

**INDOOR AIR CONDITIONS AND ENERGY  
CONSUMPTION IN AIR-CONDITIONED OFFICE  
ROOMS IN HOT-HUMID CLIMATE: TOWARDS  
BETTER ENERGY MANAGEMENT**

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**UNIVERSITI SAINS MALAYSIA**

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**By**

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## **LIST OF ABBREVIATIONS**

Btu	British thermal unit
ACMV	Air-conditioning and mechanical ventilation
CO <sub>2</sub>	Carbon dioxide
RH	Relative humidity
DOSH	Department of Occupational Safety and Health
GFA	Gross floor area
BAS	Building Automation Systems
ANOVA	Analysis of Variance
SIAQG	Singapore Indoor Air Quality Guidelines
HKSAR	Hong Kong Special Administrative Region
ASHRAE	American Society of Heating Refrigerating And Air-Conditioning Engineers
AQSIA	Administration of Quality Supervision, Inspection And Quarantine
BEI	Building Energy Index
MS 1525	Malaysia Standard 1525
DEFRA	Department for Environment, Food and Rural Affairs



**KEADAAN UDARA DALAMAN DAN PENGGUNAAN TENAGA DALAM BILIK  
PEJABAT BERHAWA DINGIN YANG TERPILIH DI IKLIM PANAS-LEMBAB :  
KE ARAH PENGURUSAN TENAGA YANG LEBIH BAIK**

**ABSTRAK**

Objektif kajian ini adalah untuk menyelidik keadaan udara dalaman dan penggunaan tenaga dalam bilik pejabat berhawa dingin yang terpilih di dalam zon iklim panas-lembap. Kajian ini juga mengkaji tren tenaga dan persepsi penghuni terhadap keadaan udara dalaman dan menganalisis hubungkait di antara penggunaan tenaga dan keadaan udara dalaman di dalam bilik pejabat berhawa dingin. Bagi mencapai objektif, penyelidikan ini telah dijalankan di dalam 30 bilik pejabat berhawa dingin yang terpilih merangkumi pengukuran keadaan cuaca luaran, keadaan cuaca dalaman, penggunaan tenaga dan kaji selidik. Keputusan telah menunjukkan bahawa keadaan cuaca dalaman berubah secara berbeza dan responden amat berpuas-hati dengan keadaan tersebut walaupun suhu dalaman dan halaju udara dalaman adalah gagal mematuhi garid Malaysia DOSH. Keputusan juga dapat menunjukkan bahawa halaju udara dalaman dikaitkan dengan kelembapan dan suhu luaran mempunyai kesan yang besar pada suhu dalaman di dalam bangunan. Hasil kajian ini juga mendedahkan kecukupan pengetahuan dan kesedaran tentang kecekapan tenaga menyebabkan kepuasan dari segi mengguna tenaga di antara responden. Walau bagaimanapun, keputusan ini mendapati bahawa penggunaan tenaga bangunan menggunakan sekira-kira 223.38 kWh/m<sup>2</sup>/tahun dan sistem penghawa dingin dikenalpasti sebagai pengguna tenaga utama, sebanyak 60.65% daripada jumlah penggunaan tenaga bangunan. Selain itu, keputusan mendapati bahawa penggunaan

tenaga bangunan juga dipengaruhi oleh suhu luaran dan purata hujan turun. Strategi untuk menggalakkan penjimatan tenaga dicadangkan, dan termasuk teknologi penjimatan tenaga dan cara meningkatkan kesedaran pendidikan mengenai penjimatan tenaga di antara responden.

**INDOOR AIR CONDITIONS AND ENERGY CONSUMPTION IN AIR-  
CONDITIONED OFFICE ROOMS IN HOT-HUMID CLIMATE  
: TOWARDS BETTER ENERGY MANAGEMENT**

**ABSTRACT**

The objectives of this research are to investigate the indoor air conditions and energy consumption in selected air-conditioned rooms in hot-humid climate zone. This research also explores the energy knowledge, attitude and practices (KAP) and occupants' perception on indoor air conditions and analyses relationship between energy consumption and indoor air conditions. This research was conducted in 30 selected air-conditioned rooms in hot-humid climate that includes measurements of outdoor climatic conditions, indoor air conditions, energy consumption and questionnaire survey. The results showed the indoor air conditions varied greatly and the respondents were satisfied with it although the indoor temperature and air velocity were failed to comply with the Malaysia DOSH guideline. The findings showed that the indoor air velocity was correlated to indoor relative humidity and the outdoor temperature also has a great impact on indoor temperature in the buildings. The findings further revealed a satisfactory energy conservation practice by the occupants due to satisfactory levels of knowledge and awareness on energy efficiency. However, the results showed that building energy index of the buildings was approximately 223.38 kWh/m<sup>2</sup>/yr and air-conditioning system is identified to be the predominant major energy consumer which consumed 60.65% of the total building energy consumption. Besides, the results found that the energy

consumption of the buildings was significantly affected by the outdoor temperature and mean rainfall. The recommended strategies to encourage energy saving are suggested, and include energy saving technologies and means of raising education awareness on energy conservation among the occupants.

# **CHAPTER ONE**

## **INTRODUCTION**

### **1.1 Background**

Occupants spend most of their life in buildings for work. Optimisation of indoor air conditions is very important to the occupants in buildings especially for nations in hot-humid climates through the year. Air-conditioning and mechanical ventilation (ACMV) system is considered an integral part of a building and play a critical role in providing their functions and maintaining acceptable indoor environmental especially in hot and humid climates. Therefore, the building energy consumption rise year by year regards to intensive requirements to ACMV system. According to International Energy Outlook, 2013, the world energy consumption is expected to increase by 56% from 2010 to 2040, from 524 quadrillion British thermal unit (Btu) to 820 quadrillion Btu, both in industrial countries and particularly in developing countries like Malaysia (U.S Energy Information Administration, 2013). Recently, many researches have been carried out in order to promote energy efficiency and at the same time to maintain or improve indoor air conditions in buildings (Al-Homoud, Abdou et al., 2009; Lakeridou, Ucci et al., 2012; N. Wang, Zhang et al., 2013).

Occupant also plays a significant role in long-term changes in energy consumption, including commercial and residential buildings. Changes in energy consumer behaviour can lead to important savings in energy use. Ouyang and Hokao (2009) conducted a study in urban residential buildings in China to carry out the energy-saving potential by improving occupants' behaviour through energy-saving campaign (Ouyang and Hokao, 2009). The results revealed that the electricity use of

the energy-saving educated households can save more than 10% on the average compared to the common households. Another study also made clear that changing energy related behaviour can potentially save about 19% of energy consumption (Uitdenbogerd, Egmond et al., 2007). Kwong and Ali (2011) believe that tropical buildings have a great potential in energy efficiency improvement and suggested that more detail studies can be conducted in such area by focusing on thermal and other environmental comfort parameters and applying field surveys, energy audits, software simulation, etc. (Kwong and Ali, 2011).

Energy management is the most efficient way to conserve and reduce energy usage. Capehart, Turner et al. (2006) defined energy management as the judicious and effective use of energy to minimise costs and enhance competitive positions (Capehart, Turner et al., 2006). The main objective of energy management is to minimise costs, followed by few sub-objectives including: 1) to improve and reduce energy use; 2) to develop and maintain effective monitoring, reporting, and management strategies for wise energy usage; 3) to encourage people to conserve energy. Sekhar et al. (2003) have conducted an integrated indoor air quality (IAQ)-energy audit in five air-conditioned office buildings in Singapore (Sekhar, Tham et al., 2003). The results revealed that the air temperature measured in the buildings was in the lower range of recommended guideline in Singapore, and raising the air temperature set-point could provide an energy saving potential.

From the above mentioned facts, it can be said that the energy management in buildings is an interaction between energy consumption, indoor air conditions and occupant behaviour in terms of knowledge, attitude and practices (KAP) as shown in Figure 1.1. In fact, good energy behaviour and appropriate indoor air conditions in a

building can improve the energy conservation, which lead to ideal energy management in a building.

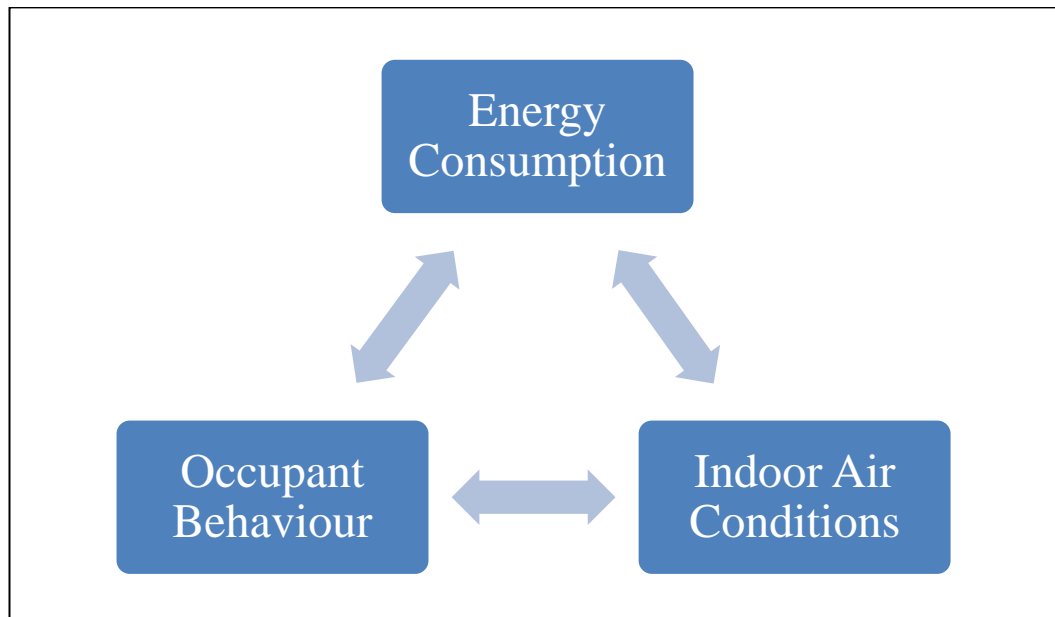


Figure 1.1 Interaction between energy consumption, indoor air conditions and occupant behaviour for buildings energy management

## 1.2 Problem Statements

Recently, energy consumption of buildings has been one of the major issues of concern in the world. It can be seen by the dramatic addition of the research and work on the building energy conservation among these developed countries like United States (Dalamagkidis, Kolokotsa et al., 2007), Australia (Ahmed, Muttaqi et al., 2012), Japan (Suzuki and Oka, 1998), Singapore (Chua and Chou, 2010) and etc, also in developing countries such as Malaysia (Moghimi, Mat et al., 2011), Thailand (Pantong, Chirarattananon et al., 2011) and China (Xudong, Ran et al., 2010). Buildings located in hot-humid climate zone are heavily dependent on air-conditioning system to provide a comfortable indoor environment for the occupants in the buildings. Due to the hot weather and occupant's comfort, the intensive requirement of air-conditioning system is likely to arise and become major energy consumer in the buildings in hot-humid climate. Therefore, air-conditioning and

mechanical ventilation system is considered as a key role for energy consumption in buildings in hot-humid climate (J. C. Lam, Chan et al., 2004; Saidur, 2009).

The sustainable development of energy stratagem in the existing buildings is very limited and the advanced technologies on energy saving might be unable to apply due to the buildings' structure. Few studies conducted in Malaysia, stated that most of the buildings are still in their original condition but being fitted with electricity, water as well as air-conditioning system. However, some of the buildings were upgraded or refurbished to a more advanced service system, which usually results in high energy consumption. This is due to the fact that buildings services are normally fitted based on the functional needs without taking any consideration of energy efficiency programme (Kamaruzzaman, Edwards et al., 2007; Kamaruzzaman and Sulaiman, 2011). Eventually, based on the results of previous works, change in occupant's behaviour is the most efficient and cost saving method to reduce energy used in the buildings (Al-Mumin, Khattab et al., 2003; Z. Yu, Fung et al., 2011). Most studies were focused on energy behaviours survey on residential sector and very few researches carried out on the commercial sector (Al-Mumin, Khattab et al., 2003; Kang, Cho et al., 2012; Nisiforou, Poullis et al., 2012).

For this reason, investigation at a more detailed level of energy behaviour and conservation on office buildings in hot-humid climate is needed to meet the high expectations for energy saving in the future. It is therefore important to obtain more knowledge on the energy consumption related part of the indoor air conditions and energy behaviours in order to understand the impact on each other towards better energy management.



### **1.3 Research Objectives**

- a) To determine and evaluate indoor air conditions in closed and open air-conditioned office rooms in hot-humid climate.
- b) To determine and analyse energy consumption, energy trends and occupants' perception on indoor air conditions in air-conditioned office rooms in hot-humid climate.
- c) To determine the relationship between energy consumption and outdoor climatic conditions in hot-humid climate.

### **1.4 Scope of Research**

This study focuses on the indoor air conditions and energy consumption in air-conditioned office buildings in a tertiary educational institution in Pulau Pinang. Measurements of 30 air-conditioned office rooms with various sizes were divided into two categories: closed office and open office, conducted for eight hours continuously for four months. In this study, data of indoor air conditions in terms of temperature, relative humidity, air velocity and carbon dioxide concentration were collected using portable data logging system and energy consumption data was obtained from electricity meter which is connected to Building Automation System (BAS) in the selected buildings. In addition, the occupants' perception and energy trend was analysed by conducting questionnaire survey in order to examine the building energy saving potential.

### **1.5 Significance of Research**

This research contributes to the assessment of indoor air conditions, energy behaviour and usage to understand the energy consumption trends in air-conditioned

office rooms in hot-humid climate zone. This research is expected to serve as a pilot application that would produce specific guidelines for the application of indoor air condition and energy measures in air-conditioned office buildings in hot-humid climate zone in the future. Besides, it provides a quantitative measurement of energy consumption and outdoor climatic conditions in order to understand the relationship between the two terms. In addition, it also presents factors that contribute to building energy consumption in order to promote sustainability energy management in office buildings in hot-humid climate zone.

## **1.6 Thesis Outline**

Chapter One presents the background of the research, problem statement, research objectives, scope and significance of research. Chapter Two reviews the studies of indoor air condition and energy performance in air-conditioned office buildings. The issues highlighted in this chapter include the current study of indoor air conditions and energy consumption in buildings. This chapter also discusses the current standards and guidelines for indoor air condition and energy consumption in buildings. Chapter Three outlines the research methodology. It describes the selection of office rooms, the demographic of the occupants, method of data collection and data analysis.

Chapter Four shows the variation of indoor air conditions in 30 selected air-conditioned office rooms and relationship between the indoor air conditions and outdoor climatic condition. It also covers the occupant's perception on indoor air condition and the parameters of indoor air conditions are compared to the existing standards and guidelines. Chapter Five details the energy consumption of the case study buildings. It describes the energy used and occupants' energy trend in the

buildings. Chapter Six concludes the research with summary of the main objectives and recommendations for future study.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

#### **2.1 Background**

Indoor air conditions in office buildings are very important, because most people spend most of their time in buildings. Malaysia, being hot and humid all through the year with average temperatures of 27 °C caused the occupants in buildings to need optimal indoor air conditions to stay comfortable (Zhang and Niu, 2003). The majority of buildings in Malaysia are served by several air-conditioning systems in order to obtain good occupants' comfort in the buildings (Zain, Taib et al., 2007). Many studies have pointed out that air-conditioning and mechanical ventilation (ACMV) system is the largest sector energy consumer in buildings (Aziz, Zain et al., 2012; Joseph C. Lam, Li et al., 2003) and found that the intensive requirement of air-conditioning system has led to increased energy demand in buildings year by year. To overcome these issues, overview of energy usage in buildings is necessary by conducting a determination of indoor air condition and actual energy consumption to achieve better management for energy conservation in buildings.

#### **2.2 Indoor Air Conditions in Air-conditioned Buildings**

Indoor air conditions are dependent on time-dependent variables such as indoor air temperature, indoor air humidity, indoor air velocity, carbon dioxide concentration, and rate of air ventilation. Some of these variables can be regulated by the ACMV system and occupant's activity (Lakeridou, Ucci et al., 2012; Theodosiou and Ordoumpozanis, 2008). The indoor air conditions are usually the most important

in buildings for providing comfortable environment to the occupants. Because of the importance to occupants' comfort, significant studies have been carried out to maintain and improve the indoor air conditions in buildings.

### **2.2.1 Indoor Temperature**

Indoor temperature refers to the average value of the temperature in space and time in an occupied zone (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2004). Many studies have been conducted related to indoor temperature in air-conditioned office room (Busch, 1992; Cheong and Chong, 2001; Mui and Wong, 2007). The results revealed that indoor temperature in air-conditioned office rooms mostly fall in the range of 22°C to 24°C. Although the indoor temperatures are compliant with indoor air quality (IAQ) standards, where the acceptable range of indoor temperature is between 20°C to 28°C, Dear, Leow et al. (1991) and Cheong and Chong (2001) stated that many occupants experienced cool thermal comfort sensations in the air-conditioned buildings (Cheong and Chong, 2001; Dear, Leow et al., 1991). There are many factors that affect indoor temperature, such as air-conditioning system (Busch, 1992), occupation density (Theodosiou and Ordoumpozanis, 2008), and outdoor climatic conditions (J. L. Nguyen, Schwartz et al., 2014). Several studies indicated that increasing indoor temperature may cause the occupants to suffer eye irritation symptoms, fatigue and headache (Mendell, Fisk et al., 2002; Mizoue, Andersson et al., 2004).

### **2.2.2 Indoor Relative Humidity**

Relative humidity (RH) defines how much moisture the air contains in percent of the air's capacity at the same temperature. In general, relative humidity is

inversely proportional to air temperature; if one holds absolute humidity constant, relative humidity decreases as air temperature increases and vice versa (Bencloski, 1982). Many studies have been carried out which are related to indoor relative humidity in air-conditioned office rooms (Cheong and Chong, 2001; Mui and Wong, 2007). The results revealed that indoor relative humidity in air-conditioned office rooms mostly fall in the range of 50% to 65% which is compliant with most of the indoor air quality (IAQ) standards. There are many factors that can affect the indoor relative humidity, such as air-conditioning system, humidity control system (Mathews, Botha et al., 2001; Qi and Deng, 2009), occupants' activity (Theodosiou and Ordoumpozanis, 2008) and outdoor climatic conditions (J. L. Nguyen, Schwartz et al., 2014). According to Sykes (1989), low relative humidity ( $\leq 30\%$ ) can dry out the mucous membranes and irritate the eyes and skin; high relative humidity ( $\geq 80\%$ ) encourages the growth of allergenic microorganisms and also causes dampness in the buildings which can lead to mould in the construction (Sykes, 1989).

### **2.2.3 Indoor Air Velocity**

Air velocity can be experienced either as draft sensation or may lead to improved thermal environment under warm conditions. It may occur due to forced air movement such as open/close window and door or ventilation system. Therefore, indoor air velocity is considered one of the most difficult environmental parameters to measure accurately and need precise data logger to record as it is a highly variable parameter and can have more than one direction. Many studies have been carried out related to indoor air velocity in air-conditioned office rooms (A. Chen and Chang, 2012; Yamtraipat, Khedari et al., 2005). The results revealed that indoor air velocity in air-conditioned office rooms mostly varied in the range of  $0.1 \text{ m s}^{-1}$  to  $0.25 \text{ m s}^{-1}$

which is compliant with most of the IAQ standards. The indoor air velocity in the office rooms, where resulting from forced ventilation system such as exhaust fan and occupants' activities have significant impact on indoor air quality and occupants' comfort. Previous studies have shown that the elevated air movement resulted by ceiling fan significant improve the occupants' comfort and energy efficient in buildings (Arens, Zhang et al., 2013; Zhai, Zhang et al., 2015).

#### **2.2.4 Carbon Dioxide Concentration**

Carbon dioxide is a natural component of air which is colourless and odourless. Human breath is the main source of carbon dioxide in the buildings and the average breath of an adult contains 35,000 ppm – 50,000 ppm (Gruber, Trüschel et al., 2014; Prill, 2000). Carbon dioxide concentration in office rooms changes with time depending on occupancy, room size, ventilation system and outdoor carbon dioxide concentration (A. Chen and Chang, 2012; Chuah, Fu et al., 1997). Many studies have been carried out in relation to carbon dioxide concentration in air-conditioned office rooms (Cheong and Chong, 2001; Sekhar, Tham et al., 2003). The results revealed that carbon dioxide concentration in air-conditioned office rooms mostly varied in the range of 450 ppm to 800 ppm which is compliant with most of the IAQ standards. Carbon dioxide may not be considered to pose serious threat to human health, yet it is often measured when trying to determine the indoor air quality of a building. However, it has been reported that high level of carbon dioxide concentration (exceeded than 1000 ppm) could cause headaches, throat and nose ailments, lack of concentration, tiredness and fatigue (Heudorf, Neitzert et al., 2009; Seppänen, Fisk et al., 1999).

Many studies claimed that carpet in office room was identified as one of the factors unsatisfactory indoor air quality and caused sick building syndrome (Norbäck and Torgén, 1989; Skov, Valbjørn et al., 1990; Sykes, 1989). This is because the carpet in an air-conditioned office room could provide an environment with enough moisture to sustain fungal growth and the amount of growth produce large carbon dioxide emissions (Kemp, Neumeister-Kemp et al., 2002).

### **2.3 Existing Standards on Indoor Air Conditions**

The standard indoor air conditions in building can prevent poor indoor air quality (IAQ) and also improve the occupants' comfort. Many nations have IAQ standards and guidelines to help occupants in buildings to minimise or eliminate the negative impacts of indoor air condition. Table 2.1 shows the indoor air quality standards of different nations, including: 1) Department of Occupational Safety and Health (DOSH), Malaysia; 2) Singapore Indoor Air Quality Guideline (SIAQG) in Singapore; 3) Hong Kong Special Administrative Region (HKSAR), Hong Kong; 4) American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE); and 5) Administration of Quality Supervision, Inspection and Quarantine (AQSIQ). From the table, it can be seen that most of the standards suggest that the comfortable range of indoor temperature for occupants is between 23 °C and 26 °C except for HKSAR and AQSIQ. The acceptable range of indoor temperature is between 20 °C to 25.5 °C for HKSAR standards and the range of 22 °C to 28 °C for AQSIQ standards. Besides, DOSH and HKSAR recommend that the acceptable range of indoor relative humidity is between 40 to 70% and SIAQG accepts 70% as maximum limit of indoor relative humidity. ASHRAE accepts only in the range of 40 to 60% for indoor relative humidity and AQSIQ prefers in the



range of 40 to 80% as the acceptable indoor relative humidity. For indoor air velocity, there was an obvious difference between the standards. SIAQG and ASHRAE accept the indoor air velocity below  $0.25 \text{ m s}^{-1}$  and AQSI recommends that  $0.3 \text{ m s}^{-1}$  is maximum limit for the indoor air velocity. HKSAR disallows the indoor air velocity from exceeding  $0.2 \text{ m s}^{-1}$  and DOSH has a greater acceptable range of indoor air velocity among the standards, with the range in between  $0.15 \text{ m s}^{-1}$  to  $0.5 \text{ m s}^{-1}$ . All five standards accept the indoor carbon dioxide concentration with the limit of 1000 ppm.

**Table 2.1 Indoor air quality standards of different nations**

Standard, Location	Temperature <sup>a</sup>	Relative Humidity <sup>a</sup>	Air Velocity <sup>a</sup>	CO <sub>2</sub> <sup>b</sup>	Reference
Acceptable range					
DOSH, Malaysia	23 to 26°C	40 to 70%	0.15 – 0.5 m s <sup>-1</sup>	1000 ppm	(Department of Occupational Safety and Health, 2010)
SIAQG, Singapore	22.5 to 25.0°C	≤ 70%	≤ 0.25 m s <sup>-1</sup>	1000 ppm	(Institute of Environmental Epidemiology, 1996)
HKSAR, Hong Kong	20 to 25.5°C	40 to 70%	< 0.2 m s <sup>-1</sup>	1000 ppm	(The Government of the Hong Kong Special Administrative Region, 2003a)
ASHRAE, US	23.0 to 26.5 °C	40 to 60%	≤ 0.25 m s <sup>-1</sup>	1000 ppm	<sup>a</sup> (American Society of Heating Refrigerating and Air- Conditioning Engineers, 2004) <sup>b</sup> (American Society of Heating Refrigerating and Air- Conditioning Engineers, 1989)
AQSIA, China	22 to 28 °C	40 to 80%	≤ 0.3 m s <sup>-1</sup>	1000 ppm	(Administration of Quality Supervision, 2002)

## 2.4 Energy Consumption in Buildings

Energy plays a vital role as a source of activities in buildings. Literatures have shown that building sector consumed a significant percentage of national energy consumption as it accounts for 21% to 41% of total energy consumption (H. M. Chen, Lin et al., 2012; Kong, Lu et al., 2012; T. A. Nguyen and Aiello, 2013; Perez-Lombard, Ortiz et al., 2008; Spyropoulos and Balaras, 2011; Yau and Hasbi, 2013). Table 2.2 shows that the final electricity consumption for each sector in

Malaysia in the year 2003 to 2013. From Figure 2.1, it can be seen that the electricity used in Malaysia increases rapidly as the energy demand increases almost 68% within the last decade (Malaysia Energy Information Hub, 2013). From the report, residential sector has the highest increment of final electricity consumption among all the other sectors, which increased by 98.67% from 2003 to 2013. This is followed by commercial sector which increased by 90.65%. In addition, the energy demand of commercial and residential sector is forecasted to increase approximately 6.46% per year.

Table 2.2 Final electricity consumption for several sectors in Malaysia

Year	Final Electricity Consumption (ktoe)					
	Agriculture	Commercial	Transport	Industrial	Residential	Total
2003	0	1818	5	3242	1248	6313
2004	0	1979	5	3340	1319	6643
2005	0	2172	5	3371	1395	6943
2006	5	2272	5	3475	1515	7271
2007	16	2480	4	3587	1598	7685
2008	19	2598	15	3687	1668	7989
2009	21	2743	12	3719	1792	8287
2010	24	3020	18	3994	1937	8993
2011	26	3172	18	4045	1974	9235
2012	30	3325	21	4509	2126	10011
2013	32	3466	21	4809	2262	10590

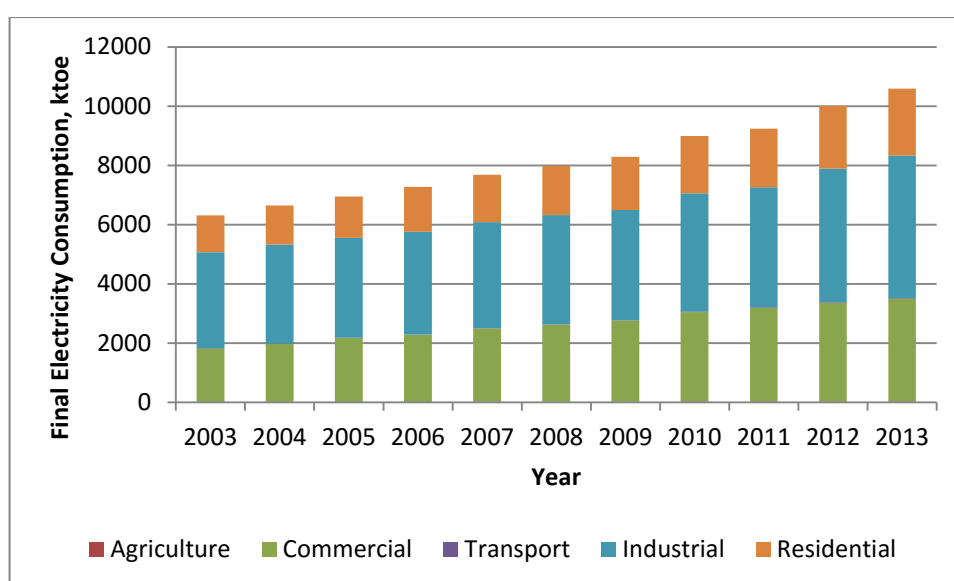


Figure 2.1 Final electricity consumption in Malaysia

(Source: Suruhanjaya Tenaga, Electricity - Final Electricity Consumption)

To better understand the energy conservation, it is important to analyse where and when energy is being used in the buildings. Energy used in office buildings can be categorised into two types: 1) energy for the maintenance/servicing of a building during its useful life such as air-conditioning and mechanical ventilation (ACMV) system, vertical transportation service like lift, and artificial lighting system in common areas including corridor, office area, and other service areas; 2) energy for occupant that goes into artificial lighting, office equipment like desktops/laptops, printers, fax machines etc. Literatures have revealed that ACMV consumed the most energy in buildings and followed by lighting system and office equipment (J. C. Lam, Chan et al., 2004; Mathews, Botha et al., 2001; Spyropoulos and Balaras, 2011).

#### **2.4.1 Factors Contributing to Energy Consumption**

##### ***Air-conditioning & Mechanical Ventilation (ACMV)***

Air-conditioning & Mechanical Ventilation (ACMV) system is responsible for about 30% to 55% of total energy consumption in building and it is essential in maintaining good thermal condition for building occupants (Al-Abidi, Bin Mat et al., 2012; Fasiuddin and Budaiwi, 2011; Mathews, Botha et al., 2001; T. A. Nguyen and Aiello, 2013; Perez-Lombard, Ortiz et al., 2008; Spyropoulos and Balaras, 2011; Yau and Hasbi, 2013). However, Dear, Leow et al. (1991) has found that indoor air conditions in air-conditioned office buildings in Singapore were overcooled (Dear, Leow et al., 1991) and it could lead to energy waste in buildings. Therefore, many studies have been carried out regarding the factor contribution of ACMV system by selecting the indoor air conditions in order to minimise the building energy consumption. Wan, Yang et al. (2009) showed the minimum energy consumption of air-conditioning system can be achieved by lower indoor temperature and elevate

indoor relative humidity (Wan, Yang et al., 2009). Similarly, Ge, Guo et al. (2013) found that the energy consumption of the buildings in China can be reduced by about 5.20% to 6.20% increasing indoor temperature by 1°C under the same level of relative humidity (Ge, Guo et al., 2013).

Besides, Japan developed 'Inverter Technology' in air-conditioning system in order to conserve energy. The inverter technology is used to control the speed of compressor motor to drive variable refrigerant flow in an air-conditioning system to continuously regulate the operate temperature. In contrast traditional air-conditioning system have fixed speed compressor and refrigerant flow rate as per cooling requirement of the room and work at one given capacity only. Therefore, variable speed of the compressor ensures not only better temperature control but they also reduces power consumption by up to half (Ohyama and Kondo, 2008).

### ***Lighting System***

Lighting system is also considered as one of the important factors to building energy consumption and it contributes generally 20% to 35% of total building energy consumption (Aziz, Zain et al., 2012; J. C. Lam, Chan et al., 2004; Mathews, Botha et al., 2001; Saidur, 2009; Spyropoulos and Balaras, 2011). Literatures have shown that lighting energy consumption in buildings is heavily dependent on occupant behaviour (Dubois and Blomsterberg, 2011; Yun, Kim et al., 2012; Yun, Kong et al., 2012). Yun, Kong et al. (2012) suggested that minimum energy consumption in buildings can be achieved by changing the occupant behavioural patterns of lighting use.

Fluorescent lamps were established after the Second World War and are still widely in use as a lighting source (Schanda, 2005). Fluorescent lamps work by

ionizing mercury vapour in a glass tube. This causes electrons in the gas to emit photons at UV frequencies. The UV light is converted into standard visible light using a phosphor coating on the inside of the tube (Tan and Li, 2014). Compared to traditional light source, energy-efficient lightbulbs such as light emitting diodes (LEDs) has the following benefits: 1) Consume less power, with energy saving up to 70% ; 2) Can last up to 25 times longer (Ryckaert, Smet et al., 2012). A study conducted in Malaysia showed that a significant reduction in annual energy consumption can be accomplished by replacing traditional lighting source to LED lamps (Khorasanizadeh, Parkkinen et al., 2015).

### ***Office Equipment***

Office equipment such as desktop, printer, fax machine and photocopy machine can easily be found in an office building. Office equipment are the fastest growing energy user in office buildings, consuming significant amount of total building energy consumption which it accounts for 17% to 25% of total building energy use (J. C. Lam, Chan et al., 2004; Mathews, Botha et al., 2001; Saidur, 2009; Spyropoulos and Balaras, 2011). Moorefield, Frazer et al. (2011) conducted a monitoring study in 25 offices in California and the results have found that desktops contributed the most energy use of office equipment energy consumption in office (Moorefield, Frazer et al., 2011). Besides, Mungwititkul and Mohanty (2006) and Webber et al. (2006) have found that energy wastage of office equipment in buildings was influenced greatly by user behaviour (Mungwititkul and Mohanty, 1997; Webber, Roberson et al., 2006).

Due to high energy demand of office equipment in office buildings, the energy-efficient programme, Environmental Protection Agency (EPA)'s Energy Star

was announced during the summer of 1993 in United States. The purpose of this programme is to let public easily identify the products especially office equipment, which meet strict energy efficiency guidelines set by the US EPA (Koomey, Piette et al., 1996). A study conducted in United State showed that Energy Star labelled products especially office equipment such as monitors and computers has been successful in reducing energy usage and carbon emission (Sanchez, Brown et al., 2008).

### ***Occupant Behaviour***

Since people spend most of their lifetime in buildings, a good and comfortable indoor environment is important for occupants' productivity and well-being. There are three basic factors that determined the quality of life in buildings: Indoor air quality (IAQ), thermal comfort and visual comfort (Dounis and Caraiscos, 2009). These three factors are mostly influenced by air-conditioning & mechanical ventilation (ACMV) system and lighting system. Therefore, a proper and high-efficient ACMV system and lighting system can improve buildings' energy consumption and occupants' comfort. However, during building operation, the interactions between the occupants and the indoor air conditions always have a direct influence on the systems' performance. For example, occupants may turn the light on or off, or change the temperature set point of ACMV system. Hence, it can be seen that the occupants are considered as the main factor that influences the energy consumption in the buildings (Ouyang and Hokao, 2009; Saelens, Parys et al., 2011).

#### **2.4.2 Energy Consumption and Carbon Dioxide Emission**

Recently, carbon dioxide (CO<sub>2</sub>) emission has gained a lot of attention in the world to the issue of reduction of CO<sub>2</sub> emission in order to slow down global warming (Liu, Mao et al., 2015; Oshiro and Masui, 2015; Suzuki and Oka, 1998; Yan and Fang, 2015). As mentioned above, building sector is the largest energy consumed and equally important source of CO<sub>2</sub> emission. The most common way to produce energy is to burn fossil fuels such as coal, petroleum and natural gases, and the burning process releases greenhouse gases like CO<sub>2</sub> into the atmosphere. In other words, CO<sub>2</sub> emission and energy consumption are closely linked together. Building energy consumption increases with the improvement in lifestyle and urbanisation process. It is forecasted that the energy demand of buildings in Malaysia will increase 6.46% per year (Malaysia Energy Information Hub, 2013). Thus, CO<sub>2</sub> reduction in building sector is believed to be one of the important issues in dealing with global warming.

#### **2.4.3 Building Energy Consumption and Building Energy Index**

Building energy index (BEI) shows amount of total energy usage for annual in building in kilowatt hours (kWh) which is divided by the gross floor area (GFA) of building in square meters (m<sup>2</sup>) (Moghimi, Mat et al., 2011). Aziz, Zain et al. (2012) mentioned in this study that in Malaysia and Singapore the average BEI was around 269 kWh/m<sup>2</sup>/yr and 230 kWh/m<sup>2</sup>/yr respectively (Aziz, Zain et al., 2012). BEI can vary significantly depending on different types of building. A study conducted in hospitals in Malaysia showed that the energy consumption of buildings fall in between 230 to 250 kWh/m<sup>2</sup>/yr (Moghimi, Mat et al., 2011; Saidur, Hasanuzzaman

et al., 2010). Meanwhile, another study conducted in hotel in Portugal showed that the BEI of the hotel was around 446 kWh/m<sup>2</sup>/yr (Gonçalves, Gaspar et al., 2012).

Department of Standard Malaysia revised the Malaysia Standard 1525: Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings (MS 1525) in year 2007 where the BEI should be below 135 kWh/m<sup>2</sup>/yr (Department of Standard Malaysia, 2007).

## **2.5 Relationship Between Outdoor Atmospheric Conditions and Building Energy Consumption**

Many studies have been carried out regarding the impact of outdoor atmospheric conditions on building energy consumption (Ahmed, Muttaqi et al., 2012; Fei and Pingfang, 2009). Fei and Pingfang (2009) studied the relationship between energy consumption of office buildings and outdoor atmospheric conditions in China. The results showed that monthly mean outdoor temperature has a great impact on energy consumption and other outdoor atmospheric variable like relative humidity has insignificant correlation with buildings energy consumption (Fei and Pingfang, 2009). Meanwhile, Ahmed, Muttaqi et al. (2012) examined the impact of climate change on the future electricity demands in Australia. He found that future electricity demand in summer and spring are more sensitive to global warming, resulting extra cooling equipment is needed due to more heating degree days in future and therefore more electricity will be consumed (Ahmed, Muttaqi et al., 2012).

## **2.6 Relationship Between Occupant Behaviour and Energy Consumption**

Occupants in buildings can greatly influence energy usage in different ways. Many studies have been carried out to determine the most valuable activities and behaviours and their impact on energy saving potential (Kang, Cho et al., 2012; T. A.



Nguyen and Aiello, 2013; Nisiforou, Poullis et al., 2012; Yun, Kim et al., 2012). The results showed that user activities and behaviours have large impact on energy consumed in all sectors of buildings and Andersen, Olesen et al. (2007) also pointed out that the occupant behaviour could affect the energy consumption in the buildings and room by up to 324% (Andersen, Olesen et al., 2007). The occupant behaviour may be influenced by many factors such as indoor and outdoor climatic conditions, building construction, general service including lighting and heating, ventilation, and air-conditioning system (Genjo, Tanabe et al., 2005).

## **2.7 Energy Management in Buildings**

In general, energy management in buildings can be classified into two types: 1) awareness/campaign and, 2) technology wise – Building Energy Management System (BEMS). Energy awareness/campaign is the most useful and cheap way to reduce energy usage (Ouyang and Hokao, 2009; Z. Yu, Fung et al., 2011). T.A. Nguyen and Aiello (2013) stated that a clear vision on energy consumption and energy awareness is the key role for proper and timely decision to reduce energy use (T. A. Nguyen and Aiello, 2013). Besides, a study conducted by Ouyang and Hokao (2009) in China showed that sufficient information and campaigns related to energy saving could help the residents to save more than 10% household electricity use (Ouyang and Hokao, 2009). BEMS is an advanced computerisation system for monitoring and controlling the building environment factors such as temperature, humidity, luminance, daily energy usage and etc. BEMS is designed to achieve highest efficiency in energy consumption without compromising occupants' comfort in the buildings (Chaiboonruang, Pora et al., 2014). During building operation, the energy utilities such air-conditioning and mechanical ventilation (ACMV) system,

lighting system and office equipment, etc. may be influenced by occupants or the environment. Therefore, various measurements and control units in buildings are needed to allow BEMS from temporarily deviating from the normal operation status to be corrected back to the ideal status. Many studies about BEMS have been carried out and it was found that significant energy consumption can be reduced in buildings (Jongwoo, Youn Kwae et al., 2014; KyungGyu, Yoonkee et al., 2011).

## CHAPTER THREE

### METHODOLOGY

#### 3.1 Description of Location

Pulau Pinang, located between 05 °35' 02" - 05 °07' 23" N and 100 °10' 33" - 100 °33' 02" E, is a state of Malaysia, hot-humid climate zone country. Pulau Pinang is composed of two parts - island and mainland. However, being an island, the atmospheric temperature is often higher than the mainland, reaching as high as 38°C during daytime. In general, the range of atmospheric temperature is between 29°C to 38°C during daytime and 24°C to 28°C during night time (Makaremi, Salleh et al., 2012). The air-conditioned rooms of three office buildings in tertiary educational institution in Pulau Pinang were selected in this research work. The reasons of choosing these buildings are due to accessibility and suitability. The buildings are located at 05 °21' 20" N, 100 °17' 49" E and denoted as A in Figure 3.1.

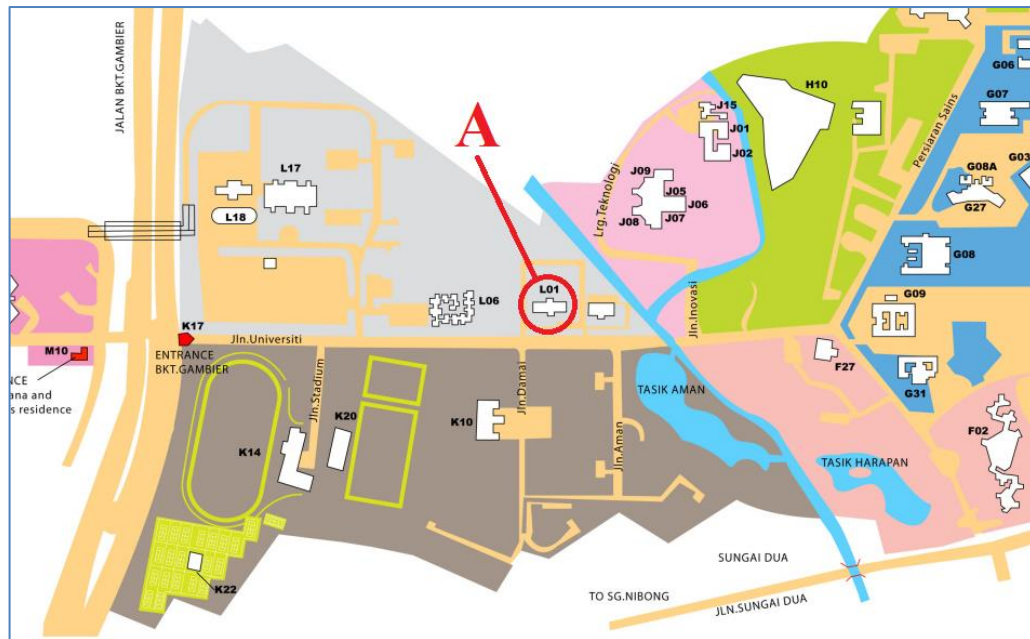


Figure 3.1 Location plan of the case study

Basically the buildings can be categorised into three sectors which are Engineering Sector, Furniture Sector and Workshop Sector. A main building which owned by the Engineering Sector is a double-storey building and the two single-storey buildings are owned by the Furniture Sector and Workshop Sector. Due to accessibility and room characteristics, 30 selected rooms were chosen to conduct the case study in three buildings. The buildings operate five days a week and the working time is from 8:00 AM to 5:00 PM. Table 3.1 shows the room characteristics in terms of type of room, gross floor area (GFA), type of air conditioning system, type of forced ventilation system and number of occupant for 30 selected rooms.

There are two types of office room in the buildings; 1) Closed office rooms and 2) Open office rooms. The closed office rooms are occupied by only one person, and most of the rooms are served by a standalone air-conditioning system except Room A1, A5 and A6, which are served by a centralised air-conditioning system. The open office rooms are occupied by two and more persons and most of the rooms are served by a centralised air-conditioning system except Room B10, D2, D3, D4 and D5, which are served by a standalone air-conditioning system. Woven carpet found in the office rooms except Room D4 and D5 which used ceramic mosaic and cement as flooring. The total gross floor area of the three buildings is approximately 3000 m<sup>2</sup>. There were three types of air-conditioning system found in the buildings; 1) centralised air-conditioning system 2) window type air-conditioner and 3) split type air-conditioner, as shown in Figure 3.2 to 3.4. Besides, forced ventilation systems such as a standing fan and exhaust fan were found in certain office rooms. Figure 3.5 to Figure 3.8 illustrate the layout plan and location of each measuring point. Figure 3.5 shows the selected sampling points which indicated as A1 to A13 and Figure 3.6 illustrates the selected rooms which are indicated as B1 to B11. Figure 3.7 presents