An- Najah National University
Faculty of Graduates Studies

Investigating Residential HVAC System COP Using Different Engineering Designs – Experimental Study

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This Thesis is Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Clean Energy and Conservation Strategy Engineering, Faculty of Graduate Studies, An-Najah National University, Nablus, Palestine.

2019

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Dedication

Dedicated to.....

My mother soul

My father

My wife

My daughters(Rand, Raghad, Rahaf & Hala)

Acknowledgments

I would like to express great thanks and sincere gratitude to my supervisor Dr. Mohammed Alsayed for his guidance, suggestions and assistance during the preparation of this thesis.

My thanks and respects go to the staff of Tulkarm Secondary Vocational School at which my experiment was carried out.

Special grateful acknowledgement is made to my family for their help and encouragement.

الإقرار

أنا الموقع أدناه، مقدم الرسالة التي تحمل العنوان:

Investigating Residential HVAC System COP Using Different Engineering Designs – Experimental Study

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List of Abbreviations

Abbreviation	Meaning
ACC	Air cooled condenser
Amp	Amber
AHRI	Air-Conditioning, Heating and Refrigeration Institute
BTU	British Thermal Unit
CFCs	Chlorofluorocarbons
COP	Co-efficient of Performance
°C	Centigrade Celsius
T_{db}	Dry Bulb Temperature
Dis.	Discharge
EIA	Energy Information Administration
EER	Energy Efficiency Ratio
GHGs	Greenhouse gases
GW	Global Warming
C_{Gt}	Giga ton of Carbon
H	Enthalpy
IEA	International Energy Agency
$\dot{m}$	Flow Rate
Mt	Million Tons
NO_X	Nitrogen Oxides
P	Pressure
pH	Potential Hydrogen (a measure of acidity)
$Q_{evap.}$	Cooling Effect

$Q_{cond.}$	Heat removed through condenser
R-410	Refrigerant
R.H	Relative Humidity
Sat.	Saturation
SO_2	Sulfur dioxide
Suc.	Suction
T_R	Ton Refrigeration
TXV	Thermostatic Expansion Valve
VCRC	Vapor Compression Refrigeration Cycle
T_{WB}	Wet Bulb Temperature

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Abstract

Palestine suffers from a shortage of electricity because of the Israeli occupation and the lack of resources. This crisis is especially evident in the summer, where temperatures and humidity in some areas are getting rise. In order to provide conditions of comfort, people resort to the use of residential air conditioners increasingly. The statistics show that there is a significant increase in consumption of electricity in the summer due to the use of air conditioners. This leads to interruptions in the supply of electricity.

The main reason for excessive power consumption in residential air conditioners is due to the high external temperature. Where the air conditioner operates in higher thermal conditions than that designed to operate on it, which leads to a reduction in the efficiency of the air conditioner. To solve the problem of excessive consumption of electricity in the residential air conditioners, engineering modifications were made to the mechanical circuit of the air conditioner.

For this practical experiment, the work steps were divided into three stages:

In the first stage, the original air conditioner was tested without any modification.

In the second stage, the capillary tube was replaced with a thermal expansion valve,

and finally, in the third stage, the surface of the external heat exchanger was reduced with a thermal expansion valve.

In the previous three cases the air conditioner was operated under external temperatures ranging from (30°C - 55°C) and the required readings were recorded.

Then performing the necessary calculations to find coefficient of performance (COP) and energy consumption. By comparing the results in the three cases, the following results are shown: The COP of the air conditioner is not affected by the increase in the external temperature when replacing the capillary tube with the thermal expansion valve while maintaining the area of the thermal exchange surface of the external heat exchanger (condenser). the coefficient performance of the air conditioner increased from 3.43 at 30°C ambient temperature to 3.99 at modified air conditioner. At 55°C ambient temperature, the coefficient of performance raised from 2.25 in the case of the original (base) air conditioner to 3.62 in the case of the modified air conditioner.

Significant decrease in the consumption of electrical energy when using the thermal expansion valve compared to the condition of the original air conditioner and reduction in harmful emissions of CO_2 by 352 kg for 3 months.

CHAPTER ONE

INTRODUCTION

This chapter provides an overview of energy crisis in the world and the impact of energy use on the environment, as well as the electrical energy situation in Palestine and the impact of using air conditioners on excessive electricity consumption. Moreover, this introduction will discuss the research objectives and hypothesis.

1.1 World Energy Crisis

The world is gradually moving towards a severe energy crisis with the ever-increasing demand for energy which exceeds its supply. The energy used daily is not unlimited, fossil fuels have become expensive and as time go by, they are depleting. There have been three major energy crises since the first time in 1973, the second in 1979, and the third when oil prices rose significantly in 1990 because of the crises in the Middle East. The energy crisis could result from a monopoly in oil markets, aging infrastructure, pipeline failures and after infrastructure damage from severe weather [1].

Due to population growth and broad economic growth, global energy demand grew by 2.2% in 2017 up from 1.2% in 2016 and above its 10 years average of 1.7%. Developing countries consumed the vast majority of this increase in global energy consumption by nearly 80%.World energy consumption will increase from (13.8) Giga tonnes of oil equivalent (Gtoe) in 2016 to (19.3) Gtoe in 2050 [2].

Despite the high expectations of non-fossil fuels, it will remain the main source of energy for more than thirty years to come. Currently fossil fuels account for 81%, but it will fall to 79% in the future, but the consumption of fossil fuels will not decrease.

1.2 Global Power Consumption

The significant growth in global energy consumption included all major sectors such as transport, industry and buildings. The increase in energy consumption in the buildings sector is due to population growth and increasing prosperity, allowing people to live and work comfortably.

Electricity is the preferred source of energy in all stages of economic development in all countries and will be relied upon more than any other source of energy and will increase its share of energy consumed from 19% to 26% [3]. At residential sector, electricity becomes a very important energy source, the electricity share of world residential energy consumption estimated to grow from 39%in 2012 to 43%in 2040 [4]. This consumption of energy in this sector is mainly affected by: income levels, household characteristics, energy prices, weather, and energy access.

In the residential sector, the demand for household appliances such as electric water heaters, refrigerators and air conditioners increased, which will increase the consumption of electricity and thus increase investment in electricity infrastructure.

1.3 Energy and Environment

To meet the rapidly increased electric demand, large investments are necessary. Although the electricity considered as a clean form of energy, but its generation and transmission affects the environment, nearly all types of electric power plants have an effect on the environment especially coal-fired power plants [5].

Among different negative consequences, the following are crucial:

1. Electric power plants need access roads, pipelines for fuel delivery and electricity transmission lines which affect the landscape.

2. Power plants which use fossil fuel (Coal, Oil, and Natural Gas) have a great effect on

the environment, according to U.S. Energy Information Administration.

About 67% of total electricity generation in 2016 was produced from fossil fuels [6]. Emissions that result from burning these fuels are:

- Carbon Dioxide (CO_2).
- Carbon Monoxide (CO).
- Nitrogen Oxides (NO_X).
- Sulphur Dioxide (SO_2).
- Particulate Matter (PM)
- Heavy metals such as Mercury.

All of these emissions have a serious effect on the environment and human health, CO_2 is a greenhouse gas, which causes a climate change by increasing global surface temperature and sea level rise (global warming). The gases emitted from burning of fossil fuels in power plants lead to global warming, which works to raise the temperature of the earth. The earth's atmosphere consists of many gases: nitrous oxide, methane, water vapour and carbon dioxide, these gases called greenhouse gases (GHGs) maintain a comfortable temperature of 15 ° C. Without these gases, the earth will be cool at -18 ° C. The gases trap the sun's heat in the earth's atmosphere by allowing the sun to pass through the atmosphere of the earth and then work to trap some of this energy in the form of heat, the warmer atmosphere holds more water vapour which is itself a powerful greenhouse gas [7].

The increase in these gases is mainly due to the burning of fossil fuels in power plants, which has increased the emission of carbon dioxide seriously, carbon dioxide is responsible for about half of the contribution greenhouse gases [8]

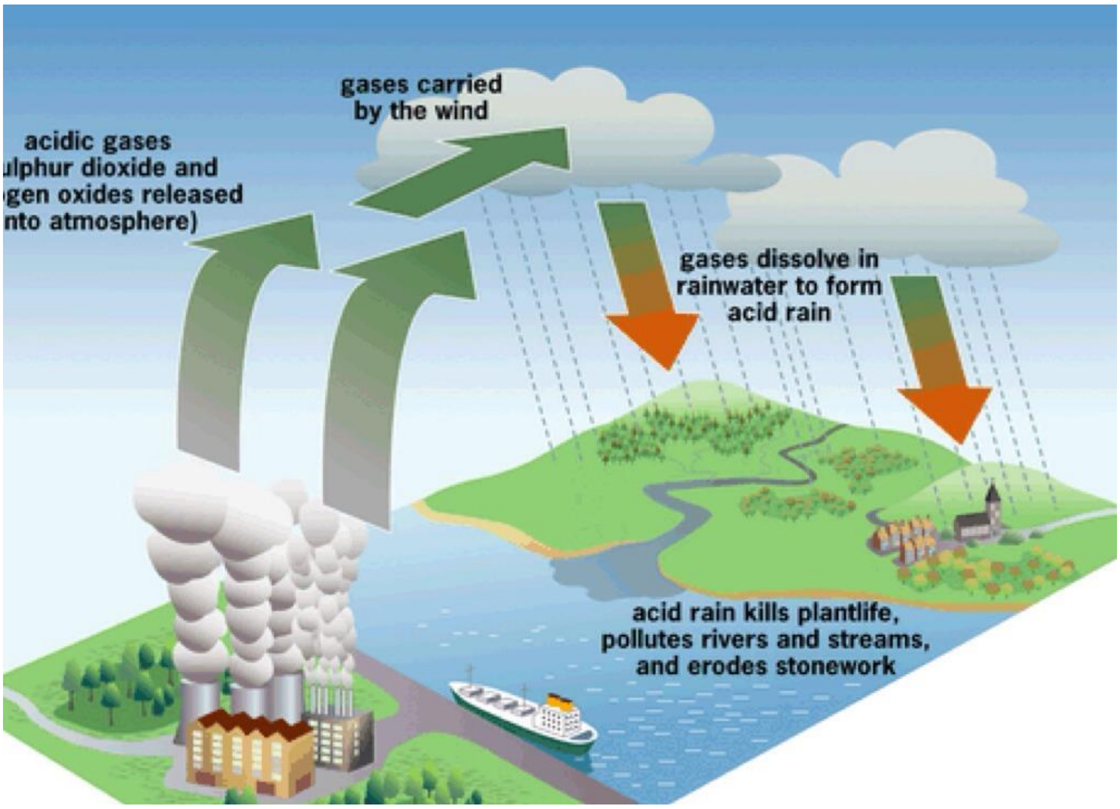

Figure (1.1): Acid rain formation process

When sulphur dioxide (SO_2) which is a corrosive acid gas and Nitrogen Oxides (NO_X) are emitted into the atmosphere and transported by wind and air currents, acid rain is formed when these gases are combined with water vapour in the atmosphere, as shown in figure (1.1) [9]. Acid rain harms forests by dissolving nutrients such as magnesium and calcium that plants need to grow, damages lakes and streams by lowering pH levels, and damages buildings and objects with peeling the paint and building stones appear old.

According to U.S. Energy Information Administration, about two third of (SO_2) and one fourth of (NO_X) in the atmosphere come from electric power generators [10].

Emissions of power plants account for about one third of all NOx rel eased into the atmosphere from human sources. NOx is the main precursor of ground level ozone.

Ozone is a layer of the atmosphere with high ozone levels, and a protective layer of the earth from harmful ultraviolet rays from the sun, which works to block large proportions of them to ensure the ecological balance of the continuity of life cycles of living organisms on Earth. Climate change and the phenomenon of global warming, two phenomena that are strongly related to the state of the ozone layer.

The ozone layer protects the Earth from high-frequency ultraviolet waves from the sun, which cause many cancers, most notably skin cancer. The human body also senses low ozone levels in the air through shortness of breath and severe exhaustion.

Greenhouse gas emissions pose the greatest risk to the ozone layer, especially nitrogen oxides and chlorofluorocarbons (CFCs) emitted from factories and power plants.

1.4 Status of Electric power in Palestine

Energy sector is considered to be one of the most important components of a country's infrastructure and a key indicator of the standard of living. Energy consumption reflects upon population growth, living standard, and the level of development in all aspects of life.The demand for electricity in Palestine now is growing faster than the current supply. Electricity is important for economic growth and development.

Palestine is composed of two territories, the West Bank and the Gaza Strip, which have different characteristics: population growth rate, energy consumption, population density, economic activities, etc.West Bank depends almost entirely on Israeli Electricity Company (IEC) for electricity supply. It is mainly supplied by three 161/33 KV substations located close to the southern, center and north part of West Bank. The maximum capacity of electricity supply to the West Bank is about 550MVA, 30% directly by IEC which supplies electricity in bulk to 215 towns and villages, and 70% indirectly by IEC through Jerusalem electricity distribution company (JEDCO) which supplies electricity to East Jerusalem and in bulk to 165 towns and villages in the West Bank. The Palestinian power grid is connected to that of Jordan at Jericho through a 33kV line via King Abdullah Bridge. JEDCO receives 20MW power supply from National Jordanian Electricity Company since February 2008 [11]. Jericho area is disconnected from the Israeli power grid, and JEDCO manages a separate electricity supply system for the customers connected to the electricity supply from Jordan[12]. In 2017, Gaza's normal energy needs are approximately 400-600 megawatts for full 24-hour supply to all residents. Gaza’s electricity is normally supplied by its sole diesel power plant, which has a nominal rating of 60-140 MW (figures vary due to degree of operation and damage to the plant) and which is reliant on crude diesel fuel, which is imported from Israel. An additional 125 MW is imported from Israel via 10 power lines, and 27 MW of power imported from Egypt [13],as shown in figure (1.2) [14].

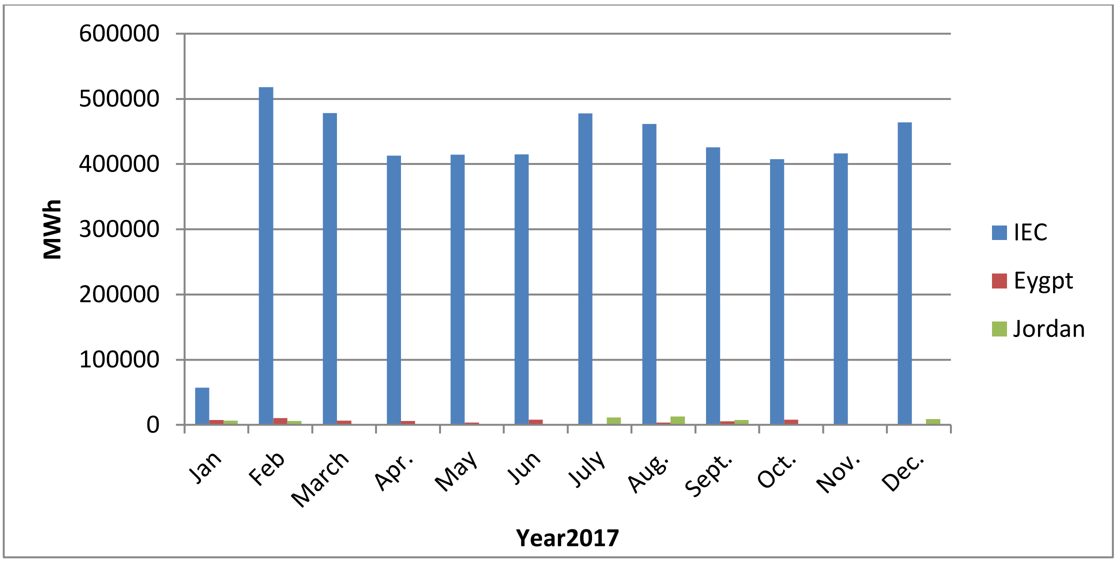

Figure (1.2): Quantity of electricity imported and purchased in Palestine by month and source, 2017.

Table (1.1): shows that the energy consumption of the house hold sector to the total.

energy consumption represents 38.4% in 2017.Among the other middle east countries, Palestinian residential sector is the highest consumption segment of final energy. [15]

Table (1.1): selected energy performance indicators in Palestine, 2014-2017[14]

Indicator	year			
	2017	2016	2015	2014
Renewable energy share in the total energy consumption %	9.7	12.9	13.2	13.3
Energy Dependency Rate (%)	87.3	84.7	84.8	80.3
Energy consumption of the Transport sector (%)	46.6	45.6	43.6	48.7
Energy consumption of the Household sector (%)	38.4	39.7	41.4	38.4
Energy consumption of the Service sector (%)	8.8	8.8	8.5	7.6
Energy consumption of the Industry sector (%)	5.4	4.8	5.2	4.2
Annual electricity consumption per capita (kWh/Capita)	**1138.3**	**1141.9**	**1151.4**	**1048**

Energy sector in the Palestine suffers from fundamental problems caused by market instability such as the lack of investment and public expenditure, high prices and high transmission losses in electricity sector and unstable political situation. West Bank is suffering from seasonal power shortage, while Gaza is struggling to meet basic electricity needs [15]. Palestinian electricity demand is growing at 3.5% annually by 2030 [16]. Failure to invest in the power sector in Palestine would lead to increase in power shortage over time.

1.5 Using Air conditioners in the residential sector

In these days, due to climate change in the world, the number of hot days in Palestine has increased, which led to excessive use of air conditioners in residential applications significantly. Using air conditioners helps in making the internal space more comfortable for human beings by adjusting the temperature and humidity. Under these conditions, the working efficiency of the human beings becomes maximum.

As it can be noticed, air conditioners are used everywhere, the rapid growth in population increasing demand for building services and comfort levels, this source of comfort becomes cheaper, especially in developing countries because of rising in income levels and standards of living, in addition to that, the problem of global warming has increased the demand for air conditioners.

In humid and high temperature climates, many people cannot see themselves living without an air conditioner which they need in their rooms, offices, and cars. As a result, air conditioners almost became compulsory for large proportion of humans.

According to International Energy Agency (IEA), global sales of air conditioners have been growing steadily and significantly. Since 1990, annual sales of air conditioners nearly quadrupled to 135 million units. The greater part of units sold are packaged and split system conditioners for residential and smaller commercial buildings. Detailed data are presented in table (1.2)

Table (1.2): Sold air-conditioning units and cooling capacity by country/region, 2016 [10]

	Installed stock						Annual sales					
	Million units			GW output capacity			Million units			GW output capacity		
	Res	Com	Total	Res	Com	Total	Res	Com	Total	Res	Com	Total
United States	241	132	374	2 295	2 430	4 726	16	8	24	314	129	443
European Union	43	53	97	192	654	847	9	3	12	34	41	75
Japan	116	33	148	407	352	759	9	2	11	47	14	61
Korea	30	29	59	129	220	348	2	2	4	19	15	34
Mexico	7	9	16	40	65	105	1	1	2	5	6	10
China	432	138	569	2 092	807	2 899	41	12	53	305	81	386
India	14	13	27	77	72	149	3	2	4	14	12	25
Indonesia	7	5	12	32	27	59	1	1	2	5	4	9
Brazil	14	14	27	59	68	127	1	0.3	1	5	1.4	6
South Africa	1	1	3	6	15	22	0.1	0.1	0.3	0.9	1.1	2.1
Middle East	30	18	47	147	153	299	4	2	6	29	16	45
World	1 093	529	1 622	6 181	5 491	11 673	94	40	135	848	359	1 207

GW: Global warming Res:Resedintial Com:Commercial

1.6 Impact of air conditioners on energy consumption

We live in a world suffering from a big crisis in energy, especially in developing countries. Electrical energy is used in the residential sector for lighting, cooking, heating and cooling, the use of air conditioners in air cooling is one of the reasons that lead to problems in energy, where air conditioning is a major consumer of electrical energy, comparing with a ceiling fan typical room air conditioner consumes (10 – 20) times more electricity than a ceiling fan. Air conditioners consume nearly 20% of the total electricity used in buildings around the world and energy demand for air conditioners will more than triple by 2050 [10].

The growing energy consumption by air conditioners will lead to increase the production and distribution of energy to meet the demand for energy at peak time, creating further stress on energy production plants and distribution networks.

Global energy demand for heating is projected to increase until 2030 and then stabilize. In contrast, energy demand for air conditioning is projected to increase rapidly over the whole 2000-2100, with heating energy demand decreased by 34% worldwide by 2100 as a result of climate change and air conditioning energy demand increased by 72% [17], this will cause an electricity crisis, especially in developing countries like Palestine, where air conditioning at extremely hot days can represent more than 70% of peak residential electrical demand according to (IEA).

1.7 Impact of air conditioners on environment

The higher demand for air conditioning will put a significant load on the electrical system in many developing countries, which will lead to an increase in the productive capacity of power plants to meet the need in peak time, which also lead to increase generated emissions, necessity for construction of power stations, or to increase plants production capacity to meet the increased demand. Unfortunately, all of these alternatives are costly.

Every air conditioner owner should know that he is contributing in environmental damage. Air conditioner means more refrigerants that contain chlorine, which cause ozone layer depletion and the greenhouse effect. The impact of air conditioners on environment is very serious, the associated CO_2 emissions for both heating and cooling increase from 0.8 Giga tonne of Carbon (C_{Gt}) in 2000 to 2.2 C_{Gt} in 2100 about 12% of total CO_2 emissions from energy use (the strongest increase occurs in Asia) [10]. Carbon dioxide emissions from air conditioning have tripled since 1990 to 1130 million tonnes (Mt), equivalent to the total emissions of Japan [17].

Therefore, it is most important to reduce the emissions of greenhouse gases produced by the electrical power plants as a result of the increased consumption of electrical energy for the use of air conditioning. It can be achieved through increasing the cooling efficiency in air conditioners and reduces their consumption of electrical energy.

1.8 Research Objectives

In Palestine, 60 percent of electricity consumption is in the residential sector. This shows that the function of energy efficiency measures in residential sector should have a significant impact on final consumption [16].

Elevation of ambient temperature in Palestine, especially during the last decade resulted in high demand on residential air conditioners. The high ambient temperature causes high pressure in the condenser which leads to low coefficient of performance (COP), the COP of air conditioner drops dramatically at increasing outdoor temperature [18], that makes the compressor consumes more electricity (higher current). In a city like Tulkarm, higher demand leads to power shortage due to local resource limitations. Tulkarm city has a hot and humid climate in summer, the outdoor relative humidity can reach to 75%which is far from the recommended humidity of (40% - 60%), as shown in figure (1.3).

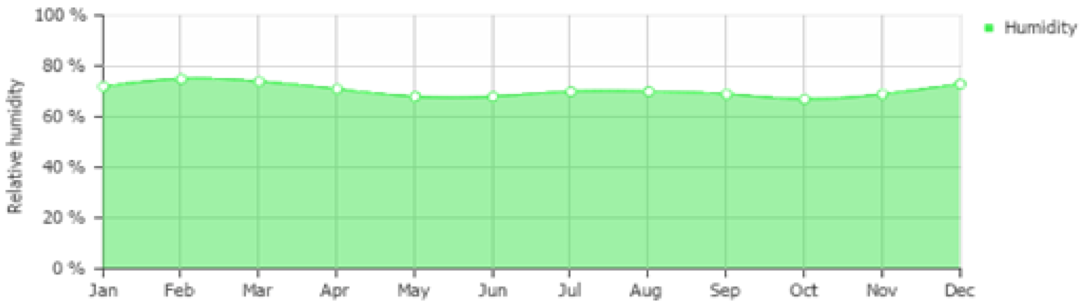

Figure (1.3): The mean monthly relative humidity over the year in Tulkarm, Palestine [19]

So there is an urgent need to use air conditioners to cool the air and to control the extremes values of humidity inside residential and commercial buildings. At the same time, the city suffers from a lack of electrical energy. Table (1.3) shows electric consumption for selective months in Tulkarm city [20].

Table (1.3): Quantities of current (Ampere) consumed in Tulkarm

No.	Month	Current(A)[At 22KV level]	
		Max.	Min.
1	7/2017	831.4	561.4
2	8/2017	822	465.5
3	9/2017	801.2	358
4	10/2017	687.6	276.4
5	11/2017	564.4	202.8
6	12/2017	575.6	202.8
7	1/2018	778.8	236
8	2/2018	719.6	247.6
9	3/2018	564.4	231.6
10	4/2018	569.2	247.6
11	5/2018	785.2	302

The use of air conditioners is the main reason for the excessive electric energy consumption in residential buildings, Therefore, working to raise the efficiency of air conditioners to reduce the consumption of electricity is very important work. Efficient air conditioners reduces the need to more capacity and thus less fuel consumption, in and CO_2 emissions. According to IEA, half of the savings come directly from the improved efficiency of air conditioners[4].

To overcome this problem, this experimental study suggests many engineering modifications to the normal split unit system such as replacing the capillary tube by thermostatic expansion valve (TXV) and investigates its real effects on COP. And energy consumption, which will benefit the reality of electricity in the country.

Research objectives:

- Investigating the possibility of replacing capillary tube with thermostatic expansion valve (TXV) on split unit COP.
- Investigating the possibility of modifying condenser heat transfer area on air conditioning unit COP.
- Defining the best design among alternatives based on COP indicator.

1.9 Research Hypothesis

The COP of Residential air conditioning systems varies significantly under different design setups and ambient conditions. This experimental study will test the following hypotheses:

- Under the capillary tube design, the COP decrease when ambient temperature increases at specific capillary tube design.

- Using TXV gives high COP than a capillary tube at higher ambient temperatures.

- Reducing the condenser surface area with TXV maintains the COP.

- The electrical energy consumption decreases by using TXV and optimal condenser surface area.

CHAPTER TWO

LITERATURE REVIEW

There are only a few publications concerned with residential air conditioner efficiency and operation at elevated temperatures.

Keith Rice.2005[21], investigated performance of R-410a air conditioner system operating under extreme ambient temperatures. Keith Rice tested the air conditioner system at three conditions: first experiment with a capillary tube, second experiment with a short tube orifice and the third experiment with thermal expansion valve (TXV). The author comparing high ambient system performance between capillary tube, short tube orifice and TXV. The author found that TXV control has less drop-off in Energy Efficiency Ratio (EER) and capacity at higher ambient temperatures than with fixed-flow controls, especially compared to capillary tube control. This is primarily due to the smaller drop in subcooling with ambient temperature.

Gawali et al.2014[22], tested the fundamental physics underlying the operation of fixed and variable expansion devices, and they compare the results. They found that: air conditioning system equipped with TXV provides energy saving even when refrigerant charge is lower than the manufactures specification, Variations of capacity over the ambient temperature range of 26 ℃ to ℃55 can cause a performance loss of %85 with a capillary tube system, a well-tuned expansion valve system will lose less than one half this amounts. they found that the energy consumption of the thermostatic expansion valve system was lower than that of the capillary tube system at higher cooling loads and at lower cooling capacities. They found that the energy consumption of the thermostatic expansion valve system was lower than that of the capillary tube system at higher cooling loads and at lower cooling capacities

Sunu et al. 2018[23], compared the performance characteristics of a water chiller air conditioning simulation equipped with thermostatic expansion valve (TEV) with those of a capillary tube. authors filled the water chiller system with the same charge of refrigerant. They performed a comparative analyses based on coefficient of performance (COP) and performance parameter of the refrigeration system, carried out at medium cooling load level with the ambient temperature of 29-31oC, constant compressor speed and fixed chilled water volume flowrate. The results show that the TEV system showed better energy consumption compared to that of capillary tube. From the coefficient of performance perspective, the thermostatic expansion valve system showed higher COP (21.4%) compared to that of capillary tube system .The overall performance parameter of the TEV system is reasonably good as compared to capillary tube system.

Bullock. (2000) [24], investigated the performance of HVAC systems working with two low-critical temperature refrigerants: R-404A and R-410A. The study included theoretical analysis of the refrigerant properties, simulations of the basic thermodynamic cycle, and simulations of three split systems: two using R-410A and one using R-404A. The main difference between the systems studied was the condenser and blower size. In Bullock's air conditioner simulation model, the compressor, expansion device, and condenser/gas cooler models were modified to accommodate trans critical system operation. The simulations show that the capacity degradation and compressor power increase become more significant with an increase of outdoor temperature when the condenser pressure is above the critical point.

Based on simulation results from the three systems, Bullock offered the following key conclusions: a typical unitary system will cross over to trans critical operation at about 57 °C to 60 °C. At the ambient temperature when the critical point is reached, the cooling capacity will be about 60 % to 70 % of the capacity at the 35°C rating point, and the compressor power will be about 110 % to 160 % of the power at the 35°C rating point (depends greatly on the compressor type). The system performance at high ambient temperatures can be improved by providing a high capacity condensing unit.

Wells et al. (1999)[25], compared the performance of R-410A and R-22 in split and window-type air conditioners. Their study included theoretical simulations, laboratory testing of split systems, laboratory testing of window units with several hardware modifications, and simulations using the heat pump model. At an ambient temperature of 51.6 °C, the capacity and EER ratios of R-410A fell 12 % below that of R-22. Similar results were obtained for the window units. Increased subcooling benefited performance at high ambient temperatures. The study also concluded that using a TXV versus a short tube restrictor or capillary tube results in less performance loss.

All previous studies agreed on that using TXV is more efficient in the air conditioning systems than the capillary tube and it makes the system less energy consumption.

CHAPTER THREE

THEORETICAL BACKGROUND

This chapter provides a definition of the vapor compression refrigeration cycle and its role in air conditioning systems, also this chapter presents the parts of the cycle and thermodynamic processes that take place in every part of this cycle.

This chapter reviews the most important types of air conditioners used in residential applications, the components of this air conditioners and the principle of its work. Finally this chapter reviews the effect of ambient temperature on the performance of the air conditioner and the principle of the work of thermostatic expansion valve.

3.1 Parts of vapor- compression refrigeration cycle

The vapor- compression refrigeration cycle consists of four main parts, which are:

the compressor, the condenser, the expansion device and the evaporator.

In the same context, refrigeration cycle divided into two main parts according to refrigerant pressure**,** which are:

- **High pressure part**
- **Low pressure part**

The points of separation between the two parts are: the expansion device and the discharge valve of the compressor.

3.2 Principle of Working

The vapor compression refrigeration cycle (VCRC) considered as the most commonly used in many applications for refrigeration among all refrigeration systems. One of the most important applications is air conditioning cycles. In this application, heat transfer from a colder source (inside the house) to a warmer source (outside the house) by using the thermodynamic properties of refrigerants takes place. The vapor compression refrigeration cycle consists of the following equipments as shown in figure (2.1**)**

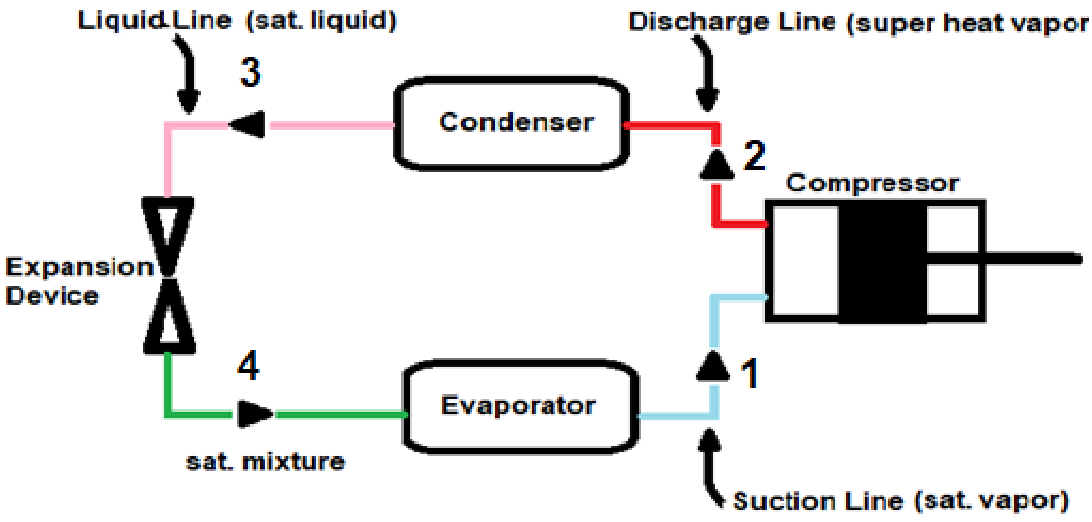

Figure (2.1): components of ideal vapor compression refrigeration cycle

The Compressor: It raises the pressure of the refrigerant from a saturated vapor state to a superheated vapor state. During this isentropic process, the temperature of the refrigerant is raised to values above that of the warm source .

The Condenser: It's a heat exchanger, refrigerant entering the condenser at a higher temperature than the warm source surrounding the condenser, the refrigerant is cooled to a saturated liquid state. This process releases the heat removed from the cold source to the warm source. It is assumed that there is no pressure loss across the condenser. Air cooled condenser becomes less effective under high ambient temperature [26].

The Expansion Device : This device throttles the pressure of the incoming saturated liquid to the evaporator pressure, resulting in a low-quality saturated mixture. This process lowers the temperature of the refrigerant to a level below that of the cold source.

The Evaporator: The actual cooling takes place here, where the low quality saturated mixture refrigerant is heated by the cold source to the state of saturated vapor. By entering the evaporator at a lower temperature than the cold source, the refrigerant removes heat from the cold source. This heat is carried by the refrigerant and expelled to the warm source. It is assumed that there is no pressure loss across the evaporator.

3.3 Pressure – Enthalpy diagram of the ideal refrigeration cycle

Studying the vapor-compression refrigeration cycle needs a knowledge about thermodynamic processes of the cycle and the relation between these processes and the effect of change in one process to the following process. The vapor-compression refrigeration cycle consists of four processes as shown in Figure (2.2)

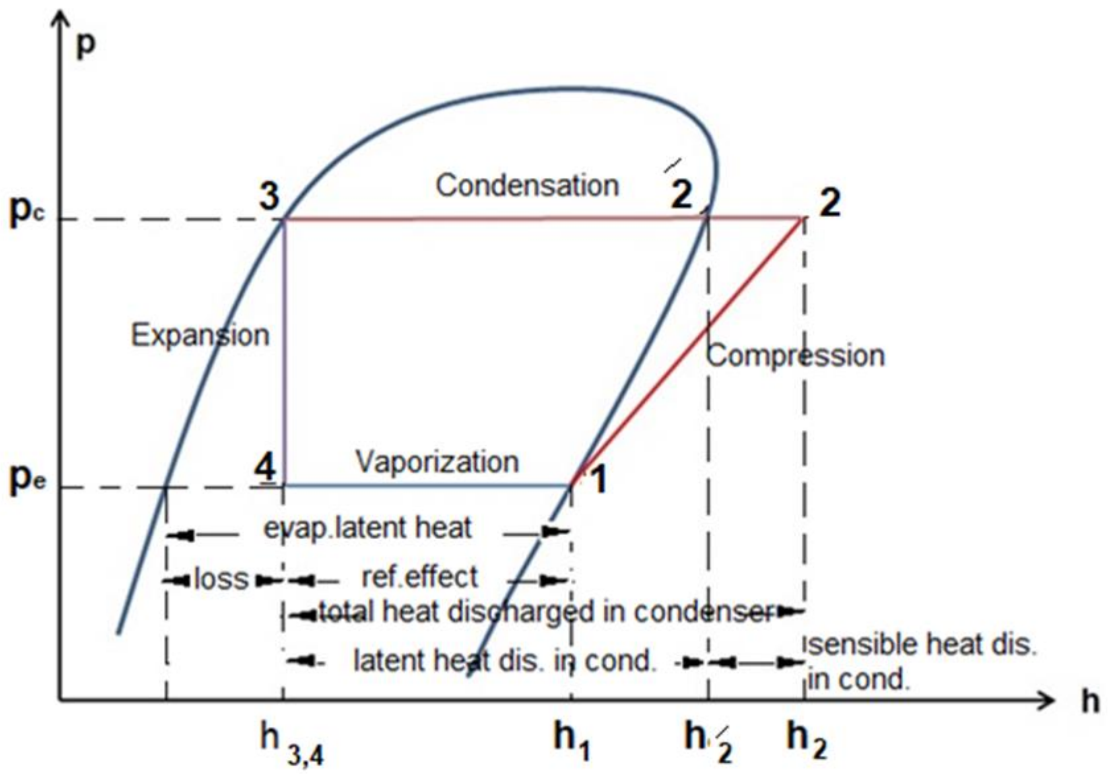

Figure (2.2): Pressure – Enthalpy diagram of the ideal refrigeration cycle

These processes can be explained as:

- **Compression process (1-2)**: Isentropic compression in a compressor.
- **Condensation process (2 - 3)**: Constant-pressure heat rejection in a condenser.
- **Expansion process (3 - 4)**: Throttling in an expansion device.
- **Evaporation process (4 - 1)**: Constant-pressure heat absorption in evaporator.

In ideal vapor-compression refrigeration cycle, the refrigerant enters the compressor at state (1) as saturated vapor and is compressed isentropically to the condenser pressure. The temperature of the refrigerant increases during this isentropic compression process to well above the temperature of the surrounding medium. The refrigerant then enters the condenser as superheated vapor at state (2) and leaves as saturated liquid at state (3) as a result of heat rejection to the surroundings. The temperature of the refrigerant at this state is still above the temperature of the surroundings. The saturated liquid refrigerant at state (4) is throttled to the evaporator pressure by passing it through an expansion valve or capillary tube. The temperature of the refrigerant drops below the temperature of the refrigerated space during this process. The refrigerant enters the evaporator at state (4) as a low-quality saturated mixture, and it completely evaporates by absorbing heat from the refrigerated space. The refrigerant leaves the evaporator as saturated vapor at state (1) and re-enters the compressor, completing the cycle [27].

3.4 Main Definitions and Mathematical Representation

1. **Refrigerating Capacity:** measures of effective cooling power expressed in

British Thermal Unit (Btu) per hour , kW, or in tons where one ton equivalent to the energy required to melt 1000 kg of ice in24 hours. A refrigeration ton equals to 12000 Btu/h or 3.51 kW. Refrigeration capacity related with:

- The flow of Refrigerant in refrigeration cycle
- The kind of refrigerant.
- The evaporating temperature and condensing temperature of the cycle.

2. **Cooling effect:** it is the amount of heat transfer rate (refrigeration capacity) absorbed by the refrigerant in the evaporator.

$$\dot{Q}_{evap.} = \dot{m}\,(h_1 - h_4) \qquad \frac{kJ}{s} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

3. **Mass of refrigerant**: it is calculated by dividing the amount of heat by the cooling effect.

$$\dot{m} = \frac{3.516}{(h_1 - h_4)} \qquad \frac{\boldsymbol{kg}}{\boldsymbol{s}}\ for\ metric\ ton \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

4. **Power required (heat compression):** it is the power theoretically required to compress the refrigerant.

$$Work\ of\ compression = (h_2 - h_1) \qquad \frac{kJ}{kg} \ldots\ldots\ldots\ldots\ldots.. (3)$$

$Power\ required\ by\ the\ compressor$

$$= \dot{m}(h_2 - h_1) \qquad kW \ldots\ldots\ldots\ldots\ldots. \ (4)$$

5. **Heat removed through condenser:** it is the heat transfer rate absorbed in the evaporator plus the power needed for the compression.

$$\dot{Q}_{cond.} = \dot{m}(h_3 - h_2) \qquad kW \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

6. **COP (coefficient of performance):** it is the ratio between the heat transfer rate at evaporator to power input to the compressor (refrigeration capacity).

$$COP = (h_1 - h_4)/(h_2 - h_1) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots(6)$$

3.5 Types of residential air conditioners

Residential split unit air conditioners are the most commonly used type in Palestine. It has many types and a wide range from small units to large systems, the outdoor unit is located outside the building and connected with an indoor unit by two pipes carrying the refrigerant.

Residential air conditioners are available in many types to match the different applications. The most commonly used air conditioners in residential applications are:

- **Window Air Conditioner:** It is a package type air conditioner. In this type, all the components, mainly (the compressor, condenser, expansion valve, and a cooling coil) are enclosed in a single box, it is the most commonly used for single rooms. This unit fits in a slot made in the wall of the room, or more commonly a window sill.

- **Packaged Air Conditioner:** this type is used to cool more than two rooms or a larger space at home. There are two possible arrangements with the package unit. In the first one, all the components (the compressor, condenser, which can be air cooled or water cooled, expansion valve and evaporator) are housed in a single box. The cooled air is thrown by the high capacity blower, and it flows through the ducts laid through various rooms. In the second arrangement, the compressor and condenser are housed in one casing. The compressed gas passes through individual units, comprised of the expansion valve and cooling coil, located in various rooms.

- **Split Air Conditioner:** it is the most commonly used types of residential applications. It consists of two parts: the outdoor unit and the indoor unit. A split air conditioner can be used to cool one or more than two rooms.

3.6 A split air conditioner

Split unit air conditioners are the most commonly used systems in Palestine. It has a wide range from small units to large systems to be appropriate for the different applications. It has many types:

- **Ductless mini-split system:** deliver cooling to a building through refrigerant that is piped from the outdoor condensing unit to the indoor evaporator mounted on a wall or ceiling. Ductless systems have advantages over ducted systems, including lower distribution losses, increased energy efficiency and increased control of temperature in each room [10].

- **Ductless multi-split systems**: allow multiple rooms to be cooled from a single outdoor unit, with a separate indoor evaporator unit(s). The main advantage of this system is the reduced number of outdoor units, while retaining the flexibility for cooling individual rooms. Variable refrigerant flow systems are a variety of multi-split systems, which have been developed to deliver variable refrigerant quantity depending on the cooling needs of each evaporator.

- **Central ducted split-systems**: deliver cooling through ducted air, whereby the evaporator is placed in a single central location, providing cooling for an entire residential or commercial building through a system of ducts. The temperature in each zone can be controlled separately.

3.7 Comparison between types of split air conditioners

In the following table there is a comparison between common used split air conditioners in Palestine.

Table (2.1): Comparison between types of split air conditioners[28]

Criteria	Ductless split air conditioners	Ducted split air conditioners
Applications	Homes, Offices, Small hotels ,…	large houses, Super markets, Restaurants, Banks,…..
Components	Outdoor unit and one indoor unit or more(multi split system).	Outdoor unit with internal air handling unit equipped with air duct network.
Capacity	Small capacity .	High capacity.
Initial and Running Cost	• Affordable capital cost. • Maximum capacity is required for each equipment. • High operating cost.	• High capital cost • Longer equipment services life to compensate the high capital cost.
Performance	Less energy efficient.	More energy efficient.
Architecture Constrains	There is no architecture constrains.	Needs a special architecture design.
Flexibility	• Ease of control. • Easy maintenance.	• Various systems are used to control its work. • There is a difficulty in the maintenance process.

3.8 Components of ductless mini-split air conditioner

A ductless mini split air conditioner is a wide commonly used in houses it consists of two main units, the first unit is the outdoor unit that contains compressor, air cooled condenser, outdoor fan and capillary tube. The second main unit is the indoor unitwhich contains: evaporator, variable speed indoor fan and control unit.

These two units are connected to two pipes of copper (liquid line and suction line).

➢ The compressor:

The compressor is considered the heart of refrigeration system, it works as vapor pump, it increases the suction pressure level to discharge pressure level. There are many types of compressors used in air conditioning systems, but the most common used in mini split air conditioner is rotary compressor.

The rotary compressor is small and light. The compressor and motor are pressed into the shell of a rotary compressor, and there is no vapor space between the compressor and the shell. This is another reason why the rotary compressor is smaller than a reciprocating compressor. The rotary compressor, which is used in small to medium-sized systems, is more efficient than the reciprocating compressor. The primary reason the rotary compressor is highly efficient is that all the refrigerant that enters the intake port is discharged through the exhaust or discharge port. There is no clearance volume as in the reciprocating compressor [29].

➢ Air Cooled Condenser

The function of condenser is condensing the refrigerant by rejecting its heat through the condenser. A fan blows air over the condenser and its fins through which the heat is exchanged to the air passing over it. The coils must be clean for the condenser to operate efficiently. The performance of the air cooled condenser is affected by the ambient temperature, when it increases, the amount of heat rejected from the condenser decreases which leads to lower COP and system capacity. As a result, the compressor consumes more power.

- **Expansion device**

The expansion device (throttling device) is an important device that divides the high pressure side and low pressure side of a refrigerating system. It is connected between the condenser and the evaporator.

The functions of expansion device are the following:

1. It reduces the high pressure liquid refrigerant to low pressure liquid refrigerant before being fed to the evaporator.

2. It maintains the desired pressure difference between the low and high pressure sides of the system, so that the liquid refrigerant vaporises at the designed pressure in the evaporator.

3. It controls the flow of refrigerant according to the load on the evaporator.

There are many kinds of expansion devices used in air conditioning systems, but the main type of expansion devices used in residential air conditioners is capillary tube

The Capillary Tube: It is a copper tube of small internal diameter and of varying length depending upon the application. The capillary tube used in small capacity hermetic sealed refrigeration units such as room air conditioners.

The liquid refrigerant comes from the condenser inters the capillary tube, due to the frictional resistance offered by small diameter tube the pressure drops. The longer the capillary tube and smaller it's inside diameter, the greater is the pressure drop created in the refrigerant flow, which means, the greater pressure difference between the condenser and evaporator [30].

The advantages of using capillary tubes in small air conditioners are:

1. It is cheaper than other kinds of expansion devices.
2. Equals the pressure between high side and low side of the system when the compressor stops.
3. There is no liquid receiver when the capillary tube used in refrigeration system.

- **The Evaporator**

The evaporator is the part where the refrigerant absorbs heat. It's located where the cold air comes from. When the blower fan draws room, hot air over the evaporator, the refrigerant absorbs heat from the room hot air.

Like condenser, the evaporator consists of: tubes made from copper, aluminium bent into u-shapes and set into panels. Aluminium fins are attached to the coil to give more surface area for better heat exchange.

Two kinds of heat must be transferred: sensible heat and latent heat. Sensible heat lowers the air temperature, and latent heat changes the water vapor in the air to condense. The condensate collects on the coil and runs through the drain [29].

3.9 Design conditions in which air conditioners operate in Palestine

Air-conditioning equipment is designed to operate at its rated capacity and efficiency at one set of design conditions. The design conditions are generally considered to be an outside temperature of 35℃ and an inside temperature of 27℃ with humidity at 50%. This rating is established by the Air-Conditioning, Heating and Refrigeration Institute (AHRI) [31].

The inside relative humidity adds a significant load to the evaporator coil and has to be considered as part of the load. When conditions vary from the design conditions, the capacity of the equipment will vary. The pressures and temperatures will also change.

3.10 The effect of condensation temperature on capacity

The condensation temperature of the refrigerant is considered to be 6°C–20°C above ambient temperature for general purposes. The condensation temperature varies according to the ambient temperature in which the system will operate. This said, the condensation temperature for applications is commonly taken as 30 - 60°C .

Factors taken into consideration in determining the condensation temperature:

- Ambient temperature.

- Thermophysical properties of the refrigerant.
- Properties of the selected compressor.
- The dimensions of the condenser.

It must always be considered that high compression temperature creates a load on the compressor that reduces efficiency and shortens its useful life. It will be quite beneficial in the design of the condensation temperature to be specified as low as possible. However, in some conditions it is not possible to take a low value for the condensation temperature. For example, in the Middle East countries where the outdoor temperature is 50°C-55°C, high condenser temperature is unavoidable .

Ambient temperature plays key role in the performance of Air Cooled Condenser (ACC). Generally ACC is advisable where ambient temperature is not rising much [32].

If the outside temperature increases from 35℃ to 38℃, the equipment will be operating at a higher head pressure and will not have as much capacity. The capacity also varies when the space temperature goes up or down or when the humidity varies. The relationship among the various components in the system also varies. The evaporator absorbs heat. When anything happens to increase the amount of heat absorbed into the system, the system pressures will rise. The condenser rejects heat. If anything happens to prevent the condenser from rejecting heat from the system, the system pressures will rise. For example, when the outside temperature is

35°C, the average condenser will condense the refrigerant at 50°C to 55°C, and the head pressure for these condensing temperatures would be 446 to 475 psig for R-410a. High-efficiency air-conditioning equipment may have a much lower operating head pressure. The high efficiency is gained by using a larger condenser surface or by using more modern alloys with more extended surfaces or fins [10].

A rule of thumb is that the COP improves by (2–4) % for each 1°C the condensing temperature is lowered [27].

3.11 Using Thermostatic Expansion Valve as a metering device

The thermostatic expansion valve (TXV), figure (2.3), is widely used in industrial and commercial refrigeration and air conditioning systems, it consists of a needle valve and a seat, a metallic diaphragm, spring, an adjusting screw and thermal bulb mounted on the suction line near the outlet of the evaporator.

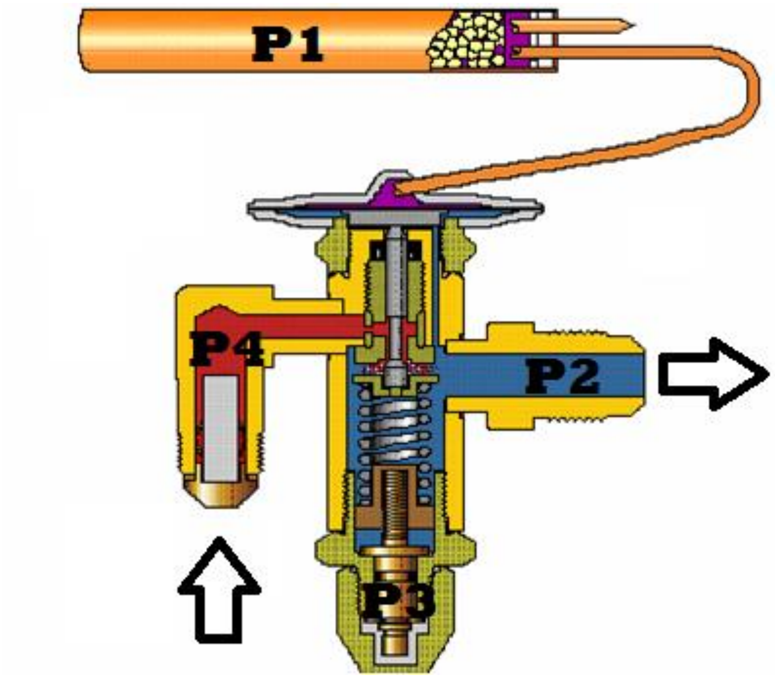

Figure (2.3): Thermostatic expansion valve

As the thermostatic expansion valve regulates the rate at which liquid refrigerant flows into the evaporator, it maintains a proper supply of refrigerant by matching this flow rate against how quickly the refrigerant evaporates (boils off) in the evaporator coil. To do this, the TEV responds to two variables: the temperature of the refrigerant vapor as it leaves the evaporator (P1) and the pressure in the evaporator itself (P2). It does this by using a movable valve pin against the spring pressure (P3) to precisely control the flow of liquid refrigerant into the evaporator (P4):

TXV Pressure Balance Equation [29]

$$P_1 + P_4 = P_2 + P_3$$

P_1 = Bulb Pressure (Opening Force)

P_2 = Evaporator Pressure (Closing Force)

P_3 = Superheat Spring Pressure (Closing Force)

P_4 = Liquid Pressure (Opening Force)

high-efficiency air-conditioning equipment often uses a thermostatic expansion valve rather than a fixed-bore metering device (capillary tube) to gain a certain amount of efficiency [10]. The efficiency of air conditioner will also incorporate TEV metering devices to keep the evaporator active under all heat load conditions and have a lesser amperage rating than standard equipment. The TXV can operate satisfactorily with a wide range of pressure differences across it [33]**.**

3.12 Energy Efficiency Ratio (EER)

It is the output in (Btu/h) divided by the input watts of power used to produce the output. the larger the EER rating the more efficient the equipment.

CHAPTER FOUR

METHODOLOGY AND EXPERIMENTAL SETUP

This chapter describes the experimental setup and procedure, the location where the research took place as well as the methodology of the research followed (the modifications made to the split air conditioner at each stage of the work and data taken at each stage).

4.1 Methodology: To execute this practical experiment, the work steps were divided into three stages:

- In the first stage, the original air conditioner was tested without any modification.
- In the second stage, the capillary tube was replaced with a thermal expansion valve.
- Finally, in the third stage, the surface of the external heat exchanger was reduced with a thermal expansion valve.

In the previous three cases the air conditioner was operated under external temperatures ranging from (30°C - 55°C) and the required readings were recorded.

After performing the necessary calculations to find coefficient of performance (COP) and energy consumption. By comparing the results in the three cases, the following results are shown:

4.2 Experimental setup:

To achieve its intended results, this experimental study was executed in Tulkarm Vocational Secondary School, refrigeration and air conditioning work shop under controlled ambient temperature. In this experimental study, a residential split unit air conditioner (Tadiran) will be considered, figure (4.1).

It consists of:

- Outdoor Unit (Rotary Hermetic Compressor, Forced Air Condenser, 4way valve, capillary tube.

- Indoor Unit (Forced Air Evaporator with variable speed fan, control system).

Figure (4.1) Mini split air conditioner- Tadiran

Tadiran Air Conditioner technical specifications and name plate as shown in Table (4.1). It can be noticed that:

Table (4.1): Air conditioner technical specifications

Operating Mode		cooling	Tadiran
Capacity (watt)	3530		
Max. input current(kW)	1.40	Indoor: DB 30℃	Source:230V/1ph/50Hz
Max. current(A)	6.3	Outdoor: DB 40℃	
Refrigerant	R410a		

4.3 First phase of the Experiment

In the first phase of the experiment, operating the original system (using capillary tube) of the air conditioner which equipped with:

- Low and high pressure gauges.
- Digital thermometers.
- Dry bulb thermometer.
- Wet bulb thermometer.

These equipments were fitted on the condenser inlet and outlet pipes, evaporator inlet and outlet pipes as shown in figure (4.2). Then the system is let to run for a period of time. Then, the following data recording procedure was implemented:

- Recording the pressure at the condenser and evaporator inlet and outlet at different ambient temperatures.
- Recording the temperature of the condenser and evaporator inlet and outlet at different ambient temperatures.
- Measuring the current consumed by the compressor at different ambient temperatures -Organizing the records in a data collection sheet.
- Plotting the cycle on the pressure-enthalpy diagram of the refrigerant (410a) then calculating the thermal power, COP and EER.

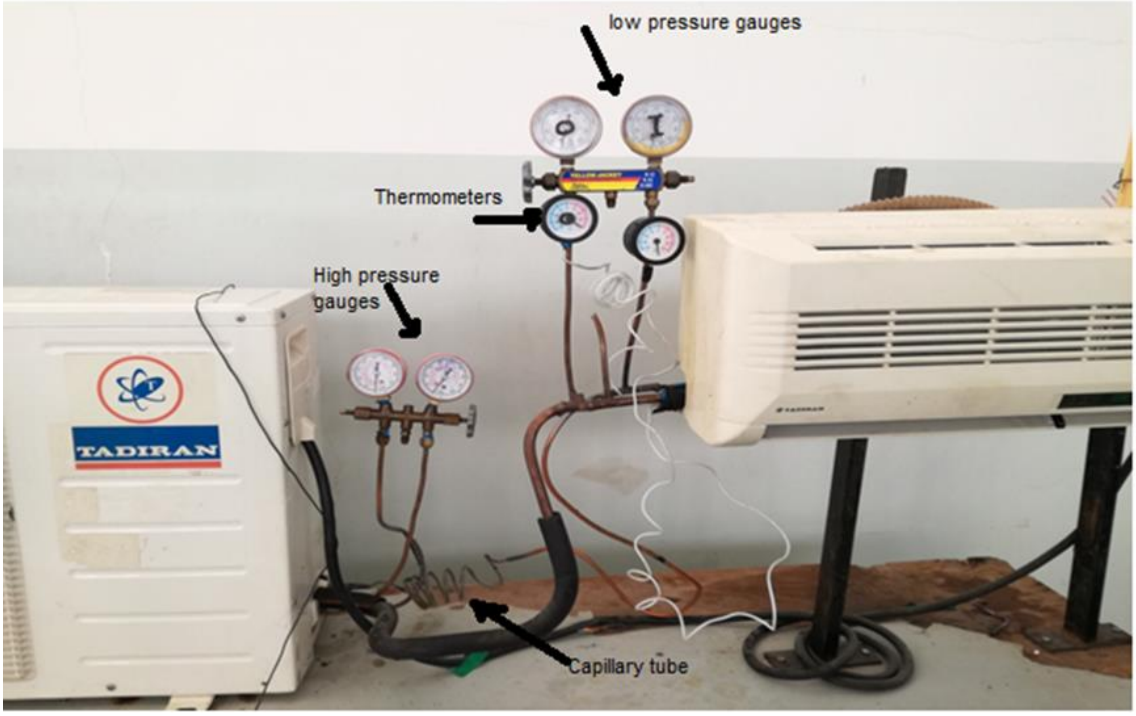

Figure (4.2): The original system for split air conditioner

4.4 Second Phase of the Experiment

At the second phase of the experiment as shown in figure (4.3), the system was modified by replacing capillary tube with:

- Thermostatic expansion valve.
- Liquid Receiver.
- 3 check valves.
- Sight glass.

To do this, Portable Vacuum, Charging Station and Electronic Leak Detector are used.

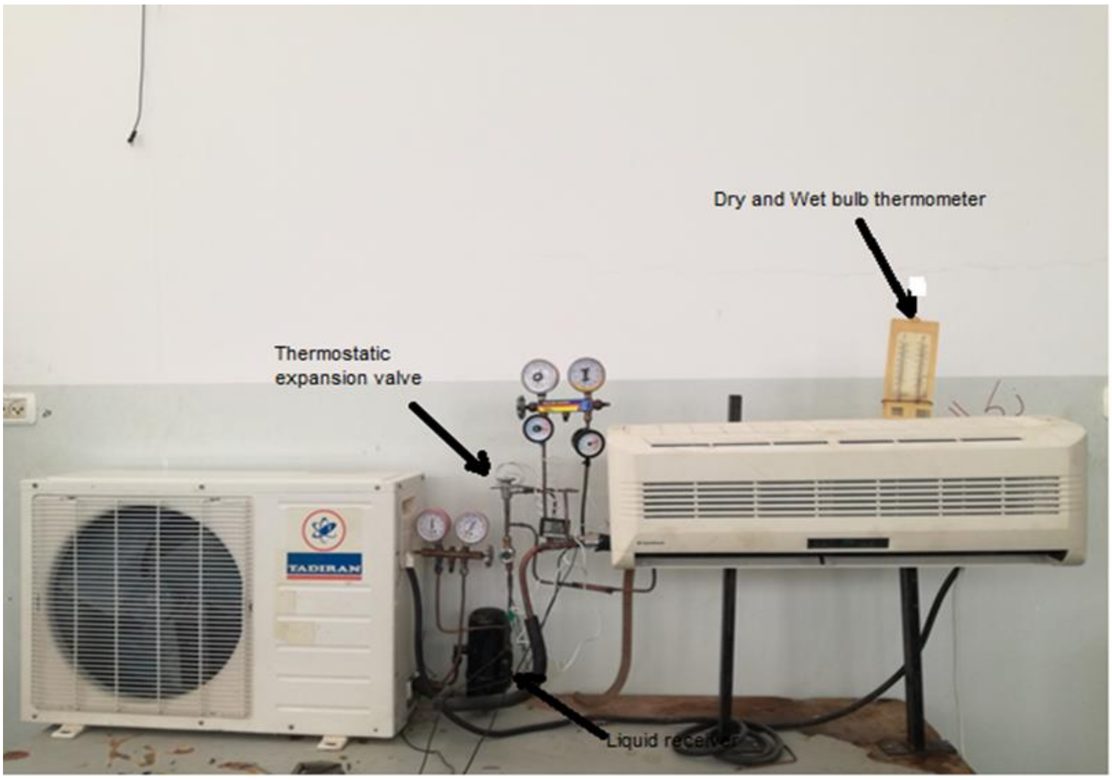

Figure (4.3): The system equipped with TEV

After recharging the system with the exact amount of refrigerant 410a, the following procedure was followed:

- Operating the system for a period of time to get the system stabilization.
- Measuring and recording the pressure in the condenser and evaporator inlet and outlet at different ambient temperatures.
- Measuring and recording the temperature of the condenser and evaporator inlet and outlet at different ambient temperatures.
- Measuring the current consumed by the compressor at different ambient temperatures -Organizing the records in a data collection sheet.
- Plotting the cycle on the pressure-enthalpy diagram of the refrigerant (410a) then calculating the thermal power, COP and EER.

4.5 Third Phase of the Experiment

At the third phase of the experiment, the surface of the condenser reduced by eliminating some rows of the condenser coil as shown in figure (4.4) while keeping the system working at TXV.

Figure (4.4): Heat exchange (condenser) surface area reduction

Then, the following procedure was adopted to execute the experiment:

- Operating the system for a period of time to get the system stabilization.
- Measuring and recording the pressure in the condenser and evaporator inlet and outlet at different ambient temperatures.
- Measuring and recording the temperature of the condenser and evaporator inlet and outlet at different ambient temperatures.

- Measuring the current consumed by the compressor at different ambient temperatures -Organizing the records in a data collection sheet.
- Plotting the cycle on the pressure-enthalpy diagram of the refrigerant (410a) then calculating the thermal power, COP and EER.

CHAPTER FIVE

RESULTS AND DISCUSSION

This chapter presents all the results and analysis of all the sections of the experiment and compare with each other and draw conclusions.

5.1 Results of the First phase of experiment (Original System)

This phase of the experiment was executed under controlled varying ambient temperature in Tulkarm Secondary Industrial School, refrigeration and air conditioning workshop at original mini split air conditioner which used capillary tube as throttling device figure (5.1) and equipped with all necessary measuring instruments (high and low pressure gages, thermometers), all average records were organized in table (5.1).

Figure (5.1): Original system equipped with capillary tube and measuring devices

Table (5.1): Results of phase one of experiment

Indoor RH%=62 %	Ambient Temperature℃											
	30		35		40		45		50		55	
	P*	T**	P	T	P	T	P	T	P	T	P	T
Evaporator inlet	133	7.7	142	9.7	150	11.4	156	12.6	165	14.4	175	16.2
Evaporator outlet	130	7	135	8.2	140	9.3	140	9.3	143	9.9	150	11.4
Condenser inlet	400	46.7	470	53.6	495	55.9	530	59	550	60.6	578	62.9
Condenser outlet	395	49.8	465	53.1	485	55	510	57.2	545	60.2	565	61.9
Measured Temperature(℃)												
Evaporator inlet	7.4		9.5		11.1		12.4		14.2		16	
Evaporator outlet	6		7.8		9		9.3		9.8		11.2	
Electrical												
Volts(V)	220		220		220		220		220		220	
Amperes (A)	4.1		4.2		4.4		4.5		4.6		4.8	
Watts(W)	767		785		823		842		860		898	
**T: saturation temperature (℃) *P: gage pressure (psi)												

By using a Mollier Chart program from (Techni Solve Software cc) to analyse refrigeration cycle in this case, we got the following results as in the table (5.2).

Table (5.2): Analysis of the results of the first section of the Experiment

Original system						
Ambient Temperature	30°C	35°C	40°C	45°C	50°C	55°C
System						
Refrigerant	R410a					
COP	3.43	2.8	2.68	2.42	2.33	2.25
Evaporator						
Temperature(°C)	7	8.2	9.3	9.3	9.9	11.4
Pressure(Kpa)	994	1031	1065	1065	1084	1133
Entering Quality	0.317	0.373	0.389	0.418	0.43	0.446
Saturated Enthalpy(kJ/kg)	424.5	424.8	425	425	425.1	425.4
Refrigeration Effect(kJ/kg)	145.3	132.3	128.1	122	118.9	114.6
Condenser						
Temperature(°C)	46.6	53.6	55.9	59	60.6	62.9
Pressure(Kpa)	2803	3277	3443	3676	3800	3984
Heat Rejection(kJ/kg)	187.7	179.6	175.9	172.5	170	165.5
Suction						
Temperature(°C)	7.1	8.3	9.4	9.4	10	11.5
Specific Volume(m^3/kg)	0.026	0.025	0.024	0.024	0.024	0.023
Enthalpy(kJ/kg)	424.6	424.9	425.1	425.1	425.2	425.6
Discharge						
Temperature(°C)	75.7	86.4	89.3	94.4	96.6	99.2
Specific Volume(m^3/kg)	0.01	0.009	0.008	0.008	0.007	0.007
Enthalpy(kJ/kg)	466.9	472.1	472.9	475.6	476.3	476.5
Liquid						
Temperature(°C)	46.5	53.5	55.8	58.9	60.5	62.8
Density(kg/ m^3)	940.72	900.7	887.42	869.45	860.14	846.76
Enthalpy(kJ/kg)	279.3	292.5	297	303.1	306.3	311
Compressor						
Swept Volume (L/s per TR)	0.634	0.671	0.67	0.703	0.708	0.702
Compression Ratio	2.282	3.179	3.232	3.451	3.505	3.516
Compressor work(kJ/kg)	42.3	47.2	47.8	50.5	51.1	51
Refrigerant Flow(kg/min)	1.45	1.6	1.65	1.73	1.77	1.84
Compressor Power(kw)	1	1.26	1.3	1.46	1.5	1.56

The figure (5.2) illustrates the relation between the ambient temperature and the heat rejection. It is noticeable that the elevation in ambient temperature leads to reduce the heat rejection from air cooled condenser to the hotter ambient. This increase the condenser internal temperature and pressure, which will affect the cooling performance of the system.

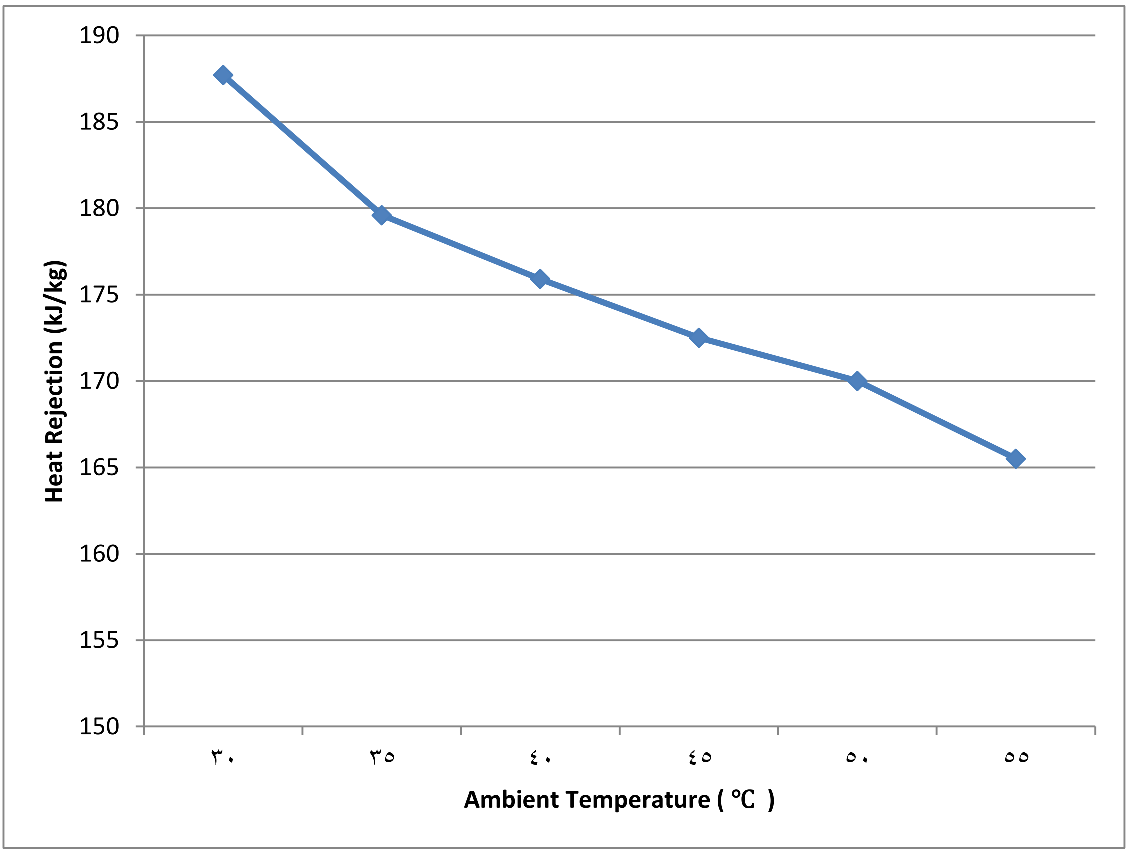

Figure (5.2): Relation between the ambient temperature and the heat rejection

Elevation of ambient temperature leads to increase in condensation temperature as the figure (5.2) shows.

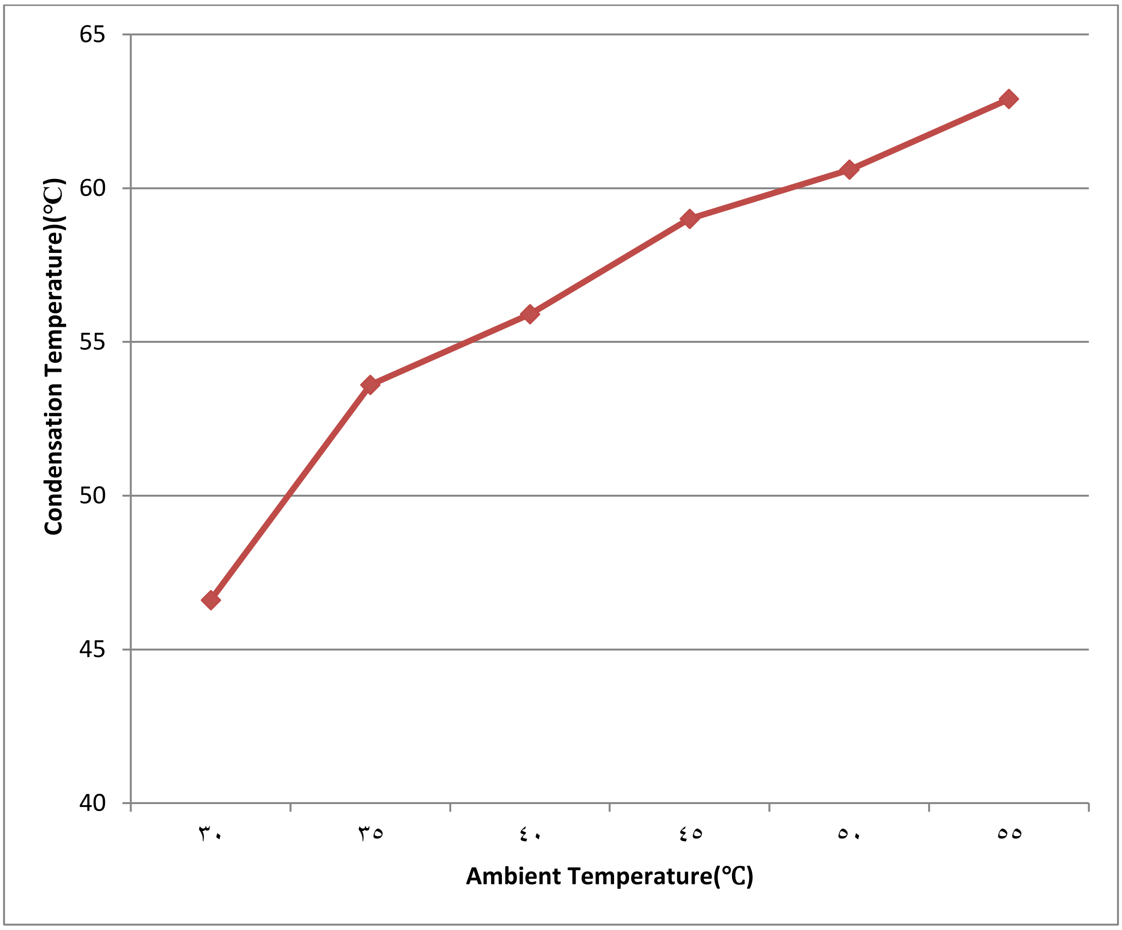

Figure (5. 3): The relationship between ambient temperature and condensing temperature

The relationship between ambient temperature and condensing temperature which shows the significant rise in the temperature of condensation with ambient temperature elevation. When condensing temperature approaches critical levels (critical temperature for refrigerant 410a is 71.3°C), cooling capacity and energy efficiency decline as shown in figure (5.4) and figure (5.5). This is because refrigerant cannot condensate well in condenser and it will remain in the vapour state, therefor it will not absorb more heat in evaporator and there will be low cooling effect. This will increase power consumption as shown in figure (5.6)

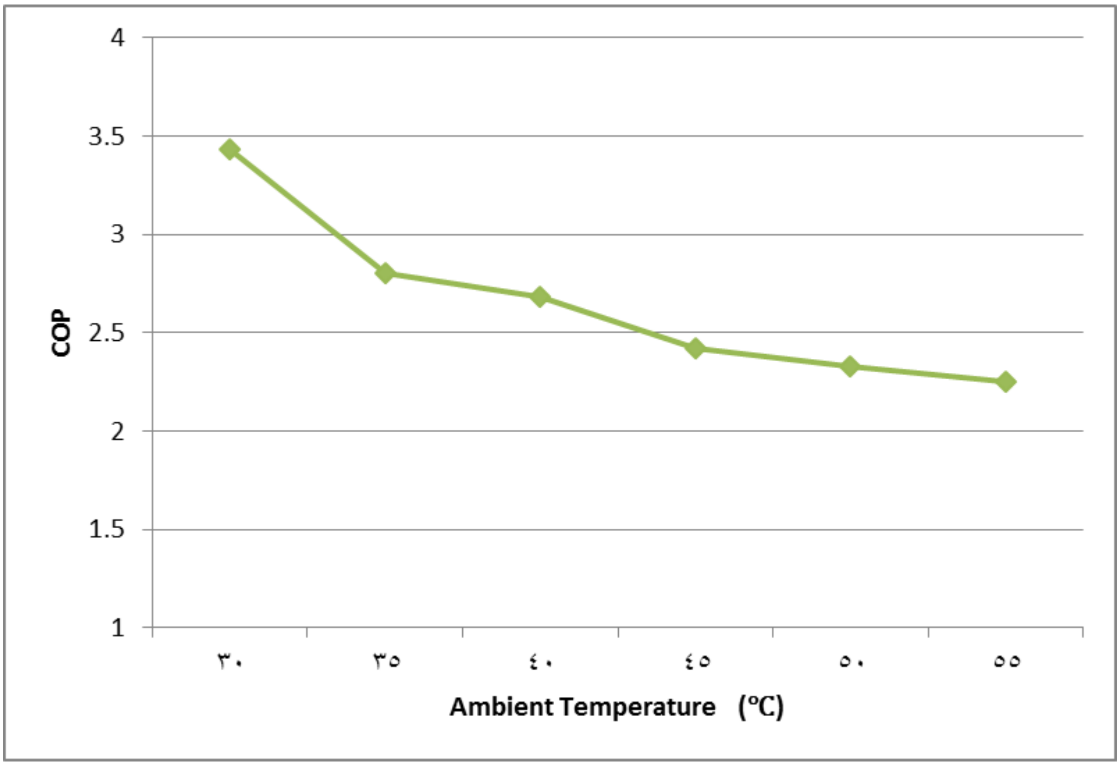

Figure (5.4): The relationship between COP and the ambient temperature

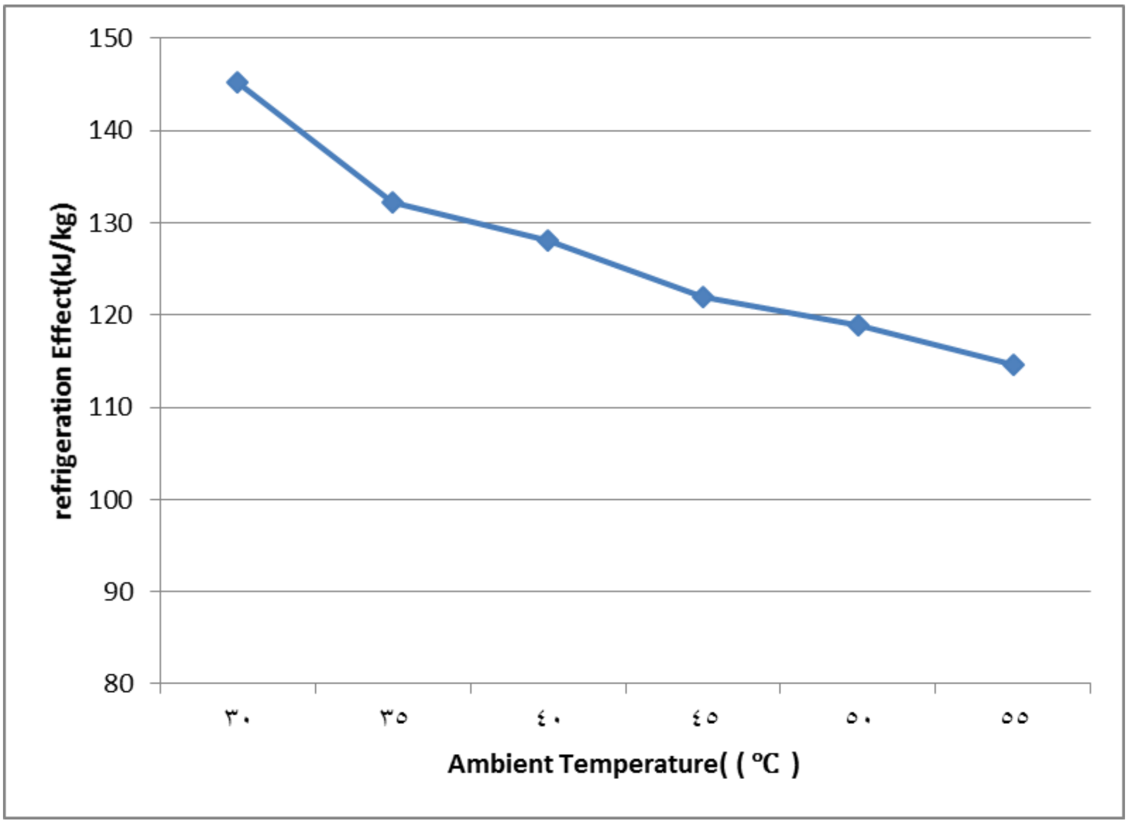

Figure (5.5): The relationship between refrigeration effect and the ambient temperature

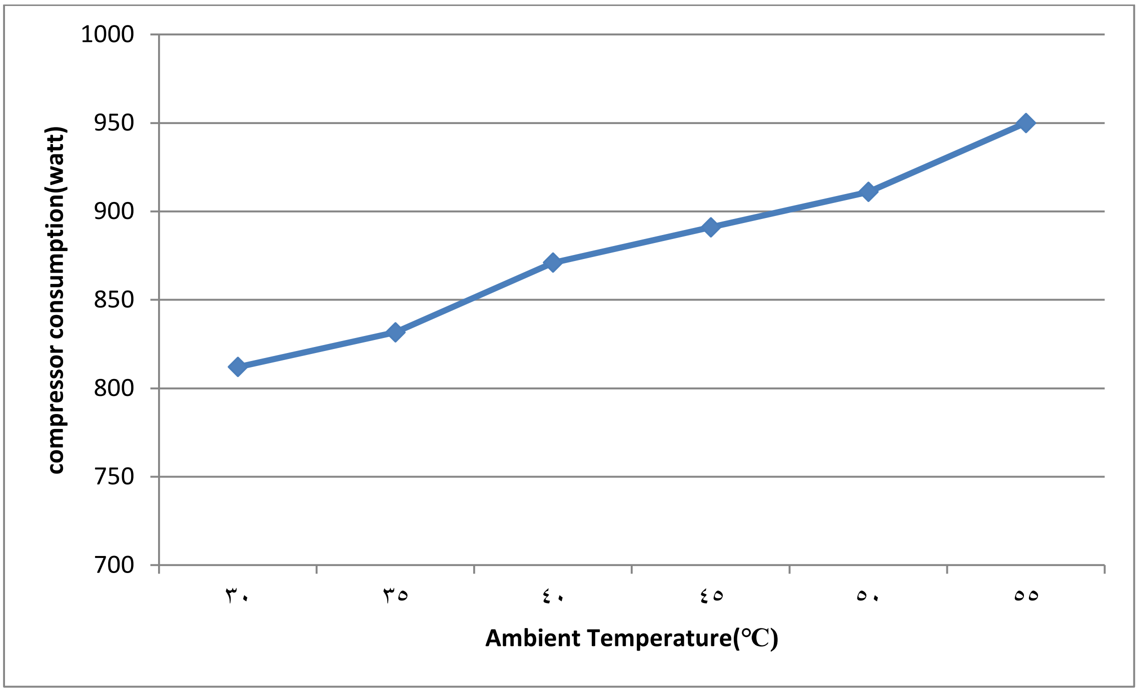

Figure (5.6): The relationship between compressor consumption and the ambient temperature

The goal of the cooling process is to remove the largest amount of heat by increasing the flow of refrigerant and reduce the compressor work.

Compression ratio is a good indication of the status of the compressor whether it is properly working or not. It is the absolute discharge pressure leaving the compressor divided by the absolute suction pressure entering the compressor. the higher compression ratio means the fewer flow of refrigerant is being moved as shown in figure (5.7), and less heat is being removed. The lower the compression ratio the more heat is removed.

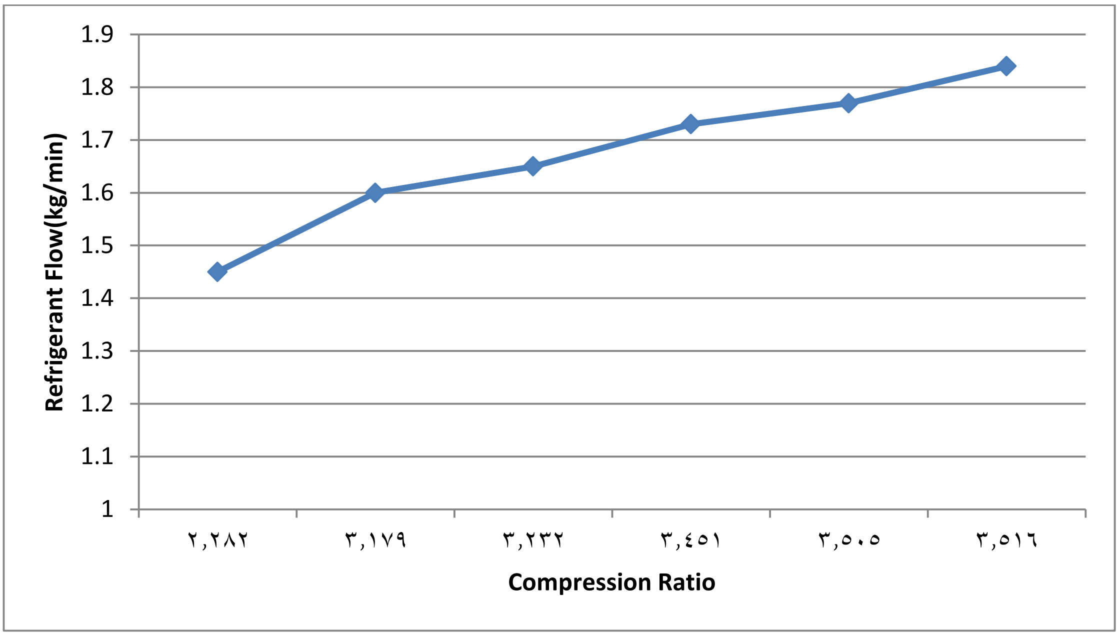

Figure (5.7): The relationship between refrigerant flow and compression ratio

The compression ratio will change as the evaporator load and the condensing temperature change as shown in figure (5.8). As equipment gets more and more efficient, manufacturers are designing systems to have lower compression ratios by using larger coils and smaller compressors.

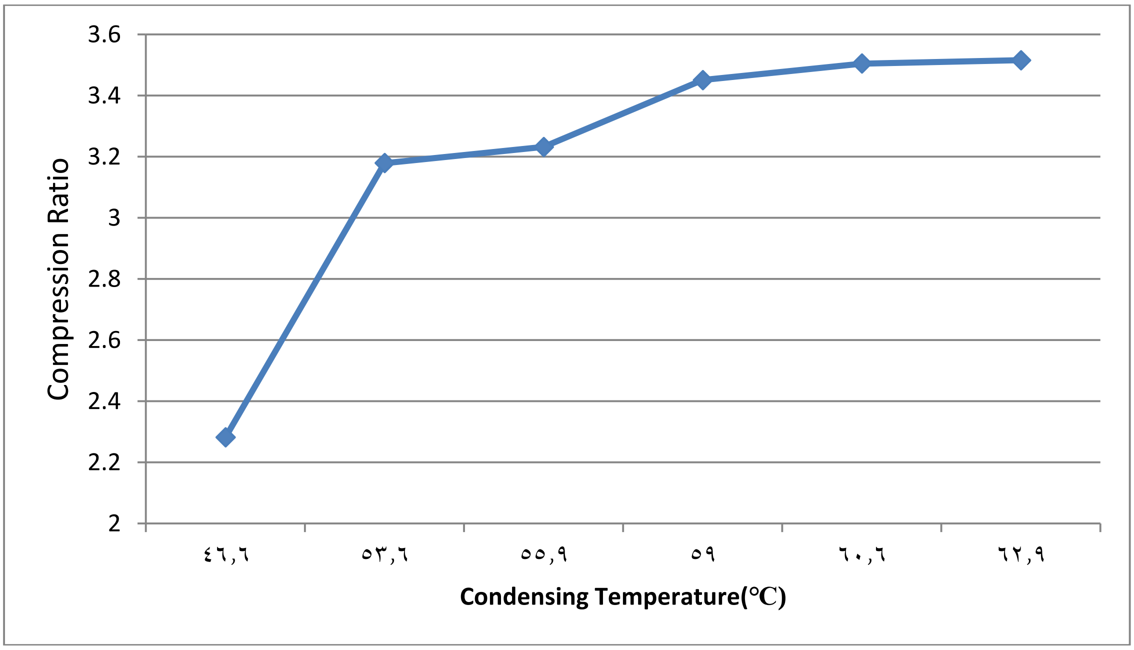

Figure (5.8): The relationship between condensing temperature and compression ratio

It can be also concluded that when the ambient temperature rises, the compression ratio increases as a result of condensation temperature elevation. The higher the compression ratio the higher the power consumption as shown in figure (5.9), low capacity and compressor overheating.

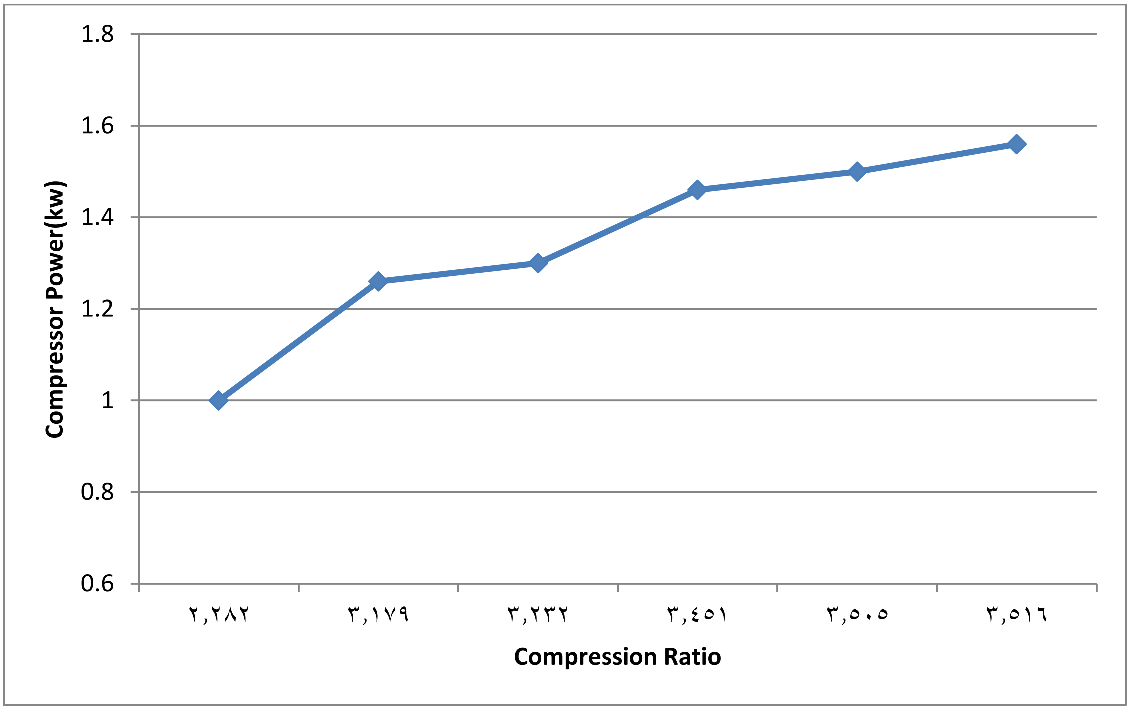

Figure (5.9): The relation between the compression ratio and the power consumption

5.2 Results of the Second phase of experiment

In this phase of the experiment the capillary tube was replaced with a thermostatic expansion valve (TXV) and some equipments were add like: liquid receiver, one way valves, sight glass and measurement devices like pressure gages and thermometers as shown in figure (5.10)

Figure (5.10): The system equipped with TEV

The experiment was executed under controlled various ambient temperature in the workshop. All average records were organized in table (5.3).

Table (5.3): Results of phase two of experiment

Indoor RH%=61 %	Ambient Temperature°C											
	30		35		40		45		50		55	
	P*	T**	P	T	P	T	P	T	P	T	P	T
Evaporator inlet	125	5.9	140	9.3	145	10.3	147	10.7	150	11.4	155	12.4
Evaporator outlet	110	2.2	112	2.8	115	3.5	118	4.2	120	4.7	120	4.7
Condenser inlet	320	37.7	325	38.3	336	39.6	344	40.6	355	41.8	365	42.9
Condenser outlet	315	37.1	320	37.7	320	37.7	325	38.3	336	39.6	346	40.8
Measured Temperature(°C)												
Evaporator inlet	5.6		9		10		10.4		11.2		12.2	
Evaporator outlet	6		6.6		7.3		8		8.5		8.7	
Electrical												
Volts(V)	220		220		220		220		220		220	
Amperes (A)	2.9		3.2		3.5		3.5		3.6		3.65	
Watts(W)	574		634		693		697		713		733	
**T: saturation temperature (°C) *P: gage pressure (psi)												

By using Mollier Chart program from (Techni Solve Software cc) to analyse the refrigeration cycle in this case. The results included in table (5.4) have been got.

Table (5.4): Analysis of the results of the second section of the Experiment

The system equipped with TEV						
Ambient Temperature	30°C	35°C	40°C	45°C	50°C	55°C
System						
Refrigerant	R410a					
COP	3.99	3.99	3.9	3.86	3.76	3.62
Evaporator						
Temperature(°C)	2.2	2.8	3.5	4.2	4.7	4.7
Pressure(Kpa)	857	874	893	913	927	927
Entering Quality	0.267	0.269	0.276	0.280	0.288	0.297
Saturated Enthalpy(kJ/kg)	423.3	423.4	423.6	423.8	423.9	423.9
Refrigeration Effect(kJ/kg)	160.4	159.4	157.3	155.7	153.6	151.6
Condenser						
Temperature(°C)	37.7	38.3	39.6	40.6	41.8	42.9
Pressure(Kpa)	2278	2311	2384	2441	2511	2577
Heat Rejection(kJ/kg)	200.5	199.4	197.6	196	194.5	193.6
Suction						
Temperature(°C)	2.3	2.9	3.6	4.3	4.8	4.8
Specific Volume(m^3/kg)	0.031	0.030	0.029	0.029	0.028	0.028
Enthalpy(kJ/kg)	423.4	423.5	423.7	423.9	424	424
Discharge						
Temperature(°C)	65.1	65.6	67.1	68.2	69.8	71.6
Specific Volume(m^3/kg)	0.013	0.013	0.013	0.012	0.012	0.012
Enthalpy(kJ/kg)	463.6	463.5	464	464.3	464.9	466
Liquid						
Temperature(°C)	37.6	38.2	39.5	40.5	41.7	42.8
Density(kg/ m^3)	990.27	986.99	979.85	974.32	967.66	961.53
Enthalpy(kJ/kg)	263	264.1	266.4	268.2	270.4	272.4
Compressor						
Swept Volume(L/s per TR)	0.669	0.66	0.654	0.647	0.645	0.653
Compression Ratio	2.659	2.645	2.670	2.675	2.71	2.781
Compressor work(kJ/kg)	40.2	40	40.3	40.4	40.9	41.9
Refrigerant Flow(kg/min)	1.3	1.32	1.34	1.36	1.37	1.39
Compressor Power(kw)	0.87	0.88	0.90	0.92	0.93	0.97

The figure (5.11) illustrates the relation between the ambient temperature and the condensing temperature. It can be noticed that the increase in condensing temperature is not big with the ambient temperature elevation.

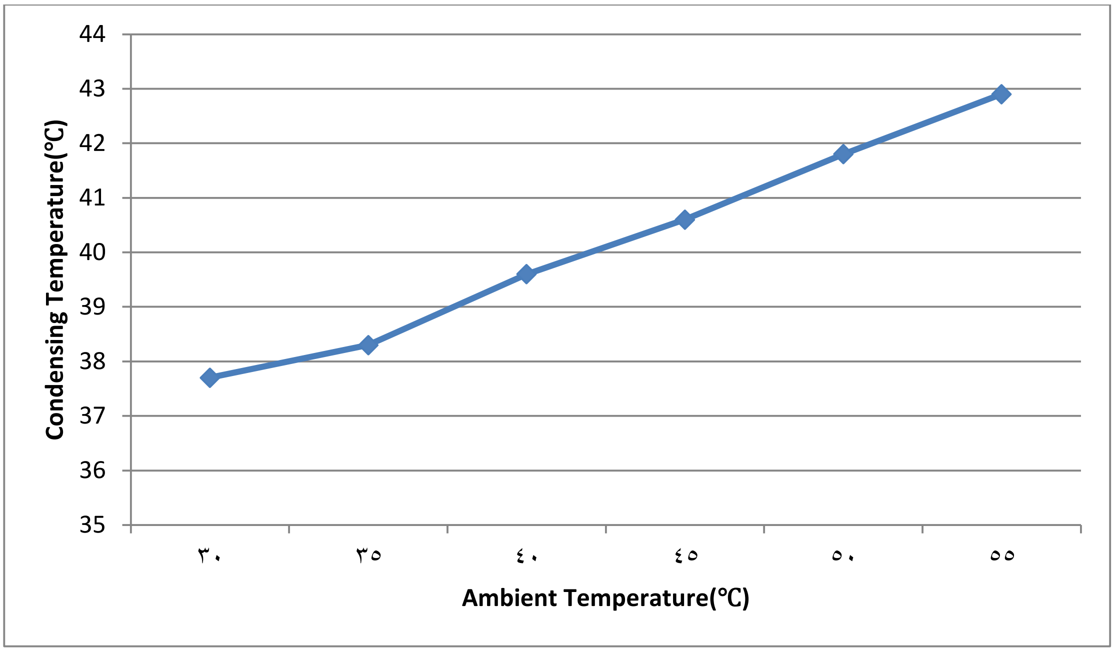

Figure (5.11): Relation between the ambient temperature and the condensing temperature

The reduction in condensing temperature will increase the heat rejection from air cooled condenser to the hotter ambient as shown the figure (5.12). The reduction in heat rejection between the highest and the lowest condensing temperature is 6.9 kJ/kg

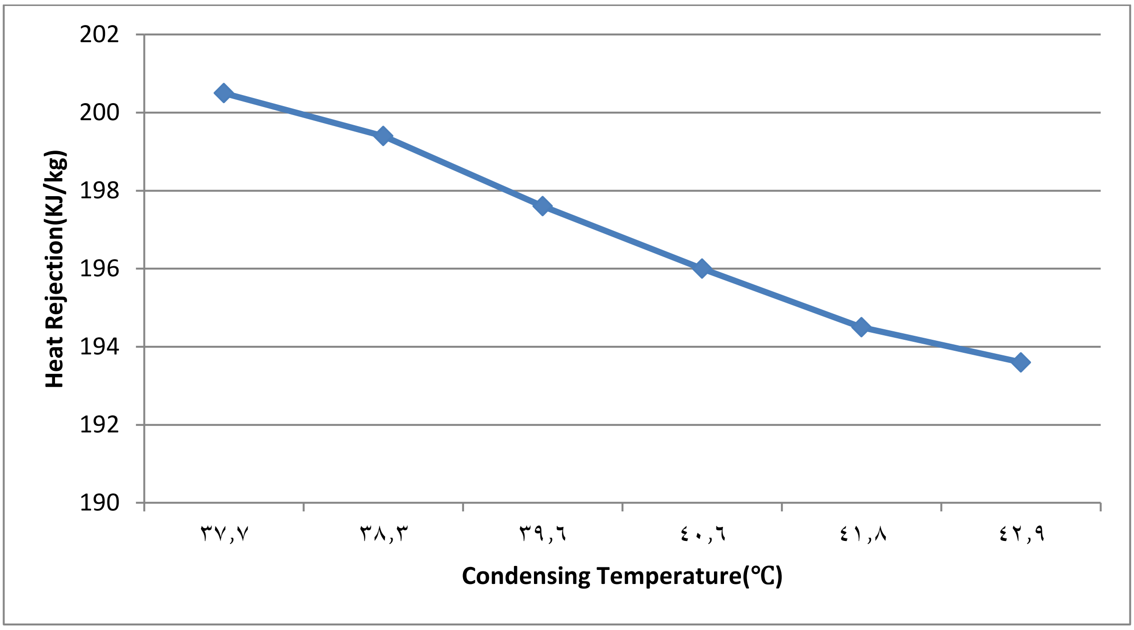

Figure (5.12): Relation between the condensing temperature and the heat reduction

Decreasing the condensing temperature will increase the refrigeration effect. In this phase of the experiment, it is noticeable that the refrigeration effect stays nearly at the same level despite the increase in ambient temperature as shown in figure (5.13)

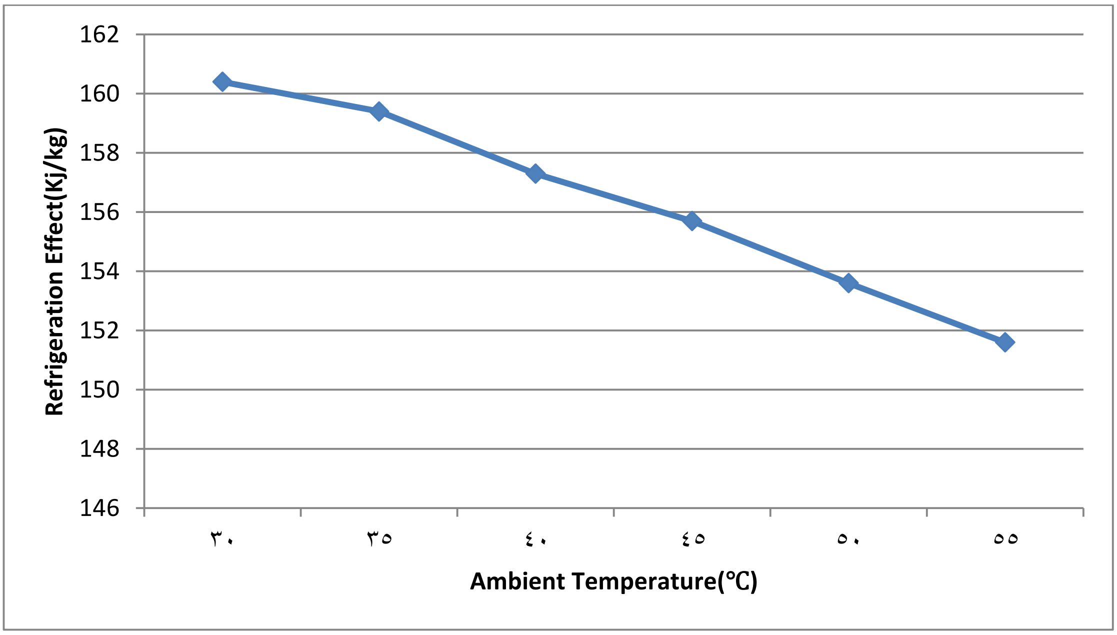

Figure (5.13): Relation between the ambient temperature and the refrigeration effect

Decreasing the condensing temperature and increasing the refrigeration effect as shown in this phase of experiment will increase the efficiency of the cooling system as shown in figure (5.14).

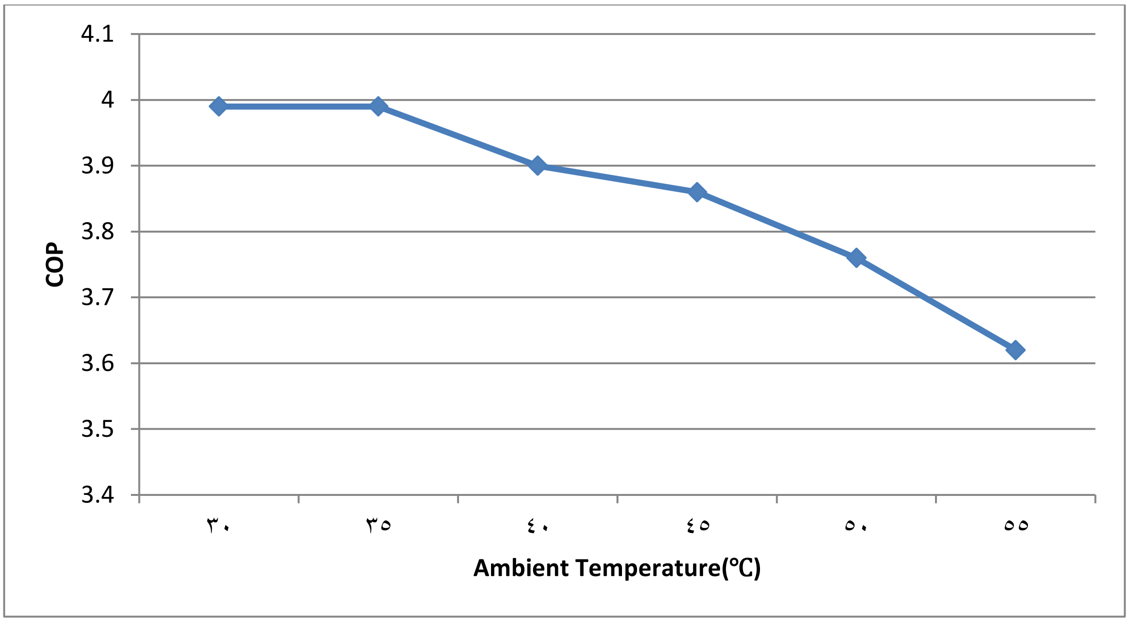

Figure (5.14): Relation between the ambient temperature and the COP

In this phase of the experiment, it is noticeable that the discharge pressure and the suction pressure is not high, therefore the compression ratio is ideal for this system as the figure (5.15) shows

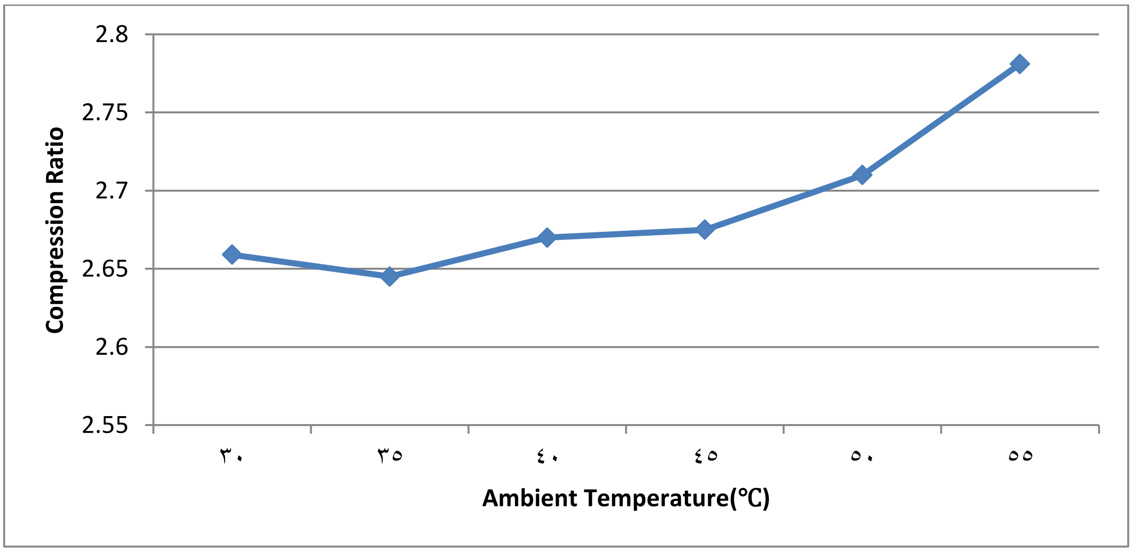

Figure (5.15): Relation between the ambient temperature and the Compression ratio

Because of the acceptable values of compression ratio, the compressor power will be decreased by comparing with other cooling systems, the figure (5.16) shows the relation between the compression ratio and the compressor power.

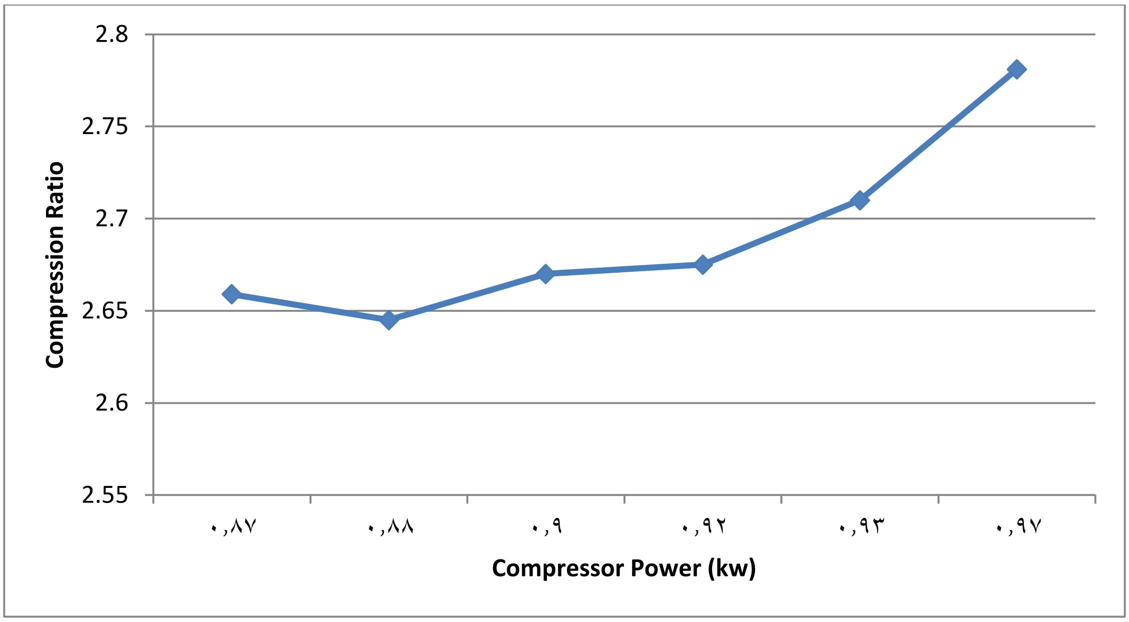

Figure (5.16): The relation between the compression ratio and the compressor power

5.3 Results of the Third phase of experiment

At this phase of experiment, the surface of the condenser coil was reduced about four rows as shown in figure (5.17) and figure (5.18), with thermostatic expansion valve (TXV) and some equipments were add like: liquid receiver, one way valves , sight glass and measurement devices like pressure gages and thermometers.

Figure (5.17): The condenser before reducing its surface

Figure (5.18): The condenser after reducing its surface

The experiment was executed under controlled various ambient temperatures in the workshop. All average records were organized in table (5.5).

Table (5.5): Results of phase three of experiment

Indoor WB=24°C RH%=66%	Ambient Temperature°C											
	30		35		40		45		50		55	
	P*	T**	P	T	P	T	P	T	P	T	P	T
Evaporator inlet	130	7	135	8.2	140	9.3	143	9.9	149	11.2	155	12.4
Evaporator outlet	120	4.7	129	6.8	133	7.7	137	8.6	140	9.3	142	9.7
Condenser inlet	345	40.7	357	42.1	365	42.9	384	45	405	47.2	430	49.8
Condenser outlet	335	39.5	346	40.8	353	41.6	365	42.9	379	44.5	405	47.2
Measured Temperature(°C)												
Evaporator inlet	6.4		7.6		9		9.7		11		12.2	
Evaporator outlet	8.5		10.6		11.5		12.4		13		13.5	
Electrical												
Volts(V)	220		220		220		220		220		220	
Amperes(A)	3.2		3.3		3.4		3.5		3.65		3.7	
Watts(W)	634		653		694		705		723		773	
**T: saturation temperature (°C) *P: gage pressure (psi)												

By using Mollier Chart program from (Techni Solve Software cc) to analyse refrigeration cycle in this case, we got the following results as in the table (5.6).

Table (5.6): Analysis of the results of the third phase of the Experiment

Ambient Temperature	30℃	35℃	40℃	45℃	50℃	55℃
System						
Refrigerant	R410a					
COP	3.91	3.9	3.88	3.84	3.63	3.35
Evaporator						
Temperature(℃)	4.7	6.8	7.7	8.6	9.3	9.7
Pressure(Kpa)	927	988	1015	1043	1065	1078
Entering Quality	0.278	0.279	0.280	0.294	0.309	0.331
Saturated Enthalpy(kJ/kg)	423.9	424.4	424.7	424.9	425	425.1
Refrigeration Effect(kJ/kg)	155.6	153.6	152.3	148.7	144	139.9
Condenser						
Temperature(℃)	40.7	42.1	42.9	45	47.2	49.8
Pressure(Kpa)	2447	2529	2577	2705	2844	3014
Heat Rejection(kJ/kg)	195.4	191.9	190.2	187.4	184.6	181.7
Suction						
Temperature(℃)	4.8	6.9	7.8	8.7	9.4	9.8
Specific Volume(m^3/kg)	0.028	0.026	0.026	0.025	0.024	0.024
Enthalpy(kJ/kg)	424	424.6	424.8	425	425.1	425.2
Discharge						
Temperature(℃)	67.9	68.5	69.1	71.8	74.9	78.9
Specific Volume(m^3/kg)	0.012	0.012	0.011	0.011	0.01	0.01
Enthalpy(kJ/kg)	463.8	462.9	462.6	463.7	465	466.9
Liquid						
Temperature(℃)	40.6	42	42.8	44.9	47.1	49.7
Density(kg/ m^3)	973.77	965.99	961.53	949.75	937.32	922.52
Enthalpy(kJ/kg)	268.4	271	272	276.3	280.4	285.3
Compressor						
Swept Volume(L/s per TR)	0.637	0.604	0.592	0.59	0.593	606.
Compression Ratio	2.641	2.56	2.538	2.593	2.67	2.797
Compressor work(kJ/kg)	39.8	38.3	37.9	38.7	39.9	41.7
Refrigerant Flow(kg/min)	1.36	1.37	1.39	1.42	1.46	1.5
Compressor Power(kw)	0.9	0.87	0.88	0.92	0.97	1

The results of this phase of experiment, shows acceptable values of COP, Heat rejection Refrigeration effect, Compression ratio and Compressor power as the figures below show.

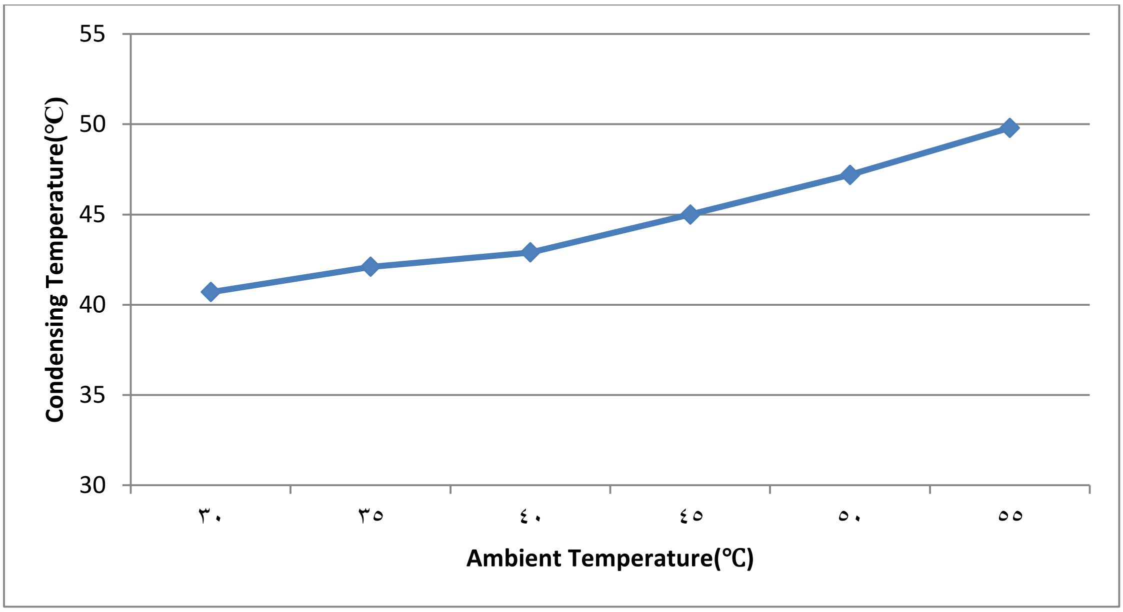

Figure (5.19): Relation between the ambient temperature and the condensing temperature

The figure (5.19) shows that the condensing temperature increased by the elevation of ambient temperature.

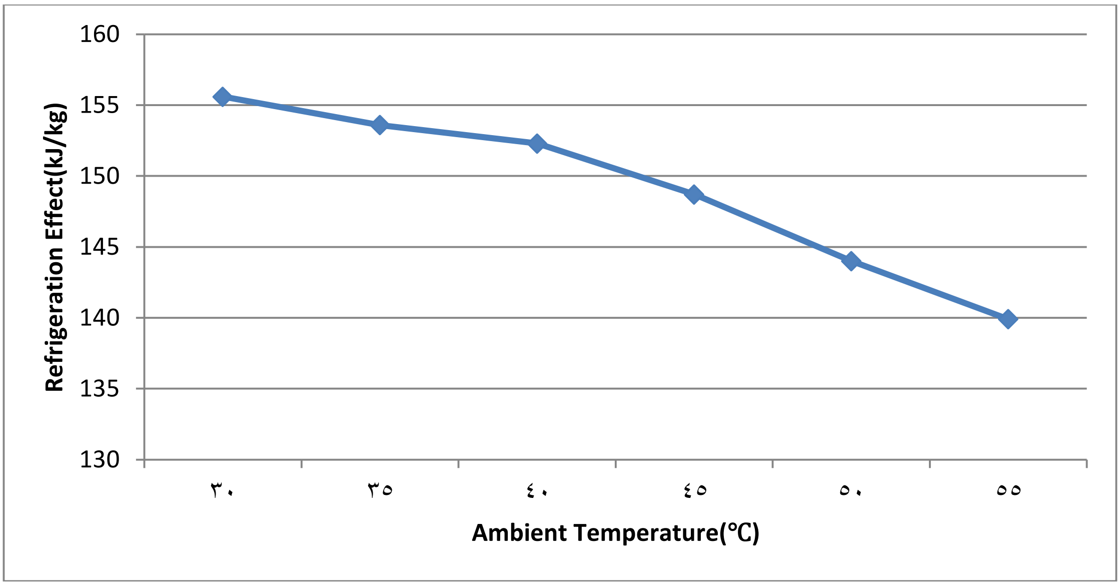

Figure (5.20): Relation between the ambient temperature and the refrigeration effect

The figure (5.20) shows the decreasing in refrigeration effect when the ambient temperature increased.

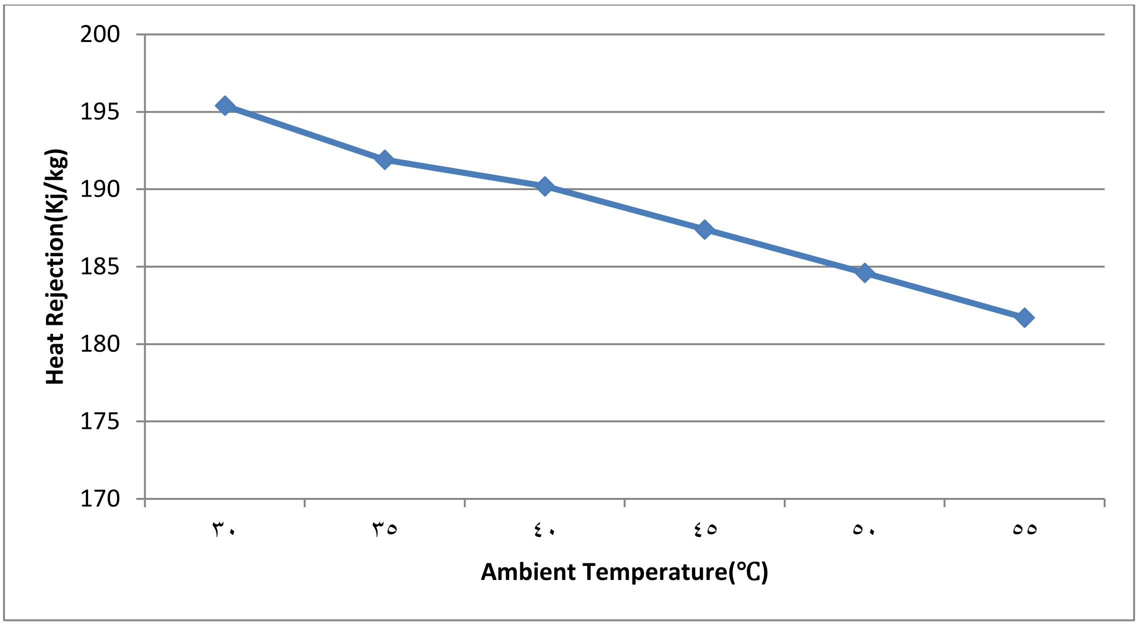

Figure (5.21): Relation between the ambient temperature and the heat reduction

Heating rejection throw the condenser is decreased when the ambient temperature increased as shown in figure (5.21).

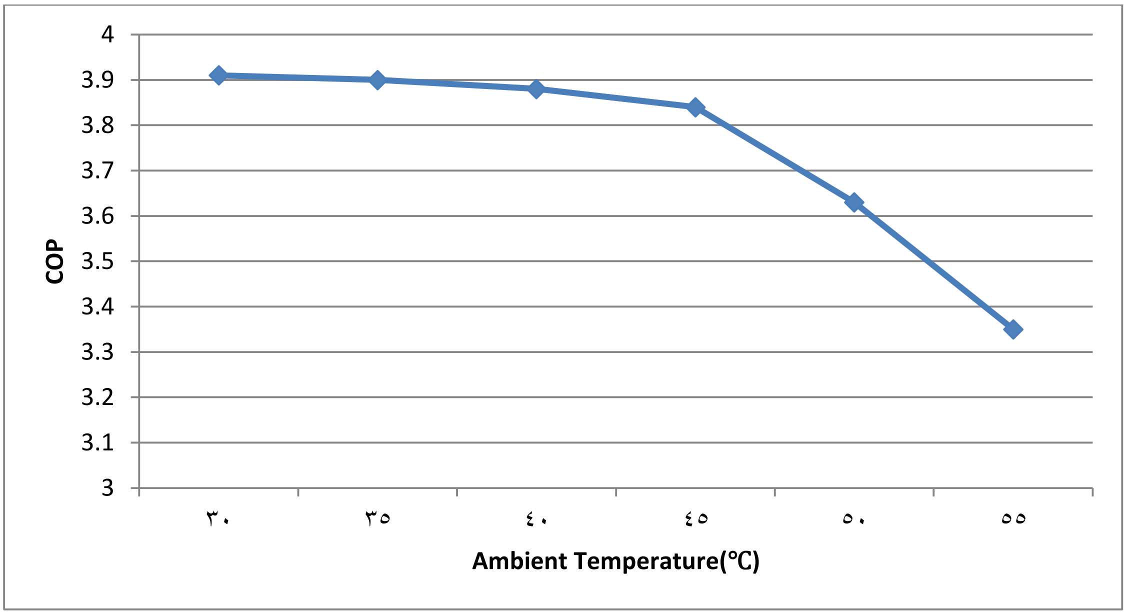

Figure (5.22): Relation between the ambient temperature and the COP

As a result of reduction in refrigeration effect the COP will decrease when the ambient temperature increase as shown in figure (5.22).

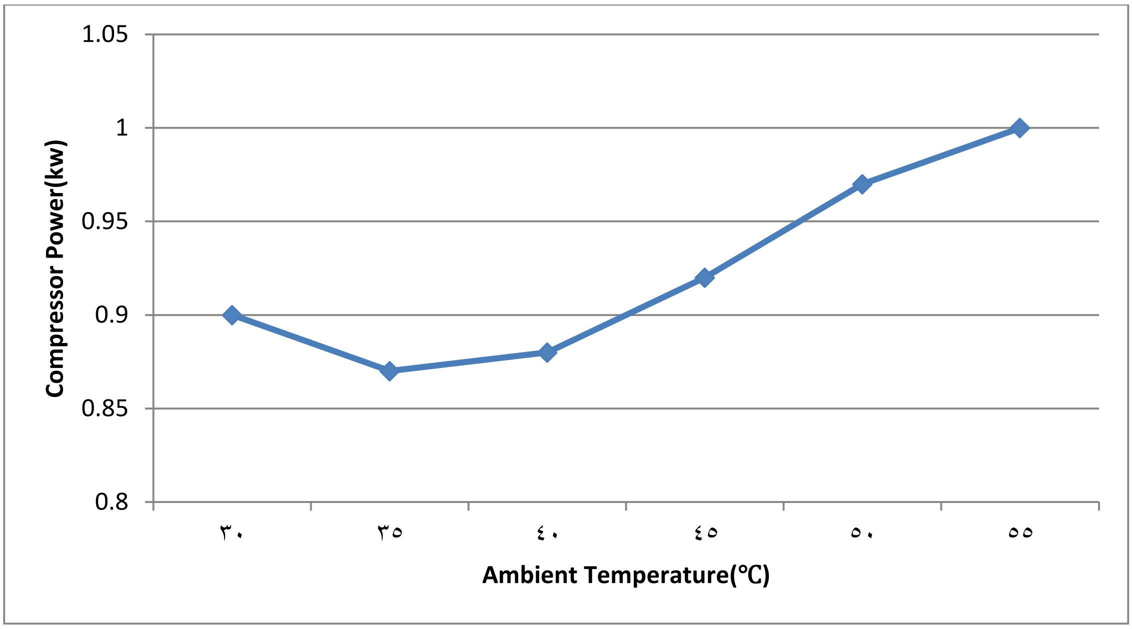

Figure (5.23): Relation between the ambient temperature and the compressor power

Because of decreasing in refrigeration effect and increasing in compressor work, the compressor power will increase by the elevation of the ambient temperature as shown in figure (5.23).

5.4 Comparison between the three phases of experiment

By making a comparison between the results of the three phases of experiment, to choose the best situation for the cooling system at which the system works properly at a different ambient temperature. The diagrams below illustrate the difference between the different air conditioning systems when compared to the physical values that have been tested.

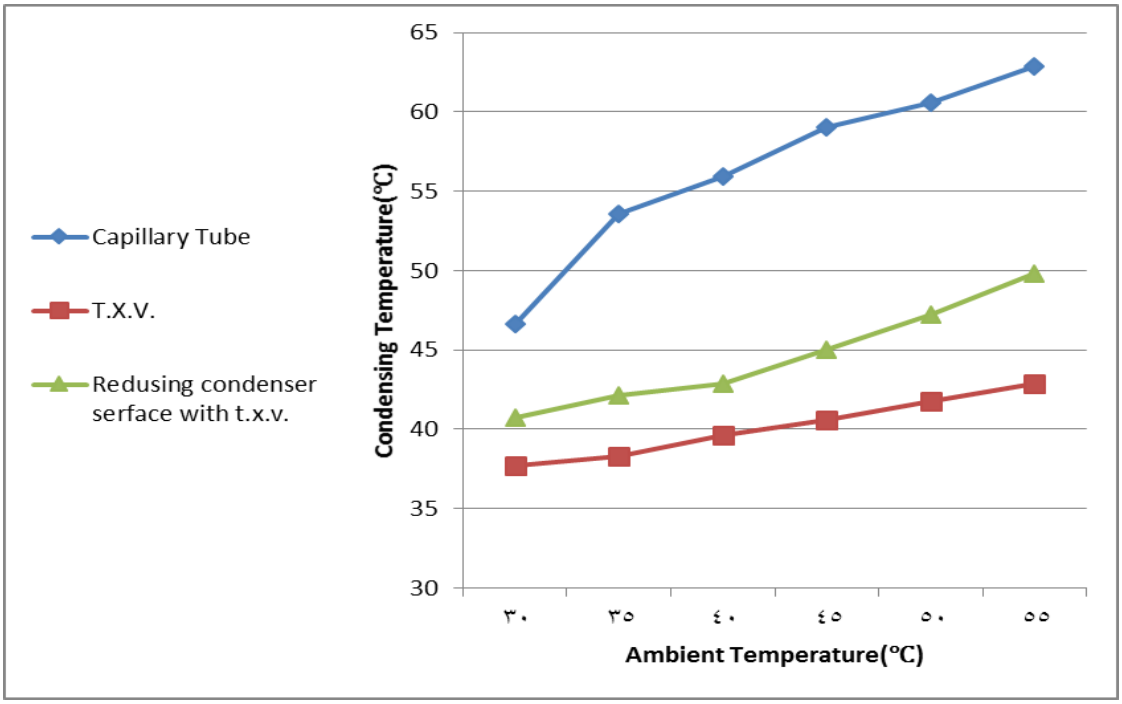

Figure (5.24): The relation between the ambient temperature and condensing temperature

The figure (5.24) shows that the air conditioner which equipped with TXV is the best system in terms of condensing temperature, when there is a comparison between the two systems working under different condensing temperatures, it is noted that the system that operates under the lower condensing degree has a high cooling capacity than the other system, as illustrated in the figure (5.25).

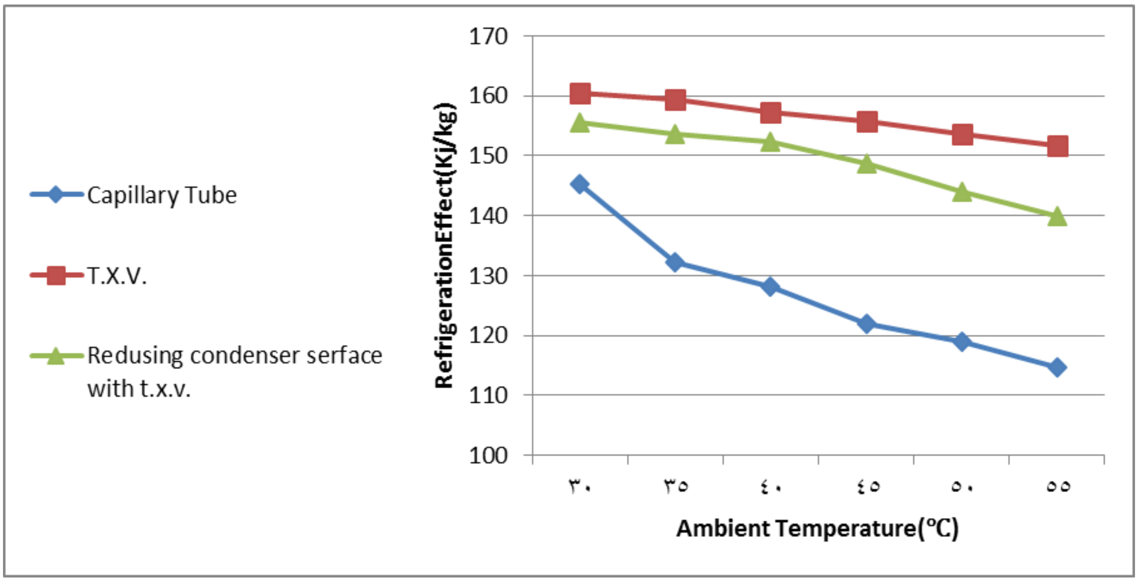

Figure (5.25): The relation between the ambient temperature and the refrigeration effect

In figure (5.26) it is noticed that the heat rejection in the system equipped with thermal expansion valve is better than the system equipped with capillary tube in the heat rejection to the ambient air, because of the decrease in condensing temperature.

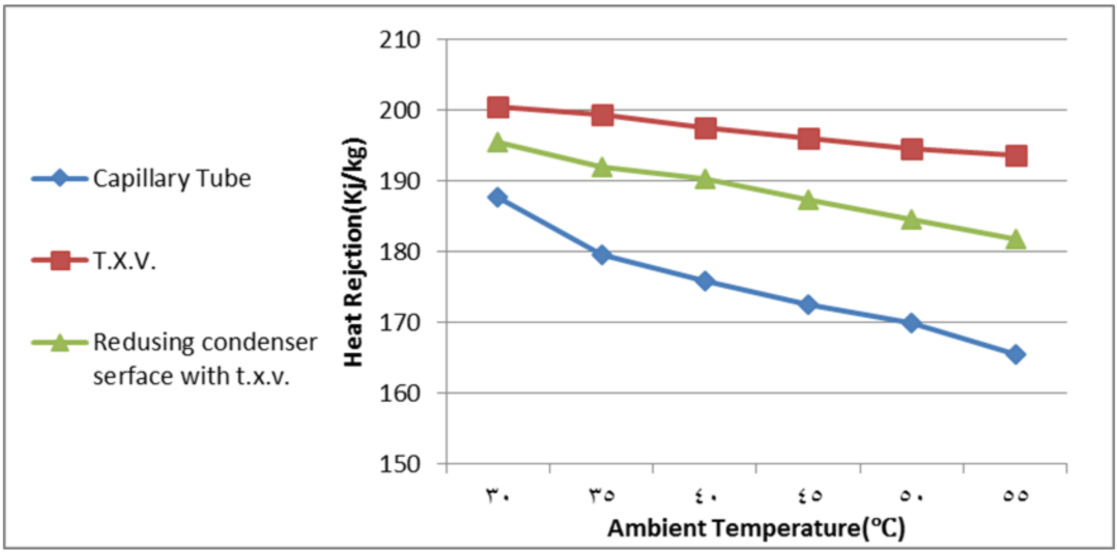

Figure (5.26): The relation between the ambient temperature and the heat rejection

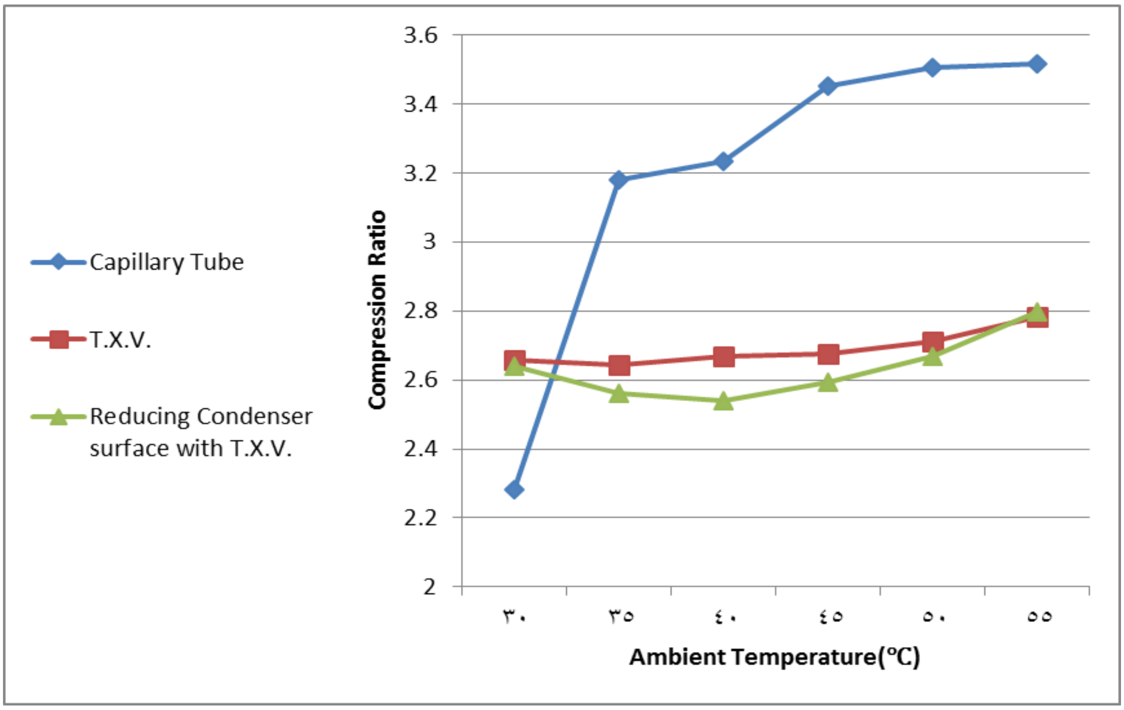

Figure (5.27): The relation between the ambient temperature and the compression ratio

Because of decreasing in discharge pressure in the system equipped with TXV the compression ratio is lower than the system equipped with capillary tube, as the figure (5.27) shows. This leads to decrease in compressor power as shown in figure (5.28)

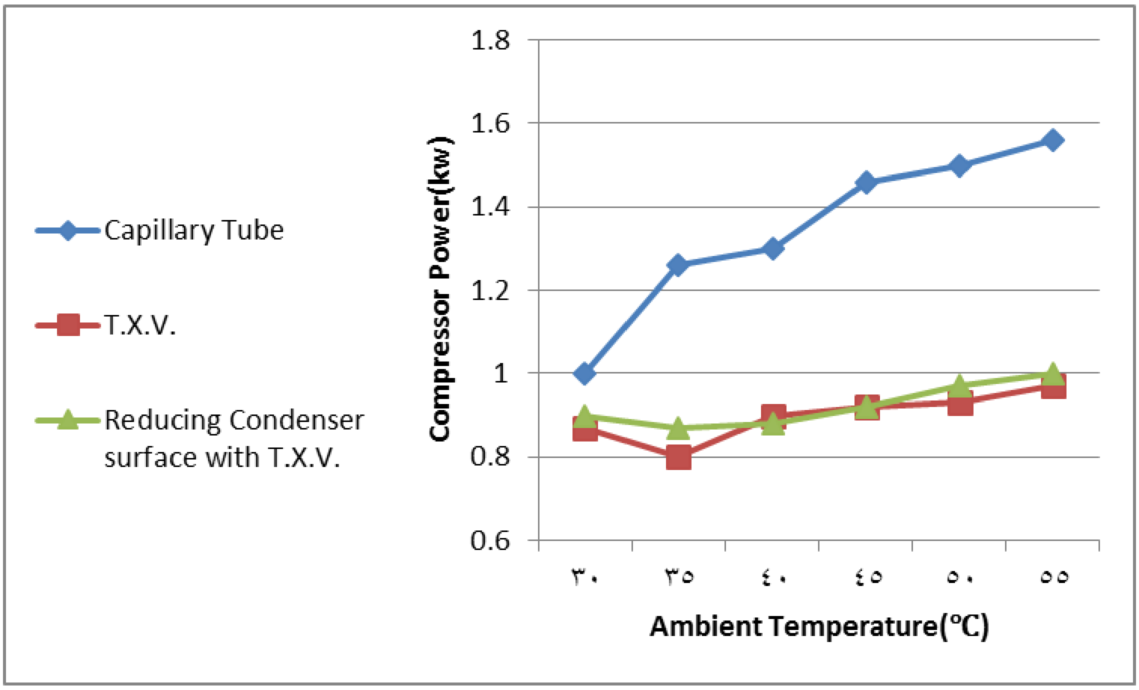

Figure (5.28): The relation between the ambient temperature and the compressor power

Overall, it is clear that the system that operates using the thermal expansion valve better in terms of efficiency than the system which uses the capillary tube as the figure (5.29) shows.

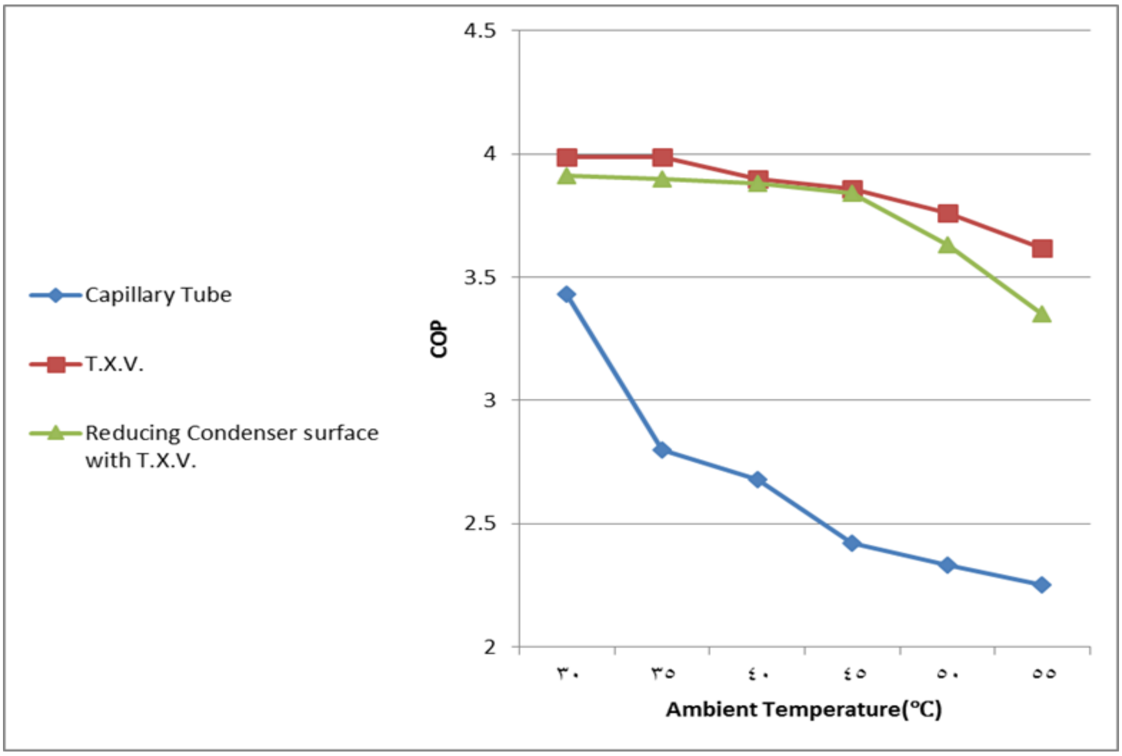

Figure (5.29): The relation between the ambient temperature and the COP

Regarding to energy consumption, it is noticeable from the figure (5.30) that the system that used the TXV is less power consumption than the system used the capillary tube.

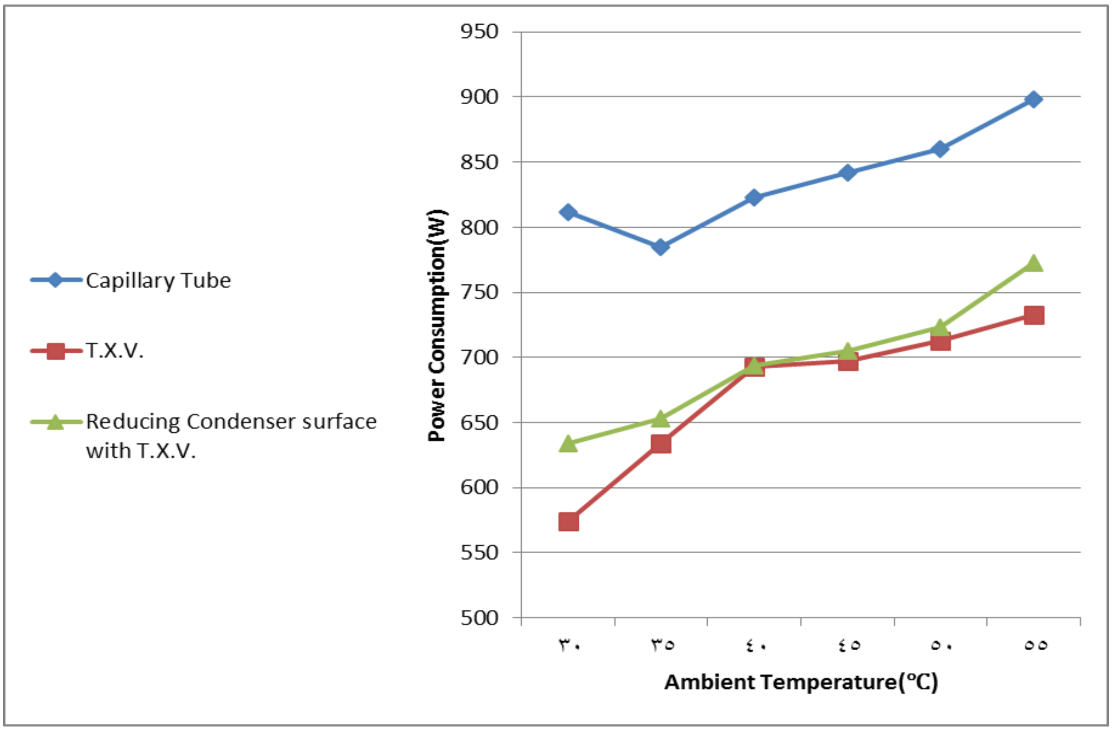

Figure (5.30): The relation between the ambient temperature and the power consumption

5.5 Saving Calculations:

Daily operating hours:10hr/day

for 3monthes (1 year): 10 x 30 x 3= 900 hr

Power consumed before modification at max. load: 1.6kW

Energy consumed before modification at max. load:

1.6 kW x 900hr =1440 kW-hr for a year

Energy consumed after modification at max. load:

0.97 kW x 900hr =873 kW-hr for a year

Energy Saving = 1440 – 873 = 567 kW- hr

kW-hr price is 0.17$

Saving for 1 year = 567 x 0.17 = 96$

Investment cost = 55$

Pay Back period = Investment / Saving

= 55 / 96

= 0.6 year (1.5 Month)

Emission Calculation:

Every 1 kW-hr $\longrightarrow$ 0.621 kg emissions of CO_2 [4]

CO_2 emission reduction = 567 x 0.621 = 352 kg

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions:

The thesis answered the main hypothesis of the research:

In the first hypothesis, it was hypothesized that: Under the capillary tube design, the COP decrease when ambient temperature increases at specific capillary tube design, and the result was decreasing in the COP when the ambient temperature increases at specific capillary tube design.

In the second hypothesis, it was hypothesized that: Using TXV gives high COP than a capillary tube at higher ambient temperatures, and the result was high COP when replacing capillary tube with TXV.

In the third hypothesis, it was hypothesized that: reducing the condenser surface area with TXV maintains the COP, and the result was reducing in COP when decreasing the condenser surface area with TXV.

In the forth hypothesis, it was hypothesized that: The electrical energy consumption decreases by using TXV and optimal condenser surface area, and the result was reducing in electrical energy consumption by using TXV and optimal condenser surface area.

6.2 Recommendations:

1. It is recommended to make an engineering adjustment to existing air conditioners

by replacing the capillary tubes with thermostatic expansion valves to reduce electric consumption and increasing COP specially in hot days.

2. Completion of the study when replacing the thermostatic expansion valve with

electronic expansion valve and observing its effect on both: the rate of energy consumption in the air conditioner and the coefficient of performance.

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التحقق من معامل الاداء لمكيفات الهواء المنزلية باستخدام تصاميم هندسية مختلفة: دراسة تجريبية

إعداد
سامر "محمد هاني" سليم الكرمي

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قدمت هذه الأطروحة استكمالًا لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وترشيد الاستهلاك بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس، فلسطين.

2019م

التحقق من معامل الاداء لمكيفات الهواء المنزلية باستخدام تصاميم هندسية مختلفة: دراسة تجريبية

إعداد
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الملخص

تعاني فلسطين من نقص في الطاقة الكهربائية بسبب الاحتلال الاسرائيلي ونقص المصادر اللازمة لتوليد الطاقة الكهربائية. تظهر هذه المشكلة بشكل واضح في فصل الصيف عندما ترتفع درجة الحرارة الخارجية ونسبة الرطوبة. لتوفير ظروف حرارية مريحة للإنسان يقوم الناس باستخدام المكيفات المنزلية. تُظهر الاحصائيات أن هناك زيادة واضحة في استهلاك الطاقة الكهربائية عند استخدام المكيفات بكثرة في فصل الصيف، مما يؤدي في بعض الاحيان الى حدوث انقطاع في تزويد الكهرباء بسبب الحمل الزائد على الشبكات الكهربائية.

يعود السبب الرئيسي في الاستهلاك الزائد للطاقة الكهربائية في المكيفات المنزلية الى ارتفاع درجة الحرارة الخارجية، حيث تعمل هذه المكيفات تحت ظروف حرارية أعلى من تلك التي صممت لتعمل عليها، مما يقلل من كفاءتها واستهلاكها الزائد للتيار الكهربائي.

للتغلب على هذه المشكلة، تم اجراء بعض التعديلات الهندسية على الدائرة الميكانيكية للمكيف، ولتنفيذ هذه التعديلات تم اجراء التجربة على ثلاث مراحل: في المرحلة الاولى: تم اختبار عمل المكيف الاصلي دون اجراء أي تعديلات عليه تحت درجات حرارية خارجية مختلفة وفي المرحلة الثانية: تم استبدال الانبوب الشعري بصمام تمدد حراري واختبار عمل المكيف وفي المرحلة الثالثة: تم تقليل سطح التبادل الحراري للمكثف مع بقاء صمام التمدد الحراري واجراء الاختبار. في المراحل الثلاث السابقة تم تشغيل المكيف تحت درجات حرارة خارجية تتراوح بين 30مْ الى 55مْ لفترة كافية وتسجيل القراءات المطلوبة، ثم اجراء الحسابات اللازمة لإيجاد معمل الاداء واستهلاك الطاقة الكهربائية في جمع الحالات السابقة.

عند اجراء مقارنة للنتائج التي حصلنا عليها، تبين ما يلي: عدم تأثر معامل الاداء للمكيف بارتفاع درجة الحرارة الخارجية عند استبدال الانبوب الشعري بصمام التمدد الحراري مع المحافظة على مساحة سطح التبادل الحراري كما هي، حيث ازداد معامل الاداء عند درجة حرارة خارجية 30مْ من 3.43 الى 3.99 في المكيف المعدل، وعند اجراء الاختبار عند درجة حرارة خارجية مقدارها 55مْ ارتفع معامل الاداء من 2.25 في المكيف الاصلي الى 3.62 في المكيف المعدل وحدث انخفاض ملموس في استهلاك الطاقة الكهربائية في المكيف المعدل عند استبدال الانبوب الشعري بصمام التمدد الحراري يقدر بنسبة 23%، بالإضافة الى حدوث انخفاض في انبعاث غاز ثاني اكسيد الكربون بمقدار 365 كغم في ثلاثة اشهر.