carbon emissions to be around 8.6 million metric tons CO_2 eqv in 2004 [1]. Carbon emissions by definition are the carbon dioxide emitted directly or indirectly caused by an activity. The main source of these emissions comes from combustion of fossil fuels for cooling, heating, lighting, and to power electrical appliances [54, 55]. Apart from that, the buildings sector is also accountable for significant non-CO_2 greenhouse gases emissions such as halocarbons, CFCs and HCFCs and hydrofluorocarbons (HFCs) due to their applications of cooling, refrigeration and in the case of halocarbons, insulation materials [1].

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) summarised the implications of climate change on the building sector as "*increased electric demand and reduced energy supply reliability*"[46] .Many studies have been carried out to predict building energy consumption in the future [97, 102, 122, 135, 217]. However, these studies generally do not consider the impacts of temperature swings on building energy consumption due to climatic variability. From the perspective of climate change impact, the buildings sector ignores the climatic variability and the consumer reaction towards temperature change, such as increasing usage of air-conditioning and natural ventilation to improve thermal comfort.

In fact, climate change is predicted to have strong effects on building's energy requirements as their heating and cooling needs are highly related to temperature conditions and variations[94, 97, 102, 108, 110, 114, 129, 218]. Climate change impacts on the building can be seen in terms of changing patterns in cooling and heating demands[85, 93-96, 104, 106], energy consumption and peak demands[57, 115, 119, 126, 219], carbon emissions [60, 63, 220, 221] and physical structures[76, 222-227]. Clearly, there will an increased in cooling demand and declined in heating demand in regions where there is a projected rise in temperature, thus the building energy consumption and carbon emissions are expected to rise dramatically during its operation phase.

Building in Malaysia comprises of commercial and residential buildings which include the government-owned building. The energy usage from this sector was approximately 7750 GWh per year [228]. With the increase in new building construction and inefficient energy utilisation in existing buildings, the annual energy consumption in this sector is expected to rise over the next few years. If its overall energy utilisation performance does not get improved, this sector will continue to contribute significantly to the national greenhouse gases emissions. For instance, in 2008, the building stock in the country amounted to about 37.81 million m^2 per area, of which 11% of the buildings were considered as Energy-Efficient buildings (the Building Energy Index of which is 136 kW/m^2 and below). In the same year, this sector emitted about 5301 ktonnes carbon into the atmosphere [228].

Moreover, the current weather files for building performance simulations are commonly derived from historical data of the period of 1961-1990, which does not reflect current climate trends and future climate projections. Buildings designed according to existing standards may become increasingly costly to operate and maintain in the future. Increases in wind speeds and extreme weather events, temperature swings, changes in levels of precipitation and relative humidity should be taken into account to ensure that current and future buildings are able to adapt to these changes, and thus minimise the potentially destructive impacts, energy use and carbon emissions.

At the moment, there is a voluntary code of practice known as MS1525:2007 that provides guidance on the building envelope designs and the implementation of energy-efficient equipments and building energy management systems. However, as the MS 1525:2007 is not compulsory, the guidance particularly in energy-efficiency aspects is often ignored by the building practitioner in the country. The adoption of this standard by the building owners and designers are usually hindered by several barriers such as institutional, policy and regulatory, information and awareness, technical and financial barriers.

In line with this, the Malaysia government has shown their full support towards sustainable development by launching the National Green Technology Policy in 2009. Since then, the demand for building equipped with green technology or the “green building” has continued to rise as it involves low building’s operating cost and high building and return on investment value. The Malaysian government had also launched the country’s green building rating system known as the Green Building Index (GBI) towards promoting the construction of environmentally-friendly buildings. Green technology has recently becoming a trend in most of the countries in the world as it promotes economic growth and is eco-friendly.

The purpose of case study is to assess the climate change impacts on the air-conditioning and mechanical ventilation (ACMV) systems in commercial building in the tropics in terms of sustainability and indoor air quality of the building. Recently, the effects of erratic weather patterns on building energy requirements and consumption have been widely discussed internationally. However, only a few studies have focused on the regional impacts, especially in the tropics. For this study, a small office in the Construction Research Institute of Malaysia (CREAM) building located in Kuala Lumpur, Malaysia has been selected as a case study.

6.2 Methodology

6.2.1 Climatic data

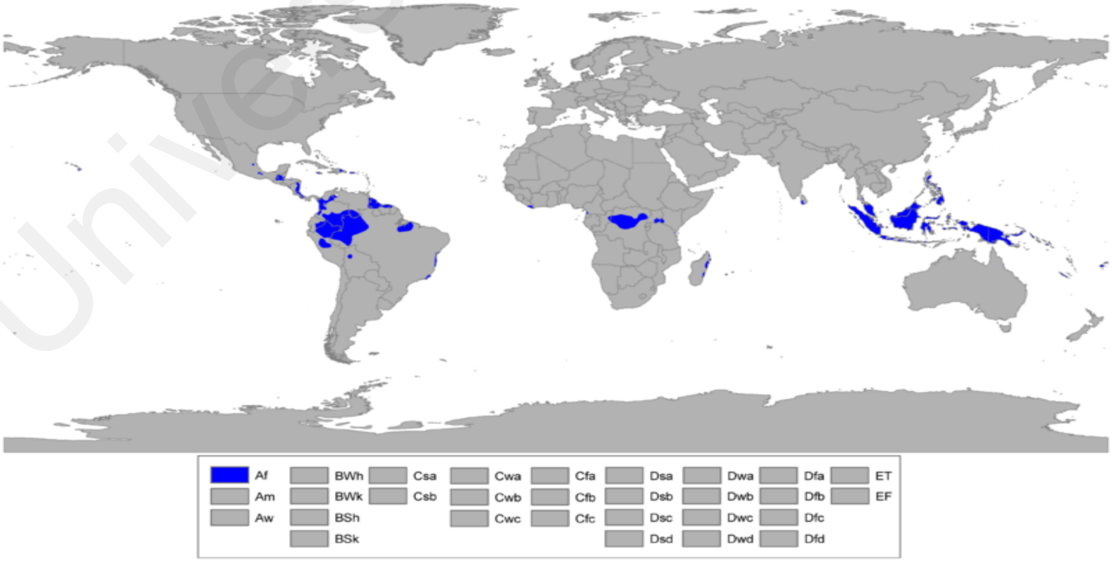

Figure 6.1: Location of Malaysia in the Tropical Rainforest Climate (AF) [229]

Kuala Lumpur, the capital of Malaysia is located in longitude 2˚30’ N and longitude 112˚30’ E with the total area of 243 km². Malaysia’s climate is categorised under the Koppen Climate Classification scheme as AF, Tropical Wet climate with some small areas of highland climate. The monsoon season sets in yearly from October to February in the northwest and from April to October in the southwest. The climate characteristics such as temperature, relative humidity and solar radiation are uniform throughout the year with no large variations. The average mean temperature ranged from 24.6 to 31.6˚C and the mean relative humidity ranged from 76 to 82%. As a hot-humid tropical climate country, Malaysia receives annual total radiation of 7-10 hour of sunshine per day thus increasing the indoor temperature which is normally required the usage of air-conditioners to keep the occupant’s thermally satisfied.

6.2.2 Building description

The CREAM building is located in Kuala Lumpur, Malaysia. Its location and Malaysia’s climatic condition explained the heat island effects experienced by the building. The building consists of two floors; where the ground floor locates the laboratories, and the first floor is mainly offices where the study took place. The office space is facing north with single glazing windows. As office, it accommodates almost 20 occupants at a time and operates nine hours per day (9.00am to 5.00 pm), five days per week (Monday to Friday). The floor area is 324m² with 2.5 m height.

6.2.3 Cooling load calculation

Cooling load calculation is commonly used to predict the building cooling capacity. The orientation of the building, physical dimension and ceiling height, material properties of wall and window, number of people, computer, and lighting are included in the calculation. As the building does not have its own building Energy Management System (EMS), the Cooling Load Temperature Difference/ Cooling Load Factor (CLTD/CLF) is applied to estimate the building's cooling load. In this method, the equivalent cooling load needed is divided into sensible heat gain and latent heat gain. The cooling load calculation performed is shown in Table 6.1 below:

Table 6.1: Cooling load calculation

Sensible heat gain					
Heat conduction					
Surface-facing	Area/m²	U,value	CLTD	CLTD c	Btu/hr
Roof	274.79	0.372	78	79.6	81276.53
Wall					
North	131.86	0.465	19	20.6	1263.09
West	592.01	0.465	21	22.6	6221.43
Glass					
North	215.28	1.92	19	20.6	8514.75
West	43.06	1.92	21	22.6	1868.46
			ΔT		
Floor	2744.79	0.488	3		4018.37
IntWall					
South	242.19	0.465	0		0
East	258.33	0.465	3		360.37
North	67.27	0.465	3		93.84
East1	161.46	0.465	3		225.24
IntGlass					
East	387.5	1.92	3		2232.0
			Subtotal Heat Conduction		**106,074.08**
Solar heat gain					
Glass-Facing	Area/m²	SCL		SC	Btu/hr
North	43.06	32		0.35	544.97
West	215.28	132		0.35	11238.91
			Subtotal Solar Heat Gain		**11,783.88**
Internal sensible heat					
Item			Quantity	Btu/hr/person	Btu/hr
Occupants		15		230	3450
Electrical Appliances	Quantity	Watt	Factor	1 W=3.4Btu	Btu/hr

				/hr	
Light	120	36	1.25	3.4	18360
Laptop	15	350	1	3.4	17850
Infiltration					
Item	Delta T	Constant	CFM		Btu/hr
Door	10	1.09	37.52	408.968	
Ventilation					
Item	Quantity	CFM/person	CFM		Btu/hr
Occupant	15	18	37.52		10130.4
			Subtotal Sensible Heat Gain		**50,199.37**
Latent heat gain					
Source	Quantity		Btu/hr/person	Btu/hr	
Occupant		15	190		2850
	Constant	CFM	Delta HR		
Infiltration	0.68	37.52	110.5		2819.25
Ventilation	0.68	37.52	110.5		2819.25
			Subtotal Latent Heat Gain		**8,488.51**
			Total (Btu/hr) or (kW)		**176,272.84 or 185,977.69**

From the results, the calculated cooling load of the office space in the office space is 186,000 kW. The cooling capacity of the air conditioning in the office space is 211,000 kW. According to the results obtained from the calculation, the estimated cooling load needed is smaller than the cooling capacity. This implicates that an over-sizing factor by 1.34 has been applied to the estimation of cooling load during installation. An oversized air conditioner contributes to occupant's discomfort and higher initial and operating cost. The oversized air conditioner in the office space greatly reduced the moisture in the office which makes the occupants feel dry. The low relative humidity makes the occupants feel as if the temperature is lower than it is even the temperature is within the acceptable range. From the observation during the walk-through, the occupants still wear extra clothing during working hours even the temperature is within the desired temperature (24-28˚C). In addition, the excessive air-conditioning makes the space feel damp and stuffy.

The over-sizing factor is often applied to the cooling load calculation to ensure that the air-conditioning system is able to provide rapid cooling and avoids any chance of not meeting the cooling demand. To deliver cooling more quickly, the oversized air conditioner runs in shorter time and required extra energy from usual which creates added demand to the electrical generation and delivery system. The short run-time does not allow the system to remove humidity effectively, which affects the occupant comfort and system reliability. On the other hand, long run time will affect's the system life span. Therefore, as the optimum efficiency is accomplished at continuous running, the properly-sized air conditioner should run accordingly to be able to cool the space efficiently. In the future, the oversized air conditioners contribute to the increase in the greenhouse gases emissions which in the end increase the climate change impacts on us.

6.2.3 Weather data profile: Temperature change

For the purpose of simulation, Typical Meteorological Year (TMY2) weather data files at different year for Kuala Lumpur, Malaysia have been created by Mark F. Jentsch in U.K. The weather files for the year of 2000, 2020, 2050 and 2080 were simulated using TRNSYS simulation Studio for one-year period.

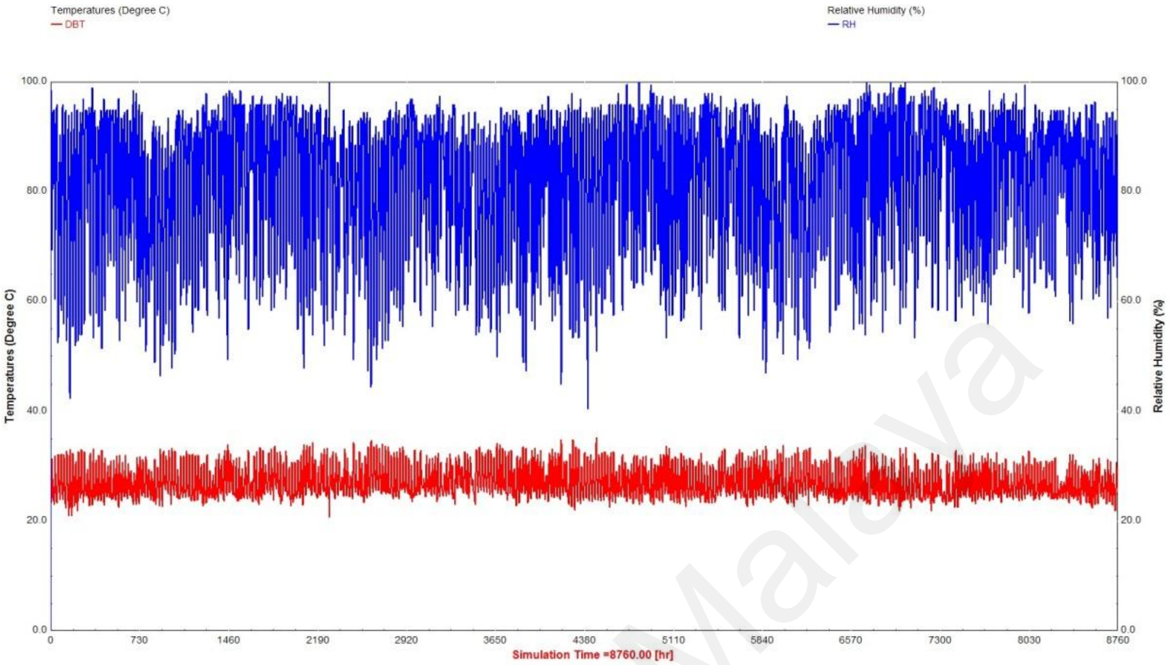

Figure 6.2: Weather data profile for the year 2000

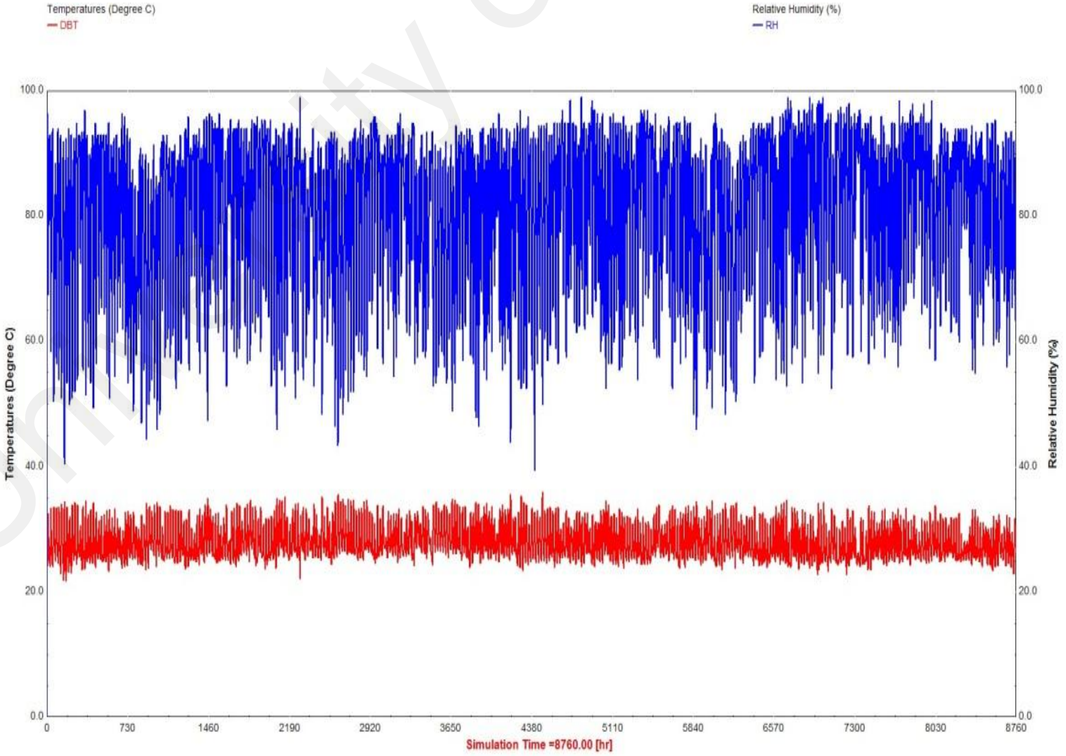

Figure 6.3: Weather data profile for the year 2020

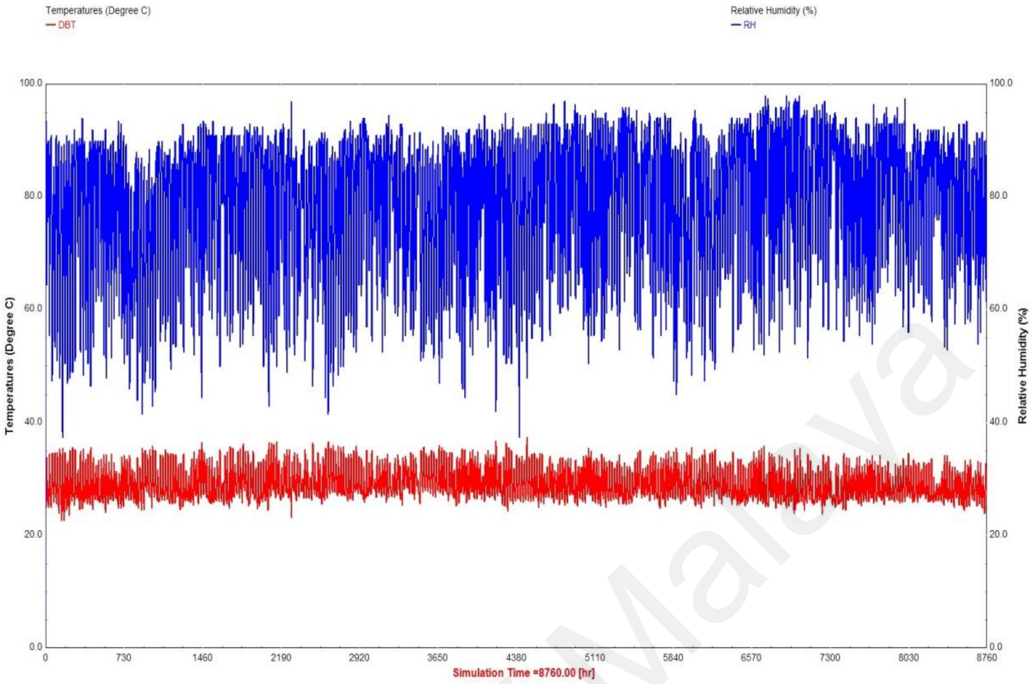

Figure 6.4: Weather data profile for the year 2050

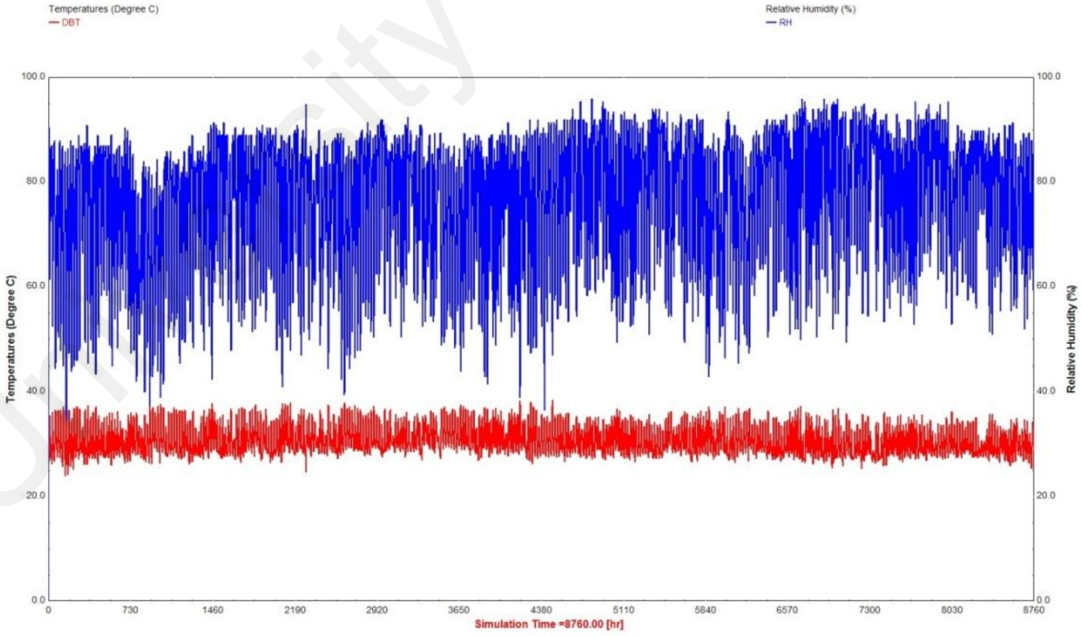

Figure 6.5: Weather data profile for the year 2080

Table 6.2: Weather data for the year 2000, 2020, 2050 and 2080

Year	Dry bulb temperature (°C)	Ambient air humidity (%)
2000	21.39-35.28	40.52-100
2020	22.56-36.09	39.77-100
2050	23.42-37.38	33.38-100
2080	24.49-38.33	32.64-100

From Table 6.2, the simulated weather data showed that the average temperature will increase around 1ºC and the average relative humidity will decrease by 1% to 2% for the next 20 years. The increase in temperature and decrease in relative humidity will strongly affect the existing air-conditioning system in terms of energy use as extra cooling capacity is needed to maintain the occupant’s comfort. The increase in temperature will definitely affects the occupant comfort due to the overheating in the office space.

6.2.4 TRNSYS simulation

The cooling capacity of an air conditioner depends on the outdoor and indoor conditions. Related to this, the impacts of climate change, for instance, the increase in temperature will definitely affect the cooling load demand in the space. The sustainability and durability of the installed system is forecasted using the TRNSYS simulation.

The baseline simulation was created using TRNSYS simulation Studio based on the design specification obtained and site study at the building. Essentially, this simulation requires several settings for certain module. In this case, the building has been modeled in the multi-zone module (Type 56a). The space geometry, orientation of the building, portion of the window in percentage, material properties of window, wall and roof, heat gain due to occupants, laptop and lighting is defined in Type 56a. In this case, only the north and west side of the office are facing the sun. The building materials used, theirs U-values and source of heat gain were described in Table 6.3 and 6.4

Table 6.3: Building materials

Building Construction	Details	U-value (W/m²K)
Wall	Plaster (0.03m) Brick (0.115m) Plaster (0.03m)	2.256
Roof	Concrete (0.24m), Insulation (0.16m)	0.233
Internal Floor	Floor (0.005), Stone (0.06m), Silence(0.04m), Concrete (0.24m)	0.834
Window	Single glazing, (height:1.219m, width 0.914m)	1.4

Table 6.4: Heat gain source

Details	Quantity
Occupants	15
Laptop	15
Lighting Fluorescent	120

The equivalent air-conditioning system for the space is created then integrated through the ventilation system with inlet air properties settings inside the multi-zone module (Type 56a). The cooling load rate, dry bulb temperature and relative humidity are plotted using the output plotter module (Type 65b). The details of the air-conditioning system are attached in APPENDIX D1. From the baseline model, the maximum cooling load required by the office space is determined by using TRNSYS Studio with four different years of TMY2 weather profile data in Kuala Lumpur, Malaysia.

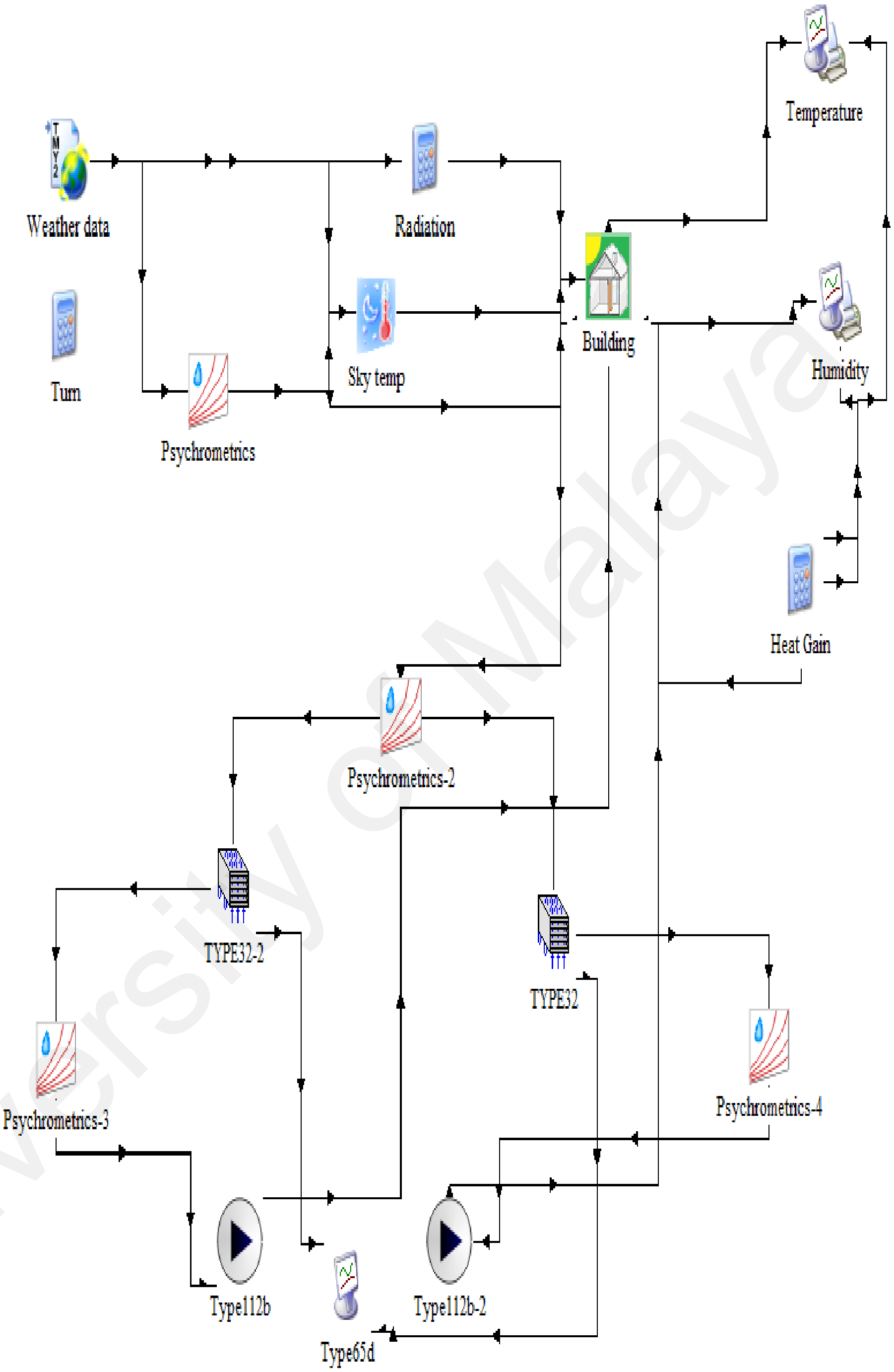

Figure 6.5: TRNSYS Baseline simulation

6.3 Results and discussion

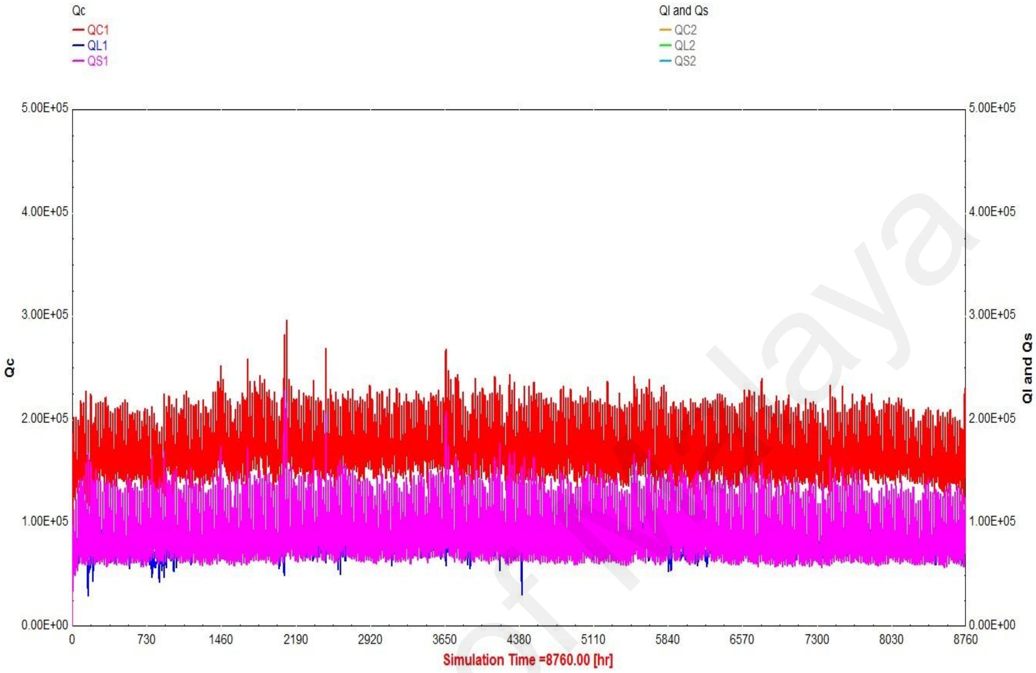

Figure 6.6: Cooling Load for the year 2000

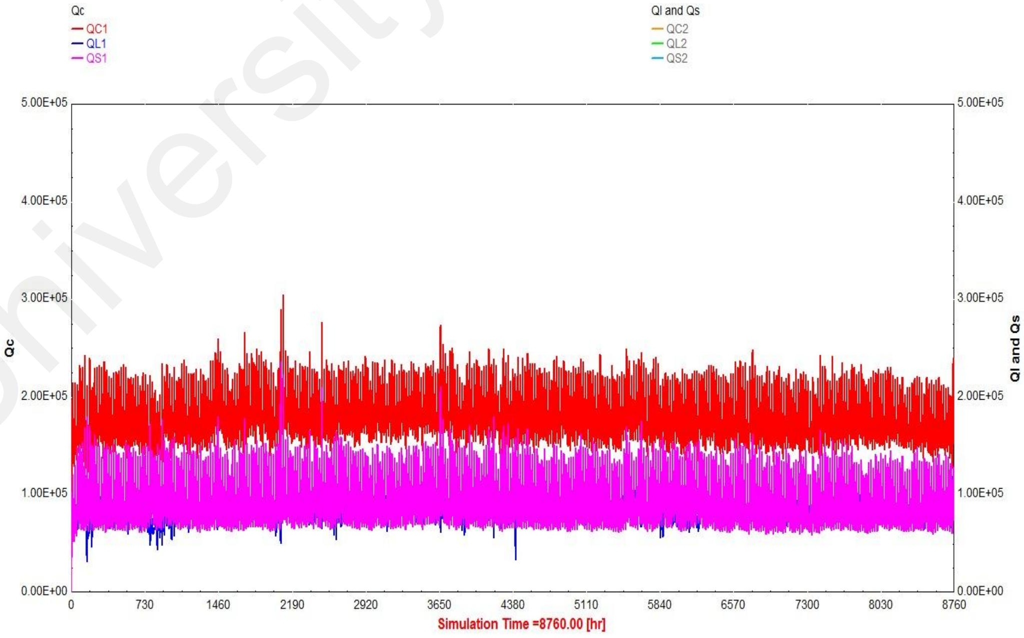

Figure 6.7: Cooling Load for the year 2020

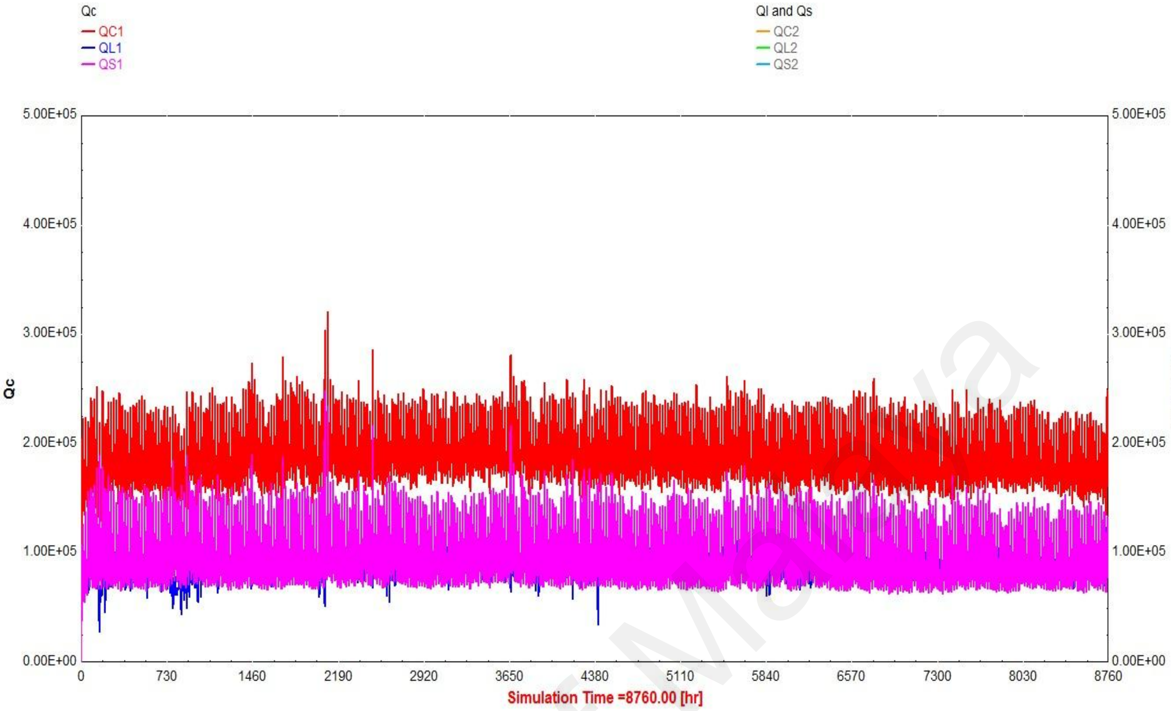

Figure 6.8: Cooling Load for the year 2050

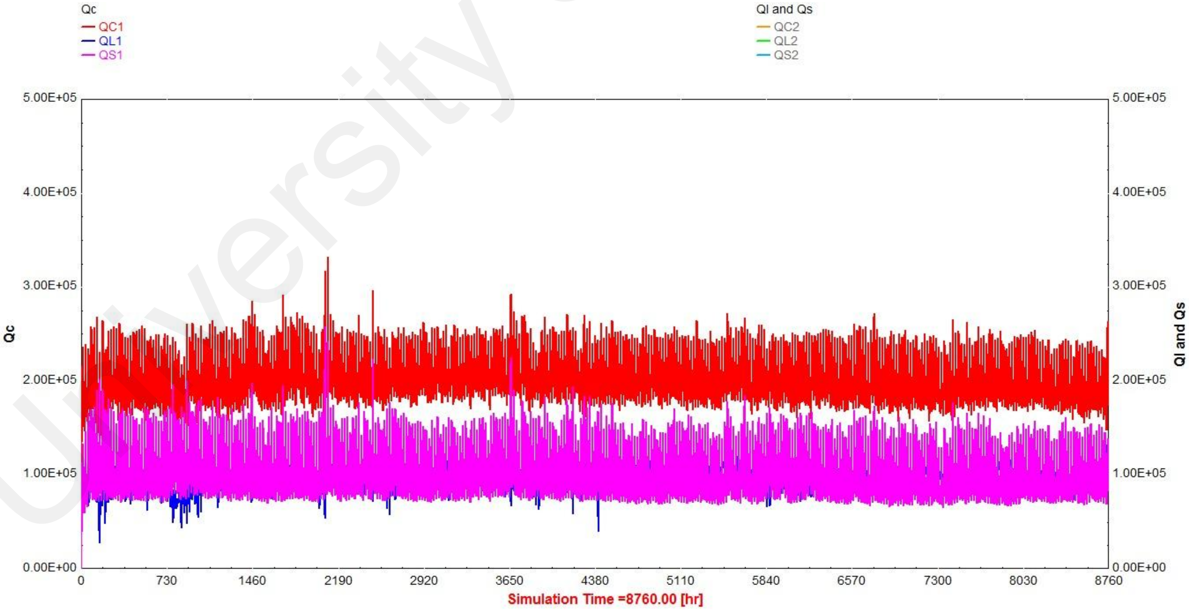

Figure 6.9: Cooling Load for the year 2080

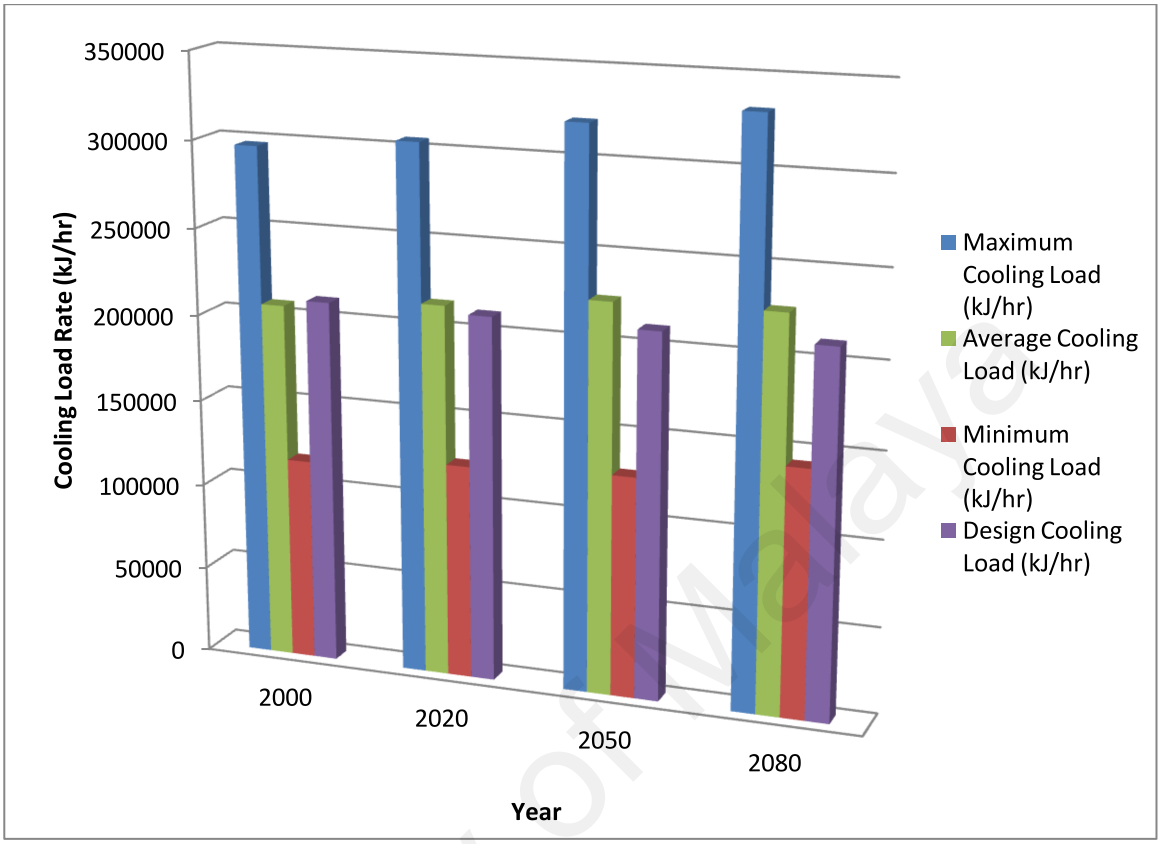

Figure 6.10: Projected Cooling Load in the Year 2020, 2050 and 2080

Table 6.5: Maximum cooling load for the year 2000, 2020, 2050 and 2080

Year	Maximum Cooling Load (kJ/hr)	Minimum Cooling Load (kJ/hr)	Average Cooling Load (kJ/hr)
2000	297 ,000	117 ,000	207,000
2020	305 ,000	124 ,000	215,000
2050	321 ,000	128 ,000	225,000
2080	332 ,000	143 ,000	227,000

Generally, some of the major climatic parameters such as the outside temperature, solar and night sky radiation, wind and rain have significant impacts on the amount of energy required by the air conditioner to cool the space. In this case study, additional cooling load is required to remove the heat from the building as the outdoor temperature continues to increase. Other buildings related factors that associated with the energy demand in the building includes its orientation, size and shape, roof system, the thermo-physical properties, construction detailing and window system.

From the simulation results, it appears that the total cooling load increases with year. The total maximum cooling load required in the year of 2000, 2020, 2050 and 2080 are 297,000 kJ/hr, 305,000 kJ/hr, 321,000 kJ/hr and 332,000 kJ/hr. If compared with the year 2000 as the reference year, the maximum cooling load needed in the years of 2020, 2050 and 2080 increases by 2.96%, 8.08% and 11.7% respectively.

The increment of cooling load by 11.7% for the next 70 years is due to the increase of the outdoor temperature, which increases the amount of heat transfer from outdoor to the indoor space through building’s wall, window and roof. It is observed that the increase in solar radiation and its heating effects have strong influence on the energy requirement needed for cooling in the tropics. Based on the IPCC report on 2001, the resulting imbalance between the incoming solar radiation and outgoing thermal radiation will possibly heated up the Earth over the next century and causing polar ice caps to melt, rising the sea levels and creating erratic global weather patterns. According to one of the NASA funded study, the amount of solar radiation emitted by the sun during times of quiet sunspot activities has rise by nearly 0.05% per decade since 1970s[230].

By referring to the simulation results, it can be seen that the climate change effects in the tropics in terms of temperature change had significant effects on cooling load required by the building. The system is predicted to be unable to provide sufficient cooling load to the office space as the maximum cooling load needed in the year 2080 is 332,000 kJ/hr compared to the design cooling load which is 211,011 kJ/hr. The incapability of the existing air-conditioning system to meet the cooling load requirement will lead to the risk of overheating in the office space. The overheating condition will affects the occupant's health and thermal comfort. Additionally, the rise in outdoor temperature will exacerbate the situation even further.

6.4 Conclusion and recommendation

The sustainability of the air-conditioning system installed in the building refers to whether the system is able to provide sufficient cooling capacity in the future with estimated climate change whilst maintaining its efficiency and performance of the overall system. The sustainability of the air-conditioning depends on its power consumption and carbon emission. Based on the simulation, in the next 70 years, the efficiency and durability of existing system is predicted to decrease.

Temperature is one of the crucial weather variables that affect the system performance. Findings from this study proved that the temperature change had significant effects on the cooling load needed by the office space and the occupant's well being. As comfort and energy always contradict each other, the increase in energy usage is expected to keep the occupant comfortable with the increase of the outdoor and indoor temperature. In years to come, existing buildings need to have an adaptation plans to manage and mitigate the risk of overheating in the office space.

Regular maintenances of the existing system are necessary to ensure the system to function effectively and efficiently throughout its year of service. As building last for decades, the existing system needs to be retrofitted to ensure that the system would be able to provide sufficient cooling required by the space without compromising the occupant comfort. The office space could be converted into the low-energy office by reducing its heat gain. Implementation of the external shading device, increasing the insulation in the walls and roof and replacing the single glazing with double glazing are some of the actions that could be taken to ensure that the building will adapt to the current changes in the climate.

This study only focuses on the effects of climate change to the building cooling load. To confront the climate threat to the building, further study should be conducted by simulating the whole building using different climate scenario. The climate change effects on the building could be studied in terms of energy consumption, building's performance and emission. Comparative study between buildings could also be carried out to have a clearer view on the climate change impacts on different types of building

This study represents the climate change effects in terms of cooling load required by existing building in the future. Findings from this study can be used in choosing suitable air-conditioning and mechanical ventilation (ACMV) systems in the future buildings as this study aimed to bridge the current and future building design. Hopefully, this study is able to translate the complex issues regarding building design and climate change into an approach that is potentially useful for building designer in the future. This study is undertaken to initiate the environmental awareness among the building designer with the issue that is often ignored.

The next Chapter will describe the air flow distribution inside a space which contributes to the occupant's comfort and indoor air quality in the building.

CHAPTER 7: EXPERIMENTAL STUDY AND NUMERICAL SIMULATION ON AIR FLOW DISTRIBUTION IN AN AIR-CONDITIONED OFFICE

7.0 Abstract

The air flow distribution inside a space contributes to the occupant comfort and the indoor air quality inside the building. The airflow characteristics influenced the temperature distribution, removal of indoor contaminants and the age of air in the occupied space. In this study, a numerical simulation of an air-conditioned office space was developed to evaluate the air flow distribution inside the space. Comparison between the experimental and simulation values was conducted. It was found that the air velocities inside the office space ranged between 0.04 to 0.15 m/s, which were relatively lower than the comfort threshold recommended by the MS 1525:2007 and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55-2010. The indoor air flows are mixture of low R and fully turbulent flows. Additionally, recommendations were made to improve the thermal comfort condition in the office space.

7.1 Introduction

The air distribution system implemented inside the office space is highly related to the indoor air quality and occupant’s thermal comfort. Several factors that influenced the airflow distribution include the type of air-conditioning systems, its operating condition and the location of supply diffuser and exhaust. The airflow distribution affects the temperature distribution, removal of contaminants and the age of air in the space which leads to occupant’s reaction towards the office space [39, 231, 232].

There are several types of air distribution system; these include the mixing systems, displacement systems, localised systems and unidirectional systems. The most common air distribution systems used in the office is the mixing system with ceiling supply and return [231, 233]. Experimental study proved that the mixing air distribution system could provide acceptable levels of thermal comfort, removal of pollutants and ventilation [214].

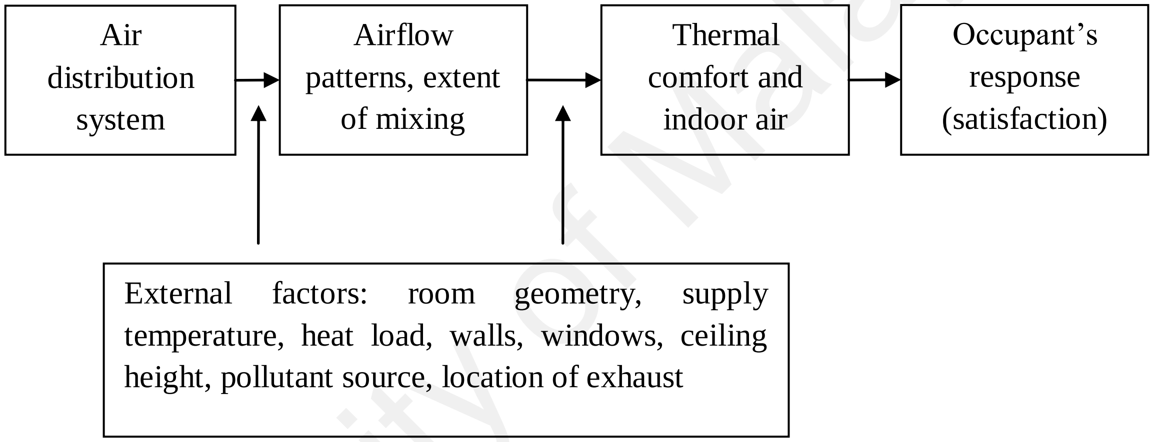

Figure 7.1: Relationship between air distribution systems and occupant’s satisfaction[214]

The pioneering study on indoor simulation was carried out by Nielsen in 1974 [234]. Since then, many studies have been carried out to assess the thermal comfort, airflow pattern and indoor air quality in a building using Computational Fluid Dynamics (CFD) [140-142, 235-239]. Most of the studies assessed the air distribution systems associated with the thermal environment and indoor air quality. The CFD simulation gives 3D virtual airflow pattern, temperature and indoor pollutants concentration in the entire domain by solving a set of conservation equations [28, 240]. By simplifying the geometry and conditions in the simulation, the time and money-consuming experimental work are greatly reduced [28, 241]. Unfortunately, according to Mathews et al, there is no general flow model to illustrate the entire complex flow distribution for the air-conditioning system [242].

Studies [140, 142, 237, 240, 243] have been carried out to assess the airflow pattern in the air-conditioned rooms. These studies proved that the CFD simulations can be used to evaluate the airflow pattern and thermal comfort condition accurately as the simulated results were in close correlation with the measured results [141]. The CFD simulation numerically modeled the physical processes happened in the fluid domain by using a set of non-linear partial differential equation such as the Navier-Stokes, continuity and energy equations. Indoor air distribution is classified by low velocity and high turbulence intensity [244]. In most of the literature, the overall flow characteristics inside room are often considered as turbulent [245], thus the k-ε model of turbulence is often used to model room air flow [246-253]. Harlow and Nakayama [254]developed the model in 1967 and further refined by Launder and Spalding [255] in 1972. The standard k-ε model is a semi-empirical model that is valid only for fully turbulent flows. The model is derived based on the transport equation for the turbulent kinetic energy, k and its dissipation rate, ε. The turbulent viscosity is computed from these scalars. The standard k-ε model has been widely used for indoor environments simulation since 1978 to 1998 and has proven to be successful in various engineering applications. The thermal buoyancy effects are also included in most of the models for room flow [256, 257] as it has little effects on the temperature and velocity but had great influence on the kinetic energy as the sensation of draft is affected by turbulence [243]. Literature review stated that in some of the CFD studies [251, 258, 259], the supply air flow was assumed to have uniform velocity and temperature and inlet which resulting in inaccurate representations of the real air flow conditions.

Despite the above studies, there are very few studies conducted on the comparison of numerical simulation with experimental studies in the case studies approaches. In this case study, the air distribution in the air-conditioned office space is evaluated by field measurement and CFD modeling. The assessment of airflow distribution is needed to evaluate the comfort condition in term of thermal, draught and indoor air quality. The study was undertaken in an air-conditioned office in a commercial building in the tropics. Field measurements of physical parameters include the air velocity, volume flow rate and the building interior design. The field measurement provided data to validate the CFD simulations. In modeling, CFD simulation software was used to simulate the air distribution in the office space. The office space model includes the turbulence model and buoyancy effects. These predicted results in the form of contour and velocity vectors complemented the measured results and provided an insight into the air distribution in the office space. The results of this study is hoped to serve as guidance in developing simulation model for an air-conditioned office space regarding indoor air quality.

7.2 Methodology

This study was carried out in an air-conditioned office in a commercial building in the tropics; with the width of 9 m, the length of 36 m and the height of 2.5 m. The office space is conditioned with split type ducting air-conditioning system which is known as Air-Cooled Ducted Blower system with the capacity range from 29kW to 59kW. The office space is operating according to office hours (8.30-5.30 pm) during workdays only.

The conditioned air is delivered to the room through 26 square diffusers mounted on the suspended ceiling while the room's air is extracted to the ceiling plenum through 16 square exhaust grilles. The dimension for each of the diffusers and exhaust grilles is 500mm x 500 mm. For the purpose of simplification during simulation, the enclosed room with a separate air-conditioning system was not included.

7.3 Field measurement

Measurements of the air velocity and volume flow rate were conducted at several locations in the occupied space as shown below. Measurements were done from 8.30 am to 5.30 pm for a week. The air velocity was measured over a 5-min period at 0.6 meter from the floor which represents the seating level in each location using the TSI VelociCalc meter at 15 sampling points. Likewise, the air flow rate was measured using the Balometer which is located below the supply air diffuser. Due to the size of the office space, no continuous data logging is conducted for the measurement of air velocity. The sampling points and supply diffusers location were shown in Figures 7.2 and Figure 7.3 below.

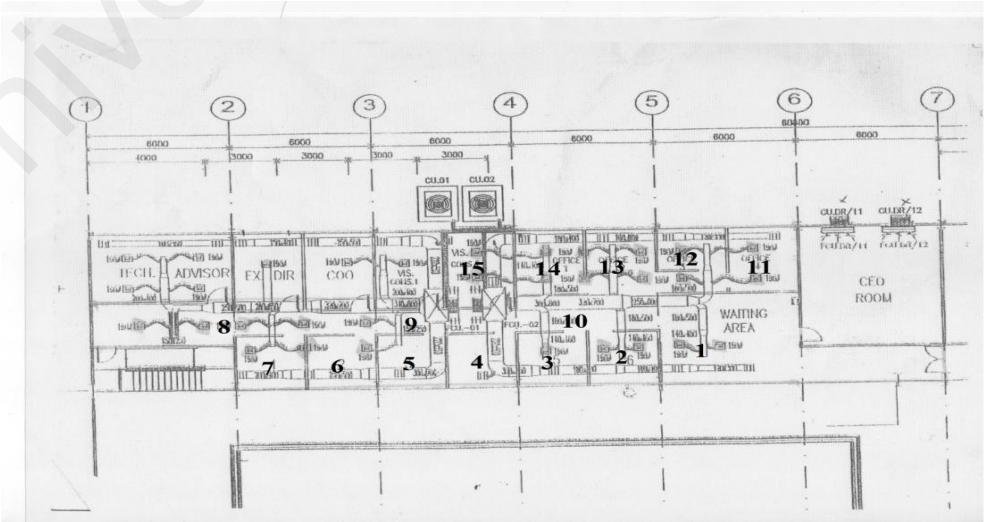

Figure 7.2: Sampling points

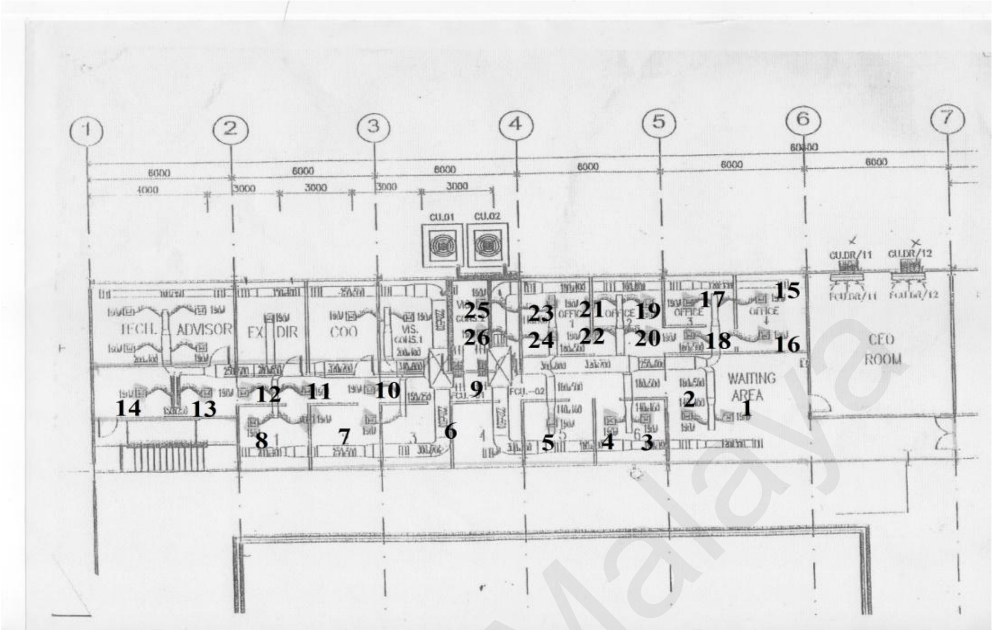

Figure 7.3: Supply diffusers location

7.4 Computational Fluid Dynamics simulation

7.4.1 Model configuration

The single air-conditioned office room has been studied from the M & E drawing. The width (x-direction) is 9 m, the height (z-direction is 2.5 m) and the length (y-direction) is 36 m. The simulation was carried out only for the large open-plan office with split type ducting air-conditioning. All of the office furniture, equipments and occupants were not included in the office room. Figure 7.4 showed the room model in the Design Modeler.

To perform the simulation calculation, a grid system of tetrahedron was implemented and used in order to study the distribution of desired parameters. Therefore, unnecessary features those were mostly unimportant to the modeling was simplified in order to avoid unnecessary extensive calculation and to simplify the examination of air distribution without compromising the actual condition of the buildings and sacrificing the integrity of the simulation itself. The total of number of nodes generated from this study is 3478710.Findings from this study are aimed to aid the development of air-conditioned office space for thermal comfort and indoor air quality simulation using CFD and serve as a guidance in maintaining the environmental quality inside the office space.

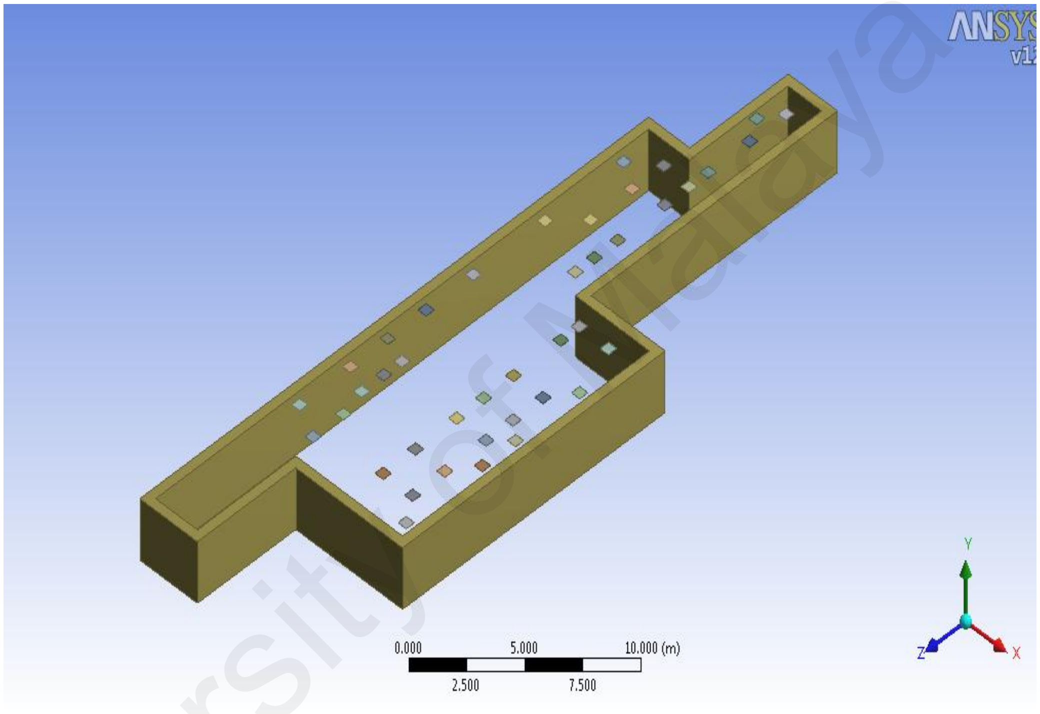

Figure 7.4: Illustration of the room model

7.4.2 Boundary condition and solution procedure

Parameters from the field measurements are used as input for boundary conditions in the CFD simulations for the purpose of assessment of current design and further improvements. The solution domain was bounded by solid surface (wall, window and ceiling) and fluid surfaces (supply diffuser and exhaust grille). In the simulation, the fluid properties were set at constant at the room temperature of 24˚C. The air density is 1.18kg/m^3 and the viscosity is 1.72 x10^{-5} kg/ (ms). All boundaries were assumed to be wall boundaries except for the exhaust grille and supply diffuser. The boundary condition at the supply diffuser was specified as velocity inlet and at the exhaust grille was pressure outlet. Constant temperature assumption (300K) was made for all interior space. The supply air boundary condition is important as the momentum from the supply diffuser dominates the room airflow. The air velocity at the supply diffuser was tabulated in Table 7.1 below.

Table 7.1: Air velocity at supply diffuser

Supply Diffuser Location	Air velocity (m/s)
1	0.20
2	0.20
3	0.38
4	0.37
5	0.35
6	0.43
7	0.61
8	0.29
9	0.33
10	0.45
11	0.52
12	0.58
13	0.50
14	0.48
15	0.36
16	0.29
17	0.36
18	0.25
19	0.45
20	0.31
21	0.33
22	0.40
23	0.29
24	0.24
25	0.55
26	0.52

Overall features of airflow inside a room are often considered as turbulent even the airflow could be laminar or weakly turbulent in some area in the room [245]. As most indoor flows are considered turbulent, the standard *k*-ε model is used to assess the air distribution in this study. The second order upwind scheme was used for all the variables (momentum, turbulent kinetic energy and turbulent dissipation rate and energy) except for pressure (standard scheme). The accuracy of the CFD simulation is attained in terms of residual which is the measurement of error. In Figure 7.5, the residual errors dropped to the minimum at the 670^{th} iterations, remained the same even the number of iterations had increased and finally stopped when there were no variations in the results.

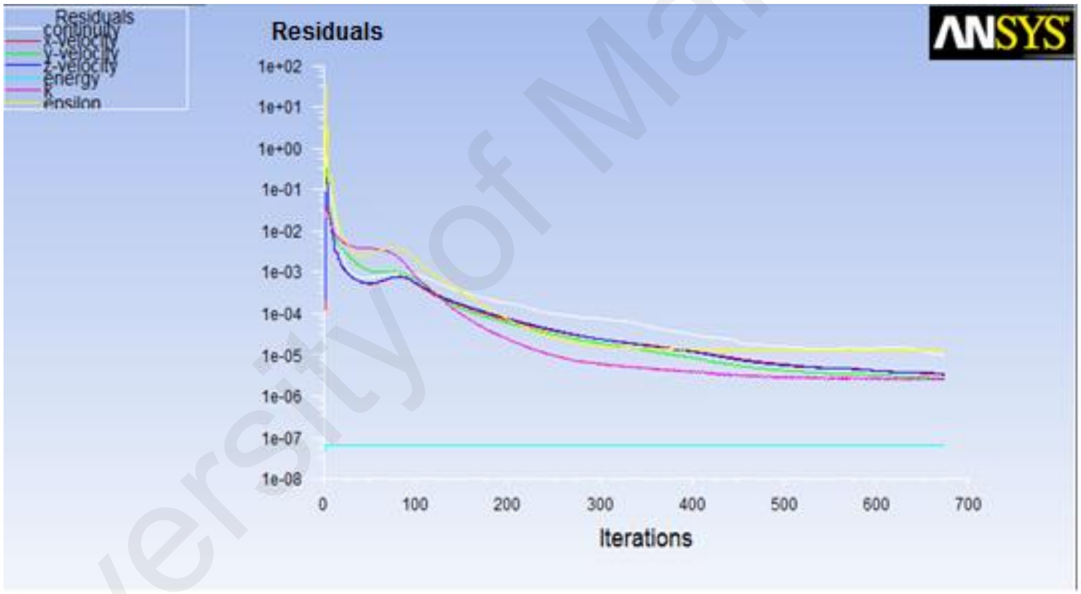

Figure 7.5: Residual plotting

7.4 Results and discussion

The main objective of this study was to assess the airflow distribution inside the office space. Hence, the air velocity and its mean were examined. The results from the predicted airflow from the CFD modeling described the spatial distribution of the airflow inside the office space.

7.4.1 Field measurement

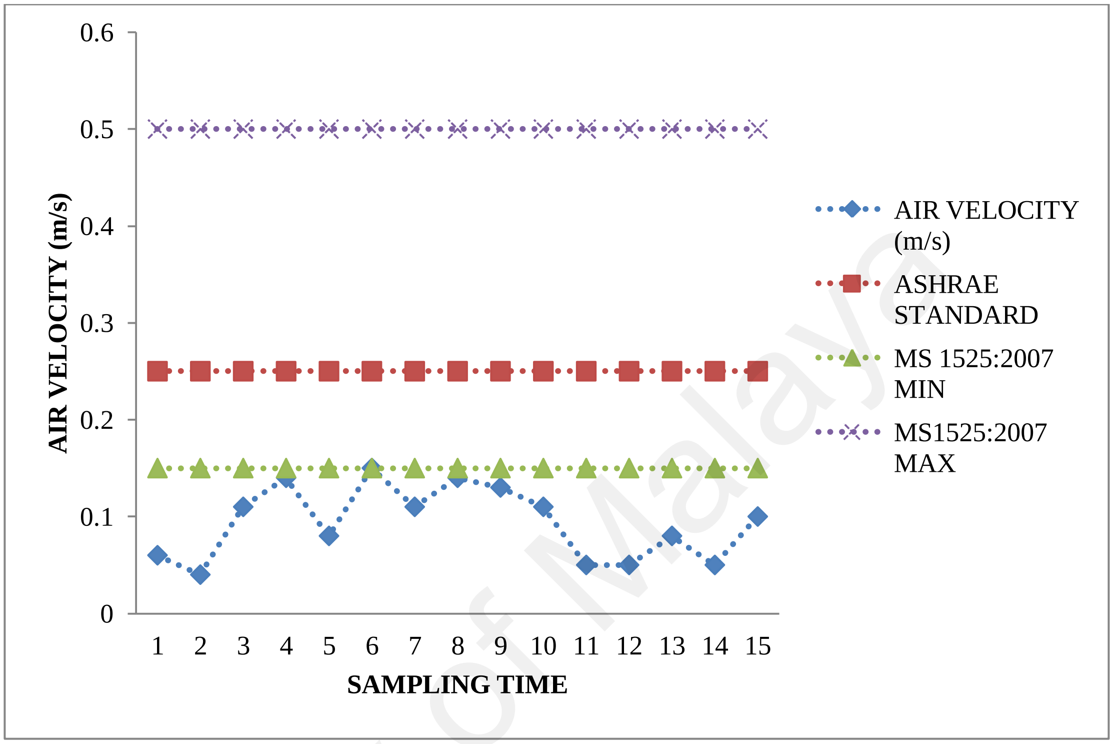

Figure 7.6: Air velocity in the office space

The acceptable air velocity inside an occupied space according to the MS 1525:2007 standard is between 0.15 to 0.50 m/s while in ASHRAE Standard 55-2010 is 0.8 m/s [17, 171]. Figure 7.5 showed that the air velocity inside the office space during operating hours were between 0.04 to 0.15 m/s, which were lower than the recommended air velocity by both standards. The mean air velocity was 0.09 m/s with a standard deviation of 0.04 m/s. The fluctuation of the air velocity throughout the day was low as represented by the standard deviation. During the building walkthrough, it is observed that in some location, the air velocity is low and almost stagnant. The low air velocity contributes to the feeling of stuffiness and promotes the accumulation of odours inside the office space. It is noted that the occupants demand for more air movement in the office space to increase comfort by using portable desktop fan. In addition, the poor design of the location of supply diffusers also contributed to the occupant's discomfort. For example, there are four grille located in a small space. The occupants near the space will definitely feel cold and thermally uncomfortable during the working hours.

7.4.2 CFD simulation

Figure 7.7 and 7.8 below showed the predicted air flow distribution in the office space at the profile y =0.6m and 1.1m that represent the sitting position, and 1.7m. The air velocity was represented by the vector and contour colour designation that symbolised the air flow. The brighter contours such as the orange and red hues signify the high air velocity while the blue and green contours signify the low air velocity.

From the experimental data, air in the range of 0.20 to 0.58 m/s was supplied from the diffuser to the space. At y = 0.6 m, the air velocity ranged from 0.03 to 0.21 m/s. Low and stagnant airflow was predicted at the seating position and can be considered as "weak draft". However, the air velocity was found to be higher near the supply diffuser (Figure 7.9). The air velocity at the higher plane ranged from 0.05 m/s to 0.5 m/s. The air velocity inside the office space was predicted to fall below the MS1525:2007 and ASHRAE Standard 55-2010. However, the supply air can be considered almost uniformly distributed (Figure 7.10) as the magnitude of the air velocity in the office space is small.

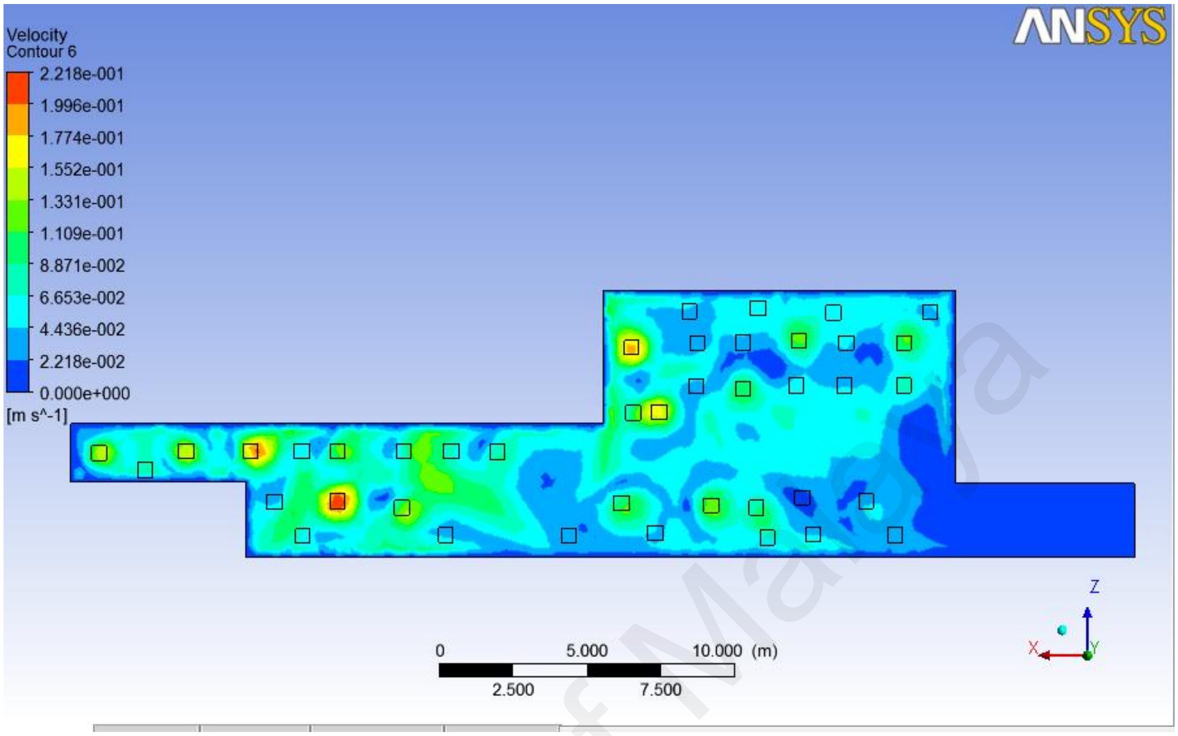

Figure 7.7: Airflow distribution at y= 0.6 m

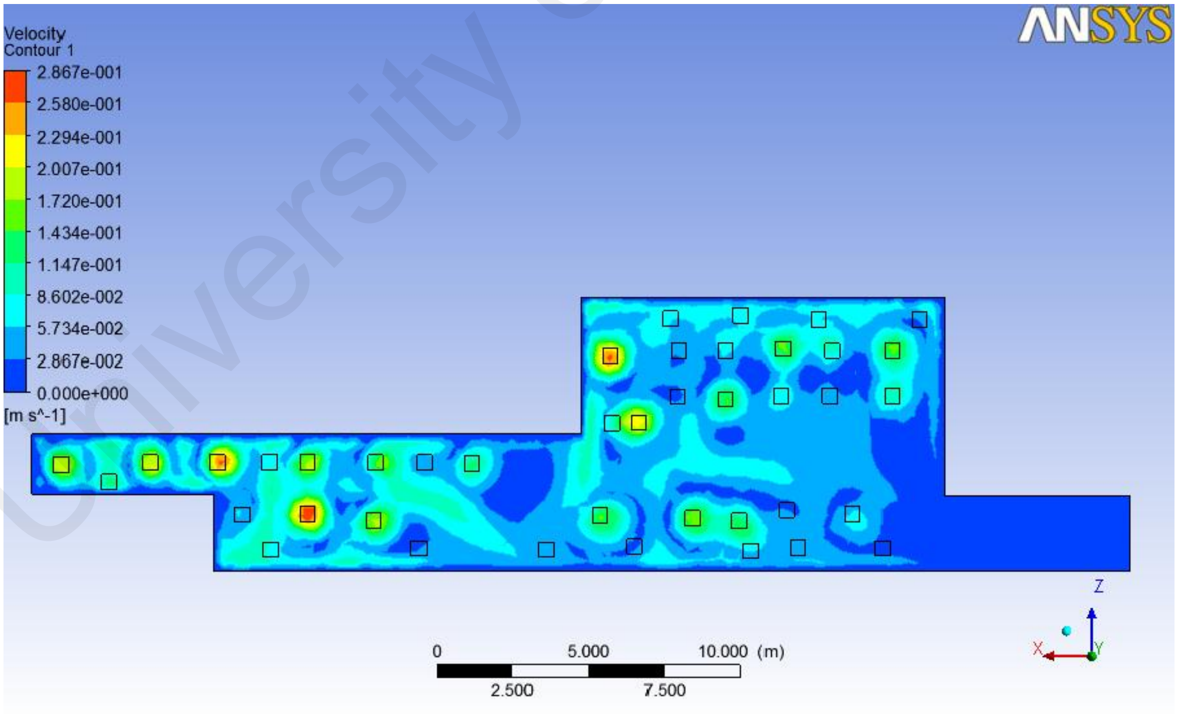

Figure 7.8: Airflow distribution at y = 1.1 m

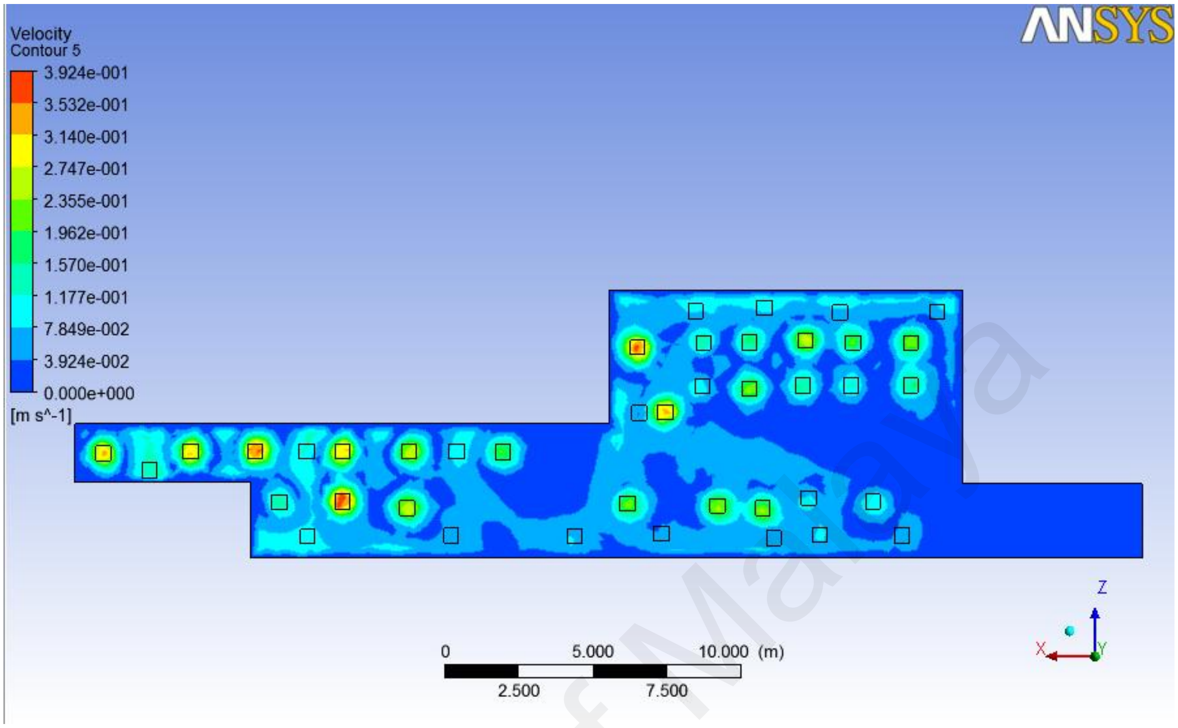

Figure 7.9: Airflow distribution at y = 1.7 m

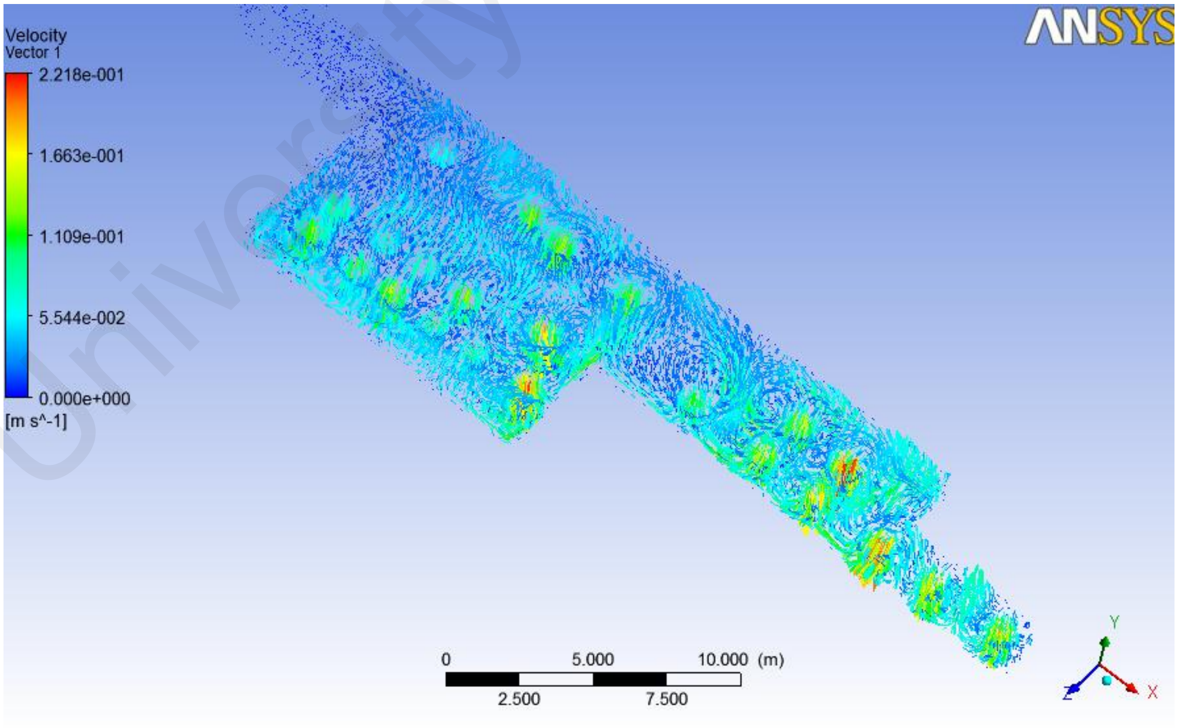

Figure 7.10: Three-dimensional view of velocity vectors at y = 0.6m, 1.1 m and 1.7m

7.4.3 Validation between empirical measurement and numerical simulation results

Table 7.2: Corroboration between empirical and numerical simulation results for air velocity

Location	Air velocity (m/s)			
	Measured air velocity (vm)	Simulation air velocity (vs)	Velocity difference (vs-vm)	%Difference (vs-vm)/vm
1	0.06	0.04	-0.02	-33
2	0.04	0.05	0.01	25
3	0.11	0.13	0.02	18
4	0.14	0.15	0.01	7
5	0.08	0.06	-0.02	-25
6	0.15	0.17	0.02	13
7	0.11	0.10	-0.01	-9.1
8	0.14	0.17	0.03	27
9	0.13	0.11	-0.02	-15
10	0.11	0.13	0.02	18
11	0.05	0.06	0.01	20
12	0.05	0.04	-0.01	-20
13	0.08	0.11	0.03	37.5
14	0.05	0.06	0.01	20
15	0.10	0.13	0.03	30

Table 7.2 showed the corroboration between the empirical and numerical results.

The discrepancies between the numerical and empirical results ranged from -9.1% to 37.5% which are relatively high. As the empirical and numerical results were not error-free, the differences in both results were expected due to certain issues. Empirical results might not be reliable due to the measurement error, the occupant's movement and location, and the condition of the room. On the other hand, the numerical simulation uncertainty is primarily due to the assumptions made by the model. The numerical simulation does not include the real condition of the room such as the furniture arrangement, occupants and heat-source equipments. Without the heat sources, the simulation will not represent the real condition. Generally, the numerical results were overestimated. However, the numerical results agreed reasonable well with empirical results with the biggest difference is being equal to or less than 0.03 m/s. Both results suggested that the supply air inlet was well-distributed.

7.5 Conclusion and recommendation

An empirical measurement and numerical simulation have been carried out to assess the air distribution inside the office space. Empirical measurements showed that the air velocity inside the office space were far below the limit recommended by the MS 1525:2007 and ASHRAE Standard 55-2010. The simulations results concurred with the empirical measurements with a fairly well-distributed airflow pattern with discrepancies between 30-40-%. It is observed that the indoor airflows are mixture of low R and fully turbulent flow. Nevertheless, most of the numerical simulation results were overestimated. It can be concluded that experimental and numerical simulation is needed to give better view and more holistic understanding of the air distribution studies.

According to studies [25, 260], boundary conditions and inclusion of occupants and furniture inside the room will strongly affects the airflow characteristics. Heat generated by the occupants, computers, printers, photocopying machine and lighting will influenced the air flow in the room as they create thermal buoyancy effects [257, 260, 261]. In addition, the air distribution also depends on the location of supply and exhaust grille, room design, air supply volume and obstruction such as partitioning. Hence, for future work, real-world geometries such as occupants and furniture should be included in the simulation for better and accurate results. Other indoor air quality parameters such as indoor temperature and contaminants could be included in the assessment. A detailed simulation which includes the non-steady state condition by including the moving occupants as a moving object is suggested. Similar studies can be extended to all other high-rise and low-rise air-conditioned offices. As indoor air flow affects the comfort and indoor air quality inside an office space, the results from these studies could serve as guidance to improve the indoor condition and operating strategies for the maintenance personal and building designer in the future.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

Research on indoor air quality and climate change impacts on air-conditioning and mechanical ventilation (ACMV) systems in commercial buildings in the tropics had been carried out. The main objectives of the research are to assess (i) the indoor air quality in the green and (ii) non-green commercial buildings, (iii) impacts of climate change on the air-conditioning and mechanical ventilation (ACMV) systems and (iv) air distribution inside the office space. All four objectives have been successfully accomplished, which formed the foundation of this research.

Field analysis has been carried out inside two green offices with radiant slab cooling in Malaysia. The first key finding is that the indoor air quality inside these two buildings complied with the standard suggested by the MS 1525:2007 and ASHRAE Standard 55-2010 and 62-2010, except for the air movement (0-0.43 m/s) which falls below the specified limit. The air-tight building design and less draught due to the implementation of the radiant slab cooling failed to meet the occupant’s satisfaction on thermal comfort as occupants in Malaysia are used with ample air movement to meet their comfort expectation [10]. The basic design of the AHU system relied on the fan power variable air volume (VAV) boxes that complement the thermal storage design of the chilled slab. The AHU chosen for chilled slab design may have less primary airflow due to the reduction in sensible heat. Secondary air flow is to be induced by the fan power VAV box at user terminal level. The subsequent omission of fan power boxes had resulted in insufficient air movement in the floor space even the dry bulb temperature is at the desired limit. With the absent of enhanced localised air movement, the occupants may feel warm with clothing level 1.0 and above. Furthermore, the occupants in the tropics are used to much higher environmental temperature and could tolerate the higher indoor condition only if ample air movement is present. However, in this case, the occupants may improve their comfort level by using a mini laptop fan to increase personal comfort. Additionally, air curtain or wall mount fan coil units could be installed to increase the air movement. As the implementation of radiant cooling system is still new and uncommon in Malaysia, the occupant's reaction with the indoor thermal comfort should be taken into account in designing green buildings with such cooling system to ensure that the passive strategies meet their purpose in providing better comfort and more energy-saving.

For the non-green building, the indoor air quality assessment in the air-conditioned office has been carried out for a week. The second key finding is that the empirical measurement showed that the indoor temperature and indoor contaminants were within the limit recommended by the MS 1525:2007 and ASHRAE Standard 55-2010 and 62-2010 except for the relative humidity (45.7-62.5%) which was relatively lower than both standards. The oversized air-conditioning system installed in the office makes the occupants feel cold even the indoor temperature was within the suggested limit. Therefore, the occupants need to wear extra clothes and were thermally uncomfortable during the working hours. Findings from this assessment are important as they provide the real indoor air quality condition inside the office space. Corrective actions such as installing a humidifier inside the office space and elevating the temperature inside the office to save energy could be taken for better thermal comfort. There are several types of humidifier that could be installed inside the office space such as the electronic humidifier, steam humidifier, impeller or ultrasonic humidifier. However, taken into consideration the cost and size of the office space, a steam humidifier is the best solution which is least expensive, hygienic and able to conditions the space accordingly. Generally, the humidification systems manifolds can be retrofitted to the existing air handling units (AHU) or the air ducts (in-ducts). Additionally, the portable steam humidifier could also be used to improve the condition.

For the third research objective, study has shown that the temperature will increase by 1˚C per 20 years. The third key finding is that the climate change in terms of temperature increase will increased the cooling load needed by the office space in the next 70 years which will lead to the decrease in the efficiency and reliability of the existing system. These findings concurred with the previous studies [97, 102, 106, 108, 110] indicating that the cooling load demand is predicted to rise with the increased in temperature. The existing air-conditioning systems might failed to maintain the indoor condition accordingly and unable to keep the occupants thermally comfortable with the increase in the outdoor and indoor temperature. In order to maintain occupant's thermal comfort, the energy usage is expected to rise and consequently contributing to the climate change even further. As buildings last for decades, existing buildings need to have adaptation and mitigation plan to manage the overheating condition in the office space. The existing system need to be retrofitted or replaced to ensure that the system is able to provide sufficient cooling needed by the space without compromising the occupant's comfort. The common and correct chiller needs to be identified and installed in building. Future climate projection needs to be taken into account when designing new building or retrofitting existing building with the aim to reduce the climate change impacts. In line with the Malaysian government initiatives to reduce 40% of its greenhouse gases emission by 2020, building industry need to reduce its carbon emissions. Passive design method and better building operating practice should be implemented to achieve this aim. This research only focuses on the impacts of climate change on building cooling load. Similar research could be conducted to simulate the impacts of climate change on indoor air quality parameters, energy consumption, building's performance and emission. Different climate change scenario and buildings type could be simulated to get better and clearer view on the climate threat to the building industry. Findings from this research are hoped to help the building designer to choose appropriate air-conditioning and mechanical ventilation (ACMV) systems in the future with the aim to reduce future cooling energy demand and climate change impacts.

The final key finding from this research showed that the air velocities inside the office space were relatively lower than the limit suggested by the MS 1525:2007 and ASHRAE Standard 55-2010 in the empirical measurements. The numerical simulation results agreed reasonably with the empirical measurement that the airflow was well-distributed inside the office space. However, most of the numerical simulation results were overestimated. In conclusion, the empirical measurements and numerical simulation give better understanding and overall view on the air distribution inside the office space. Air distribution inside office space plays an important part in determining occupant's comfort during working hours. Thus, study on air distribution is needed to evaluate occupant's comfort level and for planning corrective actions.

Overall, it is intended that the findings from this research could serve as an important guide in improving the indoor air quality and operating strategies; and facilitate building industry to adapt with the anticipated climate change impacts in the future. Building industry has the highest chance to reduce its contribution to climate change by reducing its future cooling load demand and energy usage. As climate change impacts are issues that often ignored by the building industry, findings from this study are hoped to create awareness among the building practitioners to accommodate the climate change impacts in their engineering practice.

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APPENDIX A1

INSTRUMENTATION

Figure A1-1: PP Stand Alone System Monitor

Figure A1-2: TSI AEROTRAK Particle Counter

Figure A1-3: TSI Dusttrak Handheld Aerosol Monitor

Figure A1-4: VELOCICALC Multi-Function Ventilation Meter

Figure A1-5Q-TRAK Air Quality Monitor

Figure A1-6: Alnor EBT721 Balometer

APPENDIX B1

SURUHANJAYA TENAGA SAMPLING POINT

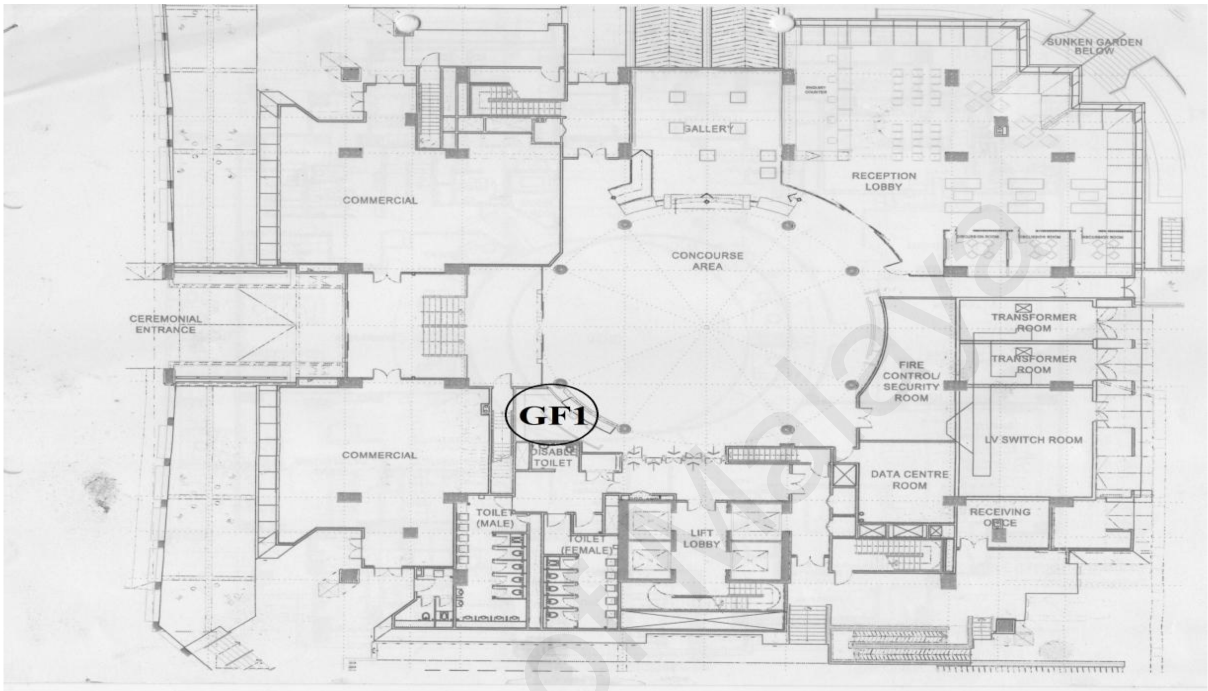


Figure B1-1: Ground Floor

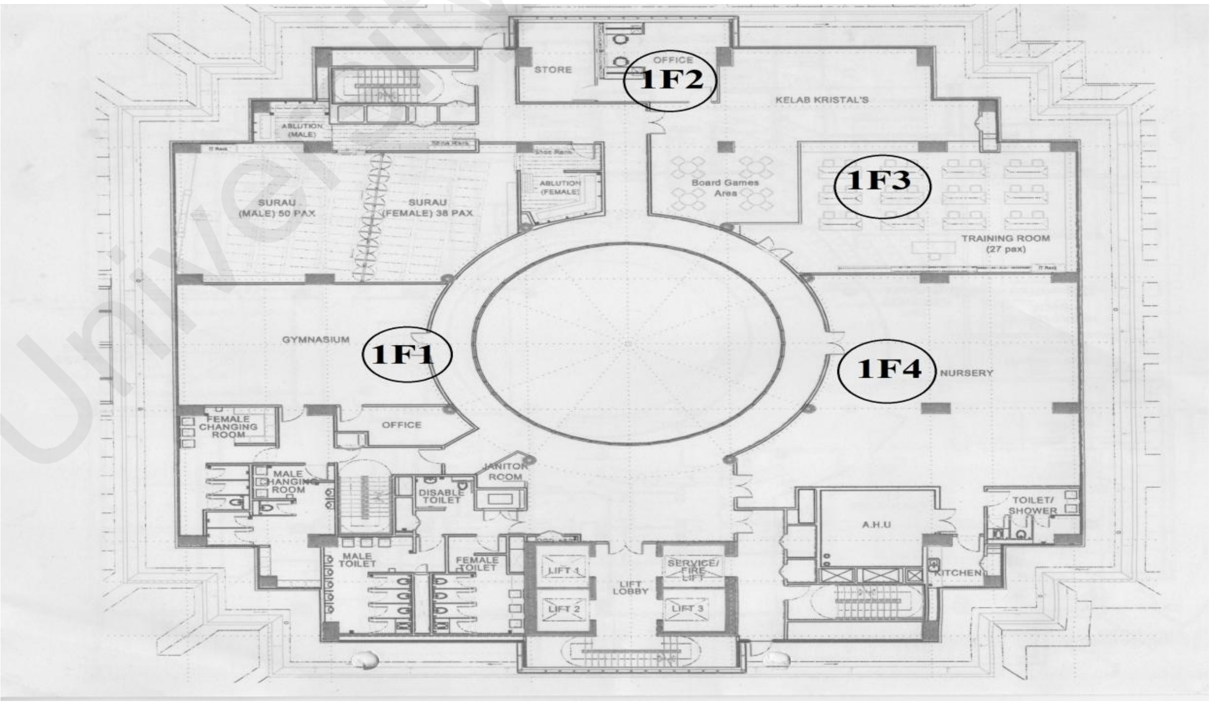


Figure B1-2: First Floor

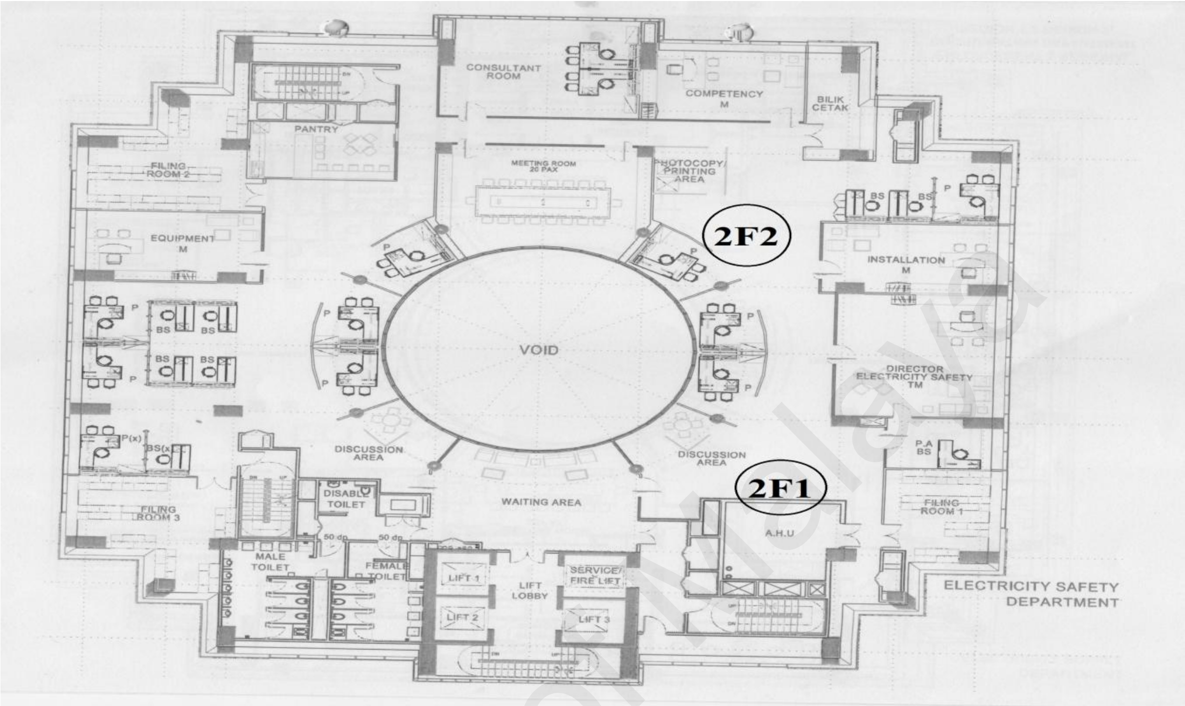


Figure B-3: Second Floor

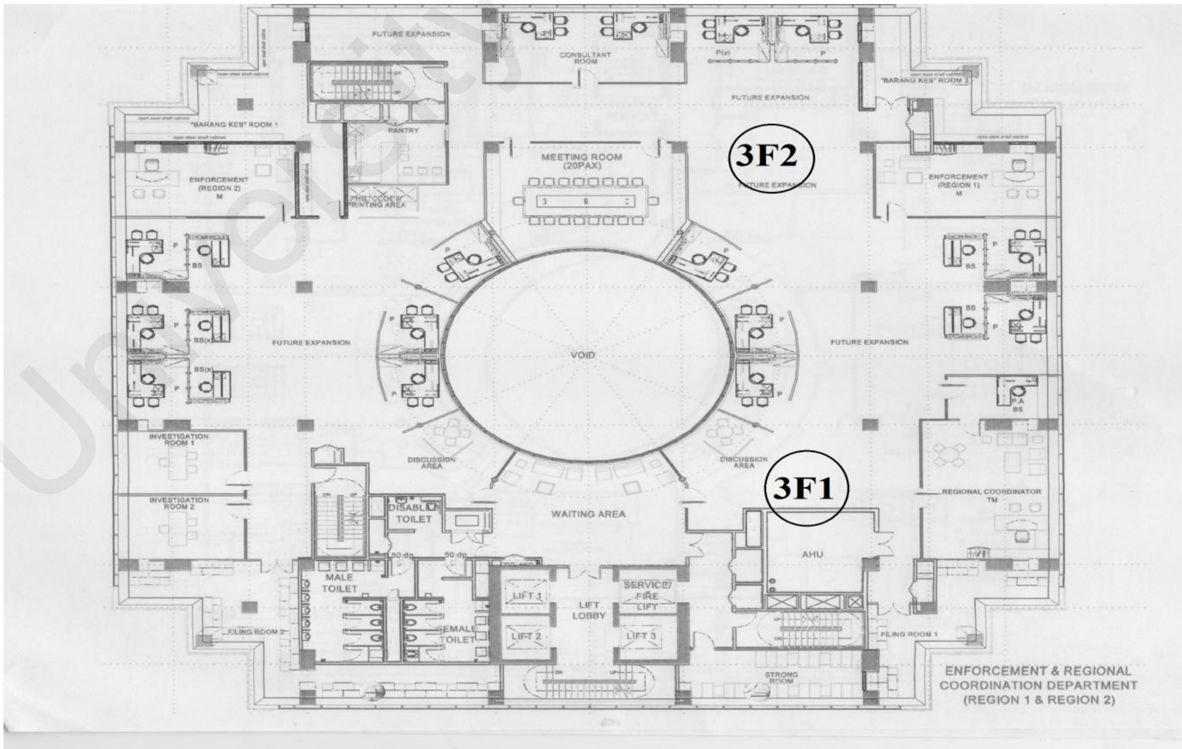


Figure B1-4: Third Floor

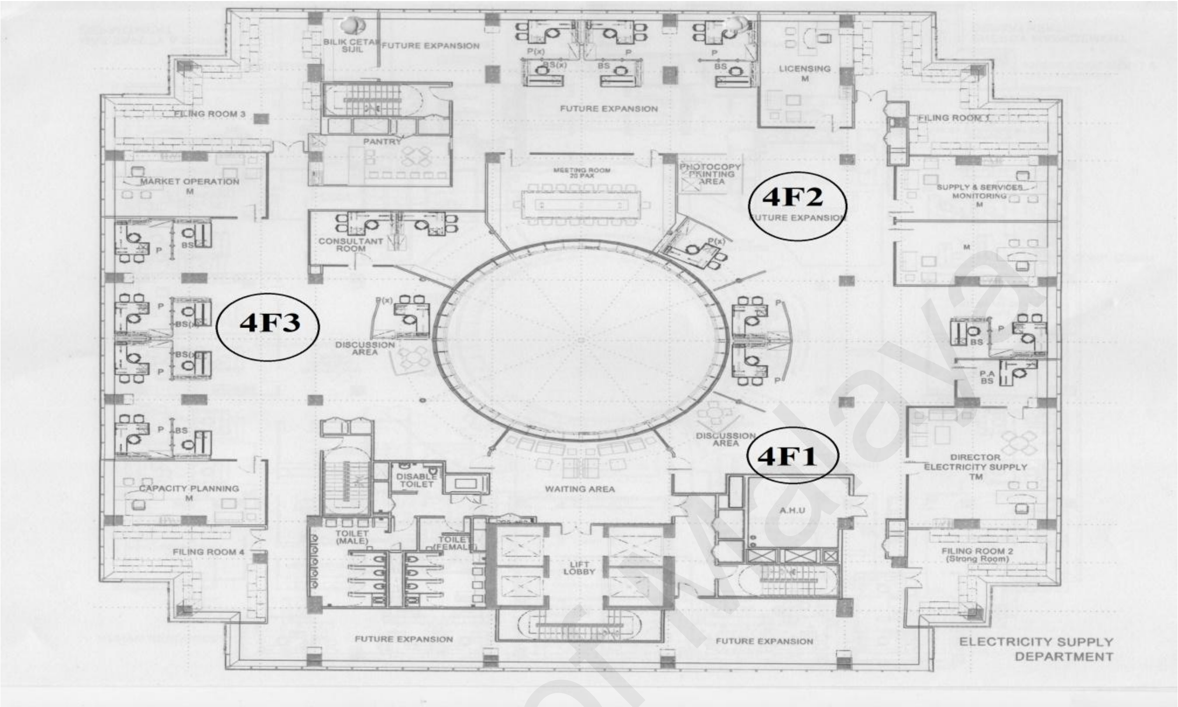


Figure B1-5: Fourth floor

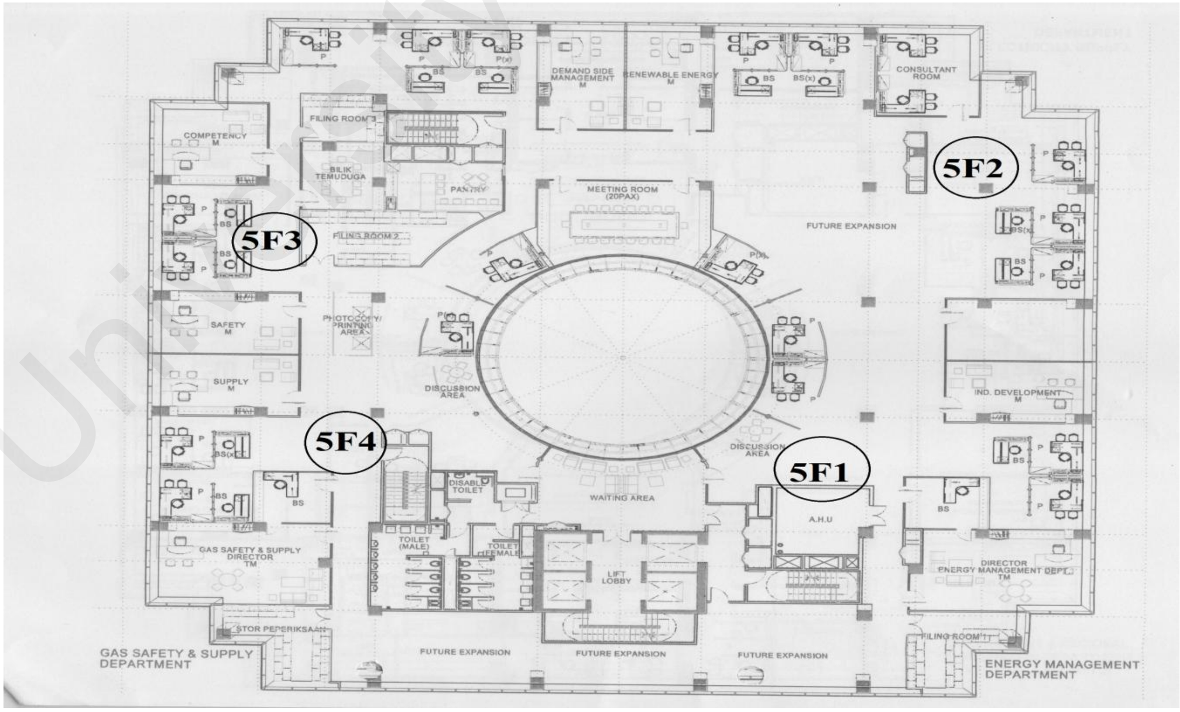


Figure B1-6: Fifth Floor

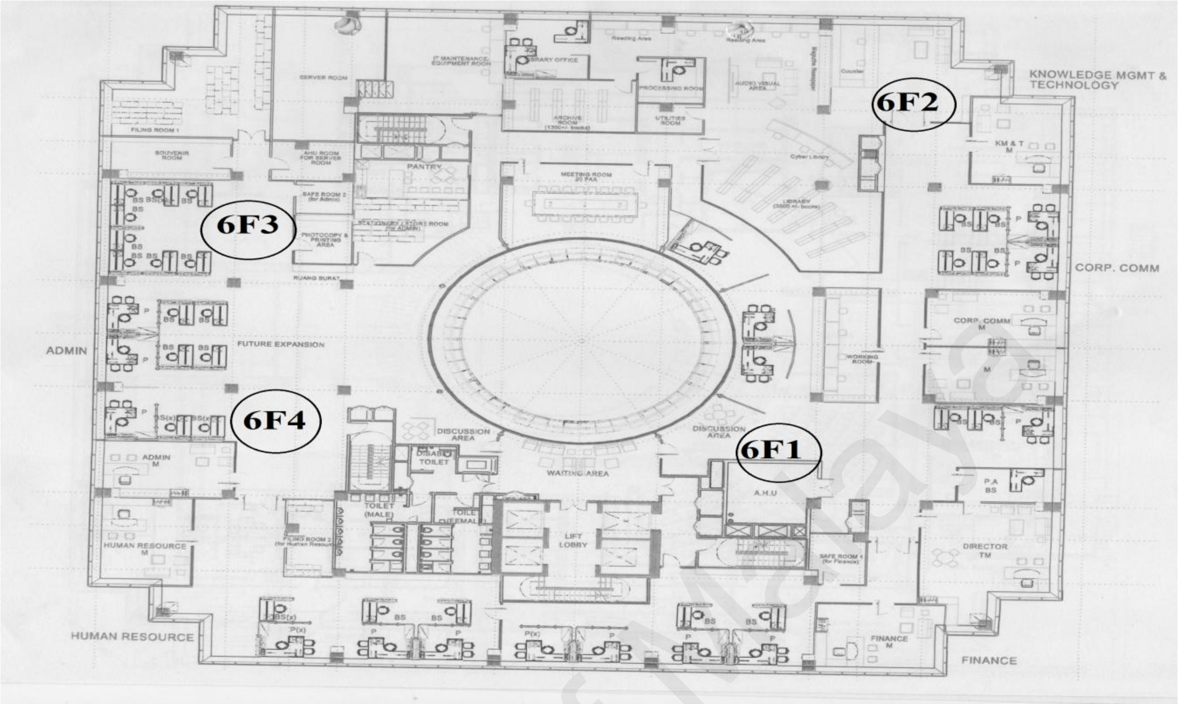


Figure B1-7: Sixth Floor

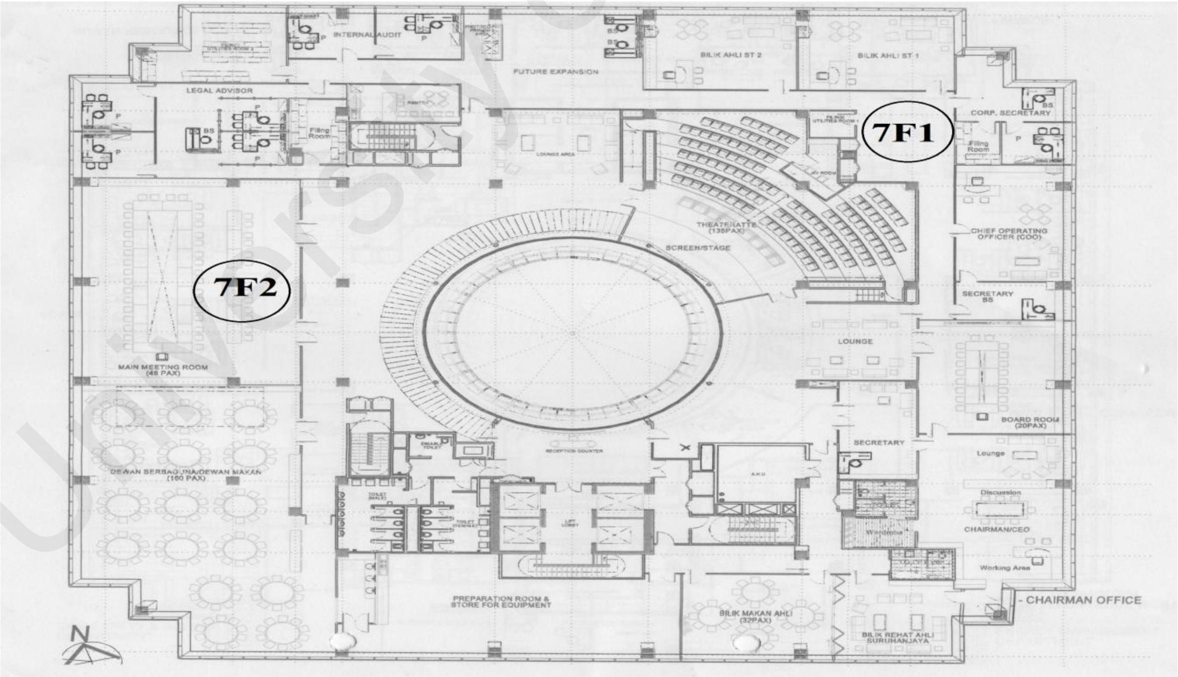


Figure B1-8: Seventh Floor

APPENDIX B2

MALAYSIAN GREEN TECHNOLOGY CORPORATION (MGTC) SAMPLING POINT

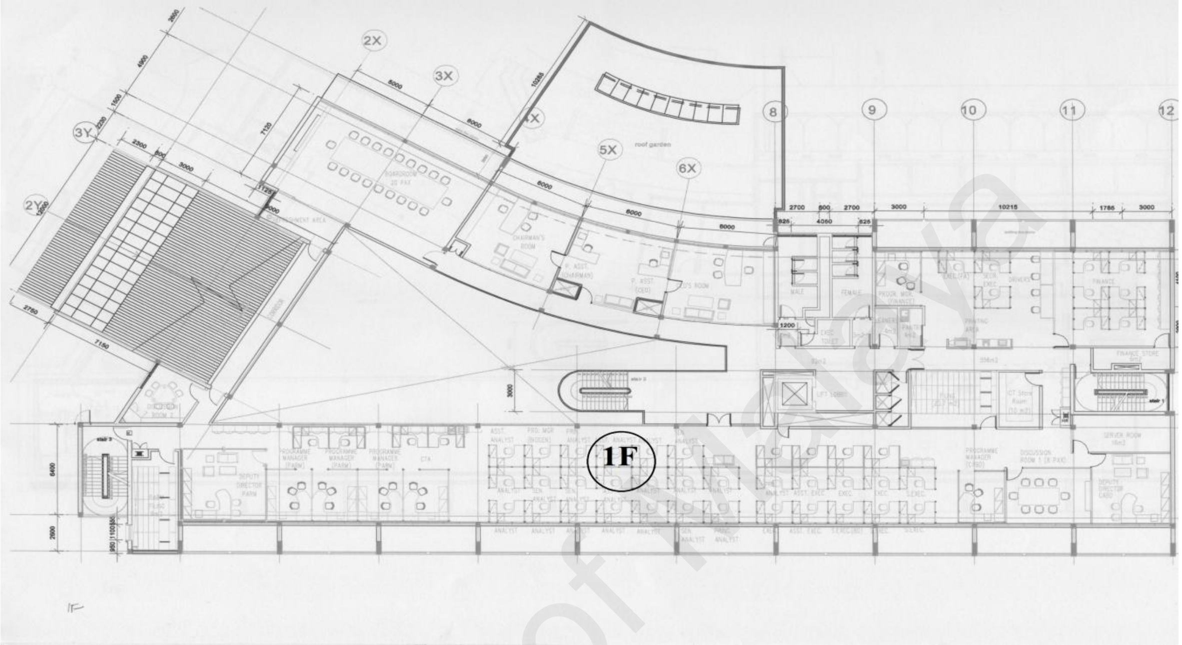


Figure B2-1: First Floor

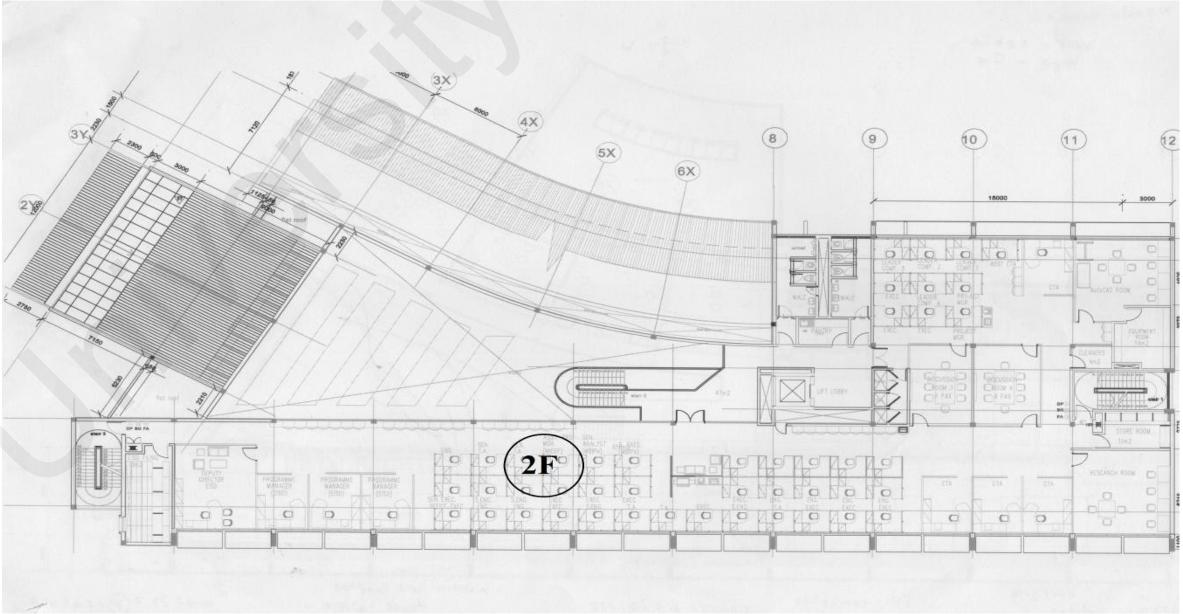


Figure B2-2: Second Floor

APPENDIX B3

INDOOR AIR QUALITY MEASUREMENTS FOR SURUHANJAYA TENAGA BUILDING, PUTRAJAYA

Table B3-1: Indoor temperature and relative humidity at main sampling point

Level		Sampling time			
		9.00 am	12.00 am	2.00 pm	4.00 pm
G	T	22.5	22.4	22.4	22.1
	RH	64.4	59.6	66.5	68.0
2	T	23.9	23.6	23.2	23.4
	RH	68.1	63.7	62.3	63.9
3	T	23.6	23.8	24.2	23.9
	RH	63.4	59.0	56.5	58.1
4	T	23.8	23.7	23.9	24.5
	RH	59.6	58.5	57.6	56.2
5	T	23.4	23.8	24.2	24.7
	RH	56.8	55.3	53.7	52.4
6	T	23.2	23.5	23.1	23.7
	RH	58.6	57.7	57.2	58.0
7	T	65.6	25.8	24.4	24.0
	RH	25.0	61.1	53.5	56.8

Table B3-2: Indoor Contaminants

Level		Sampling time			
		9.00 am	12.00 am	2.00 pm	4.00 pm
G	CO	1.903	1.319	1.069	1.906
	CO2	633	626	584	604
	Formaldehyde	0.048	0.022	0.013	0.035
	NO	0.179	0.171	0.155	0.166
	TVOC	0.573	0.322	0.409	0.429
2	CO	1.978	1.339	1.048	1.136
	CO2	626	660	663	710
	Formaldehyde	0.105	0.055	0.049	0.045
	NO	0.146	0.146	0.148	0.147
	TVOC	1.484	0.585	0.564	0.582
3	CO	2.18	1.383	1.131	1.085
	CO2	706	723	658	711
	Formaldehyde	0.076	0.041	0.053	0.028
	NO	0.168	0.152	0.154	0.143
	TVOC	0.913	0.766	0.714	0.712

4	CO	2.521	1.453	1.275	1.238
	CO2	986	719	699	776
	Formaldehyde	0.123	0.084	0.054	0.074
	NO	0.169	0.151	0.146	0.148
	TVOC	0.768	0.615	0.635	0.606
5	CO	2.196	1.732	1.263	1.201
	CO2	680	779	783	785
	Formaldehyde	0.12	0.057	0.072	0.083
	NO	0.15	0.151	0.138	0.147
	TVOC	0.486	0.432	0.411	0.398
6	CO	2.173	1.636	1.301	1.247
	CO2	730	741	741	804
	Formaldehyde	0.056	0.101	0.084	0.081
	NO	0.167	0.144	0.143	0.148
	TVOC	0.693	0.605	0.586	0.606
7	CO	2.166	1.376	1.352	1.246
	CO2	655	684	714	785
	Formaldehyde	0.134	0.073	0.081	0.067
	NO	0.172	0.182	0.157	0.125
	TVOC	0.908	0.524	0.299	0.378

Table B3-3: Particle count

Level	>0.3µm	>0.5µm	>1.0µm	>3.0µm	>5.0µm	>10.0µm
G	111209163	5078741	79209	6103	2717	878
2	22237904	1064865	61834	12504	5937	2696
3	44097188	2492120	90469	20175	9229	3322
4	32562518	1452250	57628	10694	5164	1624
5	49258712	2143959	57731	14387	6709	2704
6	22638640	1462310	90896	30882	16750	5627
7	34651776	2482110	84962	41580	9860	4172

Table B3-4: Mass concentration

Level	Session	Mass average (mg/m³)	Mass minimum (mg/m³)	Mass maximum (mg/m³)	Mass TWA (mg/m³)	Number of samples
G	AM	0.075	0.070	0.083	0.019	24
	PM	0.086	0.073	0.104	0.032	30
2	AM	0.025	0.023	0.028	0.006	24
	PM	0.037	0.032	0.042	0.007	19

3	AM	0.049	0.043	0.057	0.012	24
	PM	0.036	0.034	0.040	0.006	17
4	AM	0.040	0.037	0.043	0.010	24
	PM	0.036	0.033	0.042	0.008	21
5	AM	0.046	0.043	0.048	0.012	24
	PM	0.055	0.052	0.058	0.009	16
6	AM	0.031	0.028	0.036	0.015	48
	PM	0.031	0.028	0.036	0.015	48
7	AM	0.033	0.023	0.048	0.021	60
	PM	0.033	0.023	0.048	0.021	60

Table B3-5: Indoor temperature at additional sampling point

Level	Sampling point		Sampling time			
			9.00 am	12.00 am	2.00 pm	4.00 pm
G	1	Average	23.3	23.6	23.0	22.8
		Min	23.1	23.1	22.8	22.6
		Max	23.6	23.8	23.3	22.9
1	1 (Nursery)	Average	23.6	23.2	23.7	23.1
		Min	23.4	23.1	23.4	23.1
		Max	23.8	23.5	24.2	23.2
	2 (Training Room)	Average	23.0	23.1	23.2	22.9
		Min	23.0	22.9	23.1	22.9
		Max	23.1	23.1	23.2	22.9
	3 (Kelab Kristal)	Average	23.0	23.2	23.1	22.9
		Min	22.9	23.1	23.0	22.8
		Max	23.1	23.3	23.1	22.9
	4 (Gymnasium)	Average	23.3	23.3	23.1	23.1
		Min	23.0	23.1	23.0	23.0
		Max	23.4	23.3	23.2	23.1
2	1	Average	23.6	23.7	23.2	23.3
		Min	23.5	23.4	22.7	23.0
		Max	23.7	23.8	23.4	23.4
	2	Average	23.8	23.6	23.7	23.6
		Min	23.7	23.4	23.5	23.4
		Max	23.8	23.8	23.7	23.7
3	1	Average	23.7	23.6	23.7	23.7
		Min	23.4	23.3	23.6	23.3
		Max	23.8	23.7	23.8	23.8
	2	Average	23.2	23.1	23.1	23.1
		Min	23.0	23.0	23.0	23.0

		Max	23.5	23.2	23.3	23.3
4	1	Average	23.2	23.2	23.7	23.6
		Min	23.0	23.1	23.6	23.5
		Max	23.5	23.4	23.8	23.8
	2	Average	23.5	23.6	23.9	23.9
		Min	23.0	23.2	23.5	23.6
		Max	23.8	23.8	24.2	24.1
	3	Average	23.1	23.3	23.4	23.4
		Min	23.0	23.3	23.3	23.3
		Max	23.1	23.3	23.6	23.6
5	1	Average	23.2	24.1	24.0	24.4
		Min	22.9	23.0	23.1	23.7
		Max	23.5	24.9	24.6	24.8
	2	Average	22.9	23.7	23.8	24.0
		Min	22.7	23.6	23.8	24.0
		Max	23.0	23.8	23.9	24.1
	3	Average	22.7	23.4	23.4	23.5
		Min	22.7	23.4	23.3	23.5
		Max	22.8	23.5	23.7	23.6
7	1	Average	22.9	22.9	23.4	23.3
		Min	22.8	22.6	23.3	23.2
		Max	23	23	23.6	23.5
	2	Average	24.1	24	24.5	24.1
		Min	23.2	23.2	23.4	23.3
		Max	24.5	24.4	24.9	24.6

Table B3-6: Relative humidity at sampling point

Level	Sampling point		Sampling time			
			9.00 am	12.00 am	2.00 pm	4.00 pm
G	1	Average	70.3	63.8	66.8	64.8
		Min	69.1	62.5	66.2	64.0
		Max	71.2	66.7	67.8	66.1
1	1 (Nursery)	Average	68.5	66.5	65.8	67.4
		Min	68.3	66.1	65.1	67.0
		Max	68.7	66.7	66.4	68.0
	2 (Training Room)	Average	67.2	65.0	62.4	62.3
		Min	67.0	64.0	62.1	62.1
		Max	68.3	65.4	62.9	62.8
	3 (Kelab Kristal)	Average	68.4	63.8	61.2	60.4
		Min	68.0	63.1	60.9	59.6
		Max	70.2	64.2	61.5	61.1
	4	Average	66.1	64.5	65.3	65.3

	(Gymnasium)	Min	65.7	64.1	64.7	64.8
		Max	66.9	64.8	65.9	65.9
2	1	Average	68.8	63.1	65.9	65.2
		Min	68.5	62.4	65.1	64.6
		Max	69.3	64.8	67.6	65.5
	2	Average	65.4	64.7	63.7	62.8
		Min	64.9	64.2	63.2	62.2
		Max	66.7	65.7	65.3	63.9
3	1	Average	61.8	58.7	56.4	57.4
		Min	61.2	58.0	56.1	56.6
		Max	64.7	59.7	56.6	58.7
	2	Average	62.6	59.0	57.0	57.6
		Min	61.7	58.6	56.4	57.1
		Max	64.7	59.1	57.4	58.0
4	1	Average	60.3	58.4	57.7	58.0
		Min	59.4	57.6	57.2	57.7
		Max	60.7	58.6	58.8	59.5
	2	Average	61.2	57.6	56.7	57.3
		Min	60.0	56.6	55.7	56.4
		Max	66.0	59.8	58.1	59.0
	3	Average	60.6	57.9	56.9	56.9
		Min	60.3	57.4	56.0	56.2
		Max	60.8	58.1	57.2	57.2
5	1	Average	57.3	54.9	53.9	52.9
		Min	56.6	53.1	52.3	51.7
		Max	57.9	57.0	56.2	54.9
	2	Average	57.7	54.7	54.0	53.1
		Min	57.2	53.5	53.2	52.5
		Max	58.0	54.9	54.2	53.4
	3	Average	58.3	55.1	53.8	53.4
		Min	57.7	54.3	52.7	52.6
		Max	58.4	55.5	54.6	53.7
7	1	Average	56.9	55	53.2	53
		Min	56.6	54.3	52.7	51.6
		Max	57.4	56.4	53.4	53.3
	2	Average	55.3	52.2	50	50.8
		Min	53.8	51	48.7	49.3
		Max	58	54	52.7	52.5

Figure B3-1: Main sampling point

Figure B3-2: Additional sampling point

APPENDIX B4

INDOOR AIR QUALITY MEASUREMENTS FOR MALAYSIAN GREEN TECHNOLOGY CORPORATION BUILDING, BANGI

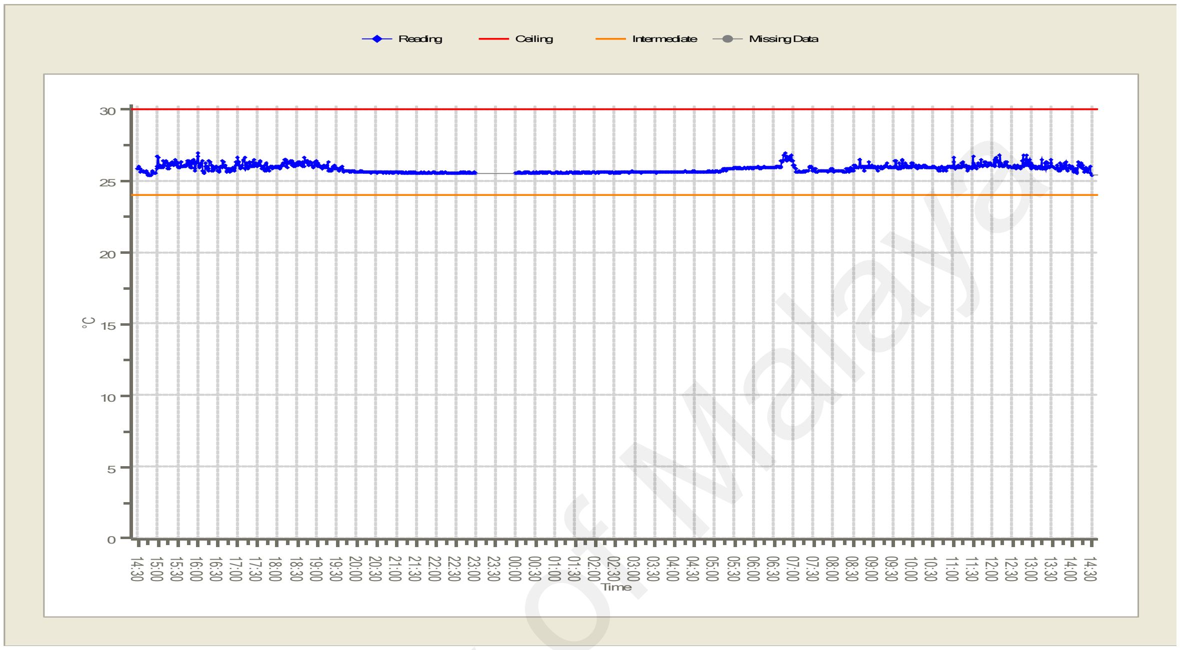


Figure B4-1: Temperature 1st floor

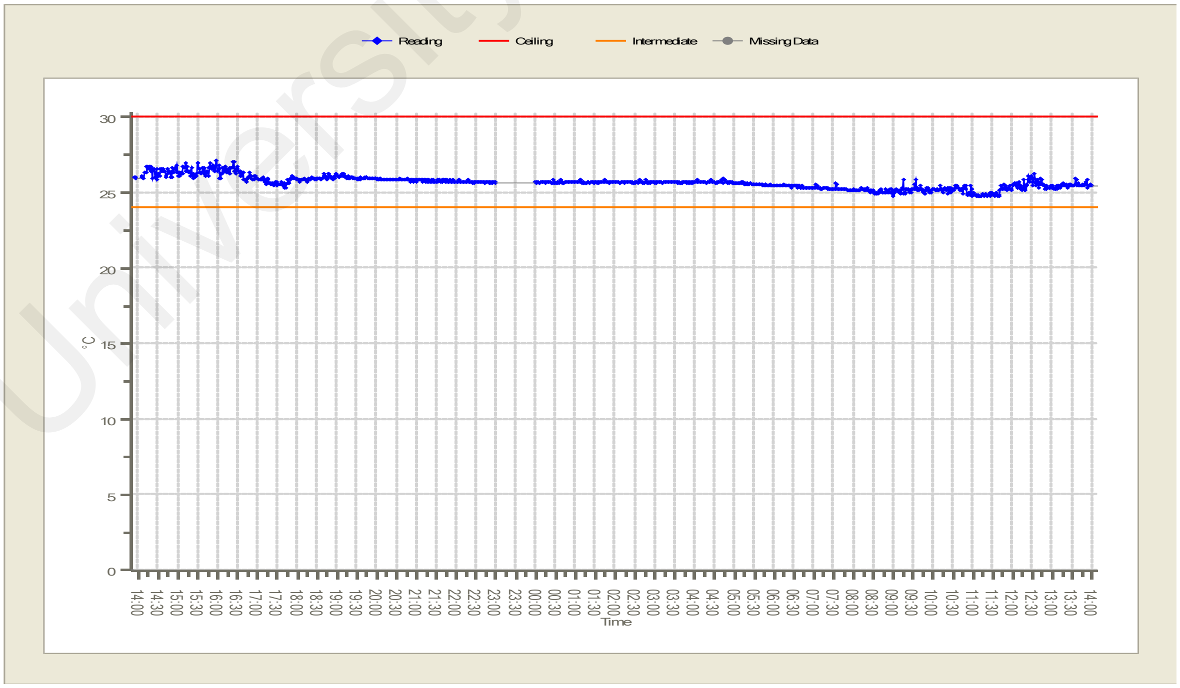


Figure B4-2: Temperature 2nd floor

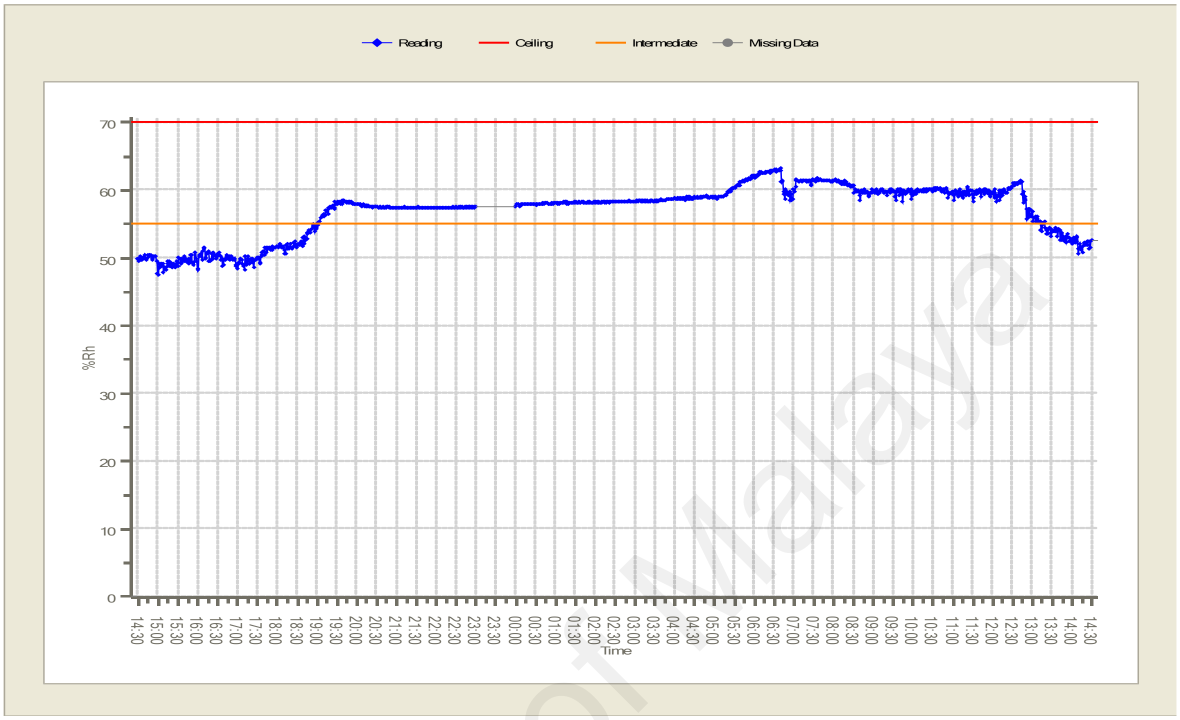


Figure B4-3: Humidity 1st floor

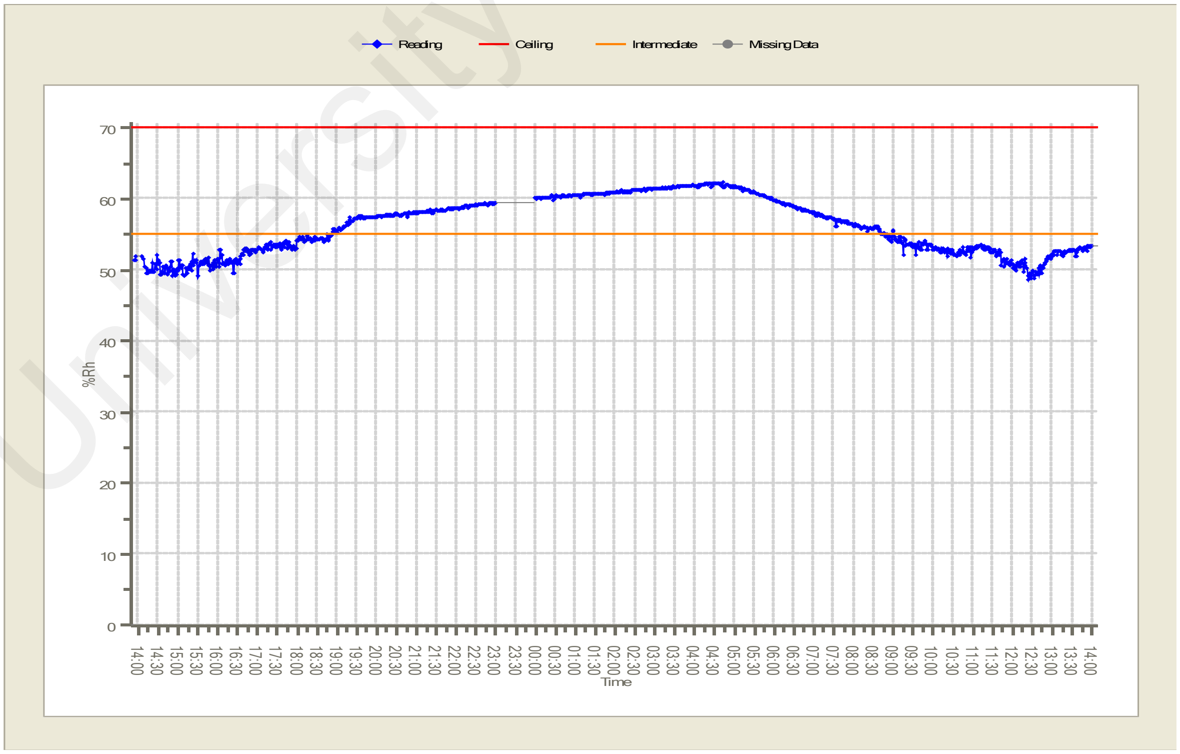


Figure B4-4: Humidity 2nd floor

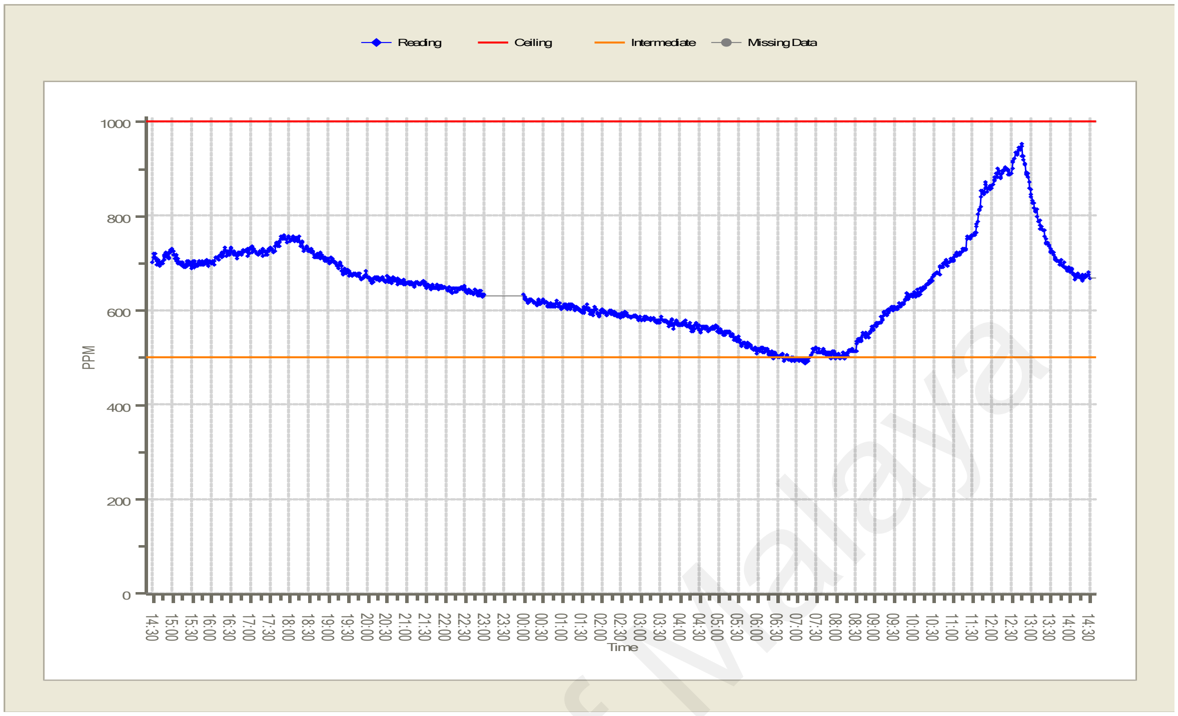


Figure B4-5: Carbon dioxide concentration 1st floor

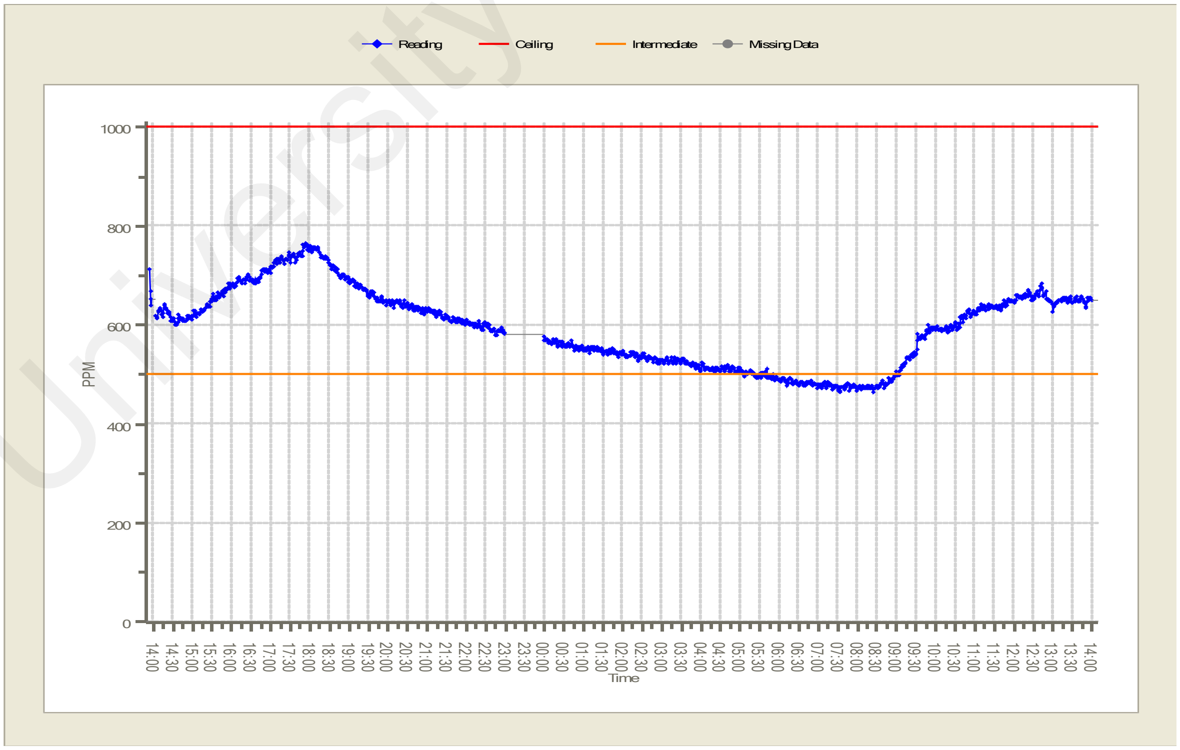


Figure B4-6: Carbon dioxide concentration 2nd floor

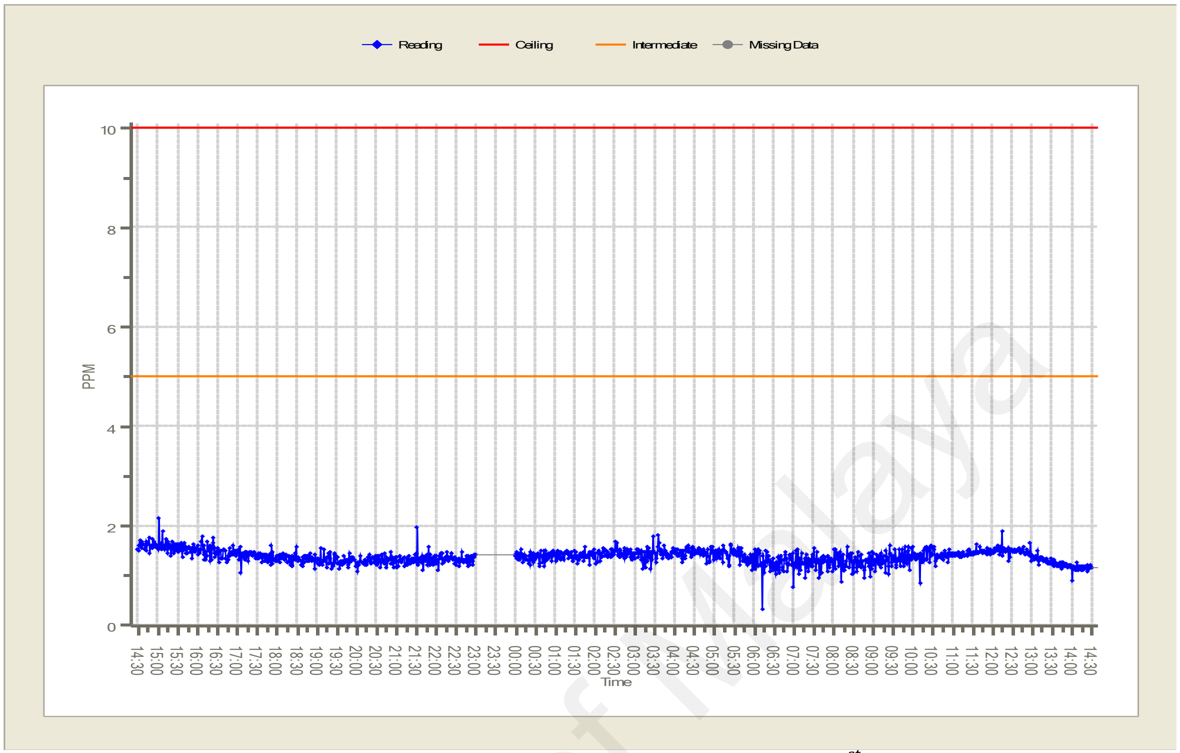


Figure B4-7: Carbon monoxide concentration 1st floor

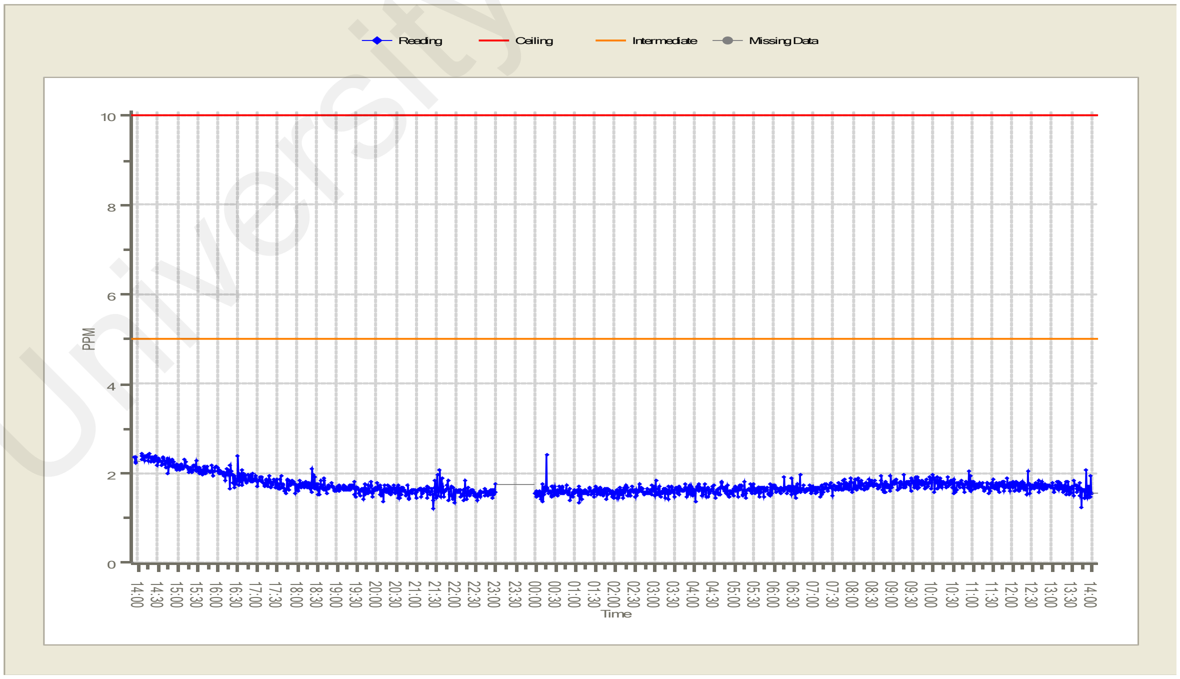


Figure B4-8: Carbon monoxide concentration 2nd floor

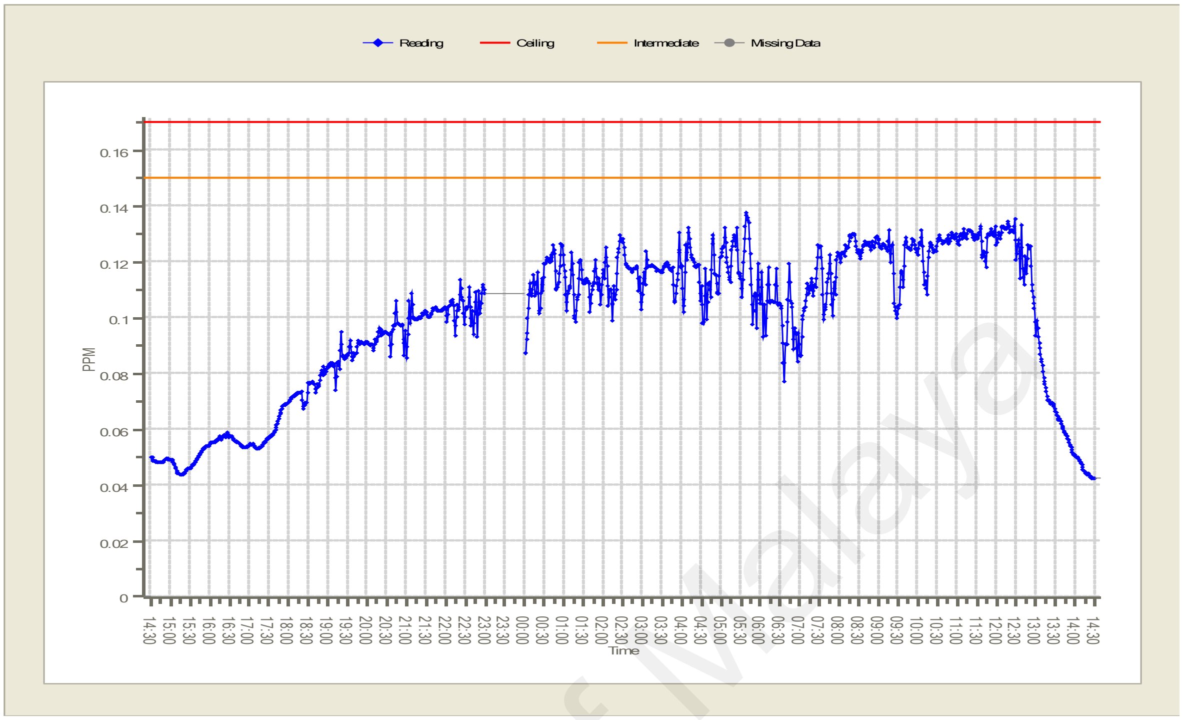


Figure B4-9: Formaldehyde concentration 1st floor

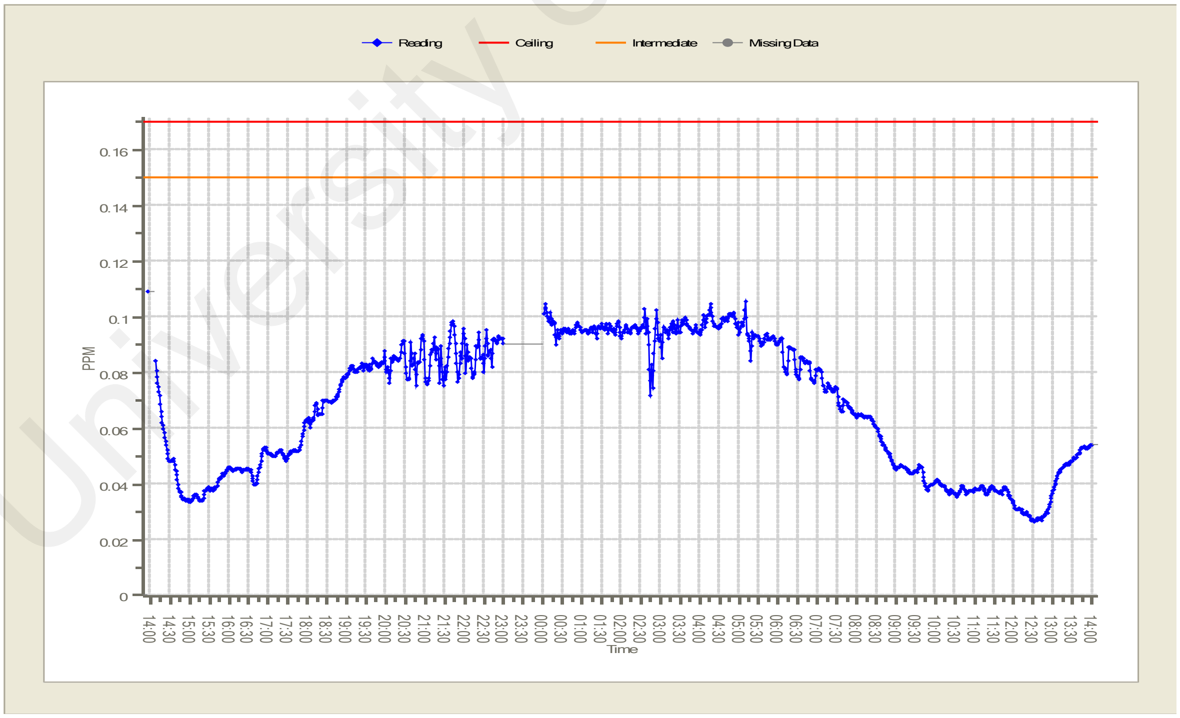
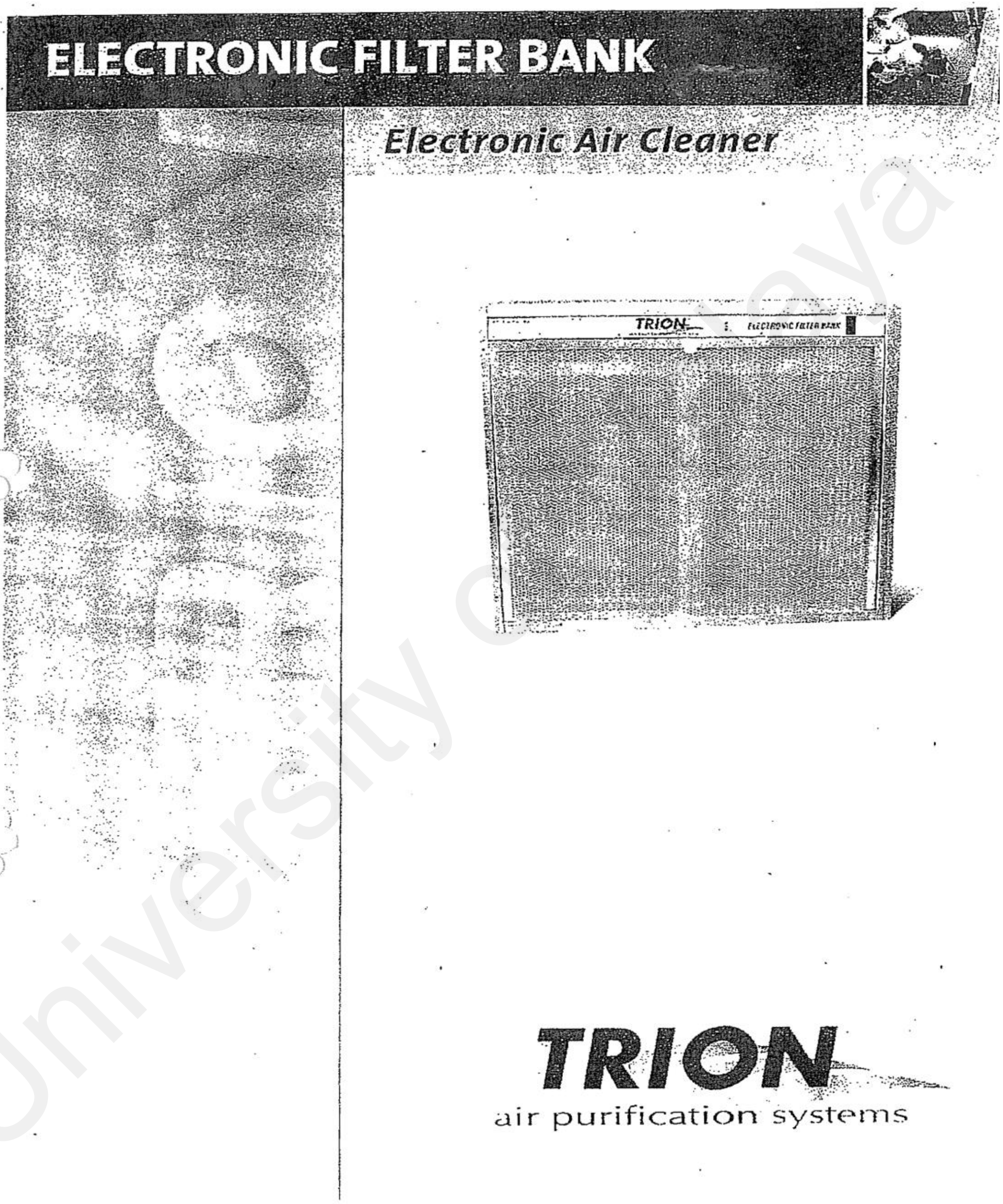


Figure B4-10: Formaldehyde concentration 2nd floor

APPENDIX B5

ELECTRONIC FILTER SPECIFICATION



ELECTRONIC FILTER BANK

Electronic Air Cleaner

TRION

air purification systems

ENGINEERING SOLUTIONS FOR CLEAN AIR

HANDLING YOUR DEPOSITS OF AIRBORNE PARTICLES

The Electronic Filter Bank (EFB) is a commercial electronic air cleaner that is mounted to packaged and custom air handling systems. *The EFB captures airborne particles 0.01 micron and larger from the air circulated through it.*

FLEXIBLE ENOUGH TO MEET YOUR NEEDS

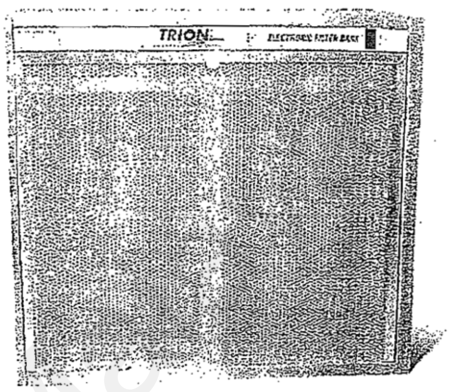
The EFB is ideal for commercial HVAC systems and provides a relay contact that can be connected to a building management system to provide remote status indication. For best results, an EFB should *not* be mounted in the discharge air duct.

FEATURES

- Capacity from 2000 CFM (3400 m^3/hr)
- Multiple units can interconnect to meet system air flow requirements
- Solid-state, self-regulating power supply which maintains peak efficiency as cell loading occurs
- Indicator lights signal proper operation
- Capable of interfacing with building management systems
- Superior high-voltage contact design
- Pre-filter screen protects cells from large dirt particles
- Automatic notification of fault conditions
- Wash indicator light — prompting you to clean the filter

BENEFITS

- Low, constant system pressure drop
- Improved indoor air quality
- Reduced HVAC system operating costs
- Easy system maintenance procedures



OUTDOOR AIR INTAKE APPLICATIONS

For applications with outdoor air intake, return air temperature must be at least 40°F (4°C) because lower temperatures can cause ionizer wire failure. If outdoor air is used, it must be preheated by:

- Making certain that the outdoor intake is far enough upstream from the air cleaner so the return and outdoor air are thoroughly mixed.
- Adding baffles upstream from the air cleaner to force thorough air mixing.
- Installing a pre-heater if large amounts of outdoor air are used. (NOTE: A thermostat can be used to control the pre-heater, and hot water or steam coils can be protected using a freeze-up control.)

Specifications

Electronic Filter Bank	
Electrical Ratings	
Voltage and Frequency	110/120V, 50/60 Hz 220/240V, 50/60 Hz
Power Consumption	45.1W max @ 120 VAC
Current Draw	0.2A @ 220V, 50/60 Hz (.45A @ 120 VAC)
Ionizer/Collector Cell Voltage	6.2 KVdc.
Capacity, Efficiency, Pressure Drop	(See Figure 1)
Temperature Ratings	Operating Ambient: 40°F to 125°F (4°C to 52°C)
Temperature of Airflow Through Cells	40°F to 125°F (4°C to 52°C)
Maximum Cell Washing Temperature	180°F (82°C)
Mounting	Mounts into the return air plenum of a commercial HVAC system.
Weight	
Electronic Cell (each):	11 lb (5.0 kg)
Shipped Weight:	43 lb (19.6 kg)
Installed Weight (Cells Included):	38 lb (17.3 kg)
Dimensions	See Figure 2
Accessories	Carbon Filter

WARNING

- Mount the Electronic Filter Bank with the power source on top.
- DO NOT mount the air cleaner with the pre-filter facing down because the latches may not hold, and the cell and pre-filter can fall unexpectedly.

WARNING

To prevent collapse of the array support structure:

- Provide adequate structural support to the array across the top and bottom of each unit, as well as cross-supports.
- Support each unit with external structural elements across the top and bottom of each unit.

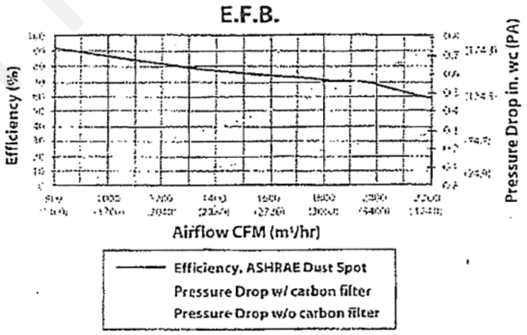


FIG. 1

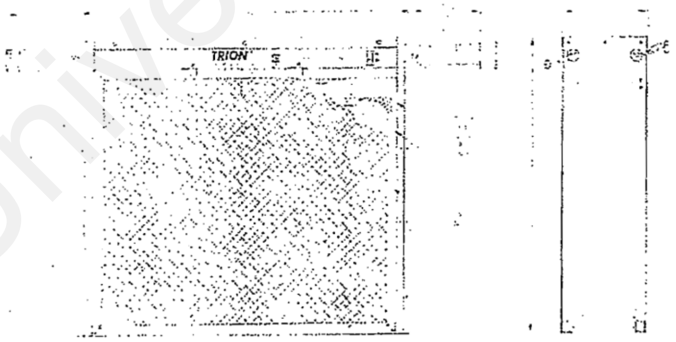
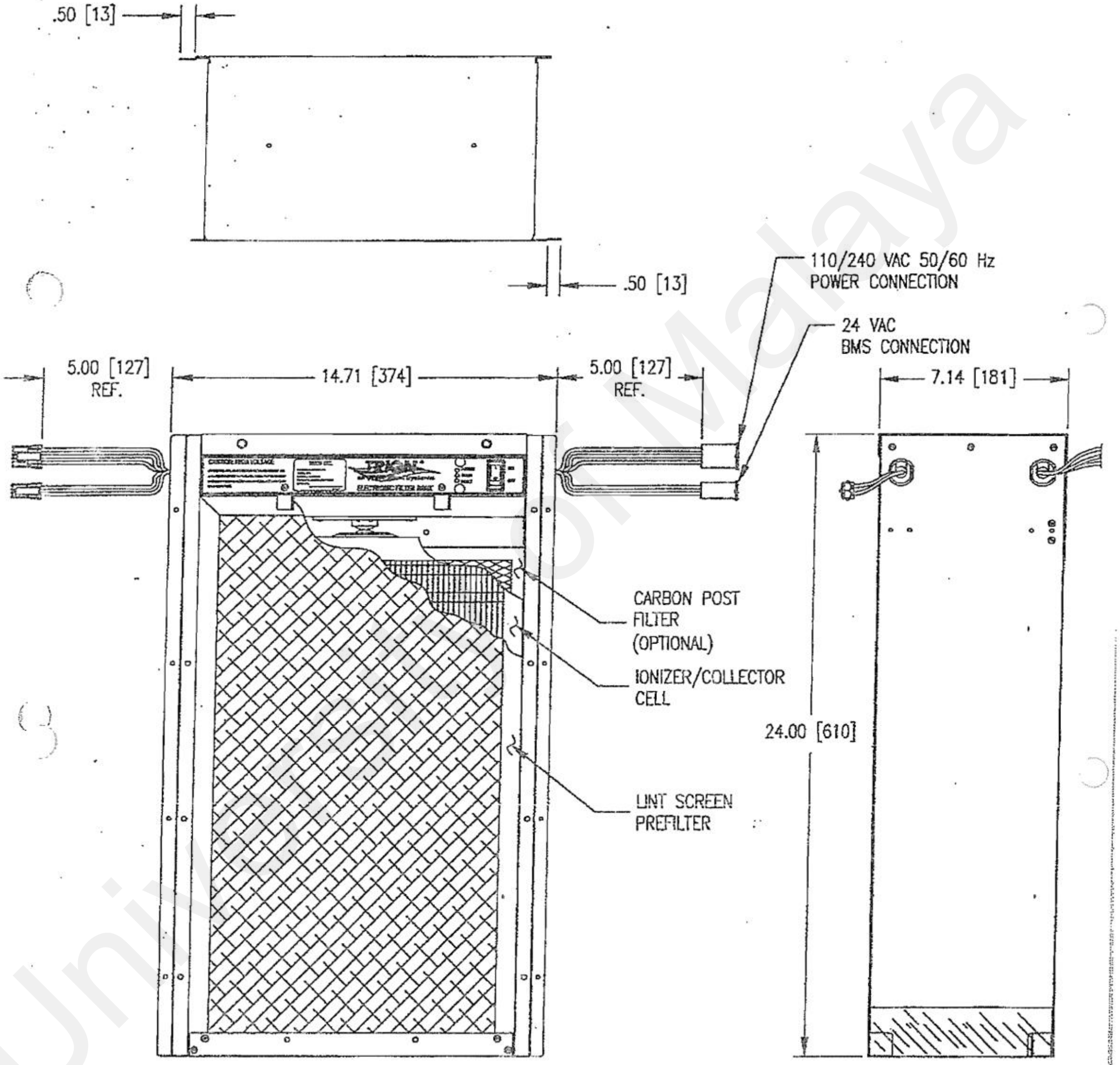
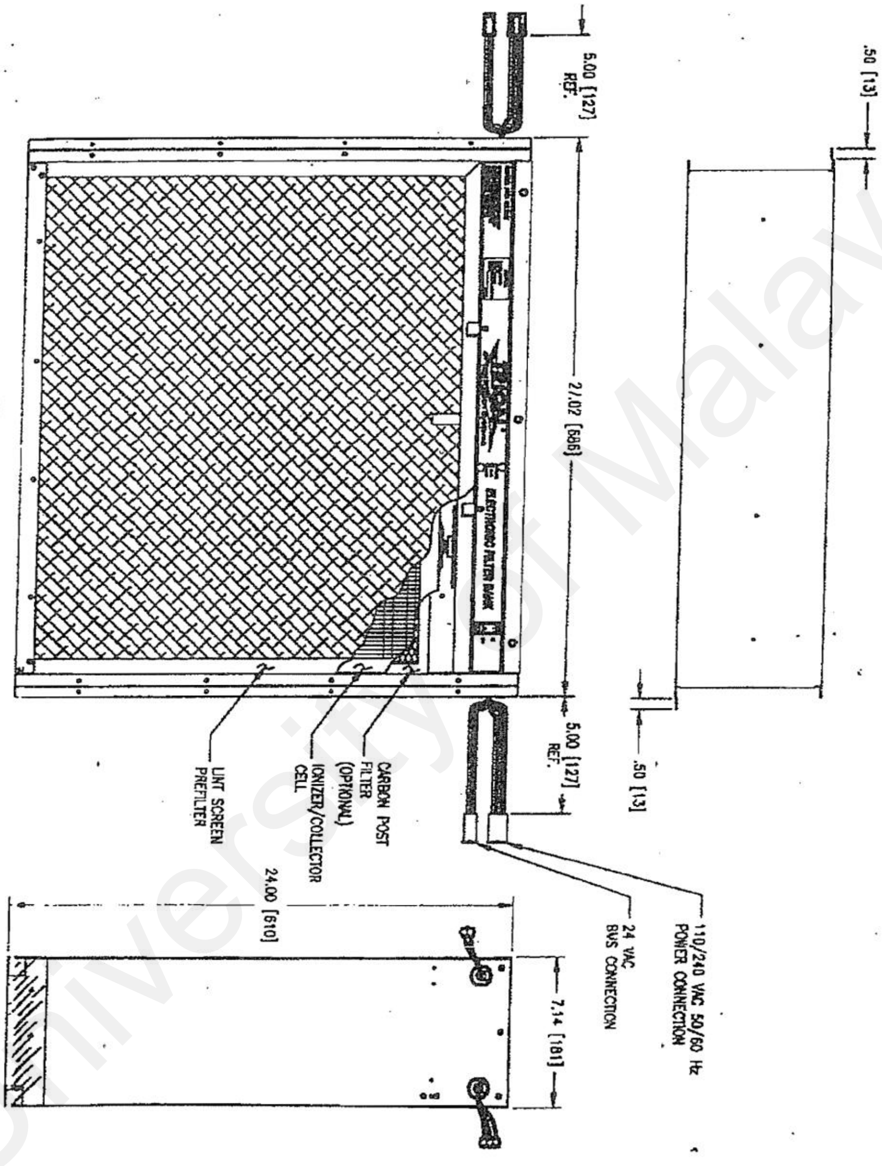


FIG. 2


.50 [13]
.50 [13]
110/240 VAC 50/60 Hz
POWER CONNECTION
24 VAC
BMS CONNECTION
5.00 [127]
REF.
14.71 [374]
5.00 [127]
REF.
7.14 [181]
CARBON POST
FILTER
(OPTIONAL)
IONIZER/COLLECTOR
CELL
24.00 [610]
LINT SCREEN
PREFILTER

Outline Drawing



EFB double cells

Electronic Air Cleaner Selection Table

Option 2 : 72 - 78% Efficiency

Project : Senandung Budiman (2C15), Putrajaya

Item	Unit No.	AHU Dimension		Air Volume	No. of EAC					Area/EAC	Total EAC Area	Face Vel. Thru EAC	EAC Efficiency	EAC Space Required		AHU Extension Required	
		W (mm)	H (mm)	(cfm)	Total	Per Column	Per Row	Full Size	Half Size	(m^2)	(m^2)	(FPM)		W (mm)	H (mm)	W (mm)	H (mm)
1	AHU L1-1	2100	1300	6150	4	2	2	4	nil	0.323	1.290	443	75%	1372	1220	nil	nil
2	AHU L2-1	2100	1300	7000	5	2.5	2	4	2	0.323	1.613	403	78%	1715	1220	nil	nil
3	AHU L3-1	2400	1400	8800	6	3	2	6	nil	0.323	1.935	423	76%	2058	1220	nil	nil
4	AHU L4-1	2800	1700	10800	6	3	2	6	nil	0.323	1.935	519	72%	2058	1220	nil	nil
5	AHU L5-1	3000	1700	13000	9	3	3	9	nil	0.323	2.903	416	77%	2058	1830	nil	130
6	AHU L6-1	3000	2100	15000	9	3	3	9	nil	0.323	2.903	480	73%	2058	1830	nil	nil
7	AHU L7-1	3000	2100	17400	10.5	3.5	3	9	3	0.323	3.387	477	73%	2401	1830	nil	nil
	Total EAC Required :							47	5								

APPENDIX C1

CONSTRUCTION RESEARCH OF MALAYSIA BUILDING SAMPLING POINT

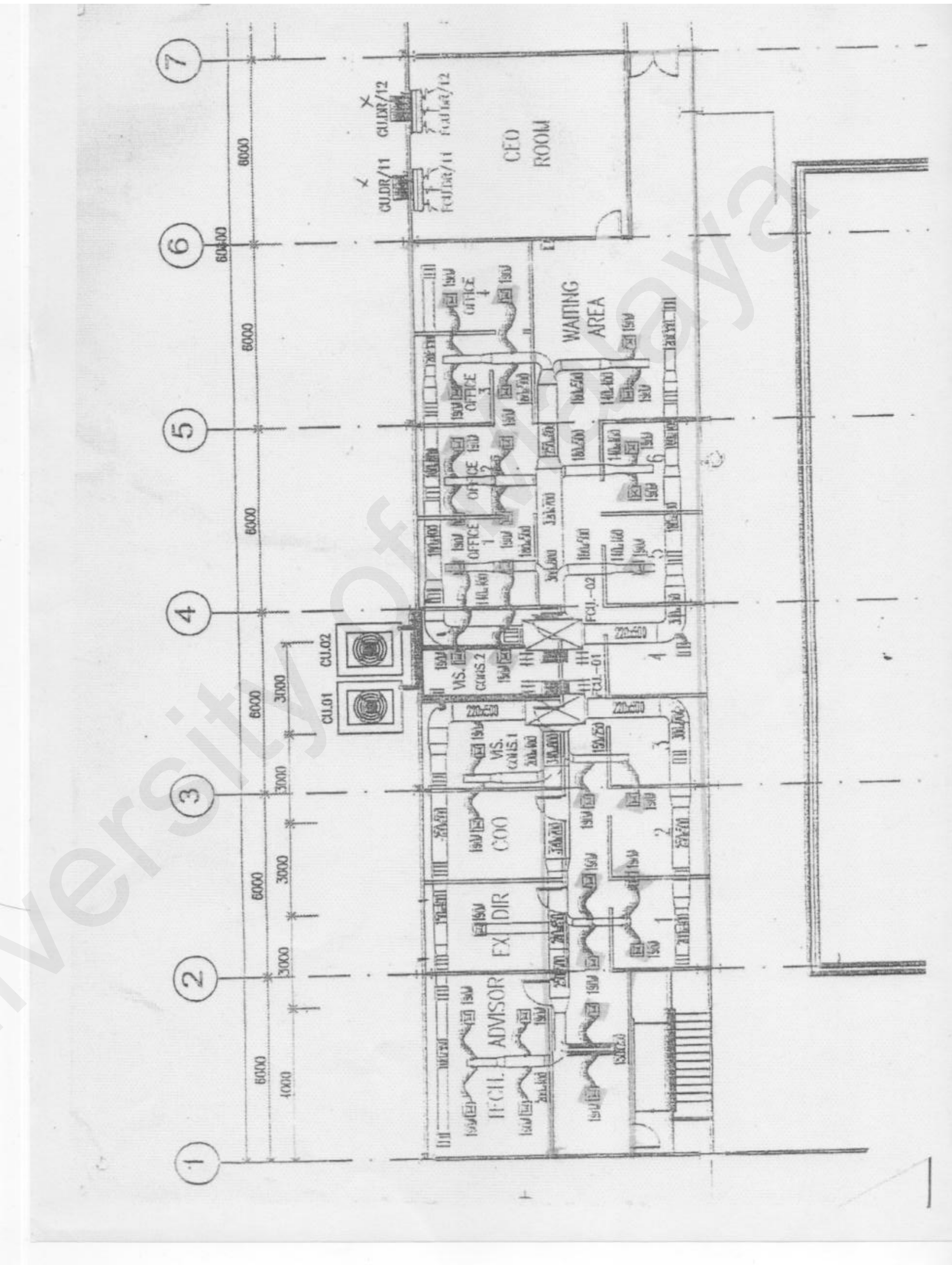


Figure C1-1: Mechanical and Electrical Drawing of CREAM building

Figure C1-2: Inside the office space

APPENDIX C2

INDOOR AIR QUALITY MEASUREMENTS FOR CONSTRUCTION RESEARCH OF MALAYSIA BUILDING, CHERAS

Table C2-1: Temperature and Relative Humidity

Date & Day		Sampling time			
		9.00 am	12.00 am	2.00 pm	4.00 pm
12/12/2012	T	21.9	21.6	26.1	20.4
Monday	RH	51.5	50.7	50.6	51.5
13/12/2012	T	24.4	26.2	26.4	22.1
Tuesday	RH	59.3	46.7	45.7	49.3
14/12/2012	T	23.5	22.1	26.4	22.3
Wednesday	RH	56.7	51	52.7	53.9
15/12/2012	T	26.1	21.9	21.5	25.2
Thursday	RH	56.8	51.5	50.9	56.9
16/12/2012	T	26.3	27.4	28.4	22.4
Friday	RH	62	56.2	58.7	49.8

Table C2-2: Indoor Contaminants

Date & Day		Sampling time			
		9.00 am	12.00 am	2.00 pm	4.00 pm
12/12/2012	CO	750	591	709	665
Monday	CO2	2.235	1.819	1.964	1.732
	Formaldehyde	0	0	0	0
	NO	0.188	0.181	0.173	0.147
	TVOC	0.069	0.065	0.101	0.067
13/12/2012	CO	680	581	550	588
Tuesday	CO2	3.377	2.087	1.814	1.156
	Formaldehyde	0	0	0	0
	NO	0.199	0.18	0.161	0.142
	TVOC	0.078	0.087	0.093	0.064
14/12/2012	CO	691	658	688	617
Wednesday	CO2	3.743	2.192	2.1023	1.705
	Formaldehyde	0	0	0.001	0.008
	NO	0.166	0.191	0.143	0.134
	TVOC	0.072	0.063	0.089	0.058
15/12/2012	CO	707	592	522	602

Thursday	CO2	5.194	2.298	1.354	2.066
	Formaldehyde	0.112	0.003	0.001	0.041
	NO	0.099	0.165	0.176	0.16
	TVOC	0.081	0.05	0.051	0.076
16/12/2012 Friday	CO	670	649	659	577
	CO2	4.076	3.503	2.98	1.797
	Formaldehyde	0.089	0.049	0.077	0
	NO	0.105	0.131	0.129	0.198
	TVOC	0.067	0.095	0.1	0.061

Table C-3: Particle count

Level	>0.3µm	>0.5µm	>1.0µm	>3.0µm	>5.0µm	>10.0µm
12/12/2012 Monday	10177829	541290	42531	18541	11211	6244
13/12/2012 Tuesday	12903557	652297	37528	9251	4661	2544
14/12/2012 Wednesday	33801260	1133379	37258	7413	4028	2407
15/12/2012 Thursday	28747224	2182692	188542	35058	11129	2264
16/12/2012 Friday	11317671	907154	53983	13115	7116	4189

Table C-4: Volume flow rate

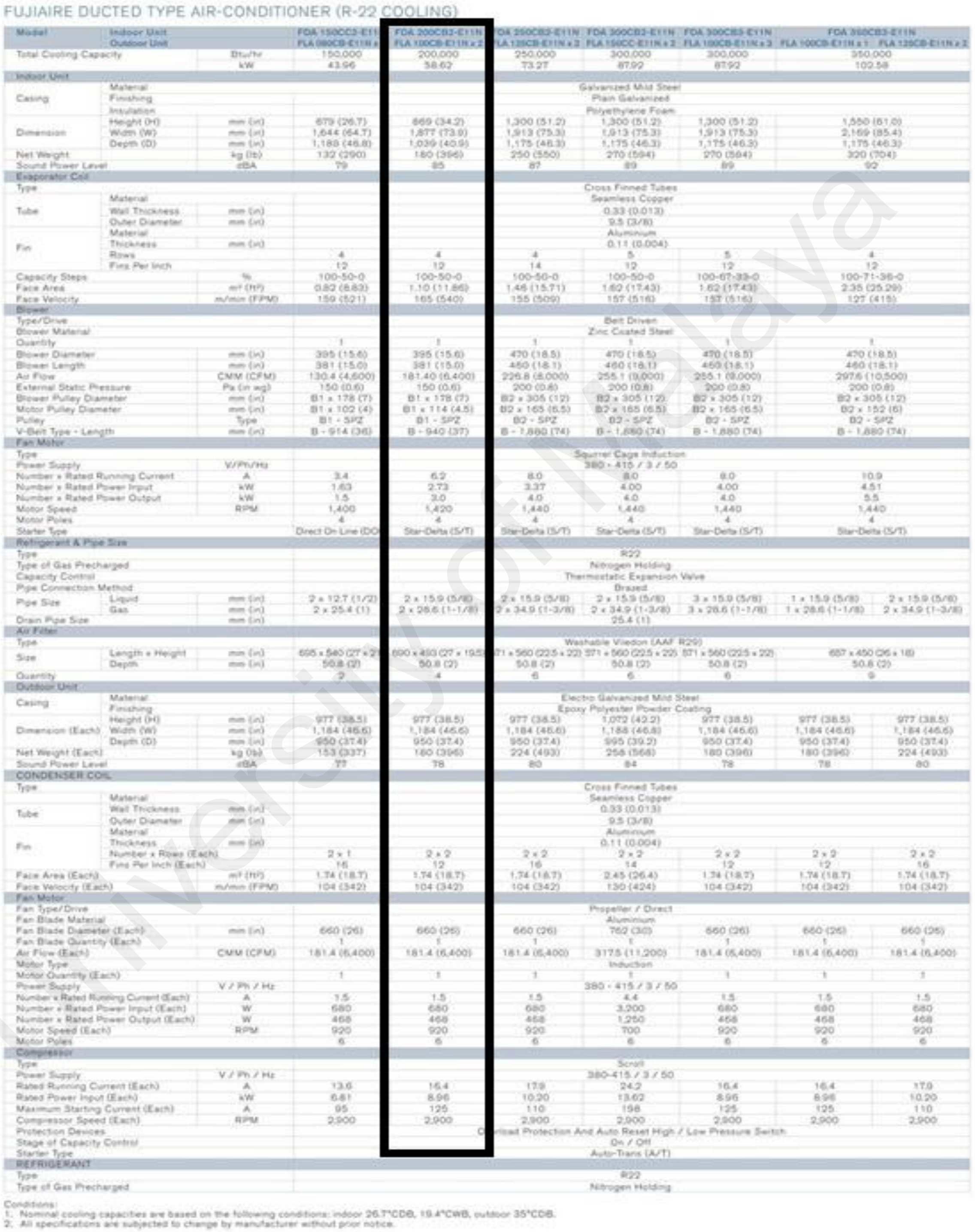
Date & day	Sampling time			
	9.00 am	12.00 am	2.00 pm	4.00 pm
12/12/2012 Monday	0.002322119	0.041511603	0.041388195	0.041474953
13/12/2012 Tuesday	0.042153399	0.041900396	0.041913219	0.042048331
14/12/2012 Wednesday	0.042048883	0.042077314	0.042081997	0.041950654
15/12/2012 Thursday	0.0421196	0.041998897	0.041964006	0.041958731
16/12/2012 Friday	0.041968003	0.041962706	0.041969512	0.04201271

Table C-5: Mass concentration

Level	Mass average (mg/m³)	Mass minimum (mg/m³)	Mass maximum (mg/m³)	Mass TWA (mg/m³)	Number of samples
12/12/2012 Monday	0.006	0.001	0.013	0.005	70
13/12/2012 Tuesday	0.013	0.006	0.027	0.013	80
14/12/2012 Wednesday	0.015	0.004	0.033	0.014	76
15/12/2012 Thursday	0.03	0.02	0.06	0.028	76
16/12/2012 Friday	0.025	0.014	0.043	0.023	76

APPENDIX D1

CREAM BUILDING: AIR-COOLED DUCTED BLOWER SPECIFICATION



FUJIAIRE DUCTED TYPE AIR-CONDITIONER (R-22 COOLING)

Model	Indoor Unit Outdoor Unit		FDA 150CC3-E11 FLA 080CB-E11N x	FDA 200CB3-E11N FLA 100CB-E11N x 2	FDA 250CB3-E11N FLA 125CB-E11N x 2	FDA 300CB3-E11N FLA 150CC-E11N x 2	FDA 300CB5-E11N FLA 100CB-E11N x 3	FDA 350CB3-E11N FLA 100CB-E11N x 1	FLA 125CB-E11N x 2
Total Cooling Capacity		Btu/hr	150,000	200,000	250,000	300,000	300,000	350,000	
		kW	43.96	58.62	73.27	87.92	87.92	102.58	
Indoor Unit									
Casing	Material		Galvanized Mild Steel						
	Finishing		Plain Galvanized						
	Insulation		Polyethylene Foam						
Dimension	Height (H)	mm (in)	679 (26.7)	869 (34.2)	1,300 (51.2)	1,300 (51.2)	1,300 (51.2)	1,550 (61.0)	
	Width (W)	mm (in)	1,644 (64.7)	1,877 (73.9)	1,913 (75.3)	1,913 (75.3)	1,913 (75.3)	2,169 (85.4)	
	Depth (D)	mm (in)	1,188 (46.8)	1,039 (40.9)	1,175 (46.3)	1,175 (46.3)	1,175 (46.3)	1,175 (46.3)	
Net Weight		kg (lb)	132 (290)	180 (396)	250 (550)	270 (594)	270 (594)	320 (704)	
Sound Power Level		dBA	79	85	87	89	89	92	
Evaporator Coil									
Type			Cross Finned Tubes						
Tube	Material		Seamless Copper						
	Wall Thickness	mm (in)	0.33 (0.013)						
	Outer Diameter	mm (in)	9.5 (3/8)						
Fin	Material		Aluminium						
	Thickness	mm (in)	0.11 (0.004)						
	Rows		4	4	4	5	5	4	
	Fins Per Inch		12	12	14	12	12	12	
Capacity Steps		%	100-50-0	100-50-0	100-50-0	100-50-0	100-67-33-0	100-71-36-0	
Face Area		m² (ft²)	0.82 (8.83)	1.10 (11.86)	1.46 (15.71)	1.62 (17.43)	1.62 (17.43)	2.35 (25.29)	
Face Velocity		m/min (FPM)	159 (521)	165 (540)	155 (509)	157 (516)	157 (516)	127 (415)	
Blower									
Type/Drive			Belt Driven						
Blower Material			Zinc Coated Steel						
Quantity			1	1	1	1	1	1	
Blower Diameter		mm (in)	395 (15.6)	395 (15.6)	470 (18.5)	470 (18.5)	470 (18.5)	470 (18.5)	
Blower Length		mm (in)	381 (15.0)	381 (15.0)	460 (18.1)	460 (18.1)	460 (18.1)	460 (18.1)	
Air Flow		CMM (CFM)	130.4 (4,600)	181.40 (6,400)	226.8 (8,000)	255.1 (9,000)	255.1 (9,000)	297.6 (10,500)	
External Static Pressure		Pa (in wg)	150 (0.6)	150 (0.6)	200 (0.8)	200 (0.8)	200 (0.8)	200 (0.8)	
Blower Pulley Diameter		mm (in)	B1 x 178 (7)	B1 x 178 (7)	B2 x 305 (12)	B2 x 305 (12)	B2 x 305 (12)	B2 x 305 (12)	
Motor Pulley Diameter		mm (in)	B1 x 102 (4)	B1 x 114 (4.5)	B2 x 165 (6.5)	B2 x 165 (6.5)	B2 x 165 (6.5)	B2 x 152 (6)	
Pulley		Type	B1 - SPZ	B1 - SPZ	B2 - SPZ	B2 - SPZ	B2 - SPZ	B2 - SPZ	
V-Belt Type - Length		mm (in)	B - 914 (36)	B - 940 (37)	B - 1,880 (74)	B - 1,880 (74)	B - 1,880 (74)	B - 1,880 (74)	
Fan Motor									
Type			Squirrel Cage Induction						
Power Supply		V/Ph/Hz	380 - 415 / 3 / 50						
Number x Rated Running Current		A	3.4	6.2	8.0	8.0	8.0	10.9	
Number x Rated Power Input		kW	1.63	2.73	3.37	4.00	4.00	4.51	
Number x Rated Power Output		kW	1.5	3.0	4.0	4.0	4.0	5.5	
Motor Speed		RPM	1,400	1,420	1,440	1,440	1,440	1,440	
Motor Poles			4	4	4	4	4	4	
Starter Type			Direct On Line (DO	Star-Delta (S/T)	Star-Delta (S/T)	Star-Delta (S/T)	Star-Delta (S/T)	Star-Delta (S/T)	
Refrigerant & Pipe Size									
Type			R22						
Type of Gas Precharged			Nitrogen Holding						
Capacity Control			Thermostatic Expansion Valve						
Pipe Connection Method			Brazed						
Pipe Size	Liquid	mm (in)	2 x 12.7 (1/2)	2 x 15.9 (5/8)	2 x 15.9 (5/8)	2 x 15.9 (5/8)	3 x 15.9 (5/8)	1 x 15.9 (5/8)	2 x 15.9 (5/8)
	Gas	mm (in)	2 x 25.4 (1)	2 x 28.6 (1-1/8)	2 x 34.9 (1-3/8)	2 x 34.9 (1-3/8)	3 x 28.6 (1-1/8)	1 x 28.6 (1-1/8)	2 x 34.9 (1-3/8)
Drain Pipe Size		mm (in)	25.4 (1)						
Air Filter									
Type			Washable Viledon (AAF R29)						
Size	Length x Height	mm (in)	695 x 540 (27 x 21	690 x 493 (27 x 19.5	71 x 560 (22.5 x 22)	571 x 560 (22.5 x 22)	571 x 560 (22.5 x 22)	657 x 450 (26 x 18)	
	Depth	mm (in)	50.8 (2)	50.8 (2)	50.8 (2)	50.8 (2)	50.8 (2)	50.8 (2)	
Quantity			2	4	6	6	6	9	
Outdoor Unit									
Casing	Material		Electro Galvanized Mild Steel						
	Finishing		Epoxy Polyester Powder Coating						
Dimension (Each)	Height (H)	mm (in)	977 (38.5)	977 (38.5)	977 (38.5)	1,072 (42.2)	977 (38.5)	977 (38.5)	977 (38.5)
	Width (W)	mm (in)	1,184 (46.6)	1,184 (46.6)	1,184 (46.6)	1,188 (46.8)	1,184 (46.6)	1,184 (46.6)	1,184 (46.6)
	Depth (D)	mm (in)	950 (37.4)	950 (37.4)	950 (37.4)	995 (39.2)	950 (37.4)	950 (37.4)	950 (37.4)
Net Weight (Each)		kg (lb)	153 (337)	180 (396)	224 (493)	258 (568)	180 (396)	180 (396)	224 (493)
Sound Power Level		dBA	77	78	80	84	78	78	80
CONDENSER COIL									
Type			Cross Finned Tubes						
Tube	Material		Seamless Copper						
	Wall Thickness	mm (in)	0.33 (0.013)						
	Outer Diameter	mm (in)	9.5 (3/8)						
Fin	Material		Aluminium						
	Thickness	mm (in)	0.11 (0.004)						
	Number x Rows (Each)		2 x 1	2 x 2	2 x 2	2 x 2	2 x 2	2 x 2	2 x 2
	Fins Per Inch (Each)		16	12	16	14	12	12	16
Face Area (Each)		m² (ft²)	1.74 (18.7)	1.74 (18.7)	1.74 (18.7)	2.45 (26.4)	1.74 (18.7)	1.74 (18.7)	1.74 (18.7)
Face Velocity (Each)		m/min (FPM)	104 (342)	104 (342)	104 (342)	130 (424)	104 (342)	104 (342)	104 (342)
Fan Motor									
Fan Type/Drive			Propeller / Direct						
Fan Blade Material			Aluminium						
Fan Blade Diameter (Each)		mm (in)	660 (26)	660 (26)	660 (26)	762 (30)	660 (26)	660 (26)	660 (26)
Fan Blade Quantity (Each)			1	1	1	1	1	1	1
Air Flow (Each)		CMM (CFM)	181.4 (6,400)	181.4 (6,400)	181.4 (6,400)	317.5 (11,200)	181.4 (6,400)	181.4 (6,400)	181.4 (6,400)
Motor Type			Induction						
Motor Quantity (Each)			1	1	1	1	1	1	1
Power Supply		V / Ph / Hz	380 - 415 / 3 / 50						
Number x Rated Running Current (Each)		A	1.5	1.5	1.5	4.4	1.5	1.5	1.5
Number x Rated Power Input (Each)		W	680	680	680	3,200	680	680	680
Number x Rated Power Output (Each)		W	468	468	468	1,250	468	468	468
Motor Speed (Each)		RPM	920	920	920	700	920	920	920
Motor Poles			6	6	6	6	6	6	6
Compressor									
Type			Scroll						
Power Supply		V / Ph / Hz	380-415 / 3 / 50						
Rated Running Current (Each)		A	13.6	16.4	17.9	24.2	16.4	16.4	17.9
Rated Power Input (Each)		kW	6.81	8.96	10.20	13.62	8.96	8.96	10.20
Maximum Starting Current (Each)		A	95	125	110	198	125	125	110
Compressor Speed (Each)		RPM	2,900	2,900	2,900	2,900	2,900	2,900	2,900
Protection Devices			O rload Protection And Auto Reset High / Low Pressure Switch						
Stage of Capacity Control			On / Off						
Starter Type			Auto-Trans (A/T)						
REFRIGERANT									
Type			R22						
Type of Gas Precharged			Nitrogen Holding						

Conditions:
1. Nominal cooling capacities are based on the following conditions: indoor 26.7°CDB, 19.4°CWB, outdoor 35°CDB.
2. All specifications are subjected to change by manufacturer without prior notice.

Figure D1-1: Air-cooled ducted blower specification