FEASIBILITY OF AN AIR-TO-AIR ENERGY RECOVERY SYSTEM FOR BUILDING IN HOT-HUMID ENVIRONMENT

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by

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HVAC	Heating, Ventilation and Air-Conditioning
SBS	Sick Building Syndrome
IEA	International Energy Agency
AC	Air Conditioning
TWh	Terawatt hours
ε	Efficiency
q	Recovered Energy
CO_2	Carbon dioxide
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
BES	Building Energy Simulation
CFD	Computational Fluid Dynamic
HERV	Heating and Energy Ventilator
ERV	Energy Recovery Ventilator
ASHRAE	American Society of Heating, Refrigerating, & Air-Conditioning Engineers
AHRI	Air-Conditioning, Heating & Refrigeration Institute
ANSI	American National Standards Institute
IAQ	Indoor Air Quality
TRNSYS	Transient System Simulation
HHCC	Two heat exchanger with cooling coil
HCC	One heat exchanger with cooling coil
COP	Coefficient of Performance

PHE	Plate Heat Exchanger
PVDF	Polyvinylidene fluoride
PES	Polyethersulfone
DC	Direct Current
V	Voltage
A	Ampere
IS	Indoor Space
IR	Insulated Room
T_{in}	Intake air temperature
T_{su}	Supply air temperature
T_{re}	Return air temperature
T_{ex}	Exhaust air temperature
T_{IS}	Indoor space's temperature
T_{IR}	Insulated room's temperature
RH_{in}	Intake relative humidity
RH_{su}	Supply relative humidity
RH_{re}	Return relative humidity
RH_{ex}	Exhaust relative humidity
RH_{IS}	Indoor space's relative humidity
RH_{IR}	Insulated room's relative humidity
PTFE	Polyetrafluoroethylene
ε_{sen}	Sensible efficiency
ε_{lat}	Latent efficiency
ω_{in}	Intake of humidity ratio
ω_{su}	Supply of humidity ratio

ω_{re}	Return of humidity ratio
ε_{tot}	Total efficiency
H_{in}	Intake of enthalpy
H_{su}	Supply of enthalpy
H_{re}	Return of enthalpy
q_{sen}	Sensible recovered energy
q_{lat}	Latent recovered energy
q_{tot}	Total recovered energy
M_{a1}	Mass flow rate of air
Cp_{a1}	Specific heat of air
h_{fg}	Enthalpy of evaporation (kJ/kg)
ΔT	Temperature difference
$\Delta\omega$	Humidity ratio difference
H_{IS}	Enthalpy of air in indoor space
DEFRA	Department for Environment, Food & Rural Affairs
DECC	Department of Energy & Climate Change
GHG	Greenhouse Gaseous
TNB	Tenaga Nasional Berhad
SESCO	Sarawak Electricity Supply Corporation
SESB	Sabah Electricity Sdn.Bhd
V_{in}	Intake air velocity
Q_{in}	Intake volumetric flow rate
RM	Ringgit Malaysia

KEBOLEHLAKSANAAN SISTEM PEROLEHAN SEMULA TENAGA UDARA-KE-UDARA UNTUK BANGUNAN DI PERSEKITARAN PANAS-LEMBAP

ABSTRAK

Aplikasi sistem perolehan semula tenaga udara-ke-udara sebagai salah satu teknologi cekap tenaga yang membantu sistem penghawa dingin tradisional dalam bangunan telah mendapat perhatian sejak kebelakangan ini kerana potensinya dalam penjimatan tenaga. Sistem perolehan semula tenaga udara-ke-udara yang direka dalam kajian ini menggunakan jenis plat tetap yang diperbuat daripada membran polimer hidrofilik dan dilengkapi dengan konfigurasi aliran silang untuk membantu penghawa dingin. Matlamat utama kajian ini adalah untuk mengkaji prestasi sistem perolehan semula tenaga udara-ke-udara berdasarkan keadaan cuaca di luar yang telah direka serta data cuaca yang dikumpul berdasarkan persekitaran panas-lembap. Sebuah kemudahan eksperimen telah direka bentuk untuk menghasilkan semula persekitaran panas lembap yang biasa dalam keadaan udara di luar dan dalam bangunan berkait dengan suhu serta kelembapan relatif. Unit ini kemudiannya diuji di bawah syarat-syarat operasi yang seimbang, yang lazimnya digunakan dalam aplikasi. Pada bahagian pertama, pengaruh parameter seperti aliran udara pada (1.0 hingga 3.0 m/s), suhu udara pada (28°C, 31°C, 35°C dan 40°C) serta kelembapan relatif pada (70%, 75%, 80%, 85% dan 90%) telah diuji di bawah keadaan berbeza bagi mengkaji prestasi sistem tersebut. Manakala, dalam bahagian kedua sistem telah diuji menggunakan data cuaca yang telah dikumpul di lokasi-lokasi terpilih, yakni Pulau Pinang, Kuala Lumpur, Kuching dan Kota Kinabalu dengan ketetapan aliran udara pada 2.0 m/s lalu diperkenalkan ke dalam sistem. Prestasi sistem tersebut telah diukur dalam bentuk kecekapan serta tenaga yang diperoleh. Kesan pengaruh parameter berdasarkan

keadaan cuaca luar yang telah direka terhadap prestasi sistem mendapati kecekapan sistem menurun apabila kadar aliran udara meningkat. Peningkatan kadar aliran udara menyebabkan peningkatan tenaga yang diperoleh. Kesan suhu udara (T_{in}) pada sistem menunjukkan bahawa peningkatan suhu udara (T_{in}), nilai kecekapan serta tenaga yang diperoleh turut meningkat. Kesan kelembapan relatif pada sistem menunjukkan penurunan kecekapan apabila nilai kelembapan relatif bertambah. Selain itu, apabila kelembapan relatif meningkat, nilai tenaga yang diperoleh kekal pada jumlah yang sama. Manakala, prestasi sistem perolehan semula tenaga udara-ke-udara berdasarkan data cuaca yang dikumpul, mencatatkan jumlah kecekapan haba deria (ε_{sen}) dan kecekapan haba pendam (ε_{lat}) yang maksimum masing-masing dicapai pada 45% dan 42% di Pulau Pinang pada keadaan 29.69°C dan 84.63%. Nilai tenaga yang diperoleh tertinggi telah dicatat di Pulau Pinang sebanyak 656 W pada keadaan 30°C dan 80%, Daripada data yang diperolehi, anggaran terhadap keupayaan sistem dalam penjimatan tenaga telah dianalisis. Bagi semua lokasi terpilih, lebih kurang 33% daripada penggunaan tenaga dan pembebasan karbon dioksida telah dikurangkan oleh sistem. Selain itu, sistem ini juga mengurangkan kos penggunaan tenaga lebih kurang 47% untuk kemudahan domestik dan 34% bagi kemudahan perdagangan dan industri. Oleh itu, berdasarkan kajian prestasi, sistem perolehan semula tenaga udara-ke-udara mampu diaplikasikan pada bangunan di persekitaran panas-lembap.

FEASIBILITY OF AN AIR-TO-AIR ENERGY RECOVERY SYSTEM FOR BUILDING IN HOT-HUMID ENVIRONMENT

ABSTRACT

Application of an air-to-air energy recovery system as one of the energy efficient technologies that assists with the traditional HVAC system in building application has gained recent attention because of its potential for energy savings. The air-to-air energy recovery system developed in this study employs a fixed plate type of air-to-air energy recovery system made up of hydrophilic polymeric membrane equipped with cross flow configuration designed to assist air-conditioning. The primary goal of this study is to investigate the air-to-air energy recovery system's performance based on the outdoor design air-condition and real weather data collected with respect to the hot-humid environment. An experimental facility was designed to reproduce the chosen typical hot-humid environment in outdoor and indoor air conditions with respect to temperature and relative humidity. Next, the system was tested under stable operation conditions as frequently used in practice. For the first part, the operating parameters which are airflow rates of (1.0 to 3.0 m/s), intake air temperature of (28°C, 31°C, 35°C and 40°C) and intake relative humidity of (70%, 75%, 80%, 85% and 90%) were varied under certain air conditions to investigate the system's performance. Meanwhile, the second part examines the system on collected weather data from selected locations, namely Penang, Kuala Lumpur, Kuching, and Kota Kinabalu with fixed airflow rate of 2.0 m/s, which were then introduced into the system. The system's performance was evaluated in the form of efficiency and recovered energy. The effect of operating parameters based on the outdoor design of air condition denoted that the effect of airflow rate on the system resulted in a decrease in efficiency as the airflow rate increased. The increase of airflow rate causes the

increment in recovered energy. The system indicates that as the intake air temperature (T_{in}) increased, efficiency and recovered energy also increased. Effect of intake relative humidity (RH_{in}) exhibited a decline in efficiency when the intake relative humidity (RH_{in}) increased. Additionally, as the relative humidity increased, the recovered energy of the system remained constant. In terms of air-to-air energy recovery system's performance based on collected weather data, the highest sensible efficiency (ε_{sen}) and latent efficiency (ε_{lat}) were achieved with 45% and 42% in Penang at 29.69°C and 84.63%. The highest total recovered energy (q_{tot}) was recorded in Penang at 656 W with a condition of 30°C and 83%. From the data obtained, estimation on potential energy savings of the system were calculated and analysed. It was found that 33% of energy consumption and carbon dioxide emission were reduced by the system in all selected locations. Besides, it has been expected that air-to-air energy recovery has reduced the cost of energy consumption of about 47% for domestic, and 34% for both commercial and industrial. Hence, based on the performance evaluation, the air-to-air energy recovery system is feasible to be utilized in hot-humid climate for building application.

CHAPTER 1

INTRODUCTION

1.1 Background of the Research

Over the past century, there has been a dramatic increase in energy consumption of the world's energy usage, which has grown to an alarming rate. This phenomenon has resulted in the global increasing pattern in buildings' energy consumption either for residential and commercial, achieve figures between 20% and 40% in developed countries (Fan and Ito, 2012). The main significant contributes to this issues include (1) the increase numbers in population; (2) the need for better comfort levels; (3) the higher demand for building services; and (4) longer duration of time spent by people inside buildings (Chua et al., 2013). Without any precautions taken into consideration, the increasing trend in energy demand will continue to expend in the future. Thus, improving energy efficiency in buildings has become a main objective for global energy policymakers nowadays (Roth, 2013).

Recently, investigators have examined that energy consumption HVAC used either by residential or tertiary sector was accounted about 50% of the total final energy demand (Chua et al., 2013). Energy demand in Southeast Asia for buildings has accounted for about 30% of total final consumption in 2011 (IEA, 2013). The demand was expected to increase due to the rapid growth of energy consumption in line with the rising living standards and urbanisation support for shifting to modern energy sources. Recent evidences by the United States Department of Energy reported that HVAC system in the United States have accounted approximately 20% out of 50% total energy consumption in buildings. Meanwhile, European Union noted that the total final energy consumption was consumed about 57% in residential area primarily for heating purpose (Chwieduk, 2003). Hence, considering buildings' energy from an environmental perspective by implementing less natural resource utilization and reducing the energy consumption and pollution to the environment would be the ideal choices to overcome this phenomenon (Junjie et al., 2010). Due to this circumstance, building engineers have closely examined building thermal insulation and air tightness in building's envelope to isolate their outdoor and indoor environment. In addition, the establishment of new building codes for the year 2000 that requires well insulated and tight buildings. This has resulted in the energy demand for heating from ventilation air and the figures was reach about 60% of the total annual energy demand for the building (Fehrm et al., 2002). Consequently, the increased of energy demand in tight building occurred due to the insufficient of fresher outdoor air to replace the contaminated air, leading to a poor indoor air quality (Li et al., 2007). In modern times, as people spend about 90% of their time indoors, the need in providing comfortable indoor environment for the occupants has highly increased. It is apparent that ventilation is indistinctly related to the energy saving aspects in buildings, however, simply reducing ventilation rates in addition to poor HVAC system maintenance and service have resulted in an unwanted outcomes on the indoor air quality (Laverge et al., 2011; Alvarez et al., 1996). Moreover, many believed that preventing the outdoor air from entering the houses would allow it to maintain cleaner and healthier indoor air. However, according to the United States Environmental Protection Agency (USEPA, 2012), indoor air are more polluted compared to outdoor air. The high accumulation of pollutants could cause health and comfort issues for occupants, leading to Sick Building Syndrome (SBS) (Syazwan et al., 2009; Fang et al., 2004; Norback et al., 1990). Hence, adequate ventilation must be provided for the outdoor air to dilute the emissions of indoor air. For that reason, larger amounts of energy have to be consumed to process ventilation air so that building space conditions will maintain within the comfortable range.

The majority of towns in Southeast Asia have experienced hot-humid climate all the year around. With regard to overcome this problem, installation of the AC unit as a common technical solution to maintain the indoor air quality was done (Lundgren and Kjellstrom, 2013). The findings by Kubota et al., (2011) showed that the average energy consumption on air-conditioning unit was 1.4 larger than without air-conditioning unit. They also claimed that the effective way in achieving energy saving objectives in Malaysia is by reducing the usage of the air-conditioning. Figure 1.1 illustrates the air-conditioning unit approach on the environmental perspective, which concluded that house will become a heat trap without electricity to power up its air conditioning unit. IEA (2013) reported that the electricity demand in Southeast Asia increased from the year 1990 to 2011 about 712 TWh by approximately five factor. As reported in Energy outlook for Asia and the Pacific, it was pointed out that the major usage of electricity is for HVAC system in either residential or commercial (Asia-Pacific Economic Cooperation, 2013). In order to generate electricity in Southeast Asia, the primary energy source is dominated by fossils fuels including the oil, natural gas and coal, which have made up more than three quarters of demand (IEA, 2013). Hence, wise steps and strategies must be taken into considerations to control the depletion of this unrenewable source. Therefore, utilising the air-to-air energy recovery system is essential to overcome this challenge in reducing the load besides providing healthy indoor condition for occupants.

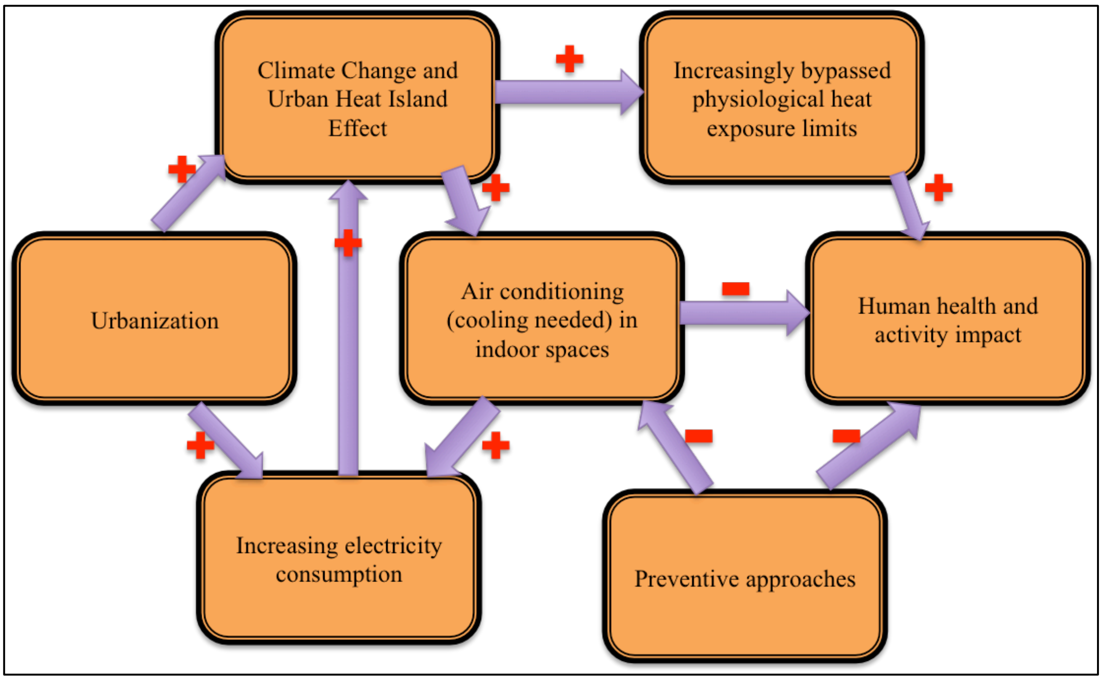

Figure 1.1 Relationship of the air-conditioning towards the environmental perspective (+ increase; - decrease) Source: (Lundgren and Kjellstrom, 2013)

Based on Chwieduk (2003), in order to create an idea of environmentally-friendly building besides from the standard energy conservations solution, innovative technologies must be implemented in the building, which suggested the installment of air-to-air energy recovery system as one of the solutions. The system aids in improving indoor environmental quality, individual health benefits and the economic benefits, thus encouraging the approach of developing sustainable buildings (Chwieduk, 2003). Moreover, air-to-air energy recovery system have shown to help in reducing the air-conditioning demand especially for the tight building by reducing the contribution of total outside air to the air-condition load (Fan, et al., 2014; Hilmersson, & Paulsson, 2006). It has also proven to reduce about 1/3 of annual cooling and heating energy consumption (Dieckmann et al., 2003). Furthermore, a significant amount of energy was recovered by the operating principle of energy recovery systems using the room exhaust air to pre-condition the ambient fresh air, which in return curtail the overall HVAC energy requirement (Nasif et al., 2010). In addition, the implementation of this system is believed to save a enormous amount of thermal load and improve the existing HVAC system that is very energy intensive to remove both sensible and latent loads (Zhang et al., 2008).

1.2 Problem Statements

World energy consumption is growing rapidly due to the increasing energy demand by emerging and developed economies. As a result, the over-reliance on the fossil fuels (coal, oil, natural gas) as primary energy sources has already raised concern over energy supply difficulties, diminishing of energy resources and environmental impacts. As it was identified that building services of HVAC systems account for 50% of the total building energy consumption, hence there is a need to combat this phenomenon. Thus, the air-to-air energy recovery system was introduced as an important component of energy efficient technology in buildings that assists in reducing the energy consumption.

Recent developments of air-to-air energy recovery system has heightened its application of the air-to-air energy recovery system in all types of the building that recognized having the potential in reducing the energy consumption and providing good indoor air quality. However, the latest finding of its application in the hot-humid environment shows contrasting results as there still has been little discussion of the air-to-air energy recovery application in hot-humid environment. This is due to the fact that hot-humid environment are still conventionally using a large amount of electrical energy for cooling system operating purpose (Rasouli, et al., 2013). To date, there have been little agreements on the air-to-air energy recovery system is prevalently designed for cold climate area and also country with both summer and winter season (Roth, 2013). There are also several studies of the system that were carried out in hot-humid environment, however the report found a weakness as it used the complex run-around type of the air-to-air energy recovery system (Hemingson, et al., 2011).

While some studies show that the utilization of the system in reducing the energy consumption eventually give advantage both on the environmental and economic benefits analysis, there is still inadequate studies which pinpointed its application in terms of the effect for both factors especially in the hot-humid environment. A number of researchers have reported the efficient performance of the air-to-air energy recovery system in hot-humid environment(Jadhav, & Lele, 2015), however, the existing account failed to identify whether the study was conducted based on the experimental approach or merely on numerical study.

Therefore in such situation, it is crucial to explore the fixed plate type of air-to-air energy recovery system that could recover or transfer both heat and mass to be used in building application either by experimental outdoor design of air condition or weather data based on hot-humid environment. This research also seeks to obtain data in the aspect of both environment and economic benefits analysis from the investigation of the air-to-air energy recovery system's performance. It is hoped that these findings could give an important contribution to the field of air-to-air energy recovery especially to its application in the hot-humid environment that may offer several important insights on the health, environment and economic aspects.

1.3 Research Objectives

This study focuses on overarching the performance of air-to-air energy recovery system in order to test its applicability in hot-humid climate based on the outdoor design air conditions and weather data. The objectives of this research are

- to develop an air-to-air energy recovery system pertinence in hot-humid environment
- to determine the effects of varying operating parameters on the performance of air-to-air energy recovery system.
- to analyse weather data based on selected hot-humid locations in identifying the applicability of air-to-air energy recovery system.

1.4 Scope of Research

This study involved experimental investigation on the performance of a laboratory scale air-to-air energy recovery system.

This experiment involved a control chamber, an insulated room, a room or indoor space and a unit of air-to-air energy recovery system. Moreover, there were also involvements of several instrumentations to record and obtain the operating parameter readings. Equally important, there were several marked points throughout the system to collect the data at specific locations. For further understanding, the airflow rates ranged from 1.0 to 3.0 m/s, fixed intake temperature of 28°C, 31°C, 35°C and 40°C and intake relative humidity ranged from 70 to 90 % were considered into the system according to the hot-humid weather conditions. Next, the data were calculated and tabulated in term of efficiency (ε) and recovered energy (q) to determine its performance. The air condition in the indoor space is set at 24°C and 54% and insulated room (28°C and 58%) in the study were constant throughout the experimental investigations.

On top of that, feasibility study of the system was performed based on the weather data at selected locations in hot-humid environment. Several locations in Southeast Asia region were chosen in the countries of Malaysia. Kuching and Kota Kinabalu were selected to represent the East Malaysia while Kuala Lumpur and Penang were represented the Peninsular Malaysia located in the west side. The weather data (temperature and relative humidity) were collected for eight (8) hours in three (3) months. Lastly, the performance of the system based on collected weather data was investigated. The calculated data was then tabulated as the same features as mentioned earlier, together with extra information on the energy analysis at chosen locations.

1.5 Significance of Research

This study is in significance of investigating the operating parameters that have effects on the system. The air-to-air energy recovery that has been tested on various conditions by employing hot-humid state indicates several operating parameters that may give effects on the system performance. The various operating parameters could become a baseline before the system being implemented in the actual building and provide useful information for employing the system in buildings that experience hot-humid condition. Besides, the results obtained from this experiment can be used as a guideline for the designation and construction of the air-to-air energy recovery system to be applied in hot-humid climate. The results obtained may affirm the principle of operating parameters theory (airflow rate and intake air conditions) on the system.

In addition, this study offers some important insights into the application of the system for building application in hot-humid environment. It may offer an alternative view or more details explanation on the system in selected countries besides becoming a benchmark for further employment of the system. Furthermore, this study might reveal the application of the system towards the achievement in promoting green buildings and enhance the reduction of energy consumption. This research might contribute to a better understanding on the air-to-air energy recovery system as one of the systems to achieve a better indoor air quality and application of energy efficient technology. Information on the energy analysis by employing this system may expose a better explanation on how the system contributes to the energy conservation in maintaining a good indoor air quality.

1.6 Thesis Overview

The overall structure of this study takes the form of six chapter with the Chapter 1 is first presented. The work in Chapter 2 contains further extend of knowledge, idea, strengths and limitations of the system together with relevant investigations pertaining the air-to-air energy recovery system. It begins by laying out the application of the system in buildings specifically in hot-humid environment. A brief discussion on the system potential in reducing energy consumption using previous works is also including in this chapter. In additional, this chapter also enclosed the theory behind the operation of air-to-air energy recovery system and selective features that had been employ in the proposed system. Furthermore, a review on previous work of air-to-air energy recovery system on the performance parameters was deeply explained to further understand its mechanism.

Chapter 3 outlines the experimental setup as a precursor to all experiments presented in the research. It covers the description of energy recovery unit, experimental setup, experimental measurement and the data analysis method. It also includes instrumentation, procedures with specific conditions to perform the system on the laboratory scale. In addition, several formulas and methods were applied to calculate the efficiency (ε) and recovered energy (q). The data recorded was tabulated into sensible, latent and total enthalpy.

Chapter 4 is concerned with the investigation on the system's performance. Several tests at specific condition were conducted to determine its performance. Factors influencing the system of working performance such as airflow rate and intake air condition were all investigated from experimental results. The fourth chapter ended with the result on the performance analysis that calculated in terms of its efficiency (ε) and recovered energy (q). Furthermore, a brief discussion and explanation were also made to support the results obtained.

Chapter 5 goes into the feasibility studies of the system at selected locations with the specific weather conditions. The weather data on the selected locations were recorded and introduced into the system to investigate its feasibility. The results were then recorded and tabulated in terms of efficiency (ε) and recovered energy (q). Besides, further work on calculated energy analysis was also carried out. The data obtained were then discussed.

Finally, works in Chapter 6 summaries all the results obtained. A number of conclusions were derived from the research. The existing problems of the system were illuminated and several thoughts on further research that stem from the present research are also presented within this chapter. The appendices were also provided for supplementary information.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

This chapter presents a comprehensive study on an air-to-air energy recovery system and its performance parameters. In addition, the extensively employed application of the air-to-air energy recovery system especially in hot-humid environment was discussed. The capability of the system in reducing energy consumption was also included. Furthermore, this chapter also covered theoretical background and the principle operation of the system in hot-humid environment. Selective features in designing the air-to-air energy recovery in this study was also deliberated in this chapter.

2.2 Application of Air-to-Air Energy Recovery System

The global demand of environmental clean energy and shortage of energy resources have led to the development of energy efficient technology in buildings. It has been identified that energy efficient technology in buildings was highlighted in which energy-related CO_2 emissions will be curtailed by 50% in the year of 2050 (International Energy Agency, 2011) besides being served as a regulation or standard to fulfil the energy buildings' codes (Roth, 2013). Hence, recent developments in the field of energy efficient have led to the advancement in innovation and economic that could enhance the design, construction and operation of air-to-air energy recovery as one of the highly energy efficient technologies in buildings that assists in reducing the energy consumption generally for space conditioning (Zhang and Niu, 2001). There is a need of large amount of energy to operate a modern day building, hence it is necessary to design the HVAC system in a building to be as energy efficient as possible. Hence, reducing the amount of electricity or other energy sources that the building consumes can save the energy that is not only important for the environment, but also reduces the cost of running large buildings (Fauchoux, 2006). Besides, Wee et al., (2008) reported that the main source of CO_2 emissions is generated from the combustion of fossil fuels in the power generation and is projected to rise more than 40 billion metric tonnes by 2030. By controlling the electricity generation, air-to-air energy recovery system is believed to reduce electricity consumption in the HVAC system and eventually minimizes the carbon dioxide emission (Moffitt et al., 2012). These conditions indicate that besides saving energy consumptions, air-to-air energy recovery can also help to reduce the carbon dioxide emissions. According to Pavel, (2010), the application of air-to-air energy recovery system basically helps in reducing the energy impacts by 45% besides providing fresh outdoor air to a house. Furthermore, the system also aids in reducing the level of indoor air contamination by providing a consistent and reliable level of ventilation, setting the occupants in control of their indoor air conditions (Fauchox et al., 2007).

Furthermore it have been recognized that the application of air-to-air energy recovery has been widely used in other countries such as China (Zhang, 2012; Kang et al., 2010; Zhou et al., 2007; Liu et al., 2010), Canada (Rafati et al., 2014), Finland (Pavel 2010; Nyman and Simonson, 2005), and Mediterranean region (Jaber and Ajib, 2012). The utilization of the system at various places proved that it is efficient to be used for all types of building application.

For residential buildings types, Kragh (2007) and Nielsen (2009) did an investigation on LCA of residential ventilation units and found that adopting the air-to-air energy recovery system will result in a net positive impact towards the environment. A study carried out by Jaber & Ajib (2012) applied of air-to-air energy recovery system in typical Jordanian residential building resulted that the system can save 16.86% from annual energy demand and reduce LCC by 4.2% by optimum heat transfer area of 11.16 m^2. In addition, an investigation on energy recovery was also carried out focusing on apartment buildings in cold climate (Alonso et al., 2015; Alonso et al., 2013). The researchers stated that energy recovered by both sensible and latent heat utilizes the membrane-based energy recovery are more promising in cold climates.

Meanwhile, for installation in commercial buildings types, further work has been carried out for the application of air-to-air energy recovery in a supermarket at China during winter season (Kang et al., 2010). It was found that latent heat is not suitable for ventilation energy saving in the region due to the internal moisture emissions that are already high, similar with the study done by Zhang (2014), which stated that latent heat are less important in cold areas. A simulation of air-to-air energy recovery system in animal housing facility based on hourly weather data for one year was investigated by Freund (2003). The findings resulted that more than 80% of the heating energy and 45% of the cooling energy can be saved by implementation of air-to-air energy recovery and conservative control settings. With regard to this, utilization of the air-to-air energy recovery system in agriculture buildings can also be considered.

Furthermore, the EPA's Labs 21 guidelines was designated to educate designers and owners of the energy impact in a laboratory building because the lab buildings consume as much as 100 times of the energy which is similar to the size of an institutional or commercial building. This guideline highlighted energy efficiency, renewable energy sources, and sustainable construction practices while maintaining high standards of comfort health and safety. It was identified that air-to-air energy recovery system is one of the main solution. This has been approved by Milbrandt (2008) and VanGeet (2006) from their research that addition of the air-to-air energy recovery system in the laboratories had the most energy savings potential even though there are several factors which can sustain in energy saving such as the building insulator or the lights usage. Fan and Ito (2012) have also explored the impacts of inlet and outlet openings arrangement through air-to-air energy recovery system on energy consumption in typical office space equipped with air-conditioning during summer climate in Japan by integrating BES and CFD. The result indicated that in the case of under-floor-type ventilation system, it highlights the effectiveness and impact of integrating BES and CFD approaches when non-uniform temperature distribution-thermal stratification, is formed in space. Therefore, it is important to select the appropriate types of air-to-air energy recovery technology, properly designing the system, meeting the applicable codes, and commissioning the system. As the system is designed, installed, and operated correctly, it will provide significant energy and environmental benefits.

Minnesota Sustainable Housing Initiative has recommended that an air-to-air energy recovery system must be sized to adjust the necessary air exchange rate based on the home size and the number of occupants for purchasing purposes. Air exchange rate was defined as the measurement volume of the air added or removed from a space divided by the volume of space (Beaton et al., 2004). In simplified terms, it describes the times of the air was replaced in a defined space either the air is uniform or mixed perfectly. The calculation of the Air Exchange Rate was calculated as the following in Equation 2.1.

$$ACH=\frac{60\ Q}{Vol} \qquad \text{(Equation 2.1)}$$

Where:

ACH: Air Exchange Rate

Q: Volumetric flow rate of the air in ft^3/min

Vol: Volume of the room

In regard to this, ASHRAE Standard 62-2001 that highlighted the Building Code requirement for fresh outdoor air ventilation requires ventilation for occupied spaces set the air exchanges rate at 0.35. Hence, to determine the minimum ventilation rate of air-to-air energy recovery required, the internal volume of the house or part of the house that is required to be ventilated was multiplied by 0.35. For an easy calculation, HVACQuick on their website has performed a software which is easier for the consumer to visualize a typical installation of the system. In this study, minimum of required ventilation rate of the air-to-air energy recovery system is. 0.00316 m^3/s. Therefore, the calculation was presented below:

Required Air Exchange Rate: 0.35

Total volume of the indoor space: 32.54m³=1149ft³

$$Q=\frac{\text{Vol x ACH}}{60}=\frac{1149ft^3 \text{ x } 0.35}{60}=\frac{6.7025ft^3}{min}=\frac{0.00316m^3}{s}$$

2.2.1 Application of Air-to-Air Energy Recovery System in Hot-Humid Environment

Hot humid climate is referred to as the region that has high temperature and high humidity level leading to an enormous discomfort. Hence, there is a necessity to provide cross ventilation between indoor and outdoor condition to conserve the better thermal comfort. Thermal comfort in the hot-humid environment has become a significant problem and numerous investigations have been done to analyze this problem (Yau et al., 2012; Laverge et al., 2011; Balakrishnaiah et al., 2011). It has been reported about 50% total energy was consumed in a building for HVAC system as well as the cooling technologies that was mainly used to remove both sensible and latent load in buildings (Chua et al., 2013). Hence, air-to-air energy recovery system was introduced to overcome this problem in hot humid environment (Liu, 2008).

There is various integration of the air-to-air energy recovery system for building application such as energy recovery in mechanical ventilation system, energy recovery assisted passive ventilation, energy recovery assisted cooling or air conditioning, energy recovery combined with dehumidification system and energy recovery coupled with photovoltaic/solar panel (Mardiana, & Riffat, 2012). Since the buildings in hot-humid environment utilized air-conditioning to maintain its thermal comfort (Lundgren, & Kjellstrom, 2013), therefore the air-to-air energy recovery proposed in this study was to assist in minimizing the heavy air-conditioning used. The system transfers both sensible (temperature) and latent (moisture) heat from the incoming fresh air to the outgoing air, thus aids in reducing the load (the ventilation) on the air-conditioning system (Ouazia et al., 2006). Furthermore, Hilmersson and Paulsson (2006) explained that the thermal load of the air-conditioning will decrease when the air is dehumidified by the air-to-air energy recovery. Instead of exhausting the inside air directly to the outside for air-conditioning usage; application of the air-to-air energy recovery system will aid in exchange of the energy in the air streams. Simplified described in terms of temperatures, the system will aid in reduce the temperature of the outside air; associated with the less energy is spent cooling the outside air supplied to the building (Nasif et al., 2010).This was also occurred in term of moisture content as the system dehumidified the moisture content of the outside air before released into the indoor space. Hence, energy saving can typically reduce the operating cost on conventional air-conditioning (Engarnevis et al., 2015) For the better understanding, a simple comparison between air conditioning cooling of a building and air conditioning cooling combined with air-to-air energy recovery can be seen in Figure 2.1.

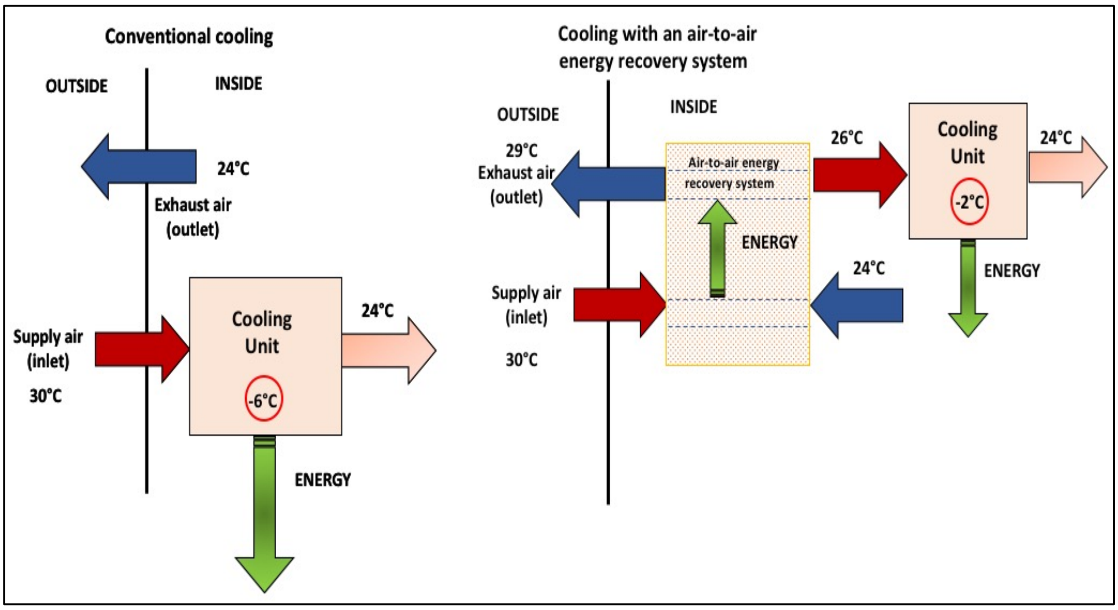

Figure 2.1 Cooling air in a building. Left: Conventional cooling, Right: The air-to-air energy recovery system assist air-conditioning Source: (Hilmersson, & Paulsson, 2006)

Another essential point is the comparison that was done between air-conditioning coupled with energy recovery and conventional air-conditioning system on energy analysis resulted in up to 8% annual energy consumption saving in tropical climate (Nasif et al., 2010). It is apparent that the system has significant contribution towards energy saving by reducing the latent load in hot-humid climate. In addition, the author also performed the system on different cities such as London, Miami, Tokyo and Dubai and noticed the decrease of energy consumption in hot-humid climate. The energy consumption in London has become substantially higher due to the cold climate condition. Similarly, the feasibility of an integrated HERV with a built economiser was evaluated quantitatively using an Excel-based analysis tool and discovered that energy recovery ventilator are more significant in hot-humid climate and provides greater energy saving (Zhang et al., 2014).

As been reported over the past century that there has been a rapid development of the system in hot-humid environment. However, there is still a limited number of experiments have been conducted on the performance of air-to-air energy recovery system especially in Malaysia, in which the experimental approach was neglected in the current theory (Al-Waked et al., 2015). Half of research on the system's performance in hot-humid environment failed to specify whether the study conducted is based on weather data or outdoor design air conditions (Ab. Razak, 2013; Nasif et al., 2010).Although the extensive installation of system worldwide is gaining more attention due to its environment and economic analysis (Rafati et al., 2014; Delfani et al., 2012; Pavel, 2010; Nyman and Simonson, 2005), there is a few studies that exist especially in the Southeast Asia (Ab. Razak, 2013; Nasif et al., 2010). Furthermore, the effect of environment and economic analysis on air-to-air energy recovery based on feasibility study in hot-humid environment data has not yet been examined in detail (Jaber and Ajib, 2012).

2.2.2 Guidelines Related to Air-to-Air Energy Recovery System

There are several documents that deal with the testing, rating and use of air-to-air energy recovery devices that have been published by HVAC industry. It includes the ASHRAE Standard 84-2008 and AHRI Standards 1060-2005. ASHRAE Standard 84 is an ANSI approved standard that was published in 1992, aimed to determine the Method of Testing Air-to-Air Heat/Energy Exchanger that highlights (1) the uniform method for testing to obtain performance data; (2) the specific data obtained, calculations to be applied, and reporting procedures for testing the performance; and (3) the specific types of test equipment for performing such test. In additional, Standard 84 provides the technique in minimizing air leakage by specifying that all tests can be carried out at zero pressure differentials between the intake and supply. However, the fan position was not mentioned in these standards. Other than that, these standards do not stipulate the performance criteria for product certification or identify laboratories in performing the test. In regards to this, AHRI Standards 1060 was established to highlight the Performance Rating of Air-to-Air Exchanger for Energy Recovery Ventilation to report the definitions, test requirement, rating requirement, minimum data requirement mainly for the published rating, marking and nameplate data and conformance conditions as well as rating conditions intended for the industry. Thus, this standard was mainly subjected to factory-made of Air-to-Air Energy Recovery device. Extended to this, AHRI 1060 has also established the Certification Program 1060 to verify ratings published by manufacturers. In general, air-to-air energy recovery must be tested in accordance with ASHRAE Standard 84, except when modified must be tested by AHRI Standard 1060. Hence, Standard 84-2008 was used as reference.to identify the performance of the designated air-to-air energy recovery system in this study.

2.3 The Use of Air-to-Air Energy Recovery System towards Reducing Energy Consumption in Building

In order to increase the efficiency of energy consumption together with the concern to meet the essentials for energy conservation and green environment, adequately manipulate the low-grade energy recovery device in building; application of air-to-air energy recovery system can be practiced (Liu et al., 2010). According to

Nyman and Simonson (2005), investigation on the inter-correlation of IAQ, ventilation and health by removing sources and ventilating the house properly have led to the application of air-to-air energy recovery system.

It has been reported that there is a rapid growth of air-to-air energy recovery installation from Codes and Building Labelling Program (Roth, 2013). ASHRAE 90.1-2010 (Energy Standard for Building Except Low-Rise Residential Buildings), a benchmark for energy codes in the United States has mentioned that 50% total energy recovery was required in commercial buildings as the States has to adopt the system by October 2013. Meanwhile in Europe, approximately 70 to 90% of total energy recovery was required in most buildings. In addition, city building codes also indicated the employment of air-to-air energy recovery ventilation for all Vancouver homes, New Ontario building code. The U.S Green Building Council in Leed is also pointed for air-to-air energy recovery from energy conservation and indoor air quality. To date, air-to-air energy recovery has been also implemented with energy star rated (Moffitt et al., 2012).

The air-to-air energy recovery system was believed to reduce the energy consumption in HVAC system by permitting smaller air conditioner to be installed and provides better indoor air quality (Hilmersson and Paulsson, 2006). When the system was applied in the summer, less moist air brought into the home has subsequently led to less work for the air-conditioner, thus it is vital to decrease the cooling energy by pioneering new cooling system besides offering energy saving for the owner (Delfani et al., 2012; Ouazia et al., 2006). The efficiency of system that is greater than 15% leads to a positive impact towards environment (Nyman and Simonson, 2005). Adaptation of the system in laboratories discovered that the system could extensively reduce the mechanical heating and cooling necessities related with ventilation air in most laboratories (VanGeet and Reilly, 2006). Moreover, air-to-air energy recovery system is aimed to provide fresh and conditioned air to a well-insulated building. As the air contains sensible (heat) and latent (water vapor), therefore, both types of energy can be recovered. Besides, air-to-air energy recovery was claimed to provide a low operating cost, aids in reducing the ventilation load on the air-conditioning system, having the balance or slight positive pressure as well as being the ventilation independent of heating/air conditioning system (Moyer, 2004).

Potential energy saving by employing energy recovery has resulted in about 35% in cold climate than 20% in hot climate for annual energy consumption (Mohammad et al., 2014). It was found that applying TRNSYS simulations for a ten-story office building depending on the climate and system effectiveness has reduced the operation of energy recovery together with moisture recovery capability by 35% in cold climate of Saskatoon and Chicago. In addition, the system that was adopted in the cold climate of Thessaloniki, Greece has denoted 43% reduction and 16% reduction in the boiler and in the chiller capacity, respectively, thus resulting to an annual energy saving by 40% in the case of full occupancy. Meanwhile, 30% saving was recorded for the half occupancy of buildings (Papakostas and Kiosis, 2014)

Delfani (2012) stated that investigation on energy recovery system for building air-conditioning in hot and humid area, which focused on various climates of Iran indicates lower energy consumption of up to 32% using HHCC compared to HCC. It was investigated that energy consumption was reduced by about 11 to 32% in hot humid environment by employing the energy recovery combining with air conditioning. On top of that, investigation of air-to-air energy recovery system was tested and calculated under various outdoor conditions in laboratory and indicated that the system could save over 60% energy for the air-conditioning operating hours

(Zhang and Zhang, 2014). Moreover, the reduction from 1.8 to 2.8% in overall energy was calculated for the whole system and is suitable in subtropical climate where the air-conditioning demands are quite high. On the other hand, further experiments on the types of membrane air-to-air energy recovery system with an air side economiser was also carried out in both cold and hot climate and reveals that it showed the greatest energy benefit (Wang and Haves, 2012). 17% reduction was found in annual HVAC energy consumption in a conventional commercial office building in Miami and Atlanta. Meanwhile, the technology raises the system COP by up to 26% in a typical summer design day for Miami climate. Even thought, there is abundant of the study of the air-to-air energy recovery system investigated in several buildings types at several locations, there is still limited study of the system in Southeast Asia especially Malaysia. As the system shows positive outcome in reducing the energy consumption and provide good IAQ in hot-humid environment (Jadhav, & Lele, 2015; Fan, et al., 2014; Yaïci, et al., 2013), there is a need for the system to be implemented in the Malaysia that experienced hot-humid climate throughout the year.

2.4 Theoretical Background of Air-to-Air Energy Recovery System

An air-to-air energy recovery system is generally a heat and humidity exchanger between the two incoming air-streams which are fresh outside air (intake) and stale room exhaust air (exhaust). It is operated by which the heat or moisture or both being converted from high to low, providing adequate ventilation in buildings (Mikkonen, 2013). The primary use of air-to-air energy recovery system is to pre-condition the outside air. It aids in preheating/humidification during winter, precooling/dehumidification during summer and eventually reduces annual operating costs by reducing the required heating and cooling capacity (York International, 2004).

The air-to-air energy recovery system use the energy difference between the two air streams without external energy being supplied to the system. As the air-to-air energy recovery system is a passive component, it needed a differential of heat and humidity between the air-streams in order for exchange (Gerspacher, 2009). A thin membrane layer made up from the vapour-permeable aids to separate the air stream for both heat and humidity to be able to pass through the membrane when they flow through the system (Dobbs et al., 2005). During cooling season, the heat and moisture in the incoming air will be transferred to the exhaust air-stream to cool and dehumidify the incoming air. In contrast, heat and humidity will be recovered from the exhaust air during heating season (Duncan, 2011).

2.4.1 Principle of Operation in Hot-Humid Environment

Generally, the principle operation of the air-to-air energy recovery system was laid behind the theory of fundamental physics. In the hot-humid environment, the system operates in which the fresh and warm outside air that contained more water than cold air triggers the temperature differences between the air streams that discharges at the same temperature. In the same time, the cold exhaust air from the room was passed through the air-to-air energy recovery system and warmed up by the outside air. Then, the exhaust air from the room was heated to approximately the same temperature and causing it likely to hold more water. Inversely, the moisture was passed through the layer of membrane to the dryer air in order to hold more water. The moisture will then diffuse through the membrane when air was struggled to be saturated with water. Meanwhile, the outside air will be cooled to approximately the same temperature as the inside air because it releases heat to the outgoing air.

Consequently, the air will now be drier and colder when it reaches the air-conditioning room. A simplified principle of this behavior can be seen in Figure. 2.2.

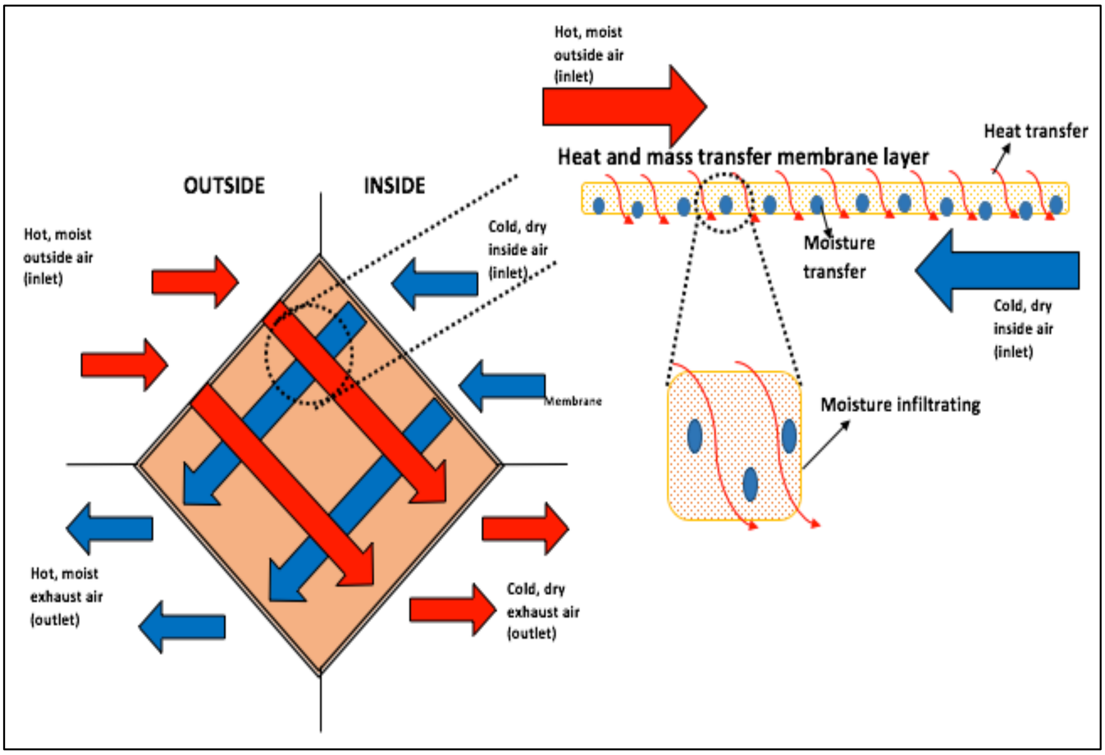

Figure 2.2 Simplified principle of a cross flow air-to-air energy recovery system in a hot-humid environment

2.5 Fixed Plate Type of Air-to-Air Energy Recovery System

There are several energy recoveries that exist in the market nowadays and have its own advantages and disadvantages. As the efficiency of the run around types of air-to-air energy can be above 80% than fixed plate types (Mardiana, & Riffat, 2012), it was discovered that far too little attention of air-to-air energy recovery system using fixed plate types was studied instead of the run around types of air-to-air energy recovery system in hot-humid environment locations (Rasouli, 2010). In this study, fixed plate type were more focused and used due to the type of energy recovery that is more promising and widely used with little problem and maintenance compared to