THERMODYNAMIC ANALYSIS OF TWO-STAGE VAPOUR COMPRESSION REFRIGERATION SYSTEMS USING ECO-FRIENDLY REFRIGERANTS

Abstract

As Nigeria continues to expand its industrial, commercial, and residential cooling needs, the demand for efficient and environmentally sustainable refrigeration systems is growing. However, the environmental impact of conventional refrigerants has raised concerns due to their high global warming potential and ozone depletion potential. This study presents a thermodynamic analysis of two-stage vapour compression refrigeration systems in Nigeria, utilizing eco-friendly refrigerants which offer low GWP and zero ODP. The refrigeration system comprises a high-pressure stage compressor and a low-pressure stage compressor with the inter stage pressure taken to be the ideal inter stage pressure. Performance analysis of R-717, R-600, R-600a and R-290 two-stage vapour compression refrigeration systems were made using seven parameters. The effect of the variation of five operating/design parameters (Evaporating Temperature (T_E), Condensing Temperature (T_C), Superheating Temperature (T_{sup}), sub cooling temperature (T_{sub}) and refrigerant mass flow rate ($\dot{m}$)) on Coefficient of Performance (COP) of two-stage vapour compression system was analysed using Engineering Equation Solver (EES) software. The results showed that as evaporating temperature decreases from 0^oC to -50^oC, COP decreased for all the four refrigerants considered. R-717 gave the highest COP value of 7.636 at T_E of 0^oC while R-600a gave the lowest value of 4.009 at the same temperature. The results also showed that the COP of all the four refrigerants increased with increase in T_{sub} and $T_{sup,}$ whereas it decreased with increase in T_C. The study revealed that except for $\dot{m}$ for all the other four operating parameters considered have significant effect on the COP of refrigeration systems considered in this study.

Keywords: Coefficient of Performance (COP), Sub Cooling, Superheating, Eco-friendly, Two-stage.

1. Introduction

The increasing demand for refrigeration and air conditioning systems in Nigeria, driven by rapid industrialization, urbanization, and population growth, underscores the importance of efficient and sustainable cooling technologies. Refrigeration plays a vital role in various sectors such as food preservation, pharmaceutical storage, and industrial processes. However, the widespread use of conventional refrigerants, such as R134a and R22, has raised environmental concerns due to their high global warming potential (GWP) and ozone depletion potential (ODP) [1,2,3]. These refrigerants contribute to the depletion of the ozone layer and global climate change, making it essential to transition towards eco-friendlier alternatives in line with global environmental agreements like the Montreal Protocol and the Kigali Amendment. To address the environmental impact of refrigeration systems, there has been increasing interest in the adoption of eco-friendly refrigerants, such as R717, R600a, and R290, which have low GWP and zero ODP [4,5,6]. These refrigerants present an opportunity to reduce the environmental footprint of refrigeration systems while maintaining or improving their thermodynamic performance. In particular, the two-stage vapour compression refrigeration system, known for its enhanced efficiency and capacity for high-temperature differentials, offers a promising framework for integrating eco-friendly refrigerants. This system, commonly used in industrial and commercial applications requiring low temperatures, is more efficient than single-stage systems, especially in tropical climates like Nigeria's, where ambient temperatures are consistently high [7,8].

Governments worldwide particularly in the developed countries are launching more stringent energy consumption policies for household and industrial refrigerators, freezers, cold rooms and air- conditioning systems almost steadily. To match the new energy regulations most of the manufacturers are seeking alternative ways of improving the thermodynamic performance of their products. There is much evidence in the literature showing that numerical simulation and optimization techniques not only may reduce the number of tests and prototypes needed during the product development phase, but also the final product cost and energy consumption [9,10]. As a result of environmental problems related to global warming and ozone-depleting effects caused by the use of synthetic refrigerants experienced over the last three-decade, the return to the use of natural refrigerants and other eco-friendly refrigerants has attracted renewed interest during the last decade. These eco-friendly refrigerants should be readily available and the new refrigerants should energy efficient with high COP [11, 12]. Hence, the main aim of this present paper is to compare the performance analysis of R-717, R-600, R-600a and R-290 two-stage vapour compression refrigeration systems.

Nigeria's climate poses unique challenges for refrigeration systems. With temperatures frequently exceeding 30°C in most parts of the country, refrigeration systems must operate under significant thermal stress, leading to increased energy consumption and operational inefficiencies [13,14]. Additionally, the country's erratic power supply exacerbates the strain on these systems, necessitating the need for more efficient technologies to reduce energy demand. The use of a single-stage vapour compression refrigeration system can only achieve effective cooling of about -40 ºC, and the efficiency begins to deteriorate rapidly below -25 ºC due to vast difference between the evaporating and condenser pressure resulting in an increase in compress ratio, reduction of volumetric efficiency of the compressor, high energy consumption and a low coefficient of performance (COP). Hence, for low evaporating temperature below -25 ºC, two-stage vapour compression refrigeration systems should be used [15,16]. In low- temperature application, including rapidly freezing, storage of frozen and cold rooms, the required evaporating temperature of the refrigeration system ranges from -40 ºC to -55 ºC, so a single-stage vapour-compression refrigeration system is inadequate, while two-stage or cascade refrigeration systems are used for such applications. [17, 18].

Two-stage vapour compression systems, when coupled with eco-friendly refrigerants, can provide improved performance by reducing energy consumption and environmental impacts. This aligns with Nigeria's commitment to sustainable development and the reduction of greenhouse gas emissions, as outlined under the Paris Agreement [3, 13]. The thermodynamic analysis of two-stage vapour compression refrigeration systems using eco-friendly refrigerants is crucial for determining the feasibility of these technologies in Nigeria. By conducting a thermodynamic analysis using eco-friendly refrigerants, this study aims to evaluate their performance in Nigeria's high-temperature environment, determining whether they can serve as viable alternatives to conventional refrigerants.

The adoption of eco-friendly refrigerants in Nigeria is not just a technical necessity but also an economic and environmental imperative. Given the growing reliance on refrigeration and air conditioning in the country, transitioning to low-GWP refrigerants can help mitigate Nigeria's contribution to global climate change while improving energy security. Furthermore, this transition aligns with global trends and regulatory requirements, making it an essential area of study for both policymakers and industry stakeholders [3, 13,20]. This study provided critical insights into the feasibility and advantages of using eco-friendly refrigerants in Nigeria's unique climate. Ultimately, the findings will contribute to the broader goal of sustainable refrigeration practices in Nigeria, supporting the country's environmental and energy policies.

2. Methodology

The two-stage vapour compression refrigeration system comprises a high-pressure stage compressor and a low-pressure stage compressor with interstage pressure taken to be ideal interstage pressure. Performance analysis of R-717, R-600, R-600a and R-290 two-stage vapour compression refrigeration systems were made using six parameters. The effect in the variation of five operating/design parameters on coefficient of Performance was analysed using Engineering Equation Solver (EES) software and then performance comparison between the four systems were made.

2.1 Theoretical Description of Two-Stage Vapour Compression Refrigeration Cycle

The system comprises a high stage compressor (I) and a low stage compressor (II). The pressure between the discharge pressure of the high stage and the suction pressure of the low stage is called inter-stage pressure. Figures 1 and 2 shows that vapour refrigerant at point (I) enters the first stage of the compressor in a dry saturated state. This vapour is compressed to the inter-stage pressure P_i at point (2). The mixture enters the second stage of the compressor at point 9. Compressed vapour refrigerant leaves the compressor at condensing pressure P_c (point 9 to 4). It is then discharged to the condenser and condenses into a liquid state (point 4 to 5). Upon passing the condenser, the sub-cooled liquid refrigerant flows through the high-pressure side flow control device that is, the expansion valve (point 5 to 6). A portion of liquid refrigerant vaporizes in the flash cooler (point 6 to 7). The flashed refrigerant cools the remaining portion of liquid refrigerant to the saturated temperature at the inter-stage pressure. The liquid refrigerant flows through a low-pressure expansion valve (point 7 to 8) a small amount of which is pre-flashed and the liquid vapour mixture refrigerant enters the evaporator. In the evaporator, all liquid refrigerant is evaporated into vapour and flows to the first stage inlet (point 8 to 1).

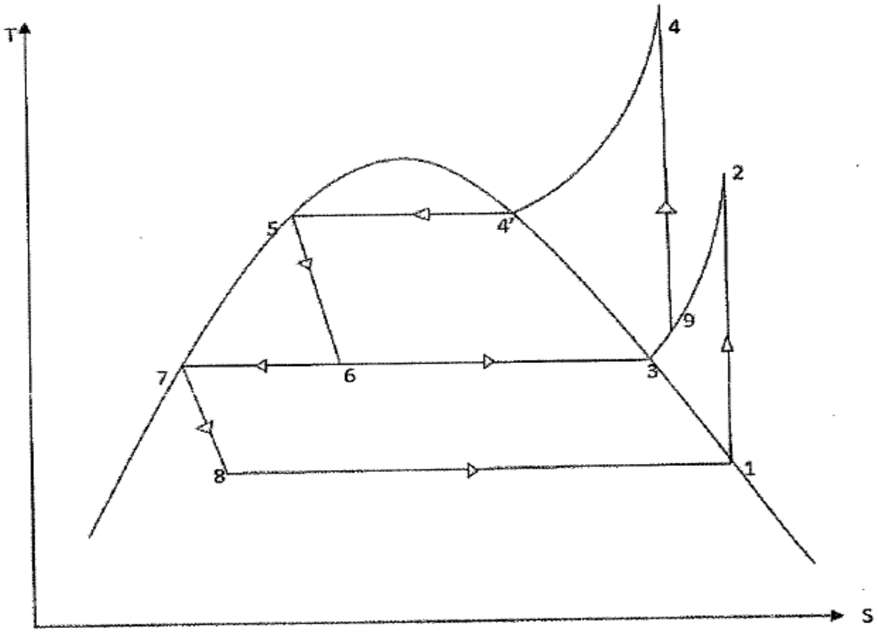

Figure 1: T-S Diagram of Two-Stage Vapour Compression Cycle

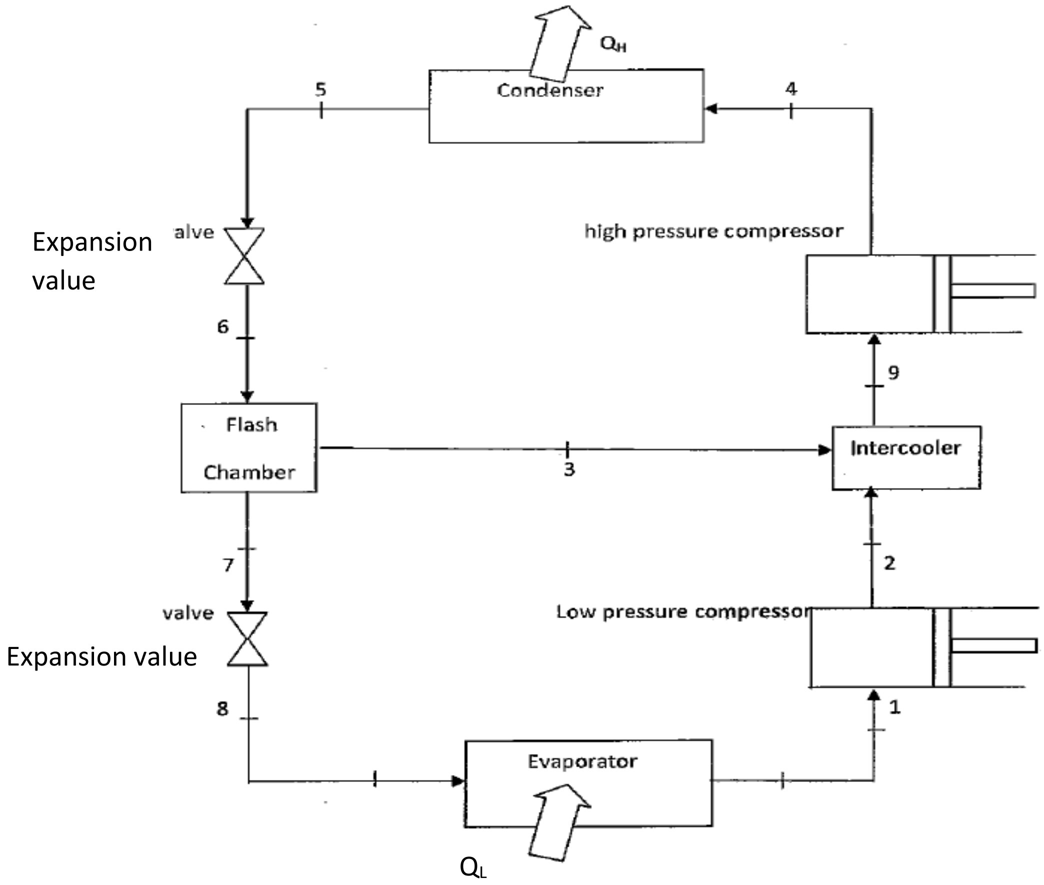

Figure 2: The Schematic Diagram of Two-Stage Vapour Compression Cycle

2.2 Thermodynamic Analysis

The thermodynamic analysis of a two-stage vapour compression refrigeration system is performed based on the following assumption:

i. Isenthalpic expansion of refrigerant in the expansion valves,
ii. Negligible changes in kinetic and potential energy.
iii. Negligible pressure and heat loss or gain in the pipe or other components,
iv. The compression process is irreversible and adiabatic

The following parameters values were used:

Condensing temperature, $T_C = 50\ ^0C$ is used as the baseline and varied from 30 ^oC to 80 ^oC.

Evaporating temperature, $T_E = -20\ ^0C$ is used as baseline and varied from 0 ^oC to -50 ^oC.

Sub-cooling temperature, $T_{sub} = 4\ ^oC$ is used as baseline and varied from 0 ^oC to 20 ^oC.

Superheating temperature, T_{sup} = 4 ^{o}C is used as the baseline and varied from 0 ^{o}C to 20 ^{o}C.

The mass flow rate of the refrigerant, ($\dot{m}$) = 0.05 kg/s is used as baseline and varied from 0.01 kg/sec to 0.11 kg/sec.

Isentropic efficiency is taken as 0.85 and inter stage pressure is taken to be ideal.

These parameters were used in the thermodynamic properties of the two cycles using the refrigerants R-717, R-600, R-600a and R-290as the working fluid in both high temperature (I) and low temperature (II) stages. Table 1 shows the thermo physical properties of the refrigerants and table 2 shows the operating parameters considered in this study.

Table 1: Thermo physical and properties of the selected refrigerants

Properties	**R-6OO**	**R-6OOa**	**R-717**	**R-290**
Chemical Formula	C_4H_{10}	C_3H_8	NH_3	C_4H_{10}
Molar Mass	58.12g/mol	44.10g/mol	17g/mol	58.12g/mol
Colour	Colourless	Colourless	Colourless	Colourless
Density	2.0098kg/m^3	2.0098kg/m^3	1.61g/l	2.51mg m/l
Boiling Point	-42.25°C	-42.25°C	-33°C	-11.7°C
Melting Point	-187.7°C	-187.7°C	-77.7°C	-159.42°C
Odour	Odourless	Odourless	Pungent	Odourless
Vapour Pressure	853.16KPa	853.16KPa	308.61KPa	204.8KPa
Ozone depletion Potential (ODP)	0	0	0	0
Global Warming Potential (GWP)	3	3	0	3

Table 2: Operating Parameters

Properties	**Base Value**	**Variation Difference**	**Variation Range**

Evaporating Temperature (T_C)	-20ºC	-5	0 → -30
Condensing Temperature (T_E)	50ºC	+5	30 → 80
Superheating Temperature (T_{SUP})	4ºC	+2	0 → 20
Subcooling Temperature (T_{SUP})	4ºC	+2	0 → 20
Mass Flow Rate ($\dot{M}$)	0.01kg/s	+0.01	0.01 → 0.11

The capacity of evaporator I is defined as:

$$Q_{el} = \dot{m}_I(h_1 - h_8) \tag{1}$$

The capacity of the evaporator (flash chamber) is given by:

$$Q_{ell} = \dot{m}_{II}(h_3 - h_6) \tag{2}$$

The work input into low stage compressor is defined by:

$$W_{CI} = \dot{m}_I(h_2 - h_1) \tag{3}$$

The work input into high stage compressor can be found by:

$$W_{CII} = \dot{m}_{II}(h_4 - h_3) \tag{4}$$

The mass flow rate of the low-temperature stage can be obtained by:

$$\dot{m}_I = {}^{Q_{eI}}\!/_{(h_1 - h_8)} \tag{5}$$

The mass flow rate of the high-temperature refrigerant:

$$\dot{m}_{II} = {}^{Q_{eII}}\!/_{(h_3 - h_6)} \tag{6}$$

The system COP is obtained by:

$$COP = \frac{Q_{eI} + Q_{eII}}{W_{CI} + W_{CII}} \tag{7}$$

The mass flow rate of refrigerant through the high stage compressor can be obtained by taking a control volume which includes the flash tank and high-temperature evaporator. This can be obtained by applying the mass and energy balance.

Mass balance:

$$\dot{m}_5 + \dot{m}_2 = \dot{m}_7 + \dot{m}_3; \dot{m}_5 = \dot{m}_{II} = \dot{m}_3 \;\&\; \dot{m}_2 = \dot{m}_I = \dot{m}_7 \quad 8$$

Energy balance:

$$\dot{m}_5 h_5 + \dot{m}_2 h_2 + Q_{eII} = \dot{m}_7 h_7 + \dot{m}_3 h_3 \quad 9$$

The solution is determined using the EES software.

3. Results and Discussion

The baseline values are T_C = 50 ^oC, T_E = -20 ^oC, T_{sup} = 4 ^0C, T_{sub} = 4 ^0C, $\dot{m} = 0.05 kg/$sec. whenever any of these parameters is varied, the other parameters remain constant at the baseline values.

3.1 Effect of Evaporating Temperature (T_E)

Figure 3 showed the effect of T_E on the COP of R-717, R-290, R-600 and R600a two-stage vapour compression refrigeration systems. The figure indicated that R-717 gave the highest COP value of 7.636 at T_E of 0^oC, while R-600a gave the lowest COP value of 4.009 at the same temperature. The percentage decreased in the value of COP of R-717 is 68.256% when T_E decreased from 0^oC to -50^oC. It can be seen that as the T_E decreases from 0^oC to -50^oC, the value of the COPs of all the four refrigerants also decreased. The COP of R-290 is higher than that of R-600 at high value of T_E, but below – 30^oC their COPs are almost equal.

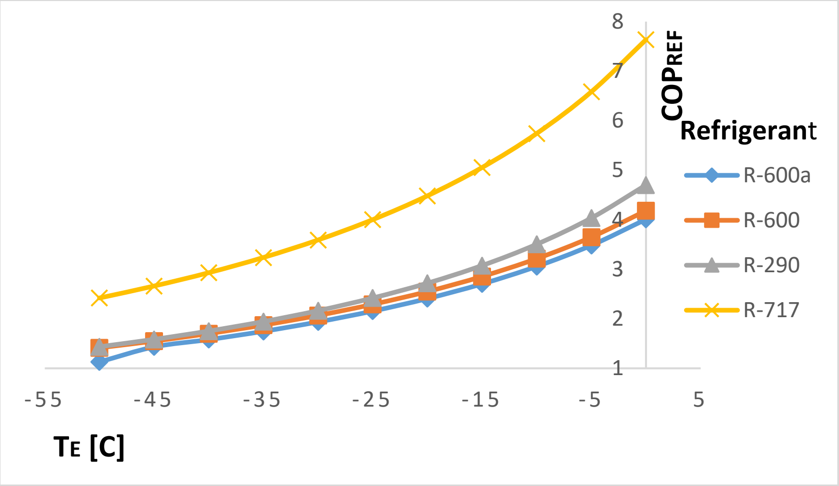

Figure 3: Effect of T_E on the COP_{REF} of Two Stage Vapour Compression Refrigeration Systems using Eco-Friendly Refrigerants.

3.2 Effect of Condenser Temperature (T_C)

Figure 4 shows that the COP of all the four refrigerants considered in this work reduced as the condensing temperature is increasing from 30°C to 80°C. R-717 gave the highest COP value of 6.608 while R-600a gave the lowest COP value of 4.078. The percentage reduction in the value of COP of R-717 when T_C increases from 30°C to 80°C is 58.04%. The COP of R-290 is higher than that of R-600 between T_C of 30°C to 60°C while their COPs are almost equal when T_C varies between 60°C to 80°C. This indicate that R-290 is more efficient than R-600 at lower T_C value lesser than 50°C.

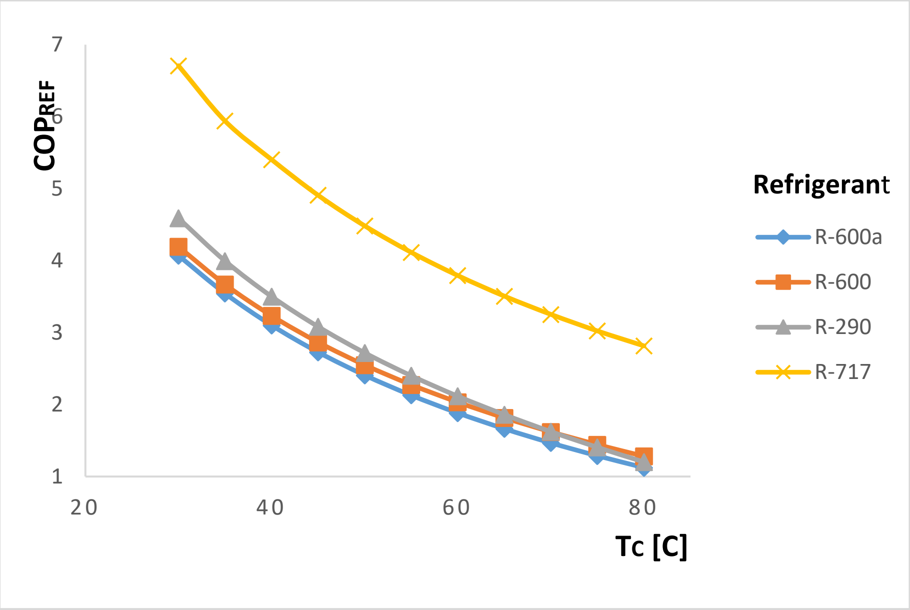

Figure 4: Effect of T_C on the COP_{REF} of Two Stage Vapour Compression Refrigeration Systems using Eco-Friendly Refrigerants.

3.3 Effect of Superheating Temperature (T_{sup})

The effect of T_{sup} on the COP is shown in figure 5, from this figure it can be seen that COP of all the four refrigerants increased as T_{sup} increases. R-717 gave the highest COP value of 5.806 at T_{sup} of 20°C followed by R-290 and then R-600 while R-600a gave the lowest value of 3.938 at the same temperature. COP of R-600 and R-600a are nearly equal between T_{sup} of 16°C to 20°C while COP of R-600 is higher at lower T_{sub} values.

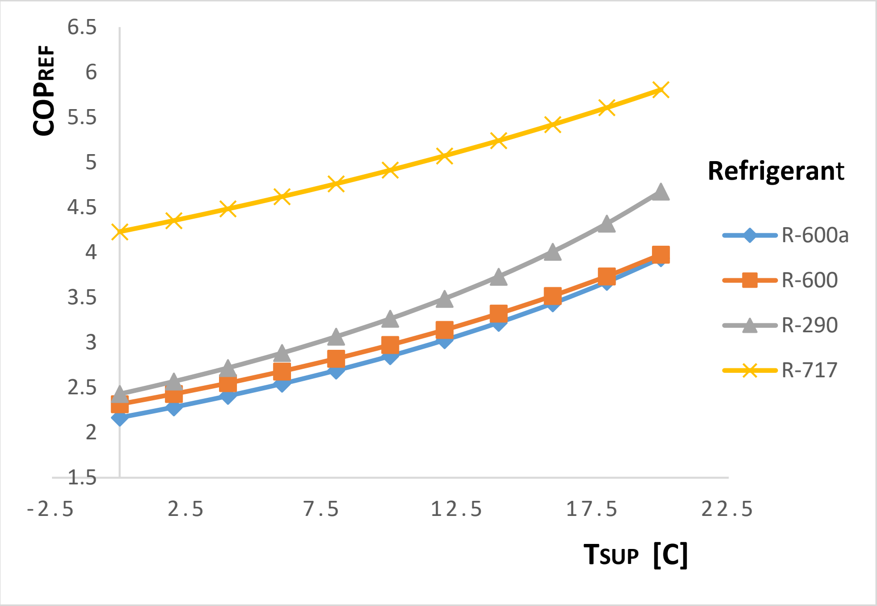

Figure 5: Effect of T_{sup} on the COP_{REF} of Two Stage Vapour Compression Refrigeration Systems using Eco-Friendly Refrigerants.

3.4 Effect of Sub-cooling Temperature (T_{sub})

Figure 6 shows the effect of sub cooling on the COP of two-stage vapour compression refrigeration system. From the figure, it can be seen that the COP of all the four refrigeration systems considered in this study increased as the T_{sub} increases from 0°C to 20°C. This indicates that sub cooling increases refrigerating effect without increase in compressor work hence COP increases. R-717 gave the highest COP value of 4.836 at T_{sub} of 20°C while R-600a gave the lowest value of 2.874 at the same temperature.

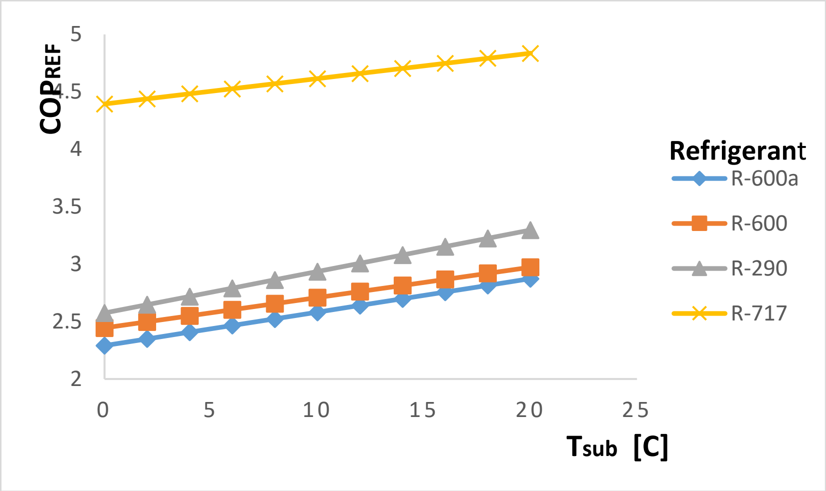

Figure 6: Effect of T_{sub} on the COP_{REF} of Two Stage Vapour Compression Refrigeration Systems using Eco-Friendly Refrigerants.

3.5 Effect of the mass flow rate of refrigerant ($\dot{M}$)

Figure 7 shows the effect of refrigerant mass flow rate on the COP of two-stage vapour compression refrigeration systems. From this figure, it can be seen that COP value of all the four refrigerants are constant with increase in $\dot{M}$. This is due to the fact that as $\dot{M}$ increases, both refrigerating effect and compressor work will increase at the same rate and since COP = refrigerating effect divided by compressor work, hence COP will be constant. R-717 has the highest constant COP value of 4.483 while R-600a has the lowest constant value of 2.408 as $\dot{M}$ increases from 0.01kg/s to 0.11 kg/s.

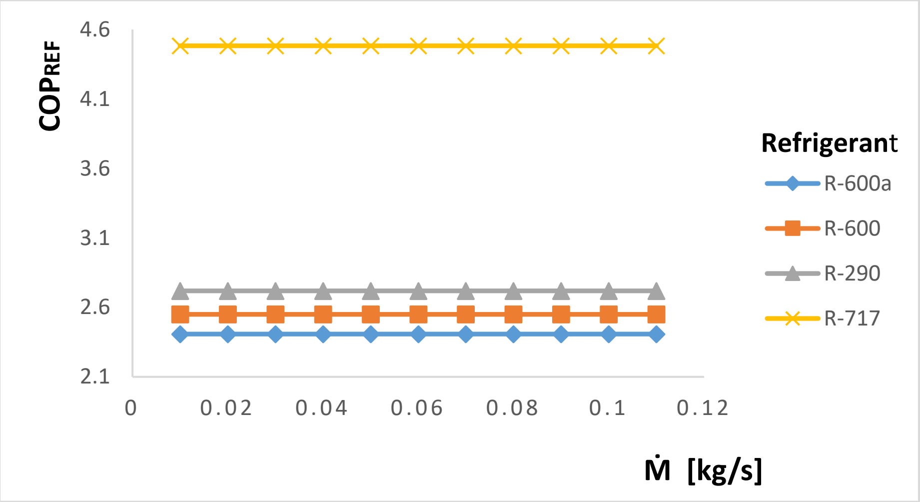

Figure 7: Effect of Ṁ on the COP_{REF} of Two Stage Vapour Compression Refrigeration Systems using Eco-Friendly Refrigerants.

4. Conclusion

The effect of parameters like the condenser temperature, evaporator temperature, superheating, sub-cooling and mass flow rate of the refrigerant on the coefficient of performance of two-stage vapour compression refrigeration system is verified by varying the different parameters. The following conclusions are therefore deduced from the thermodynamic analysis:

i. A two-stage vapour compression refrigeration system is still effective at an evaporator temperature as low as -50 ^{o}C.

ii. The COP obtained reduced as the T_C increased

iii. The mass flow rate of the refrigerant does not have effect on the COP.

iv. COP increased as the degree of sub-cooling increases.

v. COP increased as the degree of superheating increases.

vi. R-717 gave the overall best efficiency followed by R-290 and then R-600 while R-600a gave the lowest efficiency.

5. References

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