IMPROVEMENT OF AIR CONDITIONING UNIT USING A COST-EFFECTIVE SENSIBLE HEAT STORAGE SYSTEM

by

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LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
AC	Air conditioning (system)
ACTES	Air conditioning - Thermal energy storage integrated (system)
AHU	Air-handling unit
APEC	Asia-Pasific Economic Cooperation
ASF	Advance size function
ASHRAE	The American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc
ASV	Actual sensation vote
BEI	Building energy index
BSEEP	Building Sector Energy Efficiency Project
CAD	Computer-aided design
CFD	Computational Fluid Dynamic
CO2	Carbon dioxide
COP	Coefficient of Performance
EER	Energy Efficiency Ratings
EU	Europe Unites
FBM	Full body mesh
GDP	Gross Domestic Products
GHG	Greenhouse gas
GIT	Grid independence test
GreenTech	Malaysian Green Technology Corporation
GTTM	Gas - tube - tank mesh
HDPE	High-density polyethylene
HF	Heat flux
HP	Horse-power
HTF	Heat transfer fluid
HVAC	Heating, ventilation and air conditioning

IACTES	Air conditioning - Insulated thermal energy storage integrated (system)
IEA	International Energy Agency
IES	Integrated Environmental Solutions
INDC	Intended Nationally Determined Contribution
JTM	Jabatan Tenaga Malaysia
LED	Light emitting diodes
LEO	Low Energy Office
LHS	Latent heat storage
MEPS	Minimum energy performance standards
Mtoe	Milllion tones of oil equivalent
PBP	Payback period
PCM	Phase change material
PEL	Power & energy logger
RC	Relevance centre
RE	Renewable energy
Re	Reynold number
RH	Relative humidity
RMS	Residual
SHS	Sensible heat storage
SS	Steady state
SSPCM	Shape stabilised phase change material
SST	Shear Stress Transport
TES	Thermal energy storage
TS	Time step
TT	Total time
TSU	Thermal storage unit
TTGM	Tank - tube - gas mesh
UAE	United Arab Emirates
UNFCCC	United Nations Framework Convention on Climate Change
VAV-AC	Variable air volume air-conditioning

LIST OF SYMBOLS

$\ddot{q}$	Heat Flux (Wm^{-2})
β	Thermal expansion coefficient (K^{-1})
μ	Dynamic viscosity
σ	Stefan-Boltzmann constant of 5.669 x 10-8 ($Wm^{-2}K^{-4}$)
ε	Emissivity
$\dot{Q}_x$	Heat transfer rate over the area (W)
$\dot{Q}$	Total heat transfer in and out of the system (W)
α	Thermal diffusivity (m^2s^{-1})
V	Kinematic diffusivity ($m^2s\text{-}^1$)
ρ	Density (kgm^{-3})
ΔE_{system}	Total energy change within the system (J)
ΔT	Temperature difference (°C)
A	Area of section (m^2)
Cp	Specific heat capacity (JK^{-1})
D	Diameter (m)
D_{helix}	Helical coil diameter (m)
dT/dx	Temperature gradient through *x*.
D_{tank}	Tank diameter (m)
D_{tube}	Tube diameter (m)
E_{gen}	Energy generated within the system (J)
g	Acceleration due to gravity (ms^{-1})
Gr	Grashof number
h	Heat transfer coefficient ($Wm^{-2}K^{-1}$)
H	Height (m)
$\boldsymbol{h_1, h_4}$	Enthalpy of the refrigerant entering and exiting the compressor ($kJmol^{-1}$)
$\boldsymbol{h_3}$	Enthalpy of the refrigerant entering the evaporator ($kJmol^{-1}$)
$\mathrm{H_{helix}}$	Helical coil height (m)
H_{tank}	Tank Height (m)
k	Thermal conductivity ($Wm^{-1}K^{-1}$)
l	Length (m)

Lc	Characteristic length (m)
$\dot{m}$	Mass flow rate (kg/s)
N	Revolutions
Nu	Nusselt number
P	Pressure (psi)
Pr	Prandtl number
Q	Amount of heat (J)
R	Thermal resistance
Ra_L	Rayleigh number
S	Shape factor
$T\infty$	Fluid temperature (°C)
T_{amb}	Ambient temperature (°C)
T_e	Temperature readings from experimental works (°C)
T_s	Temperature readings from experimental works (°C)

Subscript

air.gap	Air (gap in between plywood and zinc)
air.in	Air (indoor)
air.out	Air (outdoor)
comp	Compressor
condenser	Condenser
cond	Conduction
conv	Convection
evap	Evaporator
f	Floor
fc	Forced convection
fw	Front wall
helix	Helical Coil
inlet	Inlet

lw	Left wall
nc	Natural convection
ply	Plywood layer
r	Roof/ceiling
rad	Radiation
riw	Right wall
room	Room
rw	Rear wall
soil	Soil
T	Total
tank	Tank
tube	Tube
wall	cabin container wall
zinc	Zinc layer

Penambahbaikan Unit Penghawa Dingin Menggunakan Sistem Penyimpan Haba yang Kos-Efektif

ABSTRAK

Projek ini mengkaji prestasi sistem penghawa dingin jenis split, dengan dan tanpa penyepaduan penyimpanan haba terma (TES). Terdapat dua jenis TES secara umum, iaitu storan haba sensible and (SHS) storan haba laten (LHS). Dalam kerja ini, TES dari jenis tiub dalam tangki dengan penggunaan storan haba sensible (tangki SHS) telah dibina dan disepadukan ke dalam sistem Split Unit AC yang digunakan untuk menyejukkan bilik kabin. Melalui proses penyepaduan tersebut, tiga konfigurasi sistem penyejukan telah ditubuhkan dan diuji. Ia termasuklah (1) Bekas kabin dengan sistem AC konvensional, (2) Bilik kabin dengan sistem integrasi tangki air (ACTES) dan (3) Bilik kabin bersepadu dengan sistem tangki air bertebat (IACTES). Daripada kerja eksperimen, penggunaan tenaga ketiga-tiga sistem yang diuji telah dinilai. Selain itu, pengedaran suhu dan kelembapan relative (RH) di dalam bilik kabin telah direkodkan dan diperhatikan untuk mengkaji kesan integrasi TES kepada keselesaan dalaman. Dari hasil eksperimen, pengedaran suhu (Te_{room}) didapati bertambah baik dengan penyepaduan tangki SHS @ TES. Sistem bersepadu IACTES telah menghasilkan perbezaan suhu (ΔT) serendah 0.81 ± 0.01° C (5.1%) apabila dibandingkan dengan suhu yang diset kepada 16°C. Sementara itu, suhu purata bagi sistem bersepadu AC dan ACTES adalah 2.96 ± 0.01° C dan 2.84 ± 0.01°C, masing-masing. Selain itu, arus elektrik kumulatif untuk ketiga-tiga sistem menunjukkan bahawa penyepaduan tangki air sebagai TES mengurangkan penggunaan elektrik sebanyak 5%, manakala penyepaduan tangki air yang terlindung dengan baik menjimatkan sehingga 8% daripada penggunaan elektrik. Bagi satu unit AC dengan kos RM360, jumlah penjimatan penggunaan elektrik dianggarkan sebanyak RM63 setahun dengan tempoh bayaran balik 1 tahun dan 318 hari. Walaubagaimanapun, dengan merujuk kepada jumlah penggunaan tenaga di Malaysia pada tahun 2016, 8% pengurangan itu sebenarnya boleh menjimatkan sehingga RM 2,323,926,776 setahun. Oleh itu, sistem bersepadu yang dibangunkan dalam projek ini dipercayai dapat menetapkan tanda aras bagi kajian terma, terutamanya dalam kerja-kerja penyelidikan dan pembangunan reka bentuk AC dan peti sejuk. Seterusnya, pengedaran suhu di dalam bilik kabin disiasat melalui pemodelan dan simulasi CFD. Model bilik dibangunkan seperti model sebenar semasa kerja pengujian. Perbandingan pengagihan suhu suhu udara meninggalkan penyejat (dari kerja percubaan) digunakan sebagai nilai masuk (T_{inlet}) untuk kerja-kerja simulasi Ansys. Model CFD disahkan dengan membandingkan pengedaran suhu yang diperoleh dari kerja-kerja simulasi ke data yang direkodkan dari kerja eksperimen yang telah dilakukan. Dalam kerja ini, kaedah baru untuk menganggarkan kehilangan haba diperkenalkan. Kehilangan haba purata dari bilik (bagi setiap dinding) masing-masing adalah 19.7, 19.0 dan 17.0 W/m^2. Nilai fluks haba yang diperoleh dari simulasi kemudian digunakan untuk menganggar COP sistem melalui kaedah pemodelan matematik. Daripada anggaran, ia menunjukkan bahawa COP sistem split unit AC ditingkatkan dengan penyepaduan tangki SHS sebagai sistem storan terma. Oleh itu, ia dapat disimpulkan bahawa penyepaduan air dalam tangki sebagai penyimpanan haba dilihat untuk mampu membantu untuk meningkatkan prestasi sistem split unit AC. Walaubagaimanapun, tangka SHS perlulah disaluti dengan penebat untuk memaksimakan keberkesanan system itu.

Improvement of Air Conditioning Unit using a Cost-Effective Sensible Heat Storage System

ABSTRACT

This project mainly investigates the performance of a split unit air conditioning system, with and without the integration of thermal energy storage (TES). In this work, the cost-effective tube-in-tank type of TES with the employment of sensible heat storage (SHS) material was constructed and integrated into a Split Unit AC system that used to cool a cabin container. From the integration, three configurations of cooling systems were established and therefore tested. It includes (1) Cabin container with conventional AC system, (2) Cabin container with water tank integration (ACTES) system, and (3) Cabin container integrated with insulated water tank (IACTES) system. From the experimental works, the energy consumption of all three tested systems was evaluated. Besides, the temperature distribution and relative humidity (RH) inside the cabin container were recorded and observed as to examine the effect of TES integration to the indoor comfort. From the experimental results, the temperature distribution (Te_{room}) is found to have improved with the integration of TES tank. IACTES integrated system has resulted the temperature difference (ΔT) to be as low as 0.81±0.01°C (5.1%) when compared to the set temperature of 16°C. Meanwhile, the average temperature for Conventional AC and ACTES integrated system are 2.96 ± 0.01° C and 2.84 ± 0.01°C, respectively. Besides, the cumulative electrical currents for the three configurations show that the integration of water tank as TES reduces the electricity usage by 5%, while the integration of well-insulated water tank saves up to 8% of the electricity consumption. For a single unit of a split unit AC system, with the cost of RM360, the total savings of the electrical consumption are estimated to be RM63 annually with payback period of 1 year and 318 days. Nevertheless, with referring to the total energy consumption for Malaysia in 2016, 8% of the reduction could save up to RM 2,323,926,776 a year. Therefore, the integrated system developed in this project is believed to set a benchmark for thermal studies, especially in AC and refrigerator design research and development works. Accordingly, the temperature distribution inside the cabin container were investigated through CFD modelling and simulation. The room model was developed matched the actual model as in experimental works. The temperature distribution of air temperature leaving the evaporator (from experimental works) are used as inlet values (T_{inlet}) for Ansys simulation works. Comparisons on temperature distribution obtained from the simulation works to the data recorded from experimental works were done. In this work, new method for estimating heat losses is introduced. The average heat loss from the room (for each wall) is found to be 19.7, 19.0 and 17.0 W/m^2, respectively. The values of heat flux obtained from the simulation are then used to estimate the COP of the system through the mathematical modelling method. From the estimation, it showed that the COP of a split unit AC system is improved with the integration of SHS tank as thermal storage system. In a nutshell, it can be concluded that the integration of water in tank as sensible heat storage is found to enhance the performance of the split unit AC system, with the SHS tank is best being insulated.

CHAPTER 1 : INTRODUCTION

The employment of air conditioning (AC) system has become a necessity to achieve better thermal comfort in buildings. Nonetheless, the usage of AC system in buildings has increases load on power used, thus increasing energy consumptions and therefore cause of high electricity tariff. A split unit air conditioner is a typical AC type that is employed for space cooling in residential buildings. A split unit AC system is composed of four main components of evaporator, condenser, compressor and expansion valve, connected by refrigerant lines. Most of the energy used in a split unit AC system is during the vapour compression process (Cengel & Boles, 2013).

In general, the power input required to the compressor increased with the influence of superheating, heat gain in the connecting line (evaporator to compressor/suction line), and pressure drops in the evaporator and the suction line. These factors have resulted the specific volume of gas to increase, hence increasing the power input required for gas compression (Cengel & Boles, 2013). The compressor work can be reduced by keeping the specific volume of gas as small as possible during the compression process. This could be attained by maintaining the temperature of the gas as low as possible during the compression since the specific volume of gas is proportional to its temperature (Cengel & Boles, 2013).

Including the energy used for space cooling, buildings consumed about 40% of the total energy consumptions (Hughes, Chaudhry, & Ghani, 2011) and considered as the primary contributor to the greenhouse gas emission (Cao, Dai, & Liu, 2016). For the last forty years, the demand for the building sector is seen to comply with an increasing trend of 1.8% annually (Jung, Paiho, Shemeikka, Lahdelma, & Airaksinen, 2018). Consistent with that, global energy consumption is seen to be increased in past decades and presumed to be continually rising (International Energy Agency (IEA), 2018). The trend of global energy consumption is shown in Fig. 1.1. The foreseen significance growth of the energy demand is induced by climatic change and economic development, which is further amplified by the expected increase of the local population (Calautit, Aquino, Shahzad, Nasir, & Hughes, 2017).

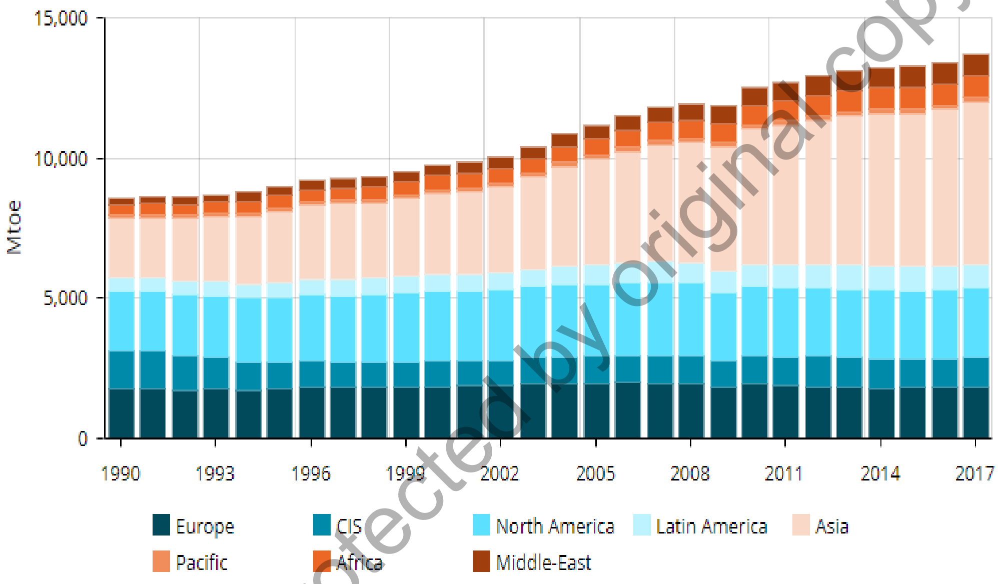

Figure 1.1 Global Energy Consumption for 1990-2017 (World Energy Statistics Enerdata, 2018)

In order to counterbalance the soaring energy demands, numerous approaches have been proposed and implemented to achieve a better "energy efficiency" in buildings (Guen *et al.*, 2018). In the building sector, achieving a better "energy efficiency" is indicating a condition that is advantageous to end-users (Pacheco, Ordóñez, & Martínez, 2012). Cao *et al.*, (2016) reported that the most substantial portion of the total energy consumption in the U.S, China and EU in 2010 are consumed for space and water heating. Remarkable efforts have been made over the years, aiming to alleviate the energy efficiency and to minimise energy consumption (Guen *et al.*, 2018; Lopes, Antunes, & Martins, 2015).

For instance, incorporation of appropriate heating and cooling design in the building is recognised as one of the viable alternatives to cut energy costs in buildings (Shoubi, Shoubi, Bagchi, & Barough, 2015). Cooling strategies with the integration of thermal energy storage (TES) system have been thoroughly discussed as one of the viable technique to achieve better energy efficiency in buildings.

1.1 Thermal energy storage (TES) system

Thermal energy storage system has attracted profound interest from researchers for their use in eliminating environmental problems with the capability to minimise the gap between energy demands and the supply (Li & Zheng, 2016; Parameshwaran, Kalaiselvam, Harikrishnan, & Elayaperumal, 2012). TES is defined as the temporary holder of thermal energy in the form of hot or cold substances for later utilisation (Mehling & Cabeza, 2008). TES system was first introduced in 1930s, to store solar heat for space heating in building (De Gracia & Cabeza, 2017).

TES system has been employed for many applications, such as for space heating and cooling of buildings (Castell, Martorell, Medrano, Pérez, & Cabeza, 2010), solar energy (Krese, Koželj, Butala, & Stritih, 2018), peak load shifting (Qureshi, Nair, & Farid, 2011), cold storage for food technology (Oró, de Gracia, Castell, Farid, & Cabeza, 2012), domestic water tanks (Cabeza, Iba, & Sole, 2006; De Gracia, Oró, Farid, & Cabeza, 2011) and seasonal storage. Meanwhile, Mahlia *et al.* (2014), discussed various types of available energy storage including flywheel energy storage (FES), pumped hydro energy storage (PHES), battery energy storage (BES), compressed air energy storage

(CAES), flow battery energy storage (FBES), superconducting magnetic energy storage (SMES), supercapacitor energy storage (SCES), hydrogen energy storage, synthetic fuels, and thermal energy storage (TES).

In TES system, thermal energy can be stored by using three different storage types, namely sensible heat storage (SHS), latent heat storage (LHS) and thermochemical energy storage. Sensible storage is the most common way of energy storage (Mehling & Cabeza, 2008) which the thermal energy is stored by raising the temperature of the storage medium (Prabhu, Shinde, & S, 2012). The energy storage density in sensible heat storage is determined by the specific heat capacity of the storage medium (such as water, rock and sand) and the temperature changes based on designed application (Mehling & Cabeza, 2008).

Meanwhile, LHS is referred to the heat stored during a phase change process, that is calculated from the enthalpy difference ($\Delta \boldsymbol{h}$) between the solid and liquid phase (Zhang, Baeyens, Cáceres, Degrève, & Lv, 2016). Latent heat storage using PCM was recognised to be more efficient when compared to the SHS as it provides higher heat storage capacity and more isothermal behaviour during charging and discharging processes (Verma *et al.*, 2008). On the other hand, thermochemical energy storage densities are claimed to be similar to PCMs but is reported to be more complex than SHS and LHS (Mehling & Cabeza, 2008).

The energy storage density in sensible heat storage is determined by the specific heat capacity of the storage media and the temperature changes based on designed application. Latent heat storage using phase change materials (PCMs) is said as one of the most efficient methods to store thermal energy because it provides higher heat storage capacity and more isothermal behavior during charging and discharging compared to sensible heat storage (Cabeza 2002). A good storage medium needs to have high specific and latent heat values (Demirbas, 2006). The small latent heat in solid-solid transition and large volumes required for gas transformations are the drawbacks of these two types of storage options. Latent heat storage by solid-liquid phase transition provides high energy storage density and has the capacity to store energy at a latent heat of fusion at a constant temperature corresponding to the phase transition temperature of the material (Demirbas, 2006).

TES system can be integrated into the buildings via two main methods, namely active or passive cooling (Givoni, 1991). The employment of both active and passive cooling system will form a hybrid cooling system. The thermal storage is classified into 'active' or 'passive' storage types based on the heat transfer fluid (HTF) for being active or not (Mehling & Cabeza, 2008). Referring to Mehling and Cabeza (2008), an 'active' storage system is mainly characterised by forced convection heat transfer and mass transfer in some cases. Meanwhile, in the case of free or no convection occurred in TES, the storage system is denoted as ‘passive'. Implicitly, passive cooling with TES can be described as a technique to cool a system without external energy resource. Whereas, active cooling strategy covers all the thermal storage being integrated into the conventional HVAC systems (Baetens, Jelle, & Gustavsen, 2010). Table 1.1 presents the storage type of TES.

Table 1.1 Storage types (Mehling & Cabeza, 2008)

Notation with respect to the method of heat transfer	**Notation with respect to the HTF being (actively moved or not)**
Storage with heat transfer on the storage surface	
Insulated environment	passive/active
No insulation and good thermal contact between storage and demand	passive/active
Storage with heat transfer on internal heat transfer surfaces	
Heat exchanger type	active
Direct contact type	active
Module type	active
Storage with heat transfer by exchanging the heat storage medium	
Slurry type	active
Sensible liquid type	active

In space cooling and heating, the primary aim of the TES integration is to keep the temperature at certain (required) temperature range. Passive cooling strategies have been proven to effectively improve comfort conditions while minimising the needs of mechanically heating or cooling systems (Taleb, 2014). In general, the flow of energy in passive design is based on natural means, radiation, conduction, convection without the use of mechanical devices to dissipate heat. It utilises on-site energy, accessible from the natural environment, together with the architectural design of building components (Santamouris & Asimakopoulos, 1996). Therefore, to have an effective passive cooling, it requires excellent natural resources as a heat sink. For instance, onsite heat sinks are soil, night sky (environment) or wind. The example of modern passive systems includes solar heating and night ventilation technique and thermal mass (Castell *et al.*, 2010), shading effect using blinds (Gratia & De Herde, 2007), use of ventilation facades and coated glazing elements (Eriksson, 2009).

In contrast to the passive cooling that is focused to be integrated directly to the core of the building, active strategies are more versatile that could be integrated with various ways. For active cooling method, building thermal inertia is commonly incorporated to improve the thermal performance of the construction systems such as floors, ceiling and walls for active cooling strategy. Nevertheless, active systems need the help of mechanical equipment to circulate HTF within the systems for forced convection to occur. The utilisation of active cooling strategies is found to be more flexible when compared to the passive strategies that are suitable for newly-designed building and found to be climate-dependent (Aziz *et al.*, 2018). The integration of active cooling in buildings with the employment of mechanical refrigeration systems has increased the tendency of achieving a better thermal comfort for a more extended period. The flexibility of this system has provided useful assistance and led to a change in lifestyles and work habits.

Despite the advantages of active cooling strategy, passive cooling strategy has been recommended as a better option since it is environmentally-harmless and could be utilised without an additional power source (Kamal, 2012). Due to the notable drawbacks of the existing integration method, this project is conducted to develop a cost-effective thermal energy storage (TES) system to be integrated into building, aiming to investigate the effect of integration in terms of energy consumption and indoor comfort of the room. This research is focusing on the split unit air conditioning (AC) system that is commonly used for space cooling in residential buildings.

1.2 Research Problems

The active cooling technique is found to be more versatile and could be integrated in many ways. However, the active cooling technique requires additional power sources to run the system. Besides, the integration of active system may result in additional issues to the building physics such as humidity issue, airtightness and thermal bridge. In contrast, passive cooling technique is agreed to be eco-friendly compared to the active cooling technique (Solgi, Hamedani, Fernando, Skates, & Orji, 2018). Nevertheless, the utilisation of passive cooling with TES system is limited due to overdependence on climatic factors, storage materials properties, and the architecture of the building itself. For both active and passive cooling techniques, the utisation of utilisation of PCMs as thermal storage is acknowledged as the most favourable storage medium. Nonetheless, Lukic, Tamburic, & Stojic, (2012) reveal that the integration of the PCMs into the building envelop (wall, floor, etc.) needs a meticulous work, especially when the integration work involves the cutting or drilling the buildings. Besides, Formato (2013) claimes that most of the PCMs are rarely available and the manufacturability of these incommodities materials is also costly hence making the PCM expensive. Henceforth, the employment of PCM as thermal storage materials to cool a common resident may be uneconomic to be implemented in residential building sector.

In a nutshell, it can be concluded that the existing integration method of TES system through active and passive techniques is high cost, thus not suitable to be applied in the residential building sector. Therefore, this study proposed cost-effective TES integration into the split unit AC system that is commonly employed in residential buildings. To keep the integration low cost, water was used as thermal storage materials as it is readily available and inexpensive.

1.3 Research Objectives

The primary aim of this project is to evaluate the capability of a cost-effective sensible heat storage (SHS) system to improve the performance of 1HP Split unit AC system used for space cooling. As for the performance measure, several objectives to be achieved are;

1) To develop and fabricate a cost-effective TES model for a split unit AC system.

2) To evaluate and compare the energy performance of the AC system with and without TES unit.

3) To determine the heat flux values and total heat transfer within the cabin container based on CFD and mathematical modelling approach.

1.4 Research Questions

This study is directed based on the research questions listed below;

- Will TES tank integration influence the performance of air conditioning system?
- How much energy can be saved from the integration of the TES system?
- Is the investigated ACTES integrated system worth to be implemented?
- Is the TES better be exposed to the environment or must it be fully insulated?

1.5 Research Scopes

This study focuses on the investigation of 1 HP split unit AC system integrated with a tube-type thermal energy storage tank that is installed to cool the cabin container with the volumetric space of 3.048 × 6.096 × 2.621 m. The experimental works are conducted in ILP Kepala Batas, Pulau Pinang, Malaysia with the tropical climate. The room experimented under the maximum performance of AC unit with setup of 16°C and full speed blower. The room was tested without any occupant present and minimum door openings.

Based on the manufacturing datasheet, the split unit AC system used in this study works with a power consumption of 830W for optimum gas (R410A) of 0.67kg. Nonetheless, AC unit installed to the cabin container (in this study) was modified with retrofitting the TES tank at the suction line. Therefore, mass of R410A is lesser than 0.67kg as the mass of the gas is optimised to stabilise the system for additional piping from TES tank integration. Hence, the power consumption (W) obtained in this work is comparable only to the similar modified system developed in this work (ACTES and IACTES integrated system), and cannot be compared to original manufactured system.

Solidworks software is used to develop both actual sized 3D models of a room (cabin container) and the TES tank. Ansys CFX software is used for all computer simulations. Simulation models are validated by comparing the room temperature obtained from the simulation to the data collected during experimental works. For thermal comfort measures, relative humidity (RH) and indoor temperature (Te_{room}) are considered.

1.6 Rationale of the Study

This research work mainly aims to develop an inexpensive approach to improve energy efficiency in buildings. TES system can be applied to residency building and ready to be optimised for industrial utilisation. The proposed TES system is predicted to be applicable in any cooling systems within the same temperature range. The validated CFD model (room) can be employed for further analysis and optimisation purposes.

1.7 Novelty of the Research Project

A new approach to integrate the TES tank into AC system is introduced. The integration is found to be able to reduce the annual electricity bills (for the investigated space). The system developed in this project is believed to have set a benchmark for thermal studies, especially in AC and refrigerator design research and development works. From the experimental results, it showed that the integration of TES tank at the suction line had influenced the temperature distribution along the refrigeration cycle. When compared to the AC system without TES tank, the integration of TES tank has resulted the temperature inside cabin container to remain within the set range of 16°C.

A working prototype of the air-conditioned room in experimental work has been regenerated in the computer model form. The developed 3D model and the simulation procedures outlined in this thesis can be used for industrial references, especially for future enhancement. A novel method to estimate heat loss from the building has also been introduced in this study. The value of heat loss obtained from the simulation work is further used to estimate COP of the system by mathematical modelling technique.

1.8 Thesis Organisation

The reporting works are presented in six chapters, namely ; (1) Introduction, (2) Literature Review, (3) Experimental Works, (4) CFD Modelling and Simulations, (5) Mathematical Modelling, and (6) Conclusion and Recommendations. The first chapter serves as a general introduction, problem statement, research objectives, research framework and scopes of the present work proclamations. This project is carried out by utilising two main methods, which are via experimental works and Computational Fluid Dynamic (CFD) modelling that are presented separately in Chapter 3 and 4, respectively. Results and discussion from each method are presented in the corresponding chapter.

Chapter 2: Literature Review

In Chapter 2, review from books, journals, conference papers and other sources were collected and presented. The topics presented in Chapter 2, include the thermal comfort assesement, and TES integration into buildings and CFD modelling works. For each topic, the term, definition, method and findings of the published literature are discussed and elaborated.

Chapter 3: Experimental Works

Chapter 3 presents details of the experimental works. The preceding subsections present the system structure and the main components of the studied system. Following that, details of experiments arrangement, including installation works of AC unit, development of TES tank, and integration of TES tank to the AC system are presented. Also, testing procedures and details of the instrumentation set up are discussed.

This chapter summarises the findings obtained from experimental works with four main measures collected that are the indoor temperature, relative humidity, energy, and temperature in the system. Results for experimental parts ended with the presentation of the most critical measure in this work, which is the calculation of the energy savings for the system.

Chapter 4: CFD Modelling and Simulation

Chapter 4 explains the details of CFD modelling to model the room discussed in Chapter 3. In this chapter, procedures in processing finite 3D models are thoroughly described. It includes geometry modelling, meshing generation and simulation setup. Other than that, boundary conditions selection, convergence test, and grid independence test are also deliberated in this chapter. Simulation results are analysed and presented in this chapter. The validated CFD models are then used for further analysis, which is finding the heat loss of the system.

Chapter 5: Mathematical Modelling

Chapter 5 presents the mathematical model representing the room discussed in Chapter 3. Significant works of literature regarding the mathematical modelling of heat resistance and heat transfer are reviewed and summarised. The theoretical thermal resistances of the building in hand are derived and presented in this chapter.

Chapter 6: Conclusion and Recommendations

Major conclusions from the entire study are presented in this chapter, together with some recommendations for future works.

CHAPTER 2 : LITERATURE REVIEW

An extensive literature review has been done. Reviewing the literatures on the targeted topics served as an abundant resource which allowed for reliable inferences and conclusions to be made in modelling the system, both experimental and in the simulation. Review on the energy landscape in Malaysia is provided to ensure the research topic is in line with Malaysia's long-term vision and mission to be more developed country. Afterwards, the review on building's thermal comfort is presented with highlighting the utilisation of HVAC system in achieving desired thermal comfort. Later, the integration works of TES system to the building are reviewed. The endeavours of TES system implementation to improve the energy efficiency in the building are highlighted and conferred. Additionally, the CFD modelling are reviewed and presented at the end of this chapter.

2.1 Energy Landscape in Malaysia

The energy landscape in Malaysia is studied and reviewed to understand factors affecting the increment of energy consumptions. Malaysia is one of the Asian countries with a total area of 329, 847 km^2, located at the southeast of the Asian continent with the coordinate of 2°30' N, 112°30' E. Generally, with uniformly high temperature and humidity, and copious rainfall throughout the year makes Malaysia's climate to be classified as the typical tropical climate (Ashraf, Othman and Ishak, 2018). The average day temperature in Penisula Malaysia is in the range of 23°C to 32°C and 20°C to 30°C at night time.

Malaysia energy landscape has grown and matured in recent years. In line with the objectives of economic transformation programs, the energy diversity, efficiency and sustainability in Malaysia have evolved accordingly. In recent, Malaysia is focusing on diversifying the energy mix with new and renewable energy (RE) sources instead of solely relied on fossil fuels as the primary energy source (Ozturk *et al.*, 2017; Shuit, Tan, Lee, & Kamaruddin, 2009; Zahurul *et al.*, 2016). Towards these missions, numerous diversification programs and policies were initiated. For instance, Malaysia is focusing to save electricity consumption (Suruhanjaya Tenaga, 2017). Based on the recorded statistic, Malaysia's total electricity consumption has increased from 1990 to 2015, with a rate of 7.9% annually (Suruhanjaya Tenaga, 2017). It is forecasted to continually ascended in further years. This increasing pattern is seen to be an obstacle for Malaysia mission to achieve a 45% reduction in its energy intensity by 2035 (Suruhanjaya Tenaga, 2017).

Henceforth, Malaysia has initiated some programs and policies to reduce electricity consumption. The Building Sector Energy Efficiency Project (BSEEP) and Minimum Energy Performance Standards (MEPS) were introduced (International Energy Agency (IEA), 2015). MEPS specify the minimum level of energy performance for appliances, such as lighting and electrical equipment. Meanwhile, BSEEP is designated explicitly for better energy efficiency in buildings (UNDP in Malaysia, Singapore & Brunei Darussalam, 2018). The policies are developed for a clear and valid monitoring system and energy improvement in buildings. Besides, BSEEP also encouraged the application of EE technologies while the building is developed. With that, green buildings are developed as a benchmark in green building development (Suruhanjaya Tenaga, 2012).

Three buildings that are constructed and implemented the green-technology are the building of Malaysian Green Technology Corporation (Figure 2.1a) in Bangi, the Malaysian Energy Commission headquarters, and Low Energy Office (LEO) building. With the development of these green buildings, it set new standards for energy efficiency and solutions for environmental sustainability. GreenTech Malaysia building was constructed with combining advanced green technologies, sustainable energy solutions, innovative energy management systems and rainwater harvesting systems. Meanwhile, the Malaysian Energy Commission headquarters (Diamond Building) is shown in Fig. 2.1 (b).

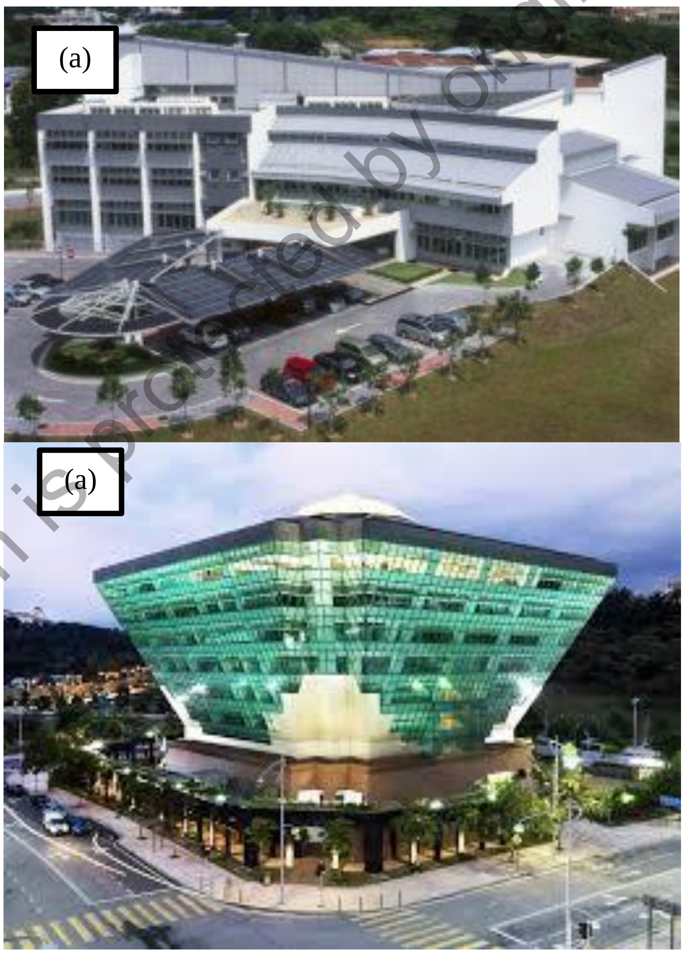

Figure 2.1 (a) GreenTech Malaysia (Greentechmalaysia.my, 2018), (b) Diamond Building (St.gov.my, 2018)

The Diamond Building was built neighbouring to the landscape garden in Putrajaya. Diamond Building is used as a showcase building as it implemented most of the latest technologies available in the country (Fig. 2.2) and also adopted both active and passive design features (Tenaga, 2012b). Diamond Building was built with the integration of the comprehensive list of energy-efficient features as shown in Fig. 2.2 (St.gov.my, 2018). The diamond shape of the building has influenced in maximising the passive design strategies of the upper floors shading the lower floors from solar heat gain (Nikpour, Kandar, Ghasemi, Ghomeshi, & Safizadeh, 2012). The cooling loads were reduced as it helps to avoid direct solar penetration.

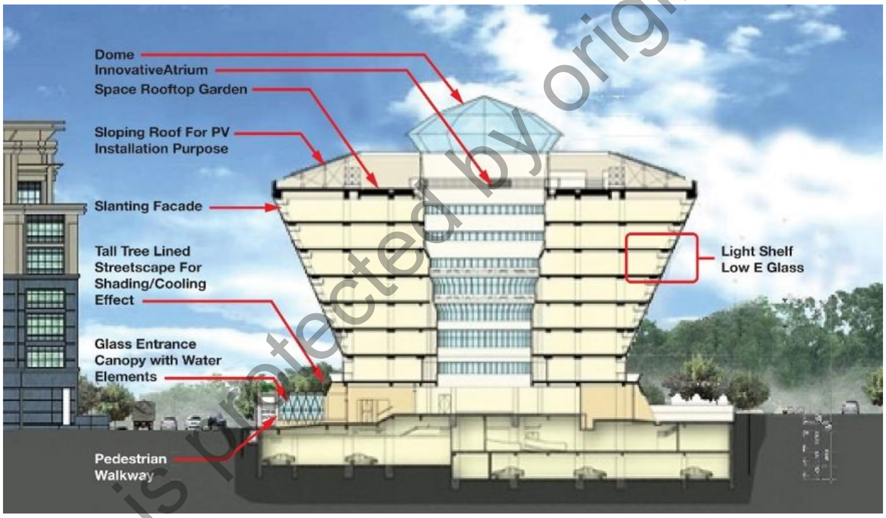

Figure 2.2 Energy efficiency features in the diamond building (St.gov.my, 2018)

Nonetheless, the utilisation of the diamond-shaped sun shading strategy has lowered the potential of using PV as an active design strategy. The PV panels were not installed on the facades as the tilted façades do not receive much direct sunlight. From another perspective, the utilisation of PV panels to generate more energy is discussed as a better option for energy performance and to achieve lower BEI in the diamond building (Xin & Rao, 2013). With that, numerous approaches were implemented and tested to increase the BEI of diamond building. As an example, the intelligent cooling system with the utilisation of embedded PERT chilled water pipe at the roof and floor slab was implemented. This system reduced the floor temperature to 20°C (at night) and it absorbed the heat gain from appliances, human and solar gain. Also, it helps to radiate cooling to the occupants during day time. Correspondingly, it contributes to energy savings. Less energy is required for air conditioning as the implementation of slab cooling has shifted the cooling task of air handling unit (AHU) to the slabs and reduced the size of the AHU room.

Besides, the energy-efficient lights and equipment were installed to the building. The mechanical and electrical system of the diamond building is all designed based on intelligent building approaches (Suruhanjaya Tenaga, 2012a). It maximises energy efficiency while optimising the comfort inside the building. It includes the usage of high-efficiency lighting systems, installed photocells, zone-based temperature sensors, variable speed drives for fan and blower controls and also the uses of star office equipment (Energy Commissioner Malaysia, 2013). With the implementation of these technologies, the Diamond Building has achieved a BEI well beyond the target value despite the inability to implement the PV panels. Nevertheless, continuous improvement for the diamond building is being carried out and it is forecasted for the BEI to be further improved (Energy Commissioner Malaysia, 2013).

Comparatively to the ongoing improvements that have been conducted for the Diamond Building and LEO to achieve its optimum performance, Malaysia is now in need for further investment, research and development in the country's power sector in order to achieve the sustainable development.

2.2 Thermal Comfort in Buildings

The American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc (ASHRAE) defines the thermal comfort as ‘that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation’ (ASHRAE, 2013). In recent years, the increment of public discussion about climate change has increased the research attention in the field of thermal comfort.

The urbanisation and climate change factors are found to affect the population forecast, especially in the city centre in which the population density is expected to rise. As humans are considered to spend 80% and 90% of their days indoors (Charlton, Rutter, East, & Sinclair, 2011), numerous researches have been performed to improve the indoor environmental quality of the buildings (Culp, 2013; de Dear, Leow, & Foo, 1991; Hussin, Salleh, Chan, & Mat, 2014; Kumar, Kumar, Ooka, Rijal, & Gupta, 2018; Luo *et al.*, 2018; Luo, Zhou, Zhu, & Sundell, 2016; Peeters, Dear, Hensen, & William, 2009; Sadat, Tahsildoost, & Hafezi, 2016).

The environmental comfort of building in the hot and humid climate has been extensively studied. For instance, Hussein *et al.* (2009) have evaluated the thermal comfort in two classrooms with fans. The subjects used are seven years old pupils from two different schools in Malaysia. From the investigation, positive results were recorded from 80% of subjects that found the thermal environment to be satisfactory despite the reading of the actual sensation vote (ASV) surpassed the range provided by ASHRAE 55. These data indicated that the individuals in Malaysia have a greater thermal tolerance (Hussein et al., 2009). Other than that, Ismail *et al.*, (2009) investigated the thermal environment of the automotive industry in Malaysia. Poor thermal condition at the workstations is recognised. Likewise, Dahlan, Jones, Alexander, Salleh, & Alias (2009) exposed the inability of buildings in Malaysia's university to deliver a comfortable thermal environment to the occupants. Meanwhile in Taiwan, Wang, Lee, Chang, Chen, & Jung, (2014) has reported that the thermal comfort and air quality of air-conditioned office were improved with the integration of heat exchanger. In Sri Lanka, Wijewardane & Jayasinghe (2008) reported that the influence of air velocity in naturally ventilated factories has resulted the workers to be able to tolerate higher temperatures of above 34°C.

Frontczak and Wargocki (2011) have listed several factors affecting the environmental comfort inside the building that includes the design of the buildings, characteristic of users and outdoor climatic conditions. From the thermal comfort factors by the occupants characteristic, it involves the occupants' age, gender, clothing, health status and their activity level in the building. Also, the physical activity of the human itself is dynamic and challenging to be assessed. There are many guidelines and methods for thermal comfort assessment that was published. Nonetheless, it is believed that specific techniques and steps are required to determine the human thermal comfort accurately. In simplifying the assessments of thermal comfort in a building, ASHRAE has provided simple guidelines to assess the thermal comfort by two factors; namely air temperature (indoor) and RH (Cengel & Boles, 2013).

The thermal comfort in the building can be assessed by measuring the building (indoor) temperature based on the range of Physiological Equivalent Temperature (PET) index. The PET index (Table 2.1) is suitable for both hot and cold climates without relying on subjective measures irrespective to clothing (clo values) and metabolic activity (met values). These guidelines are intended to satisfy the majority of building occupants wearing an average amount of clothing while working at a desk (ASHRAE, 2013).

Table 2.1 PET Index (McCullough, Jones, & Huck, 1984)

PET	**Thermal Perception**	**Grade of Physiological Stress**
Below 4°C	Very Cold	Extreme cold stress
4°C - 8°C	Cold	Strong cold stress
8°C - 13°C	Cool	Moderate cold stress
13°C - 18°C	Slightly cool	Slight cold stress
18°C - 23°C	Comfortable	No thermal stress
23°C - 29°C	Slightly warm	Slight heat stress
29°C - 35°C	Warm	Moderate heat stress
35°C - 41°C	Hot	Strong heat stress
41°C and above	Very Hot	Extreme heat stress

Likewise, RH is a measure of the moisture in the air, compared to the potential saturation level (Cengel & Boles, 2013). ASHRAE 55-1981 (McCullough *et al.,* 1984) quantified the comfort range according to the humidity ratio (g/kg). The maximum air relative humidity is at 60% (ASHRAE, 1992). This is to avoid the mould and mildew grow. In air-conditioned spaces, the higher RH might be acceptable. In Malaysia, the comfortable indoor temperature in Malaysia climate is found to be in the range of 18°C to 23°C and RH under 60%, respectively (Djamila, Chu, & Kumaresan, 2014). Meanwhile, the study conducted in Thailand has indicated that the indoor temperatures are higher in the morning of 26°C to 28°C when compared to the temperature in afternoon and evening (24.5°C to 26°C) (Ngarmpornprasert & Koetsinchai, 2010). In China, Cui, Cao, Park, Ouyang, & Zhu (2013) suggested an ideal range of temperatures 22°C to 26°C for better performance in office.

2.2.1 Heating, Ventilation and Air Conditioning (HVAC) in Building

Amongst the building energy services, the HVAC systems are the most energy-consuming devices, accounting for about 10-20% of final energy use in developed countries (Pérez-Lombard, Ortiz, & Pout, 2008). Thus, reducing the energy consumed by the HVAC system is a crucial factor in achieving better energy efficiency in building (Adhikari, Aste, Manfren, & Marini, 2012). At present, the HVAC system comprising cooling and dehumidification has become a necessity for the hot and humid climates. The HVAC system is crucial for preserving the indoor thermal comfort in the building, especially in the industrial sector, commercial and residential buildings (Saidur, 2009).

The use of HVAC system accounts for a significant share of the total energy consumed in building or facility. It could exceed 50% of the total energy consumption for the case of building in tropical climates (Rismanchi, Saidur, Masjuki, & Mahlia, 2012). This significant figure is primarily due to the heavy-duty placed on cooling technologies to remove both sensible and latent heat loads. Studies have identified that proper selection and operation of HVAC systems can provide energy saving as much as 25% while maintaining acceptable indoor condition (Fasiuddin & Budaiwi, 2011). Several aspects that are influencing the energy required in operating the HVAC system includes the internal building loads, air infiltration, window positioning and the indoor temperature setpoint (Fong, Hanby, & Chow, 2006).

Nonetheless, the factors listed above are dependent on the building type and climate (Lin & Hong, 2013). From the literature, it can be seen that there is tremendous potential to further improving the overall efficiency of the air-conditioning systems in buildings.

2.2.2 Vapor-Compression Refrigeration System

The vapour-compression refrigeration system is the predominant technology in refrigerated transport system (Cengel & Boles, 2013). Theoretically, heat is transferred from a hot to a colder body (Cengel, 2015). On the other hand, in the refrigeration system, the heat flows from a cold to a hotter body. This is achieved by the utilisation of refrigerant that absorbs heat and hence boils or evaporates at a low pressure to form a gas. The vapour-compression refrigerated system is a closed system where the refrigerant substance is circulated in the system throughout the operation. As shown in Fig. 2.3, there are four stages in the vapor compression refrigeration system.

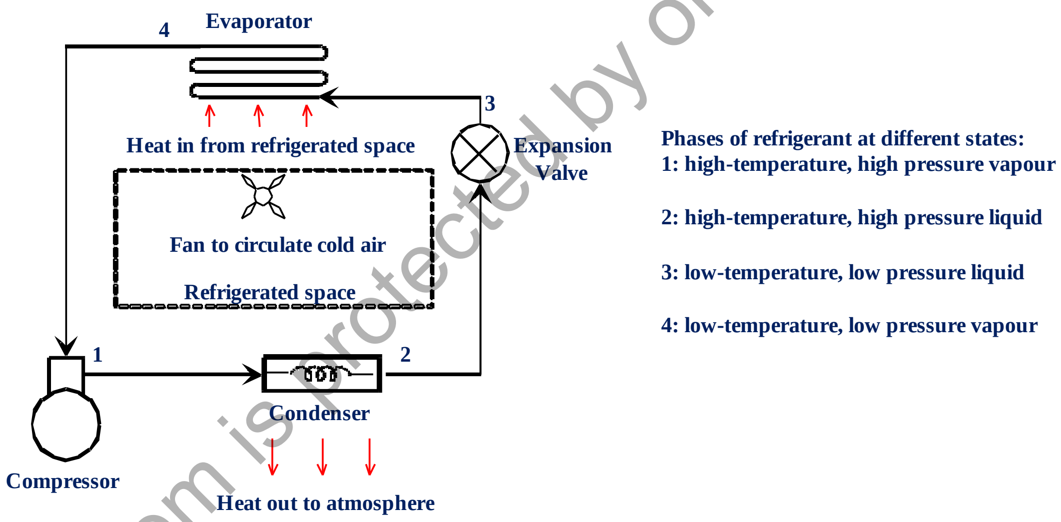

Figure 2.3 Schematic diagram of a single-stage vapour-compression refrigeration cycle (Shurepower, 2005)

At point 4, the low pressure liquid refrigerant in the evaporator absorbs heat from its surrounding, usually air, water or some other processed liquid. Therefore, the refrigerated space is cooled down. During this process, the liquid refrigerant changes it states to the low-pressure vapour. The low-pressure, low-temperature refrigerant vapour (superheated) is sucked into the compressor at point 1. The vapour is compressed, and it is discharged as the high-pressure, high-temperature refrigerant vapour (superheated) to the condenser. At point 3, the vapour condenses to high-pressure, high-temperature liquid (supercooled).

The heat is removed from the condenser to the circulating air or water. The liquid refrigerant then goes through the expansion valve, which adjusts the flow rate of the refrigerant going through the evaporator and also keeps the pressure differential between the high and low sides. The liquid refrigerant is then returned to the evaporator to continue the cycle. The performance of a refrigeration cycle is usually evaluated by a coefficient of performance (COP). It is defined as the amount of heat removed divided by the energy input to operate the cycle (ASHRAE Handbook, 2006). For a mechanical vapour-compression refrigeration system, the COP can be calculated by Eqn. 2.1.

$$COP = \frac{Q_{evap}}{W_{net}} = \frac{h_4 - h_3}{h_1 - h_4} \tag{2.1}$$

where Q_{evap} is the amount of heat removed in the evaporator; W_{net} is amount of net energy supplied, h_4 and h_1 are representing the enthalpy of the refrigerant entering and exiting the compressor and h_3 is enthalpy of the refrigerant entering the evaporator.