PERFORMANCE OF INTEGRATED ENERGY RECOVERY FOR SPLIT UNIT AIR-CONDITIONING SYSTEM IN HOT AND HUMID ENVIRONMENT

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by

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LIST OF ABBREVIATIONS

HVAC	Heating, Ventilation and Air-Conditioning
COP	Coefficient of Performance
ANOVA	Analysis of Variance
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
HPHX	Heat Pipe Heat Exchanger
GHG	Greenhouse Gases
DEFRA	Department for Environment, Food and Rural Affairs
IPCC	Intergovernmental Panel on Climate Change

LIST OF SYMBOLS

T_{pa}	Temperature of pre-conditioned air
T_{ia}	Temperature of intake air
T_{ea}	Temperature of exhaust air
T_{oa}	Temperature of outdoor air
T_{sa}	Temperature of supply air
T_{ipa}	Temperature of intake pre-conditioned air
RH_{pa}	Relative Humidity of pre-conditioned air
RH_{ia}	Relative Humidity of intake air
RH_{ea}	Relative Humidity of exhaust air
RH_{oa}	Relative Humidity of outdoor air
RH_{sa}	Relative Humidity of supply air
RH_{ipa}	Relative Humidity of intake pre-conditioned air
ω_{pa}	Humidity ratio of pre-conditioned air
ω_{ia}	Humidity ratio of intake air
ω_{ea}	Humidity ratio of exhaust air
H_{pa}	Enthalpy of pre-conditioned air
H_{ia}	Enthalpy of intake air
H_{ea}	Enthalpy of exhaust air
ε_S	Sensible efficiency
ε_L	Latent efficiency
ε_T	Total efficiency
q	Recovered energy of energy recovery unit
Q_{ac}	Cooling capacity of air-conditioning system

Q_{int}	Cooling capacity of integrated system
COP_{ac}	Coefficient of performance for air-conditioning system
COP_{int}	Coefficient of performance for integrated system
$Q_{without\ ERU}$	Potential energy recovered for stand-alone air-conditioning system
$Q_{with\ ERU}$	Potential energy recovered for integrated system
$CO2_{without\ ERU}$	Carbon dioxide emission reduction for stand-alone air-conditioning system
$CO2_{with\ ERU}$	Carbon dioxide emission reduction for integrated system
CO_{2e}	Carbon dioxide emission reduction

PRESTASI SISTEM BERSEPADU PEROLEHAN SEMULA TENAGA UNTUK PENYAMAN UDARA UNIT TERPISAH DALAM PERSEKITARAN PANAS-LEMBAP

ABSTRAK

Peningkatan penggunaan tenaga dalam penyamanan udara telah menyebabkan banyak tenaga haba dibazirkan terutama dalam iklim panas lembap. Dalam hal ini, dengan memasang unit perolehan tenaga, tenaga haba dipindahkan dari aliran udara luar ke dalam untuk memperoleh tenaga yang terbazir. Matlamat utama kajian ini adalah untuk menganalisis prestasi perolehan tenaga unit persendirian dan penyaman udara unit terpisah, untuk menilai prestasi sistem bersepadu serta untuk membuat perbandingan prestasi antara penyaman udara unit terpisah dan sistem bersepadu dengan parameter suhu 28ºC, 31ºC, 34ºC dan 40ºC, kelembapan relatif 65%, 75% dan 85% serta halaju udara 1 ms^{-1}, 2 ms^{-1} dan 3 ms^{-1}. Eksperimen dijalankan di dalam satu bilik pejabat di dalam bangunan rendah dalam persekitaran panas dan lembap. Kecekapan dan keperolehan tenaga oleh unit perolehan tenaga serta pekali prestasi (COP) dan kapasiti penyejukan oleh penyaman udara unit terpisah telah dinilaikan dalam lingkungan 42-78%, 0.4-3.4 kW, 1.0-2.6 dan 0.7-1.9 kW. COP, kapasiti penyejukan, potensi keperolehan tenaga dan pengurangan pelepasan karbon dioksida daripada sistem bersepadu adalah dalam linkungan 1.5-4.0, 1.2-2.9 kW, 217-1849 kWh, RM 94-804, 0.1-0.9 $MgCO_{2e}$. T-test menunjukan bahawa prestasi sistem bersepadu adalah berbeza dan lebih baik daripada unit persendirian disebabkan oleh fungsi penyejukan dan penyahlembapan. Untuk aplikasi praktikal, data penyelidikan ini boleh menjadi rujukan dalam bidang pemulihan tenaga untuk penyaman udara unit terpisah kepada penyelidik, jurutera dan arkitek.

PERFORMANCE OF INTEGRATED ENERGY RECOVERY FOR SPLIT UNIT AIR-CONDITIONING SYSTEM IN HOT AND HUMID ENVIRONMENT

ABSTRACT

The escalating energy consumption in conditioning fresh air causes abundance of condensing heat energy wasted especially under the hot and humid climate. In this context, by installing energy recovery unit, thermal energy is transferred from outgoing to incoming air streams which recovers the wasted energy. The main objectives of this research are to evaluate the performance of stand-alone energy recovery unit and split unit air-conditioning system, to assess the performance of integrated system and to compare the performance between stand-alone air-conditioning unit and integrated system by varying parameters of temperature of 28ºC, 31ºC, 34ºC and 40ºC, relative humidity of 65%, 75% and 85% as well as air-velocity of 1 ms^{-1}, 2 ms^{-1} and 3 ms^{-1}. Experiment has carried out in a low-rise commercial office room within hot and humid environment. Efficiency and recovered energy of the energy recovery unit as well as Coefficient of Performance (COP) and cooling capacity of the split unit air-conditioning system are evaluated in the range of 42-78%, 0.4-3.4 kW, 1.0-2.6 and 0.7-1.9 kW respectively. COP, cooling capacity, potential energy recovered and carbon dioxide emission reduction of integrated system assessed are in the range of 1.5-4.0, 1.2-2.9 kW, 217-1849 kWh, RM 94-804, 0.1-0.9 $MgCO_{2e}$ respectively. T-test presents the performance of integrated system is statistically different and better than stand-alone unit due to its pre-cooling and dehumidification functions. In practical application, this research provides reference data on the application of energy recovery in split unit air-conditioning system for researchers, engineers and architects.

CHAPTER 1

INTRODUCTION

1.1 Background

Most people spend 90% of their time indoors where it is the main arena for them to live and work (Zhang and Zhao, 2015). Research concluded that quality and comfortable interior space affect work efficiency and productivity of the occupants within building. Since that, concerns have been raised over the quality of indoor air to provide higher standard of living and work performance (Pichatwatana et al., 2017). Nevertheless, there are cases of buildings fail to meet the requirements of indoor air quality which causes the occupants suffering from Sick Building Syndrome (SBS) (Silva et al., 2017). Symptoms of SBS such as fatigues, dizziness, headaches and sore throat occurred, are attributable to the poor physical parameters of indoor air quality, which are indoor temperature, relative humidity and airflow (ICOPIAQ, 2010). Hence, ventilation such as air-conditioning system is examined to be the most effective way to address indoor air quality (Steinemann et al., 2017). It is the process of mixing or replacing indoor air with outdoor fresh air to cool, dehumidify as well as reduce the level of indoor contaminants (Awbi, 2017). In the meantime, by determining the air change rate (ACH) of the conditioned space, thermal comfort can be maximized while ensuring the sufficient amount of fresh air for the conditioned space (ASHRAE Standard 62.1).

Heating, ventilation and air-conditioning (HVAC) systems are among the largest energy consumers of the building sector which account for 20-40% of the total energy used in developed countries (Zhang et al., 2017). This amount grows rapidly due to the high usage of air-conditioning system for good thermal comfort

(Mirrahimi et al., 2016). Ergo, the design of energy-efficient air-conditioning system is emphasized to reduce the escalating energy demand, costs and associated environmental problems (Zhang et al., 2017).

One of the ways to reduce global energy crisis is by employing energy recovery unit in buildings. Energy recovery is a process which recovers sensible and latent heat energy from the exhaust stale air by inducing fresh air during ventilation (Mardiana and Riffat, 2011). It applies heat exchanger which transfers thermal energy from outgoing to incoming air streams. By applying energy recovery and air-conditioning system, the waste condensing heat from air-conditioning system can be recovered (Mardiana and Riffat, 2012).

1.2 Problem Statement

Under the hot and humid climate, humidity control is a significant problem faced by the occupants, hindering the attainment of thermal comfort. The common practice in the hot and humid climate such as Malaysia is by setting a low-temperature set-point of around 23 °C and the humidity level is reduced inherently. However, the practice does not provide the advantageous of thermal comfort and energy friendly (Aziz et.al., 2017). To achieve comfortable interior space, high demand of air-conditioning causes a significant increase in the building cooling loads (Fatouh et al., 2017). In Malaysia, statistics showed that the operating cost of air-conditioning system has contributed more than 50% of the electricity bill and it has exceeded 100,000 GWh in 2011 (Yau and Pean, 2014). It is forecasted that there will be an increase of 29.7% of energy demand from 2011 to 2020 with an average annual growth rate of 3.3% (Birol, 2015). With the escalating energy demand, it is highly imperative to increase the efficiency of air-conditioning system to mitigate the effect of global warming and energy resources depletion. One bottleneck for the conventional air-conditioning system is the low performance when the air temperature escalates. As outdoor temperature increases, the temperature and pressure of the condenser (outdoor unit) and evaporator (indoor unit) increase considerably which causes reduction in cooling capacity and escalation in heat energy loss to the environment (Alhamdo et al., 2015; Sharma et al., 2016). Therefore, it is essential to pre-cool the air temperature, which reduces the work load for condenser (outdoor unit) and evaporator (indoor unit), to increase the performance of air-conditioning system.

Despite numerous studies on the performance of air-conditioning system in different climatic zones (Dutta and Aritome, 2000; Tang and Huang, 2005; Yumoto et al., 2006; Oropeza-Perez, 2016), there is still a research gap in energy-efficient building application in hot and humid environment. To narrow the research gap, field measurements are performed in this study on integrated energy recovery for split unit air-conditioning system by simulating hot and humid conditions which pre-cools and pre-conditions the outdoor fresh air to reduce the workload of air-conditioning system.

1.3 Objectives

In this research, the aim is to determine the performance of integrated energy recovery for split unit air-conditioning system by simulating hot and humid conditions. The sub objectives are as below:

a) To evaluate the performance of stand-alone energy recovery unit as well as split unit air-conditioning system and the effects of its operating parameters

b) To assess the performance of integrated energy recovery for split unit air-conditioning system and the effects of its operating parameters

c) To compare the performance between stand-alone air-conditioning unit and integrated energy recovery for split unit air-conditioning system in terms of coefficient of performance (COP) and cooling capacity

1.4 Scope of Research

This study is to determine the performance of integrated energy recovery for split unit air-conditioning system in low-rise commercial office room by simulating hot and humid conditions.

In field measurements of stand-alone energy recovery unit and split unit air-conditioning system as well as integrated energy recovery for split unit air-conditioning system, hot and humid conditions such as intake temperature and relative humidity are simulated at 28ºC, 31ºC, 34ºC and 40ºC as well as at 65%, 75% and 85% respectively which are as similar as in various countries (Licina and Sekhar, 2012; Delfani et. al., 2012; Damiati et al., 2016; Lau et al., 2016). In hot and humid climate, when the outdoor temperature increases, relative humidity reduces because of the increase saturation of water vapor, causing the air to hold more moisture than at low temperature does. In this study, temperature and relative humidity of 40ºC and 85% are included as extreme conditions such as in Shanghai with temperature and relative humidity of 40-41 ºC and 81-82% respectively are considered (Xu et al.,2015).

Performance of energy recovery unit as in efficiency and recovered energy are assessed at air-velocity of 1 ms^{-1}, 2 ms^{-1} and 3 ms^{-1}. Following that, performance of split unit air-conditioning system as in COP and cooling capacity are studied and compared between the stand-alone unit and integrated system to evaluate the improvements of the integrated system. Subsequently, the research results are analyzed using statistical analysis of variance such as one-way ANOVA and T-test. In addition, by minimizing the wasted heat energy from split unit air-conditioning system, potential energy recovered and annual carbon dioxide emission reductions are assessed in the integrated system.

Despite the main purpose of split unit air-conditioning system is to provide comfort and good indoor air quality for the indoor spaces, this research does not include studies in these two areas due to experimental limitations. Besides that, numerical simulation is not covered in this research which is beyond the scope of study. Nonetheless, this research provides a reference data on integrated energy recovery for split unit air-conditioning system in laboratory condition under hot and humid environment.

1.5 Significance of study

This study provides a reference data on integrated energy recovery for split unit air-conditioning system in hot and humid environment by recovering energy lost and enhancing efficiency of split unit air-conditioning system. Integrated energy recovery for split unit air-conditioning system has been investigated in different operating set points to determine the performance of the system. It can be provided as a benchmark for future research in energy recovery for researchers, engineers and architects. Consecutively, it can be a baseline to save energy and electricity by implementing the heat and moisture transfer mechanism within hydrophilic polymeric membrane of energy recovery unit while providing thermal comfort and good indoor air quality for the occupants in small office room within low-rise commercial building.

On the other hand, due to lack of experimental data under hot and humid environment, this research serves as a reference on the performance of energy recovery by simulating hot and humid intake air. As a result, this research could be a guideline for practical application of integrated energy recovery for split unit air-conditioning system in hot and humid environment.

Besides that, in terms of practical applications, integrated system is one of the approach in obtaining necessary credit points for Green Building Index (GBI). Even though energy recovery unit recovers the condensing energy of air-conditioning system which increases efficiency of the building, this study does not consider the assessment criteria for minimum Energy Efficiency (EE) in Green Building Index due to the size of air-conditioned space is less than 4000 m^2 (Green Building Index, 2011). In the meantime, the integrated energy recovery for split unit air-conditioning system complies to the assessment criteria for minimum IAQ performance (EQ1) whereby the minimum requirement of ventilation rate in ASHRAE 62.1 has met. Furthermore, the performance of integrated system is referred to ASHRAE Standard 62.1 and Malaysia Standards MS 1525 to comply with the minimum standards of air change rate and energy efficiency to be implemented in small office room within low-rise commercial building. Therefore, this research plays a crucial role in ventilation and energy efficiency which benefits the industry players such as Department of Occupational Safety and Health (DOSH), Ministry of Energy, Green Technology and Water, Energy Commission, and the Malaysia Energy Centre.

1.6 Thesis Outline

This thesis contains six chapters in total. Brief discussions on these chapters are emphasized as below in Figure 1.1. Chapter 1 dictates the general overview of this research, problems that have been raised, research aims, significance of this research as well as the outline for the thesis. Basically, this chapter determines the scope and guidelines for the research progress.

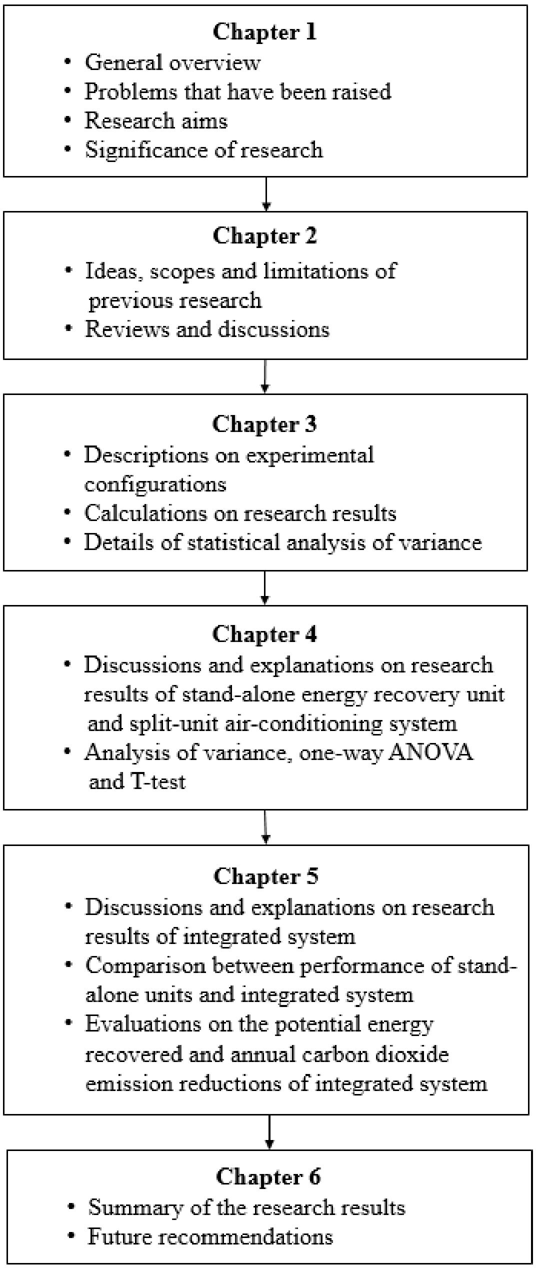

Figure 1.1 Flowchart of thesis outline

Chapter 2 incorporates the ideas, scopes and limitations of previous research by providing criticisms on them. Reviews and discussions on performance of stand-alone energy recovery unit, split unit air-conditioning system and integrated energy recovery for split unit air-conditioning system in terms of efficiency, recovered energy, coefficient of performance (COP), cooling capacity and potential energy recovered in hot and humid climate are further presented in Chapter 2.

Chapter 3 presents the general descriptions and experimental configurations of energy recovery unit, split unit air-conditioning system and integrated energy recovery for split unit air-conditioning system. Following that, experimental measurements on temperature, relative humidity, air velocity, current and voltage to determine the performance of the systems are further discussed in this chapter. Detailed explanations on evaluating research results are included with statistical analysis of variance to assess the significance difference of the research results.

Chapter 4 relates the research results of the performance of stand-alone energy recovery unit and split unit air-conditioning system. The changes of temperature, relative humidity and humidity ratio in stand-alone unit, which dictate the performance of the systems by varying different operating parameters, are illustrated. Chapter 4 analyzes the performance of energy recovery unit as in efficiency and recovered energy as well as the performance of split unit air-conditioning system as in cooling capacity and coefficient of performance (COP). Analysis of variance, one-way ANOVA is employed to determine the significant difference of operating parameter of air velocity on the performance of stand-alone energy recovery unit. T-test is applied on the research results of stand-alone split unit air-conditioning system to regulate the significant difference of data between the drying and cooling mode.

Chapter 5 outlines the performance of integrated energy recovery for split unit air-conditioning system. The effects of temperature, relative humidity and humidity ratio affecting the performance of integrated energy recovery for split unit air-conditioning system in cooling capacity and coefficient of performance are depicted in this chapter. Comparison between the performance of stand-alone units and integrated system are assessed by employing T-test. Potential energy recovered and annual carbon dioxide emission reductions in integrated energy recovery for split unit air-conditioning system are evaluated to reduce its impacts to global warming.

Last but not least, Chapter 6 discusses the summary of the research results which resolves several problems issued by previous research. Future recommendations are raised for improvements of the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

This chapter discusses literature review of previous research. Effects of hot and humid conditions on energy recovery unit, performance of stand-alone energy recovery unit, split unit air-conditioning system and integrated energy recovery for split unit air-conditioning system are further explained below.

2.2 Energy Recovery Unit in Hot and Humid Climate

Energy recovery unit applies mechanism which recovers sensible and latent heat from the exhaust stale air with pre-conditioned fresh air (Mardiana-Idayu and Riffat, 2012). However, there are challenges which affect the efficiency of energy recovery such as frosting in cold and dry climate (Nasr et al., 2014; Liu et al., 2016) and high humidity in hot and humid climate (Zhang and Niu, 2001). Comparisons of challenges and characteristics facing in cold and dry climate as well as hot and humid climate are further discussed below.

In cold and dry climate, the average outdoor temperature and relative humidity are in the range of 4-13 ˚C and 55-69% (Zhang et al., 2016; Pyrgou et al., 2017). Problems such as condensation and frosting are more likely to occur in the exhaust side of energy recovery unit due to non-uniform temperature and humidity distributions across cross-flow exchanger (Nasr et al., 2014). In this respect, plentiful methods in overcoming frosting limits have been investigated. Liu et al., (2016) developed a theoretical model to predict the critical operating conditions for frosting limits in cross-flow heat and energy exchangers. In another study, Nasr et al., (2016) proposed a new frosting detection method which has low uncertainties based on the temperature measurements.

On the other hand, one of the climatic characteristics in countries located in a hot and humid climate zone, such as Dubai, Jeddah, Masirah, Ramsar is the relatively high humidity of 60-83% with the annual average air temperature of 29-42 °C (Licina and Sekhar, 2012; Delfani et. al., 2012). In hot and humid climate zone such as Malaysia, Indonesia, and Singapore, the annual relative humidity and air temperature are in the range of 77-88% as well as 20-34 °C (Damiati et al., 2016; Lau et al., 2016). As such, the high humidity level is a significant challenge to maintain good indoor air quality and thermal comfort in indoor spaces. With the capability of absorbing humidity in hydrophilic polymeric membrane, energy recovery unit helps reduce humidity level in indoor spaces and thus contribute to thermal comfort among the occupants.

By developing energy recovery unit, its main goal is to tackle the problem of high humidity level. However, several challenges are faced on the installation. For instance, latent efficiency of energy recovery unit would be seriously compromised under the extreme conditions in hot and humid climate, which may in turn undermine the final energy saving effect (Zhang and Niu, 2001). Thereby, considerable amount of research to enhance efficiency of energy recovery unit are examined. Min and Su, (2010) established a mathematical model to predict the performance of membrane-based energy recovery unit in hot and humid climate with three different temperatures of 32°C, 35°C and 38°C and relative humidity of 50%. They concluded that the total heat transfer rate increases with large total surface area. In another study, Zafirah and Mardiana, (2012) analyzed the performance of energy recovery unit under different temperatures and airflow rate in hot and humid climate. Efficiency up to 85% was obtained at temperature 40ºC and airflow rate of 1 ms^{-1}. Likewise, Masitah et al., (2015) discovered that the air velocity has large influence on efficiency and transferred heat of energy recovery unit. Nevertheless, relative humidity was not included in the performance investigation due to the large moisture transfer resistance despite high humidity in hot and humid climate. Due to the problem of humidity control in hot and humid climate which causes high energy consumption, it is essential to investigate on energy-efficient solutions in ventilation system. Thus, in this research, performance of integrated energy recovery for split unit air-conditioning system in hot and humid environment is studied by using hydrophilic polymeric membrane. Few studies related application of energy recovery in air-conditioning in hot and humid climate are further discussed in Section 2.5.1.

2.3 Performance of Energy Recovery Unit

Innumerable research regarding energy recovery unit has been discovered. In fact, there are few types of energy recovery unit being studied such as fixed plate heat exchanger. The plate exchangers are assembled by thin plates that are stacked together with several internal airstreams, which transfers thermal energy from outgoing to incoming airstreams (Mardiana-Idayu and Riffat, 2012).

Fixed-plate heat exchangers constitute a competitive technology in energy recovery unit owning to their superiorities in weight-lightness, cheapness and abilities in transferring both sensible and latent heat simultaneously (Mardiana and Riffat, 2013; Zhang, 2008). It is normally configured by ultra-thin materials such as paper, plastic films and hydrophilic membranes which provide the advantages of mechanically strong, compact and highly efficient (Min and Su, 2010).

Furthermore, the membrane comes with corrugated structure which ensures a continuous flow in the change direction (Gendebien et al., 2013). Corrugated channels are piled up together to form 90° orientation angle between the neighboring plates. Efficiency improvement is contributed by the flow pattern which associates with the abrupt turnaround, contraction and expansion (Zhang, 2012). Meanwhile, maximum heat transfer efficiency can be achieved when there are two opposite directions in the airflow arrangement (Shurcliff, 1988).

2.3.1 Efficiency and Recovered Energy

There are two measurements on the performance investigation of energy recovery unit which are efficiency and recovered energy. Efficiency is described in terms of sensible (heat), latent (moisture) and total (heat and moisture) with respect to the balanced airflows, steady-state conditions and no heat transfer between the heat exchanger and its surroundings and no gains from cross-leakage. On the other hand, recovered energy can be defined as the rate and direction of the heat and moisture transfer between the intake air and pre-conditioned air. As stated by ASHRAE Systems and Equipment Handbook, (2000), efficiency and recovered energy can be represented by Equation 2.1 and 2.2 respectively:

$$\text{Efficiency} = \frac{\text{Actual transfer (heat or moisture energy)}}{\text{Maximum possible transfer between two airstreams}} \tag{2.1}$$

$$\text{Recovered energy} = \text{mass flow rate x enthalpy difference} \tag{2.2}$$

In the meantime, numerous research found out that temperature, relative humidity, airflow and airflow arrangement are the main factors affecting the performance of energy recovery unit (Shao and Riffat, 1998; Zhang and Jiang, 1999; Min and Su, 2010). For instance, Min and Su, (2011) discovered that outdoor air state in terms of temperature and humidity affects the efficiency of energy recovery unit due to the membrane moisture and thermal resistance. Yet, in the middle of energy crisis, there were no discussion on the relationships between the efficiency and energy recovered of energy recovery unit. On the other hand, research by Liu et al., (2010) investigated saved energy with different enthalpy efficiencies in different cities of seasonal weather. The results showed that high enthalpy efficiency which mainly depends on sensible efficiency in winter and latent efficiency in summer, increases the percentage of saved energy. Besides that, experimental investigation by Yau (2007) was carried out to show that temperature has minimal effect on the performance of energy recovery unit. In another study, Rasouli et al, (2010) analyzed the optimum operating condition for energy recovery unit to reach energy saving state. They concluded that energy saving can be achieved by having higher enthalpy or temperature of outdoor air than indoor air. In this case, up to 20% of annual cooling energy can be saved depending on the location and efficiency of energy recovery unit. Energy saved was found significant in humid climate due to the reduction in dehumidification load. Likewise, Wu et al., (2016) identified profit pattern, in which 65.23% of energy can be saved, to minimize energy consumption of energy recovery unit.

2.4 Performance of Split Unit Air-conditioning System

Air conditioning is a process that conditions the air, transports it, and introduces it to the conditioned space. It maintains the temperature, humidity, air movement and air cleanliness within predetermined limits for the comfort and health of the occupants of an indoor space. There are few types of air-conditioning system which are central air conditioning and unitary packaged. In general, central air conditioning unit is installed in high-rise buildings, large commercial complexes, and precision manufacturing areas for a more precisely controlled, healthy, and safe indoor environment. Apart from that, unitary packaged air-conditioning system is mostly employed in residential and low-rise commercial building due to easy installation and low cost (Wang, 2001; Yau and Pean, 2011). It contains two split units which are installed indoor with evaporator coils to absorb heat as well as outdoor with compressor, condenser and expansion valve to release heat. Split unit air-conditioning system applies air or water as the medium to transferring heat from indoor to outdoor (Wang, 2001). In this study, focus would be on unitary packaged system of split unit which is commonly installed in low-rise commercial office room due to simplicity of the design and easy installation (Yau and Pean, 2011).

In terms of practical application of split unit air-conditioning system, air change rate (ACH) is required to ensure sufficient fresh air required for the conditioned space. Air change rate is the fresh air volume added to or removed from a space divided by the volume of the space which serves the main purpose of maintaining thermal comfort and indoor air quality for the conditioned space (ASHRAE Standard 62.2, 2013). Few researchers examined the effect of air change rate on the indoor air quality of the conditioned space. For instance, Gilbert et al.,

(2008) found out that the air change rate effectively reduces formaldehyde concentrations to provide good indoor air quality. Besides, Klein et al., (2009) concluded that the laboratory air quality was proportional to the ACH rate which is significantly affected by the air velocity of the room. Furthermore, Hou et al., (2017) studied the effect of ACH on the occupants' health by running experiments in 410 homes in Tianjin, China. In this context, ACH improves indoor air quality which is the main factor for thermal comfort among the occupants. In regards to this, a series of publications and standards by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) on air-conditioning system are found related to thermal comfort which is the condition of mind that expresses satisfaction with the thermal environment (Gou et al., 2017). Its reliability, control and efficiency to reach thermal comfort under extreme conditions are the primary reasons of using air-conditioning system (Oropeza-Perez, 2016).

One of the ways to increase air change rate is by installing air-conditioning system which fulfils the immense occupant comfort demands for comfortable indoor environment in the aspect of temperature and humidity (Bassuoni, 2014; Sun et al., 2014).

2.4.1 Cooling Capacity and Coefficient of Performance (COP)

Several approaches in assessing the performance of air-conditioning system have been explored (Dutta and Aritome, 2000; Tang and Huang, 2005; Yumoto et al., 2006; Othman et al., 2013; Oropeza-Perez, 2016). As stated by ASHRAE Handbook of Fundamentals (2005), coefficient of performance (COP) dictates the performance of air-conditioning system by defining the amount of heat removed divided by the net energy supplied in the form of work from compressor (outdoor unit), fans or pump to operate the refrigeration cycle of which can be interpreted as Equation 2.3:

$$\text{COP} = \frac{\text{Cooling Capacity}}{\text{Required Energy Input}} \tag{2.3}$$

COP shows the efficiency of air-conditioning system with the lowest energy input to produce the highest cooling capacity. On the contrary, cooling capacity indicates how much heat load of the unit can be eliminated within a time limit. High COP consumes less electricity which helps reducing energy loss (Yau and Pean, 2014).

There is a study by Dutta and Aritome, (2000) studied several types of compressors (outdoor unit) by simulating few tropical ambient temperature conditions. They concluded that COP was highly affected by the ambient air temperature. Yet, the results were purely estimation based on the conditions set. In another study, Tang and Huang, (2005) investigated the energy performance of air-conditioning system by including the component of energy consumption, cooling load parameters, COP and so on. Othman et al., (2013) evaluated the performance of an actual building packaged air-conditioning system based on COP with thermal comfort analysis in Malaysia. Despite COP was included in the study, there was no stressing on the outdoor temperature of which affects on the performance of air-conditioning system.

Besides that, there are few research on the performance air-conditioning system by relating actual weather conditions. Yumoto et al., (2006) set various actual outdoor conditions in summer and winter on the performance investigations of stand-alone air-conditioning system. On the other hand, Oropeza-Perez, (2016) calculated the energy performance of air-conditioning system according to the actual weather data of Mexico and found out that the indoor temperature decreased due to COP of air-conditioning system. In this research, energy recovery unit is integrated split unit air-conditioning system to improve the cooling and dehumidification functions by simulating hot and humid actual weather conditions which acts as a reference and advancement of knowledge in terms of energy-efficient building applications to the industry players, engineers and architects.

2.5 Performance of Integrated Energy Recovery for Split Unit Air-conditioning System

Minimizing energy demand and enhancing energy efficiency are broadly considered as the most promising, fastest, cheapest and safest means to reduce the effects of global warming (Sorrel, 2015). In this respect, integrating energy recovery split unit air-conditioning system has been investigated with several types of energy recovery unit at different climatic zones (Nasif et al., 2010; Delfani et al., 2012; Rasouli et al., 2013; Wang et al., 2015; Yang et al., 2015) to reduce thermal ventilation losses of building while lowering the required energy support (Mardiana-Idayu and Riffat, 2012). In the meantime, this study focusses on hot and humid climate which tackles on the high humidity problem by applying hydrophilic polymeric membrane of cross-flow energy recovery unit to absorb humidity in the air. From Figure 2.1, parameters such as temperature, relative humidity and air velocity are the independent variables affecting the performance of energy recovery unit as stated in Section 2.3.1. As such, by integrating energy recovery unit and split unit air-conditioning system, the performance of integrated system such as coefficient of performance (COP), cooling capacity, potential energy recovered and carbon dioxide emission reductions are affected by the independent variables.

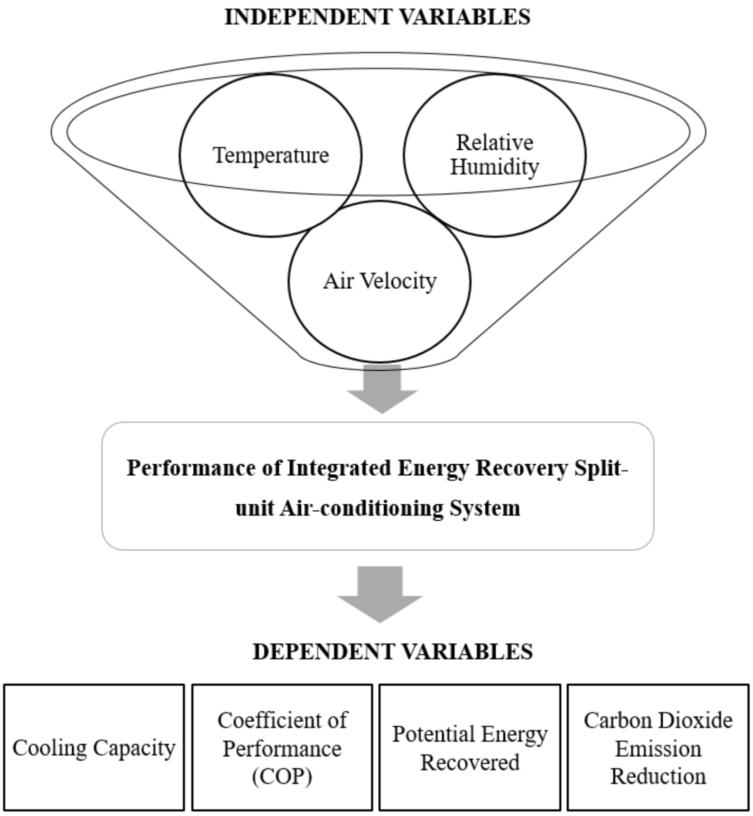

Figure 2.1: Variables affecting the performance of integrated energy recovery for split unit air-conditioning system.

2.5.1 Potential Energy Recovered

Majority energy consumption originates from heating, ventilating and air-conditioning (HVAC) system, leading to exhausted condensing heat to the environment (Gong et al., 2008). In regards to this, several approaches have been performed on different types of air-conditioning system coupling energy recovery unit to appraise the recovered energy (Yau, 2007; Nasif et al., 2010; Rasouli et al., 2013; Ahmadzadehtalatapeh, 2013; Wang et al., 2015; Yang et al., 2015; Jadhave and Lele, 2015; Fucci et al., 2016). Figure 2.2 displays the process of potential energy recovered of the integrated system.

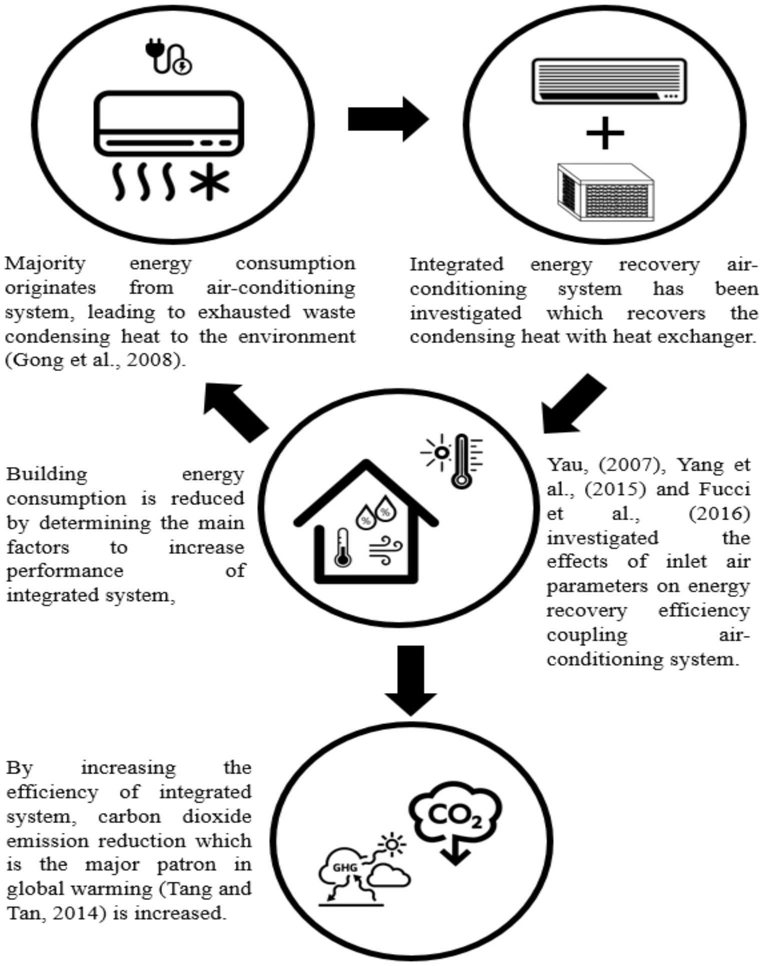

Figure 2.2: Process of potential energy recovered of the integrated system.

For instance, Delfani et al., (2012) compared annual energy use for cooling and heating of each system in various locations by modeling air-conditioning system integrated membrane Z-flow heat exchanger. They concluded that integrated system can significantly reduce latent load under varying operating conditions in hot and humid climate. Furthermore, Wang et al., (2015) analyzed various operation strategies and potential energy savings by integrating membrane-based energy recovery unit into conventional variable air volume systems for commercial buildings in four selected climates. In this study, they compared their results with a baseline case in compliance with ASHRAE Standard 90.1.

On the other hand, Rasouli et al., (2013) presented the uncertainties of actual building HVAC energy use and economic benefits of energy recovery unit due to uncertainties in building and HVAC system parameters. On the contrary, Yang et al., (2015) found out that the temperature difference of indoor and outdoor has major influence on energy recovery efficiency and energy saving in energy recovery unit of heat pipe heat exchanger coupling air-conditioning system. Additionally, Delfani et al., (2012) implemented and compared energy consumption for four types of cooling systems which comprised of different amount of membrane heat exchangers to provide fresh air to indoor spaces in hot and humid climate zone.

Apart from that, Jadhave and Lele, (2015) simulated the performance of energy recovery unit of heat pipe heat exchanger with air-conditioning system. The results showed that the potential energy saving varies with variation in input parameters. Anyhow, parameters such as plant operating conditions, pressure drop, additional fan power consumption which affect the performance of energy recovery unit are not included in this study. In another study, Ahmadzadehtalatapeh, (2013) concluded that the energy recovery unit improves the energy consumptions of the integrated system by using heat pipe heat exchanger in hot and humid climate.

In contrast, Fucci et al., (2016) evaluated the energy performance of integrated energy recovery for air-conditioning system by setting different simulated outdoor temperature and a fixed simulated indoor temperature. On the other hand, Yau, (2007) investigated the effects of inlet air parameters of dry-bulb temperature, relative humidity and air velocity on heat pipe heat exchanger for tropical building

HVAC system in hot and humid climate. Yet, there is no further discussion on how the efficiency of energy recovery unit affects the energy performance of integrated system. In this study, to reduce the building energy consumptions and emissions of carbon dioxide, the main factors increasing the performance of integrated energy recovery for split unit air-conditioning system are investigated with hydrophilic polymeric membrane which aids in the process of moisture transfer in hot and humid conditions.

In another aspect, to mitigate the impacts of energy consumption which stands about 40% of total energy consumption in buildings (EIA, 2014), integrated energy recovery for split unit air-conditioning system, which is a low carbon energy-efficient technology (Mardiana and Riffat, 2015) was investigated (Jadhav and Lele, 2016; Yau, 2007). Carbon dioxide emission reduction, the major patron in global warming (Tang and Tan, 2014), is evaluated for performance enhancement of the integrated system in this study by employing Department for Environment, Food and Rural Affairs (DEFRA) guidelines, which provides blueprint for measurement and reporting criteria for greenhouse gases (GHG) emissions (Tauringana and Chithambo, 2014; Hill et. al., 2013).

CHAPTER 3

METHODOLOGY

3.1 Background

This chapter describes the procedure of investigating the performance of stand-alone unit and integrated system. There are four phases in this research study which are experimental configuration, experimental testing, analysis of variance, and potential energy recovered analysis. Overview of the methodology can be referred to the Figure 3.1.

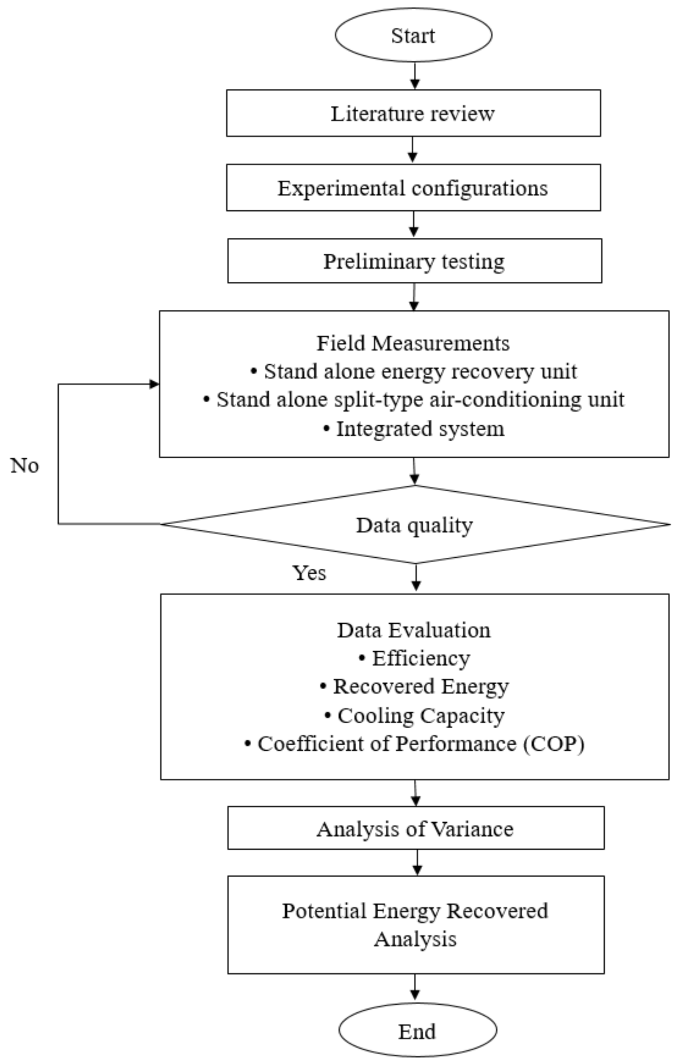

Figure 3.1: Overview of methodology for experimental study.

3.2 Description of Integrated System

The integrated energy recovery for split unit air-conditioning system comprises of split unit air-conditioning system and energy recovery unit. The evaporator (indoor unit) is integrated to the cold stream of pre-conditioned air in energy recovery unit (Zhang, 2006). Details of the system are discussed further below.

3.2.1 Energy Recovery Unit

A prototype fixed-plate heat exchanger core of energy recovery unit with dimension of 0.25 m x 0.25 m x 0.1 m, which was custom made according to the design parameters, is applied in this research. It consists of 12 layers of flat and sinusoidal plate of hydrophilic polymeric membranes which were purchased internationally and 22 channels in total with each channel pitch of 0.0025 m as shown in Figure 3.2. The membrane layers are organizing in cross-flow for heat and moisture transfer concurrently as displayed in Figure 3.3. A 0.4 m x 0.6 m x 0.2 m core casing as displayed in Appendix A, which is made of 0.001 m of aluminum plate and 0.025 m polystyrene sandwich panels is built to envelope the fixed plate heat exchanger core.