Thermodynamic Performance Analysis of Hydrocarbon Based Domestic Refrigeration System

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ABSTRACT

The use of synthesized refrigerants has several environmental concerns. The most widely used substances like hydro fluorocarbons (HFCs), chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) have either high global warming potential (GWP), high ozone depletion potential (ODP) or long atmospheric life time. With the growing demand of healthier atmosphere, the study of other alternative substances is very important. This paper presents theoretical thermodynamic performance analysis of hydrocarbon based domestic vapour compression refrigeration system. Propane (R-290), isobutane (R-600a) and butane (R-600) were used. Then, the results were compared with the performance of currently most commonly used tetrafluoroethane (R-134a). These hydrocarbons have zero ODP and very negligible GWP. Different parameters, like coefficient of performance (COP), refrigeration effect, compressor work input and compressor discharge temperature were investigated. Evaporator and condenser temperatures, subcooling, superheating and compressor isentropic efficiency were the variables used for this study. MATLAB software has been used in the mathematical analysis. COP values were found comparable to that of R-134a. All the hydrocarbons investigated gave beyond 150% refrigeration effect compared to R-134a for the same mass flow rate. But this was at the expense of higher compressor work input. This research also revealed that the compressor discharge temperature is much lower for R-600a and R-600. Generally, these hydrocarbons showed that they are a good alternative to R-134a based on the thermodynamic point of view.

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1. INTRODUCTION

This chapter discusses background and what initiated for the study of eco-friendly refrigeration system. Additionally, the objectives that are expected to be accomplished at the end of this research are identified. Finally, what will the contribution of this research is presented.

1.1. Background of the Study

It has been a long time since the concept of refrigeration and air conditioning become a big concern. In the early stages of refrigeration naturally existing substances such as ammonia, water and carbon dioxide were used extensively. Then, because of their excellent thermodynamic and chemical properties, the chemically synthesized halogenated refrigerants CFCs, HCFCs and HFCs are still commonly used working fluids in vapour compression refrigeration system [1]. But, the undesired properties like high global warming effect and ozone depletion rate are phasing them out. Therefore, energy efficient environmentally friendly refrigerants are in demand. As a result, the world is turning in to the naturally existing substances like hydrocarbons.

Despite zero ODP and extremely low GWP, large usage of hydrocarbons as working fluid in refrigeration and air conditioning industries is hindered by their flammable nature [2]. But, for domestic refrigeration purpose, where there is small charge requirement, the use of hydrocarbons with proper precaution and care is an important environmental solution.

1.2. Statement of the Problem

The earth's average temperature is increasing in an increased rate over the past decades. The emission of different greenhouse gases from different industries, vehicles and appliances are the main reasons behind this. These gases allow the short wave length radiations from the sun to reach the earth's surface. But they act as a blanket for the returning large wave length radiations not to escape beyond the atmosphere. Every time these radiations are trapped, the average temperature of the earth increases. As a result of increasing this average temperature, life on earth is getting complicated due to associated environmental changes. One of the direct effects of global warming is the land climatic change. This has endangered the natural land ecosystem. The glaciers and ice caps around earth’s poles are melting; therefore, increasing the sea level. This is a threatening effect on some islands and coastal cities. Oceans are also becoming warmed and the whole ocean ecosystem is hugely influenced because of the interdependence of all members of the ecosystem.

Also, when the ozone layer is degraded, amount of ultraviolent ray radiation reaching the Earth’s surface increases. It is one of the main causes of human skin cancer. Consequences of ultraviolent radiation are not only limited to human being, but also to different land animals, plants, aquatic ecosystems and several materials.

Contribution of the widely used refrigerants, CFCs, HCFCs and HFCs is not something that can be ignored. Some of these synthesized refrigerants have high atmospheric lifetime. So, in the long run, their consequences will get adverse as they have high GWP or ODP or both. Therefore, replacing them with energy efficient environmentally friendly substitutes is something engineers, scientists and researchers should do. Replacing these refrigerants with hydrocarbons will, therefore, avoid the release of greenhouse and ozone depleting gases from refrigeration systems.

Evidences showing that hydrocarbons are good alternative to the currently widely used refrigerants are very important for their extensive use. Though so many researches and experimental investigations, the detailed thermodynamic performance analysis of hydrocarbon-based vapour compression refrigeration system is not given an emphasis. Most researchers have studied only a few thermodynamic properties. It is, therefore, very essential to investigate how different parameters that characterize the refrigeration system behaves when one variable is manipulated. This will greatly help vapour compression refrigeration system users to select refrigerants that will fulfil their demand. This research is devoted to such thermodynamic performance analysis.

1.3. Objective

1.3.1. General Objective

Analysing thermodynamic performance parameters of hydrocarbons and get fuller understanding about how they behave thermodynamically when used as refrigerants.

1.3.2. Specific Objectives

This will specifically address the following objectives.

i. To examine the effect of evaporator temperature on COP, Refrigeration effect, compressor work input, condenser duty, compressor discharge temperature and volumetric cooling capacity.

ii. To investigate the effect of condenser temperatures on system COP, refrigeration effect, compressor work input, condenser duty, compressor discharge temperature and volumetric cooling capacity.

iii. To look into sub-cooling effect on system COP, refrigeration effect and compressor power consumption

iv. To observe super-heating effect on system COP, refrigeration effect and compressor power consumption

v. Finally, effect of compressor isentropic efficiency on the system COP will be investigated.

1.4. Significance of the Study

These days, naturally existing refrigerants are becoming popular from small to large refrigeration systems. Especially, hydrocarbons are attracting a huge attention in domestic refrigeration more than ever. This investigation will assist users to select refrigerants based on the specific demand they wanted to be fulfilled. It will also help researchers working on overall feasibility of these refrigerants by integrating with other analyses, like economic feasibility. The analysis will also assist environmentalists to justify their advocating for environmental protection. Besides, policy makers will get a great deal of knowledge on which substances can be accepted as eco-friendly refrigerants. Furthermore, this research can be used as a foundation for other researchers working on this and similar topics.

2. LITERATURE REVIEW

The evolution of refrigerant usage has been passing through different phases. The naturally existing substances like ammonia (R-717), Sulphur dioxide (R-764), R-290, methyl-chloride (R-40), carbon dioxide and R-600a were first used. But properties like flammability, toxicity, non-stable chemical nature and incompatibility with different system components limited their usage. Then the second generation of refrigerants appeared as their substitutes. This generation comprises CFCs and HCFCs with numerous suitable properties, like non-flammability, non-toxicity, chemical stability, material compatibility and other thermodynamic properties. Though all these properties, they were found to diffuse into the stratosphere easily. Then, the ultraviolent radiation from the sun releases their chlorine atoms, which then reacts with the ozone layer to deplete it. This depletion of ozone layer makes the absorption of high energy content ultraviolent ray in danger and allows reaching the Earth’s surface to attack human being and other living organisms. This environmental impact associated with the ozone layer depletion resulted in the phase out of these refrigerants. The HFCs came to existence as the third generation of refrigerants to solve the ozone layer depletion. These refrigerants have zero ODP; however, they have high global warming effect, which is one of the most critical environmental concerns. All these problems led scientists and researchers to find out refrigerants with zero ODP and very low GWP [3].

Currently, it is clearly known the chlorine contribution of CFCs to the stratosphere, which acts as a catalyst to deplete the ozone layer. Many actions and regulations have been brought by several countries and international organizations to minimize the production and usage of CFCs. An international environmental agreement, the Montreal Protocol, was reached to phase out the ozone depleting CFCs in 1987. Initially HCFCs were thought to be the ideal alternatives of CFCs. But, due to their high GWP and ODP, it is also planned to phase them out in 2030 worldwide. Having these environmental risks, it is clear the abandonment of R-134a as a refrigerant in the near future. So, finding its replacement without much decrease in the overall performance of the refrigerator is a concern for engineers. Considering their environmental friendliness, chemical stability, and refrigerant charge, hydrocarbons and their mixtures are supposed as the best candidates to replace R-134a [4].

R-600a, one typical hydrocarbon, was first used in Germany in 1996 as a refrigerant. Richardson and butterworth also used R-290 and R-600a separately and by mixing for refrigeration system [5].

Different experimental analysis has been conducted in search of environmentally friendly, sustainable and energy efficient refrigerants by different scientists and researchers. Today, the substitution of R-134a as the main refrigerant for domestic refrigeration has become the main environmental concern. Recent experiments and researches are focusing on naturally existing substances as their environmental effects are less damaging than those fabricated ones.

Research was done to see the possibility of using hydrocarbons in cooling and heating purposes in the vapour compression system using R-600a and R-290. To determine the thermo-physical properties of the refrigerants, REFPROP 7.0 software was used for analysis purpose. The research showed R-600a and R-290 as an energy efficient alternative substance for refrigeration and air conditioning purposes [5].

Saidur et al.[6] conducted an experiment on the possibility of using hydrocarbons and their blends to work on a refrigerator previously designed to use R-134a refrigerant. Effects of condenser and evaporator temperatures on COP, refrigeration effect, condenser duty, work of compression and heat rejection ratio were considered. REFPROP7 software was used to find the enthalpies from the measured data of pressures and temperatures. The energy consumption of refrigerator with R-134a and the hydrocarbons was measured. In this experiment, compressor consumed 3% and 2% less energy when iso-butane and butane were used instead of R-134a at 28ºC ambient temperature. The COP of the refrigerants was studied by varying the evaporator temperature at 25ºC and 28ºC of ambient temperatures. Then, the COPs of the domestic refrigerator were found comparable to that of R-134a.

Huan et al. [4] investigated the properties of refrigerants R-152a and R-600a as an alternative to R-134a theoretically. Theoretical vapour compression refrigeration system was used to study the performance parameters with the help of REFPROP 9.0. They studied parameters like COP, power per ton of refrigeration,

refrigeration effect, volumetric refrigeration capacity and compressor input work. The COP of R-152a was found higher than that of R-134a and that of R-600a was lower but comparable. Refrigeration effects of R-600a and R-152a were found higher than that of R-134a when studied at the same condenser temperature by varying the evaporator temperature, though higher compressor input work for both R-600a and R-152a.

As R-152a contains the element fluorine its global warming effect is not to be left unconsidered. So, its environmentally friendliness is questionable. Having in mind the future requirements of refrigerants, it is difficult to consider this refrigerant as a best substitute to R-134a and its properties for its discard is imminent.

In search of eco-friendly refrigerants, an experimental analysis was done by [3] on a retrofitted vapour compression refrigeration system using refrigerants R-510a and R-600a. To compute values of the performance parameters of these refrigerants, the REFPROP software was used. The results were then compared with that of R-134a. Performance parameters like COP, refrigeration effect and volumetric cooling capacity were considered for the study. The results showed higher refrigeration effects for both R-510a and R-600a than that of R-134a. The volumetric cooling capacities of all the refrigerants studied were comparable. The analysis also showed higher values of COP for both the alternative refrigerants than that of the conventional one.

Duarte et al. [7] made thermo-economic and environmental analysis of small capacity vapour compression refrigeration system using R-290, R-1234yf and R-600a then, the results were compared to that of R-134a. Its main objective was to study the thermo-economic and environmental characteristics of the refrigerants by analysing sample parameters like COP, exergy efficiency and total equivalent warming impact (TEWI). The steady state model was developed using Engineering Equation Solver (EES). Exergy efficiency of R-290 was higher than that of the other refrigerants under study by far. While COPs of R-600a, R-134a and R-1234yf were comparable, the COP of R-290 was found a little higher. Regarding to the environmental warming impact, TEWI values of the alternative refrigerants were lower than that of R-134a.

Emani and Mandal [8] also studied several natural refrigerants for the purpose of refrigeration and air conditioning processes. The likes of water, carbon dioxide, ammonia, pure hydrocarbons and their mixtures were investigated. Main purpose of the research was to find out natural refrigerants with zero ODP and very low GWP to substitute the conventional CFCs and HFCs. In this review, pure hydrocarbons, R-290 in place of R-22 and R-600a instead of R-12 and R-134a were suggested for air conditioning and refrigeration systems respectively.

3. METHODOLOGY

3.1. Materials

In this research, three different hydrocarbons, R-290, R-600 and R-600a are used for the thermodynamic study. Their behaviours under different requirements of refrigeration conditions are evaluated using MATLAB programming language. Online Autodesk AutoCAD was also used for some drawings.

3.1.1. Refrigerants

In the selection of these substances mainly the environmentally viable properties are considered. When you think off eco-friendly properties, zero ODP, very low global warming effect and lower atmospheric lifetime are very critical criteria. The selection is based on Table 1 below.

Further properties considered when these substances were chosen are the following [10].

- Low boiling point
- High latent heat of vaporization
- High thermal conductivity
- Low freezing point
- Non-toxicity
- Low vapour specific volume
- Low viscosity

Table 1. Environmental properties of refrigerants [9].

Refrigerant	Atmospheric Lifetime, years[a]	ODP[b]	GWP_{100}[a]
CFC-11	45	1	4660
CFC-12	100	0.73	10 800
CFC-13	640	1	13 900
CFC-113	85	0.81	5820
CFC-114	190	0.50	8590
CFC-115	1020	0.26	7670
HCFC-22	11.9	0.034	1760
HCFC-123	1.3	0.01	79
HCFC-124	5.9	0.02	527
HCFC-142b	17.2	0.057	1980
HCFO-1233zd(E)	0.071	0.00034	1
HE-E170	0.015[b]	0.00	1[b]
HFC-23	222	0.00	12 400 (11 700)[c]
HFC-32	5.2	0.00	677 (650)[c]
HFC-125	28.2	0.00	3170 (2800)[c]
HFC-134a	13.4	0.00	1300 (1300)[c]
HFC-143a	47.1	0.00	4800 (3800)[c]
HFC-152a	1.5	0.00	138 (140)[c]
HFC-227ea	38.9	0.00	3350 (2900)[c]
HFC-236fa	242	0.00	8060 (6300)[c]
HFC-245fa	7.7	0.00	858
HFO-1234yf	0.029	0.00	<1
HFO-1234ze(E)	0.045	0.00	<1
HFO-1336mzz(Z)	0.07	0.00	2
PFC-116	10 000	0.00	11 100 (9200)[c]
PFC-218	2600	0.00	8900 (7000)[c]
C318	3200	0.00	9540 (8700)[c]
HC-290	0.034[b]	0.00	5[b]
HC-600		0.00	4[b]
HC-600a	0.016[b]	0.00	~20[b]
HC-601a	0.009[b]	0.00	~20[b]

3.1.2. MATLAB Software

MATLAB is a powerful and interactive computing programming language used in different researches and scientific investigations. It is an important tool to mathematically model, analyze and simulate physical systems. This programming language helps to visualize relationships of different variables using graphs and simulations. In this research the performance parameters of domestic refrigerator are modelled and analysed using MATLAB 17b version.

3.2. Methods

The following methods, techniques and procedures are followed in doing this research.

3.2.1. Literature Survey

A number of literatures were assessed to know how different researchers and scientists have been dealing with similar problems. Several articles and journals were already referred before all the mathematical modelling and analysis was done.

3.2.2. Data Collection

Data necessary for the analysis purpose is primarily the thermodynamic property tables of different refrigerants and other environmental property data. These data were collected from different books and websites. Thermodynamic property tables were taken from National Institute of Standards and Technology (NIST) Web book [11].

3.2.3. Determination of State Properties

Simple idealized vapour compression refrigeration cycle was used to study the parameters. All state properties are based on the T-S diagram on Figure 2.

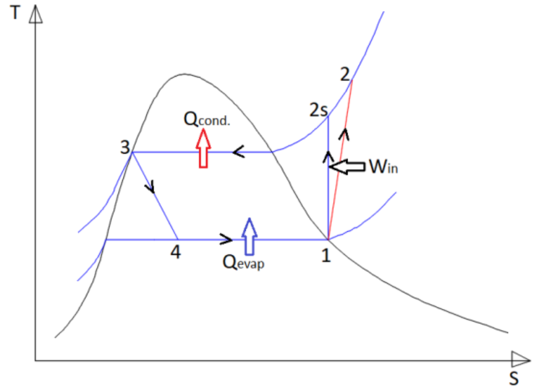

Figure 1. T-s diagram of an Idealized vapour compression refrigeration cycle

h_1 = specific enthalpy of refrigerant at the exit of evaporator or entry of compressor. It is the saturated vapour specific enthalpy of refrigerant at the given evaporator temperature and is found by interpolating saturation temperature and vapour specific enthalpy at the evaporator temperature in kJ/kg

s_1 = refrigerant entropy at the evaporator exit or compressor entry. Similarly found as h_1.

h_{2s} = refrigerant specific enthalpy at compressor exit or condenser entry, found by interpolating s_1 and h (specific enthalpy of superheated refrigerant) at the given condenser temperature from the refrigerant superheated property table considering isentropic compression in the compressor. It is also h_2 when compressor efficiency is not considered. (kJ/kg)

h_2 = actual specific enthalpy of refrigerant at compressor exit or condenser entry and is found from the isentropic efficiency relation of compressor given by:

$$h_2 = h_1 + \frac{h2s - h1}{\eta} \quad (3.1)$$

Where η is the compressor isentropic efficiency

h_3 = specific enthalpy of refrigerant at the condenser exit or expansion valve entry found by interpolating the given condenser temperature and saturated liquid specific enthalpy of refrigerant (h_f). (kJ/kg)is

h_4 = specific enthalpy of refrigerant at the exit of expansion valve or entry of evaporator. For ideal expansion process it is assumed to be equal with h_3.

T_2 = compressor discharge temperature in °C and is found by interpolating h_2 and pressure at the give condenser temperature.

v_1 =saturated vapour specific volume at the evaporator exit or compressor entry which is found by interpolating saturation temperature and saturated vapour specific volume at the given evaporator temperature.

3.2.4. Mathematical Modelling

Several mathematical equations were used to model the main physical components of the household refrigerator. Conservation of energy equations for steady state fluid flow were applied for the energy transfer parameters. For the purpose of simplicity of analysis, one kg per second of refrigerant mass flow rate is used.

- Refrigeration Effect:

$$Q_{evap} = h_1 - h_4 \quad (3.2)$$

- Compressor power consumption:

$$W_{in} = h_2 - h_1 \quad (3.3)$$

- Coefficient of performance:

$$COP = \frac{Qevap}{Win} \quad (3.4)$$

- Condenser duty:

$$Q_{cond} = h_2 - h_3 \quad (3.5)$$

- Volumetric cooling capacity

$$V_{cc} = \frac{Qevap}{v1} \quad (3.6)$$

3.2.5. Mathematical Analysis

Mainly quantitative data analysis is used to clearly figure out the relationships between different parameters. Graphs of these parameters are plotted to know how one variable behaves when another variable is varied, keeping others constant. Large devotion is given to study of performance parameters by varying the evaporator and condenser temperatures one at time. Effect of varying both evaporator and condenser temperatures on COP, refrigeration effect, compressor power consumption, compressor discharge temperature and volumetric cooling capacity were studied. Studying compressor discharge temperature is very important. Especially for hydrocarbons, it should be examined carefully, as they are flammable in nature. If oxygen leaks to the system, it may ignite easily at higher temperatures. Lubricants may also loss their desirable properties.

During selection of condenser temperature range, the ambient temperature should be taken in to account, especially for air cooled condensers. In these types of condensers energy carried by the refrigerant from the evaporator and work input to the compressor is normally dissipated to the air through condenser tubes. Generally, the refrigerant inside the condenser tube condenses at 30°F (16.667°C) higher temperature than the ambient air temperature[12].

To make the research geographically and different working environment more inclusive, an ambient temperature range of 0°C-55°C (approximated condenser temperature range of 15°C-70°C) is considered.

Temperature range of refrigerated space of the refrigerator compartment changes from 47°F to 60°F (8.333°C – 15.5°C) for high temperature applications to low temperature food storage application from 0°F (-17.778°C) up to -20°F (-28.889°C) [12]. A temperature difference of 10°C between the refrigerated space and the evaporator coil is assumed. Then an evaporator temperature range of -40°C to 5°C was considered.

Other investigations performed were the sub-cooling and super-heating effects on the system COP, refrigeration effect and compressor power consumption. Lastly, effect of compressor isentropic efficiency on the system COP was studied.

4. RESULTS AND DISCUSSION

In this chapter, different performance parameters of the working fluids for different conditions are presented graphically. These graphical presentations show the comparison among R-134a, R-290, R-600a and R-600. They are further explained how and why the parameters change when some variables are manipulated.

4.1. Effect of Evaporator Temperature

Varying the evaporator temperature from -40°C to 5°C with a difference of 5°C, its effect on COP, refrigeration effect, compressor energy consumption, condenser duty, compressor discharge temperature and volumetric cooling capacity is discussed for the selected substances. The condensing temperature is kept at 50°C.

1. **COP:** Figure 3 shows that as evaporator temperature increases from -40°C to 5°C, the COPs of all four fluids increase in an exponential pattern. This is because the refrigeration effect is increasing while compressor work input is decreasing simultaneously from the lower to the higher temperature limits of the evaporator temperature. Though the values are very close to each other, COP of R-600 and R-600a are higher than that of R-134a and R-290.
2. **Refrigeration Effect:** Figure 4 shows direct relationship between evaporator temperature and refrigeration effect. The reason behind this is an increase in exit enthalpy at constant entry enthalpy of the evaporator. Besides, the alternative hydrocarbons have higher evaporating capacity at all temperature ranges. It implies that the mass flow rate requirement of R-134a is much higher than the others for the same refrigeration load. For example, at -10°C R-600a and R-134a can refrigerate about 218.87kJ and 121.04kJ per kg of mass respectively. This indicates that additional 0.808kg of R-134a is needed for the same load that can be refrigerated using 1kg of R-600a.
3. **Compressor Work Input:** generally, compressor energy consumption decreases for all substances. This supports the concept of decrease in compressor work input for decrease in pressure ratio of condenser and evaporator. This happens when the evaporator temperature is increased keeping the condensing temperature constant. Compared to the others, this demand is much lower for R-134a. For example, as it can be seen from Figure 5, the compressor consumes about 39.3100kJ per kg of R-134a at -10°C. But, R-600a, R-600 and R-290 consumes about 68.2493kJ, 76.0540kJ and 75.2760kJ respectively per kg of each substance.

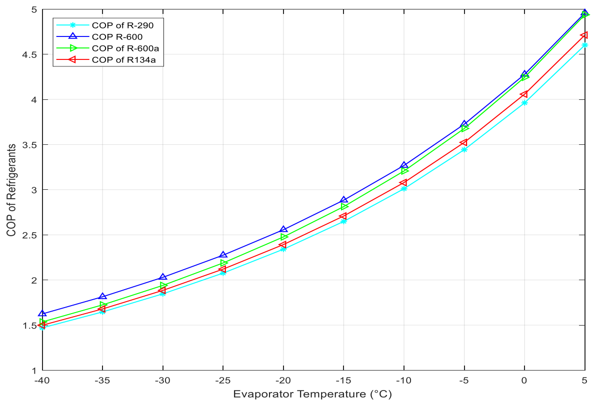

Figure 2. Effect of evaporator temperature on COP

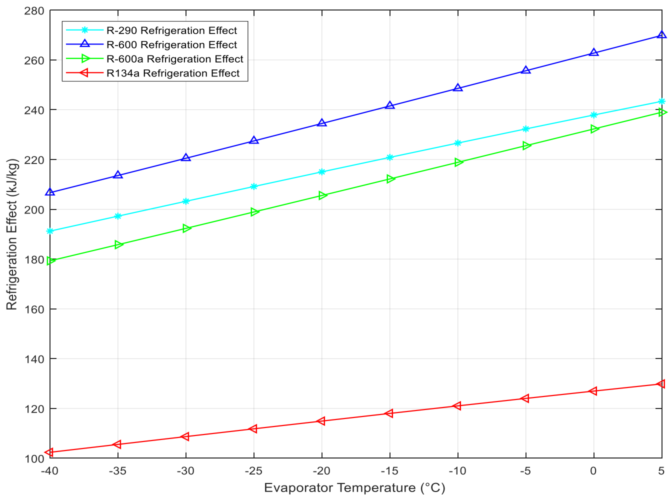

Figure 3. Effect of evaporator temperature on refrigeration effect

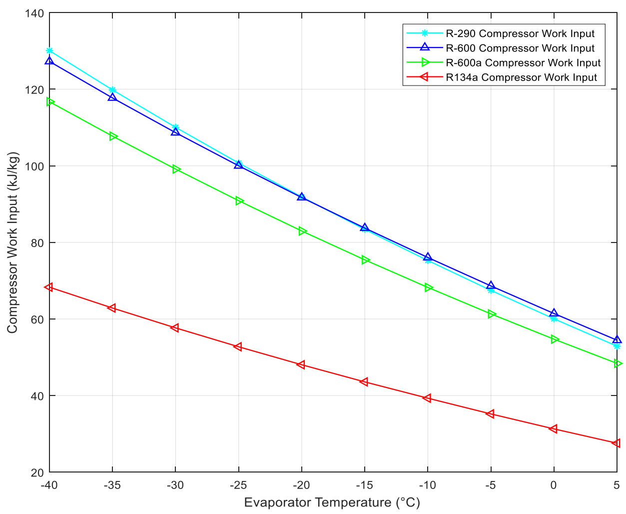

Figure 4. Effect of evaporator temperature on compressor work input

4. **Condenser Duty:** fairly, the condenser duty remains almost constant throughout the range of temperatures. As we know, condenser duty is the summation of energy absorbed from the cooled medium and energy input to the compressor. In this case, the increase in refrigeration effect is accompanied with decrease in compressor consumption. That is why the heat rejection needed to the environment remained almost constant. As it can be seen from Figure 6, the heat energy that should be dissipated is much higher for the hydrocarbons for same evaporator temperature and flow rate. This implies that a larger heat exchanger is necessary for the higher temperature side of the refrigerator when these hydrocarbons are used instead of conventional R-134a.

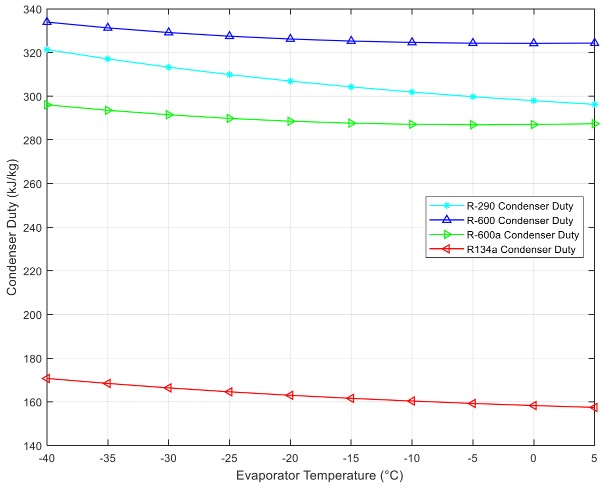

Figure 5. Effect of evaporator temperature on condenser duty

5. **Compressor Discharge Temperature:** For all fluids the higher temperature of the system decreases while increasing the evaporator temperature keeping the condenser pressure constant. Moreover, Figure 7 is a good implication for the usage of R-600a and R-600 as their temperature at the exit of the compressor is very low. But R-290 has high compressor discharge temperature, which is undesirable property for a refrigerant.

6. **Volumetric Cooling Capacity:** finally, the volumetric cooling capacity of the fluids is examined. This parameter increases with increase in evaporator temperature fixing the condensing temperature at 50°C. In Figure 8 it is indicated that R-290 has higher value than the others. Considering this criterion, R-290 could be a good substitute for R-134a.

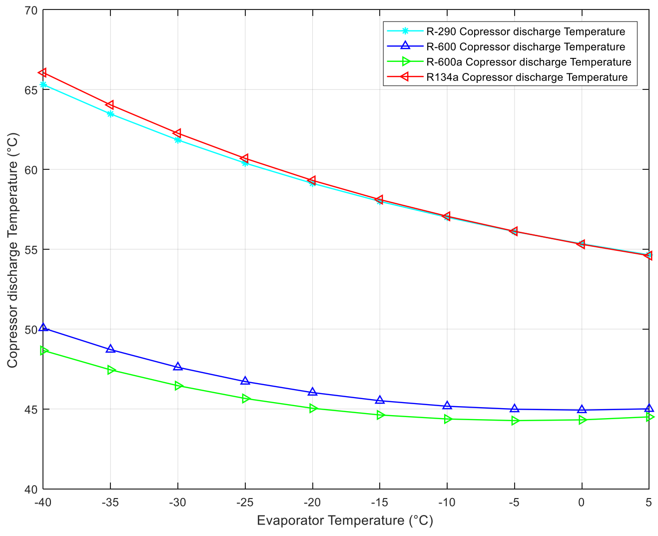

Figure 6. Effect of evaporator temperature on compressor discharge temperature

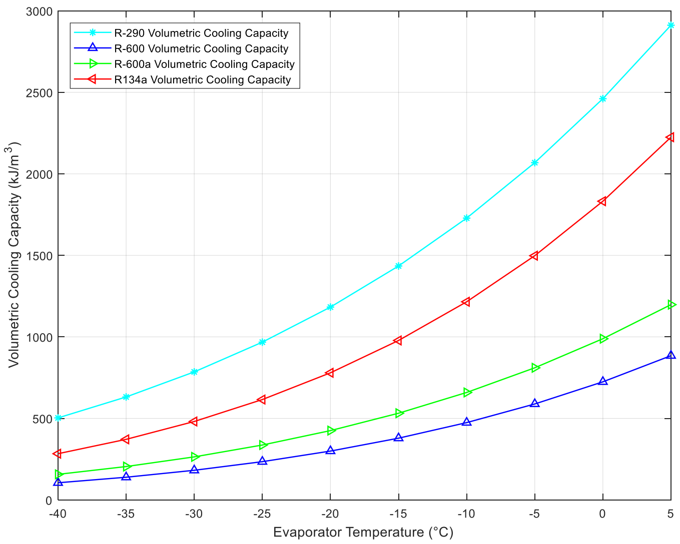

Figure 7. Effect of evaporator temperature on volumetric cooling capacity

4.2. Effect of Condenser Temperature

The investigation is done by varying the condenser temperature from 15°C to 70°C with a difference of 9°C. Then, its effect on COP, refrigeration effect, compressor energy consumption, condenser duty, compressor discharge temperature and volumetric cooling capacity is discussed for those substances. The evaporator temperature is kept at -10°C.

1. **COP:** it is obvious that the COP of R-134a and the other alternatives is decreasing with increase in condenser temperature at constant evaporator temperature/pressure. The decrease in refrigeration effect and increase in compressor work input is the reason for this pattern. But as it is shown on Figure 9 the values are very close to each other as it is in variation of evaporator temperature. For instance, at 37°C the COP of R-600 is about 0.1781 higher than that of R-134a, while that of R-290 is only 0.0644 less than that of the ordinary R-134a. Even the COPs of R-600a and R-600 are a bit higher for the entire range. Hence, in terms of COP, it clearly shows that the alternative refrigerants can replace R-234a without any concern.
2. **Refrigeration Effect:** as it is figured out in Figure 10, condensing temperature and refrigeration effect have inverse relationship. Refrigeration capacity decreases nearly linearly for all the fluids. The reason for this phenomenon is that the fluids are admitted at increasing energy level and exiting at the same state for the increasing trend of temperatures at the evaporator. This reduces the path from entry state to the exit state; hence, the decrease in refrigeration capacity. But this value is much higher for the hydrocarbons relative to that of R-134a. For example, at 37°C refrigeration effect of R-600, R-600a and R-290 are 100.30%, 79.26% and 88.32% respectively higher than that of R-134a.
3. **Compressor Work Input:** though it converges at lower condensing temperatures, compressor energy needs of the hydrocarbons are generally higher than that of R-134a as it can be depicted from Figure 11. As an example, if we look into it at 37°C condensing temperature, R-134a consumes 32.1054kJ/kg, while R-600a, R-290 and R-600 consume 56.2468kJ/kg, 61.3643kJ/kg and 61.7978kJ/kg respectively. This means more power is needed for the compressor of the refrigerator working with the substitute hydrocarbons than R-134a for the same evaporator temperature.
4. **Condenser Duty:** Figure 12 shows that the condenser duty decreases with an increase in condensing temperature. This is because the decrease in refrigeration effect is higher compared to the increase in compressor input energy for all the working fluids investigated. Further, the results imply that the heat rejection to the hot medium is higher for the hydrocarbons at fixed evaporator temperature of -10°C. At 37°C condensing temperature the values are 308.4800kJ/kg, 343.6410kJ/kg and 326.3510kJ/kg for R-600a, R-600 and R-290 respectively while that of R-134a is 172.8130kJ/kg.

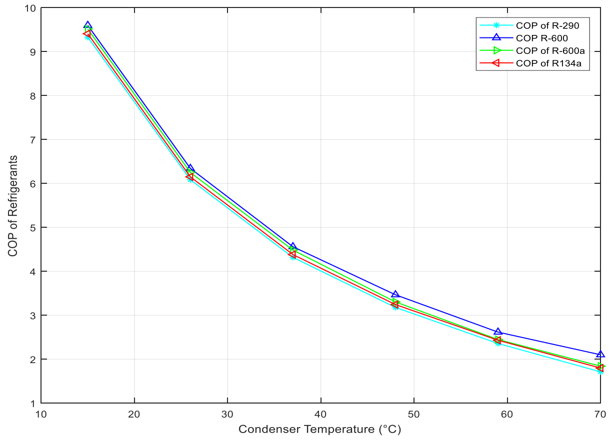

Figure 8. Effect of condenser temperature on COP

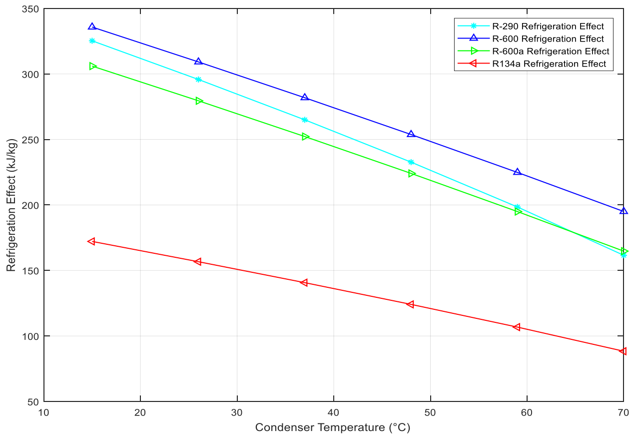

Figure 9. Effect of condenser temperature on refrigeration effect

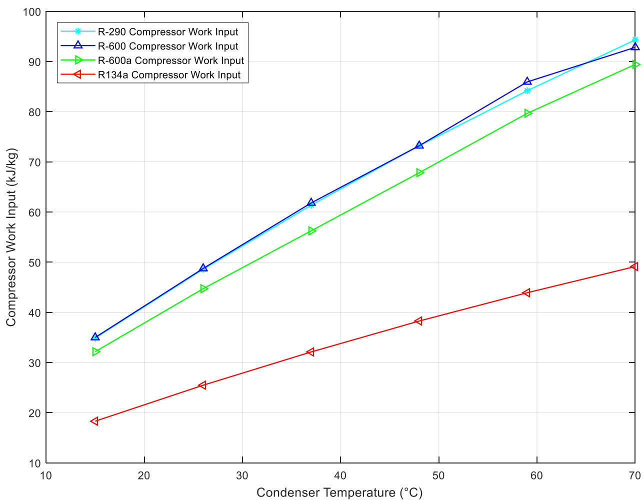

Figure 10. Effect of condenser temperature on compressor work input

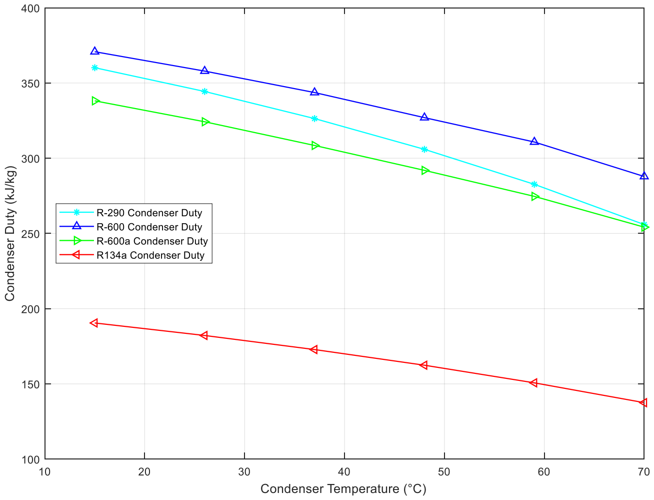

Figure 11. Effect of condenser temperature on condenser duty

5. **Compressor Discharge Temperature:** the results in Figure 13 show that the increase in condenser temperature results in an increase in compressor exit temperature. There is almost no difference in the values of R-134a and R-290 for the entire range. But when compared with R-600a and R-600 they have a bit higher trend. For R-134a and R-290 the discharge temperature increases from 19.0257°C and 18.9671°C at 15°C condensing temperature to about 78.9061°C and 78.8522°C respectively at 70°C. But for R-600a and R-600 it varies from 14.1792°C and 14.6503°C at 15°C condensing temperature to 63.1835°C and 60.4948°C respectively at 70°C.

6. **Volumetric Cooling Capacity:** generally, for all working fluids the volumetric cooling capacity decreases with increase in condensing temperature keeping the evaporator temperature at –10°C. Additionally, when Figure 14 is noticed, this value of R-290 is very high compared to that of the other two hydrocarbons for the whole investigated range of temperature. R-134a has an intermediate value.

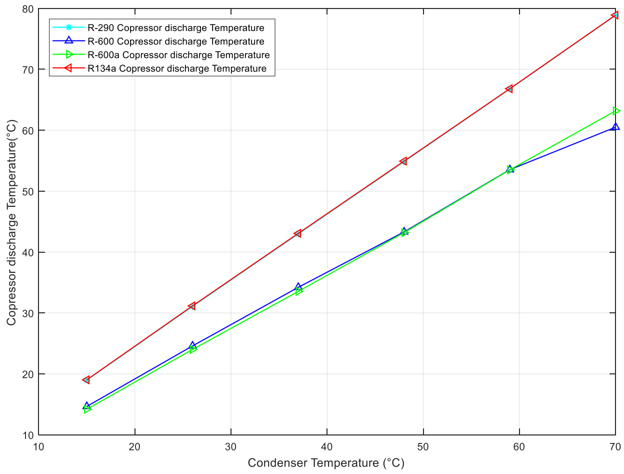

Figure 12. Effect of condenser temperature on compressor discharge temperature

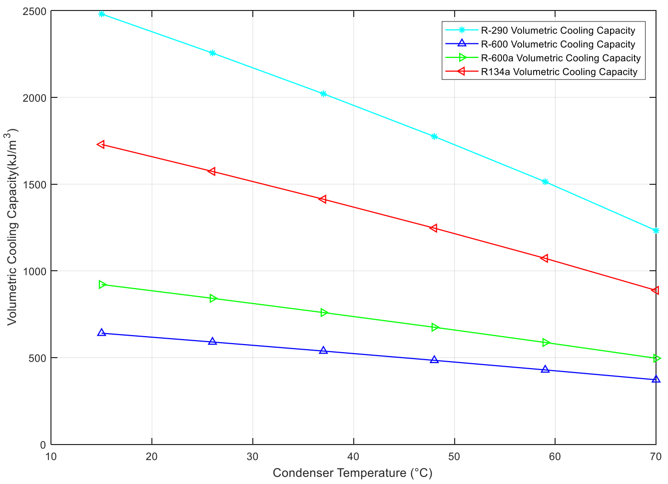

Figure 13. Effect of condenser temperature on volumetric cooling capacity

4.3. Effect of Subcooling

Effects of subcooling on COP, refrigeration effect and compressor energy consumption are discussed here. This investigation is done by cooling the fluids from 50°C condensing temperature to 20°C holding the evaporator temperature at -10°C.

1. **COP:** clearly as it can be seen from Figure 15 the COP of all substances is increasing when the fluid is subcooled during its exit from the condenser. The reason for this scenario is an increase in refrigeration effect at constant compressor energy consumption. With further observation on how the subcooling affects the refrigerants, its effect is more pronounced for R-600a, R-290 and R-134a. Subcooling is less affecting for R-600 compared to the others.

2. **Refrigeration Effect:** this effect increases with increasing degree of subcooling. As it can be observed from T-s diagrams the area under evaporating line clearly increases when the condenser exit temperature decreases at constant pressure. But when the effect on the rate at which it is increasing for each working fluid is closely noticed, its effect is more noticeable on the alternative hydrocarbons. For instance, Figure 16 shows that when R-134a and R-600a are subcooled from 50°C to 20°C at -10°C evaporating temperature, the refrigeration effect increases from 121.040kJ/kg and 218.870kJ/kg to 166.244kJ/kg and 294.346kJ/kg respectively. In this case, the subcooling effect on R-600a is 30.272kJ/kg higher than that of R-134a for the same range of temperature.

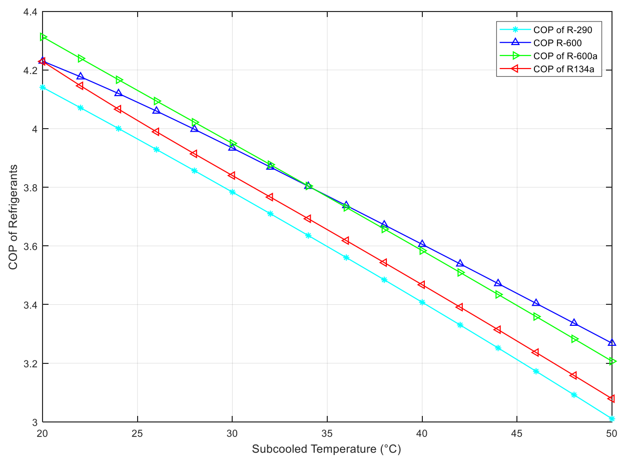

Figure 14. Effect of subcooling on COP

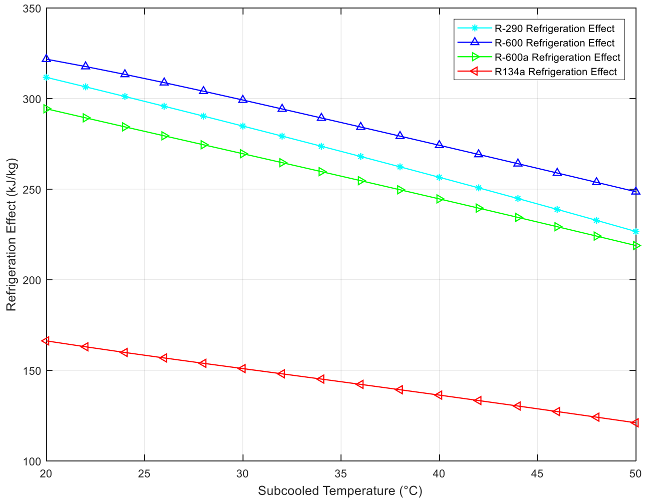

Figure 15. Effect of subcooling on refrigeration effect

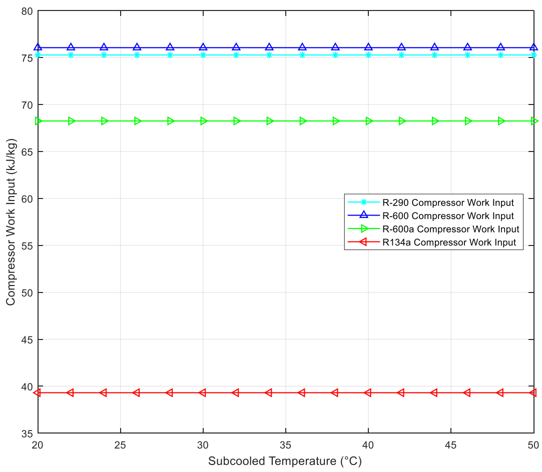

Figure 16. Effect of subcooling on compressor work input

3. **Compressor Work input:** the result of Figure 17 is not wondering as it is just horizontal line. Subcooling does not have any relation with the compressor work input at constant condensing and evaporating temperatures. Thus, it remains constant for all the fluids throughout the temperature ranges. The states between which the compressor operates remain unaltered with subcooling.

4.4. Effect of Superheating

Similarly, as for subcooling, superheating effects on COP, refrigeration effect and compressor energy consumption for both the alternative hydrocarbons and R-134a is discussed here. This study is done by varying evaporator exit temperature from -10°C to 10°C with a difference of 2°C.

1. **COP:** during superheating, both refrigeration effect and compressor energy consumption increases. But, the rate at which refrigeration effect increases is higher compared to that of the compressor work input. Hence, COP of each substance under study increases with increased degree of superheating. Figure 18 shows COP values of R-134a, R-290, R-600a and R-600 increases from 3.080-3.178, 3.011-3.121, 3.207-3.321 and 3.268-3.420 respectively when evaporator exit temperature varies from -10°C to 10°C. This shows COP increase of 3.18%, 3.66%, 3.57% and 4.63% for R-134a, R-290, R-600a and R-600 respectively at these temperatures. From this it can be easily understood that superheating has higher effect on R-600 COP more than that of the others.

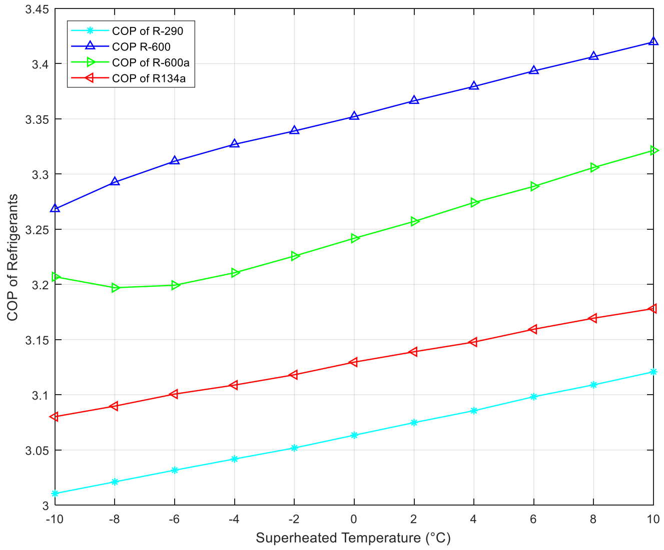

Figure 17. Effect of superheating on COP

2. **Refrigeration Effect:** as the degree of superheat increases the refrigeration effect also increases. It can be noted from Figure 19 that this performance parameter has linear relationship with the evaporator exit temperature. Additionally, if we closely look into the graph, the steepness of the lines differs from one to another. The substitute hydrocarbons have greater slope than R-134a. This indicates that superheating has more effect on these hydrocarbons than on R-134a in refrigeration effect. The result also shows that the refrigeration effect of these hydrocarbons is roughly about twice of that of R-134a.

3. **Compressor Work input:** like refrigeration effect, the compressor work input is almost linearly proportional to the degree of superheat as it is revealed in Figure 20. We can figure out that this effect is also more on the hydrocarbons. Specially, values for R-600a and R-290 are greatly affected by this parameter.

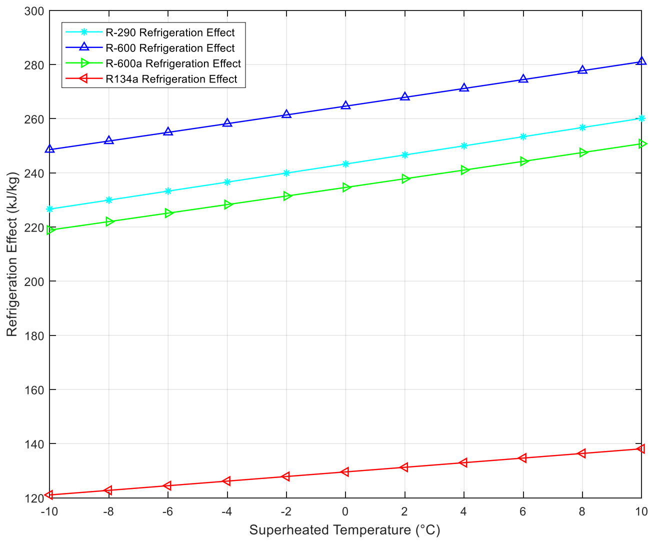

Figure 18. Effect of superheating on refrigeration effect

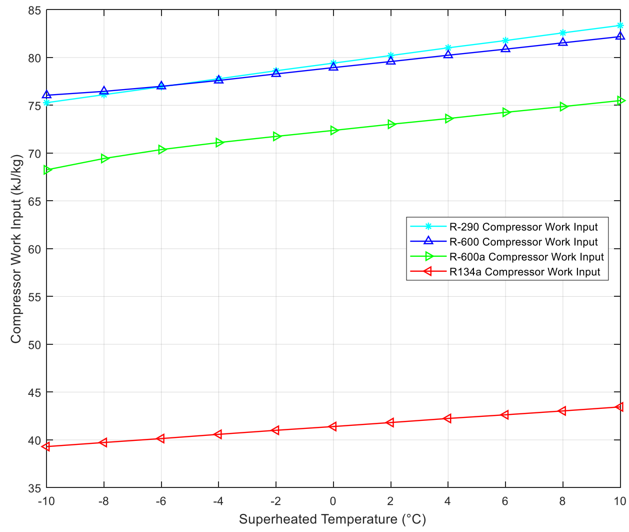

Figure 19. Effect of superheating on compressor work input

4.5. Effect of Compressor Efficiency on COP

This performance parameter has direct relationship with the value of COP. It supports the idea that when more efficient compressor is used the COP value of the system increases. As compressor performance is one that is used to characterize COP of the refrigerator, its influence is highly noticeable from Figure 21. But when we see which working fluids are influenced by compressor efficiency differently, the effect is more or less the same for all throughout the range.

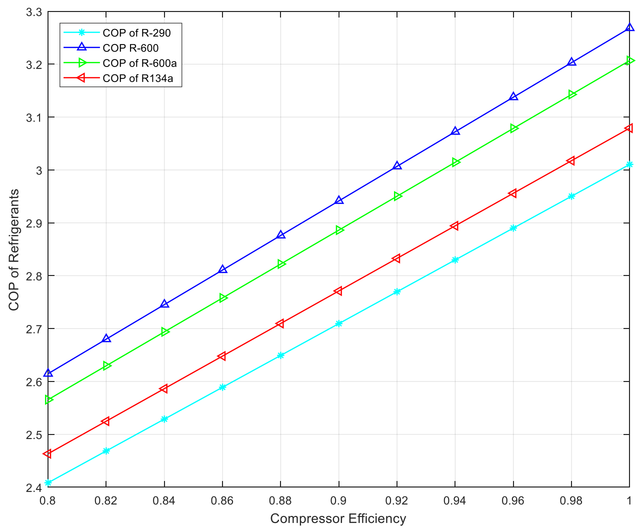

Figure 20. Effect of compressor efficiency on COP

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Hydrocarbons with zero ozone ODP and very negligible GWP were investigated as possible alternative of R-134a in domestic vapour compression refrigeration system. Based on the thermodynamic performance analyses on the theoretical vapour compression refrigeration cycle the hydrocarbons have generally given positive results. Depending on the results obtained, the following conclusions can be drawn.

♦ COP values of hydrocarbons are comparable to that of R-134a. Even a bit higher for R-600 and R-600a at different conditions. This means that these alternative substances can be used without any concern regarding to the COP. They give nearly the same refrigeration capacity for the same power input.

♦ The refrigeration effect is higher when hydrocarbons are used instead of R-134a for different cases. They all give beyond 150% capacity for the refrigerator previously used R-134a as its working fluid for the same mass flow rate. But this is at the expense of higher energy consumption.

♦ Work input of the system is considerably higher when the hydrocarbons are used for all cases studied for the same mass flow rate. However, this is compensated by the much higher refrigeration capability. This means a smaller mass of these substitute substances can be used for the same heat removal from the cold medium. So that, it can be reduced the larger amount of compressor energy consumption.

♦ The heat removal from the system to the environment is higher for the hydrocarbons at constant evaporator and condenser pressures for the same mass flow rate. But this is not that much concern as they can give higher refrigeration effect for the same circulation of mass for this steady state condition.

♦ As it was stated, the highest temperature of the system is very essential for hydrocarbons. For the varying evaporator and condenser pressures/temperatures the compressor discharge temperature, which is the highest temperature of the system, is much lower for R-600a and R-600. This is a good compensation for their flammable nature.

♦ The COP of domestic refrigeration is further enhanced by subcooling the fluid exiting the condenser and superheating while exiting from the evaporator.

Generally, these thermodynamic performance parameter analyses give very supportive suggestions towards the usage of hydrocarbons as possible substitute of the conventional R-134a, which is going to phase out for its high global warming effect in the near future. It is good indication that they can replace this fluid in domestic refrigerators previously designed to operate optimally with.

5.2. Recommendation

This research can be modified further by the following.

♦ For hydrocarbons to be used as the direct substitute of R-134a, the flammability is their hindering property. So, studying deep into how they are flammable, this undesirable property can be modified by different alternative methods that will not minimize other positive characteristics. This might be eliminated by adding foreign materials.

♦ As this study is done for refrigeration system previously designed for R-134a, with some component modifications, it could be possible to design for more efficient performance.

♦ Moreover, this research can be made more comprehensive by studying parameters other than thermodynamic properties.

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