Original Research Article

THERMODYNAMIC ANALYSIS OF SINGLE-STAGE VAPOUR COMPRESSION REFRIGERANTION SYSTEM IN NIGERIA USING NATURAL REFRIGERANTS

Abstract

Refrigeration systems play a critical role in various sectors of Nigeria's economy, particularly in food preservation, healthcare, and industrial processes. However, the use of conventional synthetic refrigerants, which contribute significantly to global warming and ozone depletion, poses environmental challenges. This study presents a thermodynamic analysis of single-stage vapor compression refrigeration systems in Nigeria, focusing on the use of natural refrigerants as eco-friendly alternatives to identify eco-friendly refrigerant alternatives for Nigeria's climate. This study conducts a thermodynamic analysis of single-stage vapor compression refrigeration systems in Nigeria, evaluating natural refrigerants such as ammonia (R-717), propane (R-290), and isobutane (R-600a) as alternatives to synthetic refrigerants that contribute to global warming and ozone depletion. Using Engineering Equation Solver (EES) software, the study assesses the impact of varying operational conditions on the coefficient of performance (COP) for each refrigerant The effect in the variation of five operating parameters of refrigeration system such as Condensing Temperature (T_C), Evaporating Temperature (T_E), Subcooling Temperature (T_{Sub}), Superheating Temperature (T_{Sup}) and refrigerant mass flow rate ($\dot{M}$) on the Coefficient of Performance (COP) of are R-600a, R-600, R-717 and R-290 refrigeration systems were investigated and performance comparison was made to get the most suitable replacement for the older systems. The results showed that R-717 yields the highest coefficient of performance of 3.858 when evaporating temperature (T_E) is 0^{o}C while R-290 (Propane) gave the lowest Coefficient of Performance of 3.555 when evaporating Tempearture (T_E) is 0 ^{o}C. The results showed that as T_C increases from 30 ^{o}C to 80 ^{o}C, COP decreased for all the four refrigerants. As T_E decreases, COP reduced, also COP increased as T_{Sub} increases from 0 ^{o}C to 20 ^{o}C. COP of R-717 is consistently higher than that of the other three natural refrigerants. Findings reveal that R-717 yields the highest COP under Nigerian climatic conditions, positioning it as a promising, eco-friendly replacement. This research supports efforts to adopt sustainable refrigerants in Nigeria, contributing to climate goals and guiding policy and industry stakeholders in selecting efficient refrigerants for high-temperature regions.

Keywords: Coefficient of Performance, Sub-cooling, Super-heating, Eco-friendly, Vapour compression system, Natural refrigerants.

1 Introduction

Refrigeration systems are essential for a wide range of applications in Nigeria, particularly in industries such as food storage and preservation, healthcare, and manufacturing. The country's growing population and increasing demand for cold storage and air conditioning have amplified the use of vapour compression refrigeration systems. However, many of these systems rely on synthetic refrigerants, such as hydrofluorocarbons (HFCs), which contribute significantly to global warming and ozone depletion. In light of international environmental protocols such as the Kigali Amendment to the Montreal Protocol, there is an increasing push towards phasing out high global warming potential (GWP) refrigerants in favour of more sustainable alternatives. This shift has created an urgent need to explore the use of natural refrigerants, which offer both low environmental impact and favourable thermodynamic properties [1, 2, 3].

Natural refrigerants, including carbon dioxide (CO_2), ammonia (NH_3), and hydrocarbons (HCs) like propane (R290) and isobutane (R600a), are gaining attention as viable alternatives to conventional synthetic refrigerants. These refrigerants are environmentally friendly, with zero ozone depletion potential (ODP) and low or negligible GWP. Moreover, natural refrigerants exhibit promising thermodynamic performance, making them suitable for use in vapour compression refrigeration systems. Despite these advantages, their adoption in countries like Nigeria has been limited due to factors such as flammability concerns (for hydrocarbons), toxicity (for ammonia), and high operating pressures (for CO_2). Additionally, Nigeria's hot climate poses further challenges in ensuring the efficiency of refrigeration systems using natural refrigerants, as high ambient temperatures can reduce system performance [4,5,6].

Several studies have explored the use of natural refrigerants in vapor compression systems globally. However, limited research has been conducted specifically in the context of Nigeria’s unique climatic conditions, which are characterized by high ambient temperatures that can affect refrigeration system performance. Energy efficiency from an economical aspect, ozone depletion and greenhouse emissions from an environmental aspect is the major parts of interest when discussing domestic refrigeration. It is quite clear from several studies done in the past that in a typical household the refrigeration system consumes a major part of the total energy used [7, 8]. It is, therefore, necessary that in the case of new refrigeration systems the aim will be to reduce energy consumption considerably, also it is now a very important point of view that the refrigeration industry escapes from criticism for contributing to global climate change. The developing countries are still far behind the progress made in these areas in the developed countries [9, 10, 11]. In developing countries like Nigeria, many of the vapour compression refrigeration system still runs on chlorofluorocarbons (CFC’s) and Hydro Chlorofluorocarbon (HCFC’s) with their attendant adverse effect on the environment due to their high ozone depletion potential (ODP) and high Global Warming Potential (GWP). Consequently, it is necessary to use alternative refrigerants which are eco-friendly refrigerants such as R-600a, R-600, R-717 and R-290 [12, 13, 14]. They must not be less energy efficient than the refrigerants that they replace. They must be proven to be safe, for both the immediate neighbourhood and global environment. They be must be simple to use and cost-effective, immediately available and ideally they should not require any significant new or unfamiliar technology [15,16,17].

This study focused on the thermodynamic analysis of single-stage vapour compression refrigeration systems in Nigeria, using natural refrigerants as alternatives to synthetic refrigerants. The primary objective is to evaluate the performance of natural refrigerants under typical Nigerian operating conditions. Key performance indicators such as the coefficient of performance (COP), refrigerating capacity, and compressor work are examined to determine the suitability of these refrigerants for use in Nigeria's climate. This study supported policymakers, industry stakeholders, and engineers in selecting refrigerants that offer both high performance and low environmental impact. Additionally, the findings could guide the development of regulations and policies that promote the use of eco-friendly refrigerants, contributing to Nigeria's commitment to global climate change mitigation efforts.

2 Methodology

The performance analysis is a measure of testing the effectiveness of the refrigeration system. The analysis is done to be able to identify the system with the highest performance by varying the thermodynamic properties. The effect in the variation of five operating parameters of refrigeration system such as Condensing Temperature (T_c), Evaporating Temperature (T_E), Sub-Cooling Temperature (T_{sub}), Superheating Temperature (T_{sup}) and refrigerant mass flow rate ($\dot{m}$) on the coefficient of performance (COP) of R-600a, R-600, R-717 and R-290 refrigeration systems were investigated and performance comparison were made to get the most suitable replacement for the older systems. The resulting equations were solved and performance comparison made using Engineering Equation Solver (EES) software. The simulations carried out on the EES software were eleven runs using the thermodynamics properties of a vapour compression single stage Vapour Compression Refrigeration System which is shown in Table 1. The runs were intended to determine the effects of changing the values of each of the five parameters while keeping the other parameters constant at their base values throughout the runs.

Table 1: Thermodynamics Properties and their Base Values considered

Properties	Base Value	Variation Difference	Variation Range (used for 11 runs)
Evaporating Temperature (T_E)	-20°C	-5	0 → -50
Condensing Temperature (T_C)	50°C	+5	30 → 80
Superheating Temperature (T_{SUP})	4°C	+2	0 → 20
Sub cooling Temperature (T_{SUB})	4°C	+2	0 → 20
Mass Flow Rate ($\dot{M}$)	0.05kg/s	0.01	0.01 → 0.11

2.1 Theoretical description of single-stage vapour compression refrigeration cycles

Figures 1, 2 and 3 below show the schematic diagram, T-S diagram and P-h diagram of a single-stage refrigeration system respectively. Two cycles were considered and the working fluids used in these cycles are R-600a, R-600, R-717 and R-290. At point 1, the circulating refrigerant enters the compressor as a saturated vapour. From point 1 to point 2, the vapour is isentropically compressed and exits the compressor as a superheated vapour. From point 2 to point 3, the vapour refrigerant travels through part of the condenser in superheated form. Heat is rejected to the surroundings, and refrigerant leaves the condenser at point 3 as a saturated liquid at constant pressure. Between points 3 and 4, saturated liquid refrigerant passes through the expansion valve and undergoes an abrupt decrease in pressure which results in adiabatic flash evaporation and auto refrigeration of part of the refrigerant. The refrigerant leaves the expansion valve as low quality saturated mixture and enters the evaporator. Between 4 and 1, the refrigerant vaporizes in the evaporator by absorbing heat in the cold space. The refrigerant enters the compressor again as saturated vapour and the cycle is completed.

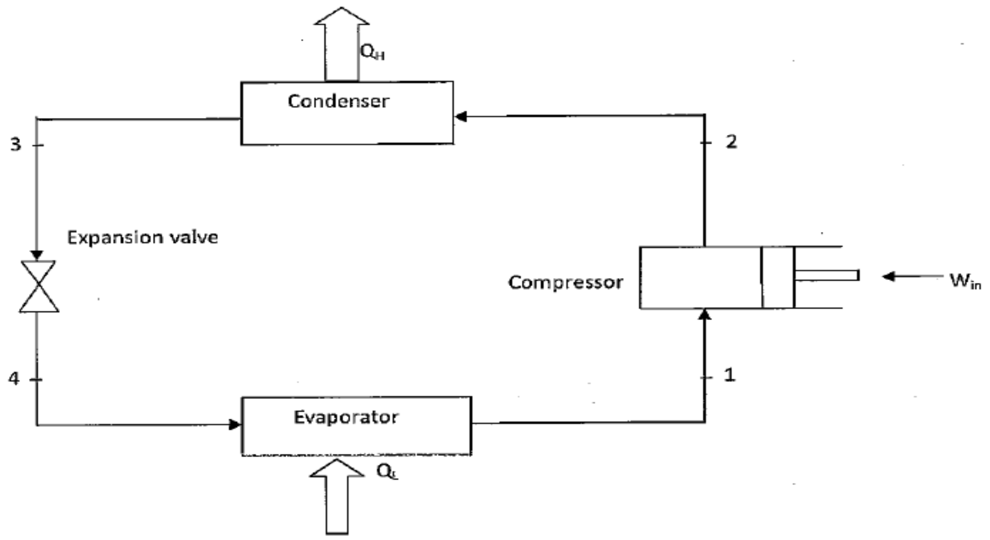

Figure 1: Schematic Diagram of a Single-Stage System

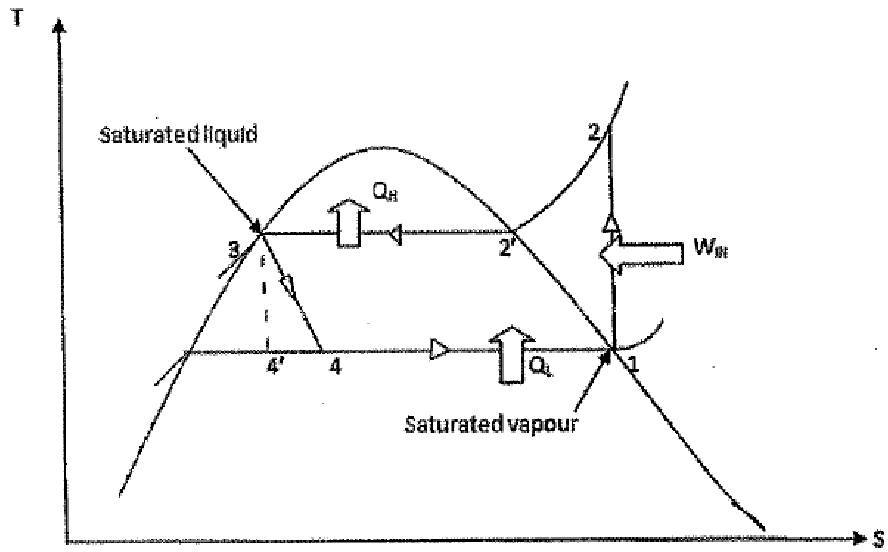

Figure 2: T-S Diagram of a Single Stage Vapour Compression Cycle

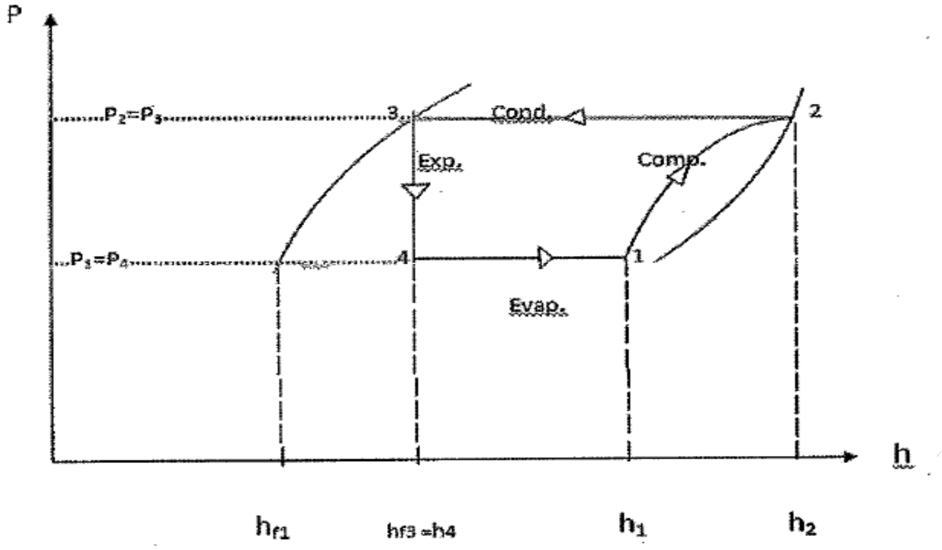

Figure 3: P-h Diagram of Single Stage- Vapour Compression Cycle

2.2 Thermodynamic analysis

In the performance analysis of this system, the following parameters were used according to [2,15]:

Condenser Temperature (T_C) of 50 ^oC is used as the baseline and varied from 30 ^oC to 80 ^oC.

Evaporator Temperature (T_E) of 20 ^oC is used as the baseline and varied from 0 ^oC to -50 ^oC.

Superheating Temperature (T_{sup}) of 4 ^oC is used as the baseline and varied between 0 ^oC and 20 ^oC.

Sub-cooling Temperature (T_{sub}) of 4 ^oC is used as the baseline and varied between 0 ^oC and 20 ^oC

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

Isentropic efficiency is taken as 0.85.

With regards to these assumed parameters, thermodynamic analysis was carried out and the resulting equations were solved using the EES software. The analysis is based on the first law of thermodynamics using the energy equation at steady-state and assuming that changes in kinetic and potential energies are negligible.

Mass balance

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (1)$$

Energy balance

$$Q - W + \sum_{in} \dot{m}h - \sum_{out} \dot{m}h = 0 \quad 2$$

The refrigeration capacity is defined by

$$Q_L = \dot{m}(h_1 - h_4) \quad 3$$

Work input into the compressor is given by

$$W_{in} = \dot{m}(h_2 - h_1) \quad 4$$

Condenser load is calculated by

$$Q_H = \dot{m}(h_3 - h_2) \quad 5$$

For the throttling process

$$\dot{m}h_3 = \dot{m}h_4 \quad 6$$

The coefficient of performance of the cycle is

$$COP = {Q_L}/{W_{in}} \quad 7$$

3. Results and Discussion

The values used as baseline for the system are T_C = 50 ^oC, TE = -20 ^oC, T_{sup} = 4 ^oC, T_{sub} = 4 ^oC, $\dot{m} = 0.05\ kg/$sec. whenever any of these factors are varied, the rest of them remain at the baseline values.

3.1 Effect of Evaporating Temperature, T_E

Figure 4 shows the effect of evaporating temperature on the coefficient of performance, from this figure it can be seen that R-717 gave the highest COP value of 3.858 at T_E of 0 ^oC. The COP value decreased as T_E reduces from 0 ^oC to -50 ^oC for all the four natural refrigerants under investigation. R-600a refrigerant gave COP value of 3.682 at 0 ^oC and a value of 1.078 at -50 ^oC. The figure shows that the COP of R-600a and R-290 have about the same value from T_E of -20 ^oC to -50 ^oC, a maginal difference was however observed from -20 ^oC to 0 ^oC.

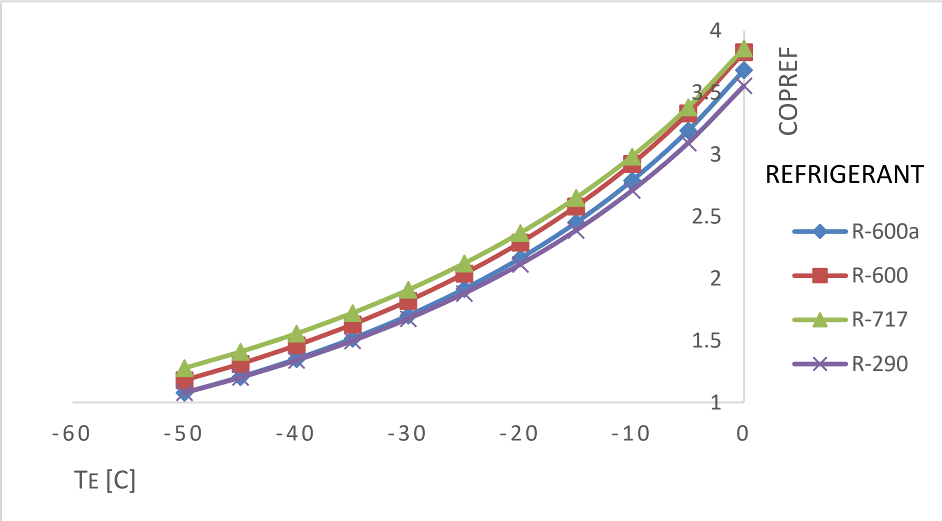

Figure 4: Effect of Evaporating Temperature (T_E) on the Coefficient of Performance (COP_{REF}) Using Natural Refrigerant

3.2 Effect of Condensing Temperature T_C

Figure 5 shows that the Coefficient of Performance (COP_{REF}) of all the four refrigerants decreased as the condensing temperature is increasing from 30°C to 80°C. R-600 gave the highest COP value of 3.63 at T_C of 30°C while R-717 gave a value of 3.571 at the same T_C, whereas at T_C of 80°C, R-717 gave the highest COP value of 1.461 while R-600 gave a lower value of 1.191. This shows that R-600 is more efficient at lower value of T_C while R-717 is more efficient at a higher value of T_C. The result also show that there is marginal difference in the COP values of R-600a and R-290 particularly at lower values of T_C.

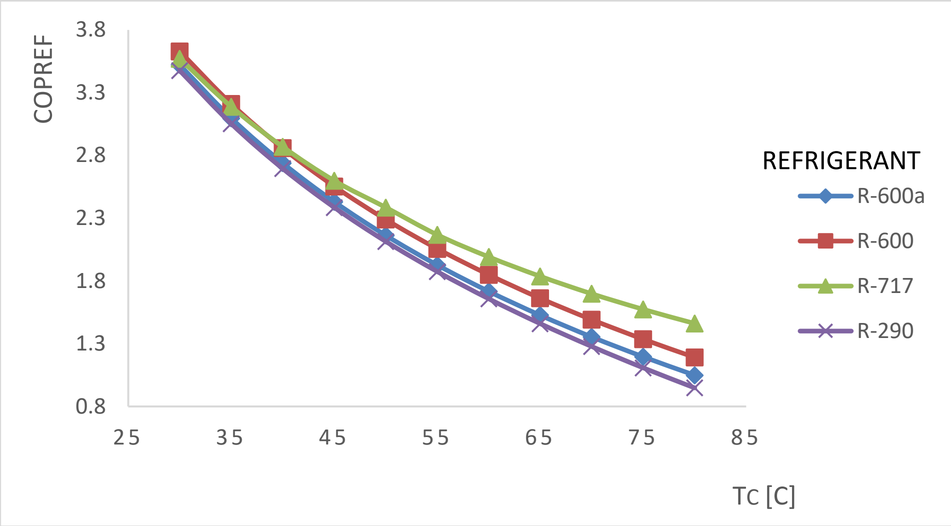

Figure 5: Effect of Condensing Temperature (T_C) on the Coefficient of Performance (COP_{REF}) Using Natural Refrigerant.

3.3 Effect of Degree of (T_{sup})

Figure 6 shows the effect of superheating on the COP of the single stage vapour compression system. From the figure, it can be seen tha the COP of R-600, R-600a, and R-290 icreased moderately with increase in the degree of superheating while the COP of R-717 reduces with increase in the degree of superheating, this is due to significant increase in compressor work when R-717 is superheated compared with other three refrigerants. R-717 has higher COP value of 2.383 at T_{sup} of 0°C while R-600 has a lower value of 2.273, but at T_{sup} of 20°C, R-600 has a higher COP value of 2.36 while R-717 has a lower value of 2.318. This result indicate that R-717 is more efficient at lower value of T_{sup} while R-600 is more efficient at higher value of T_{sup}.

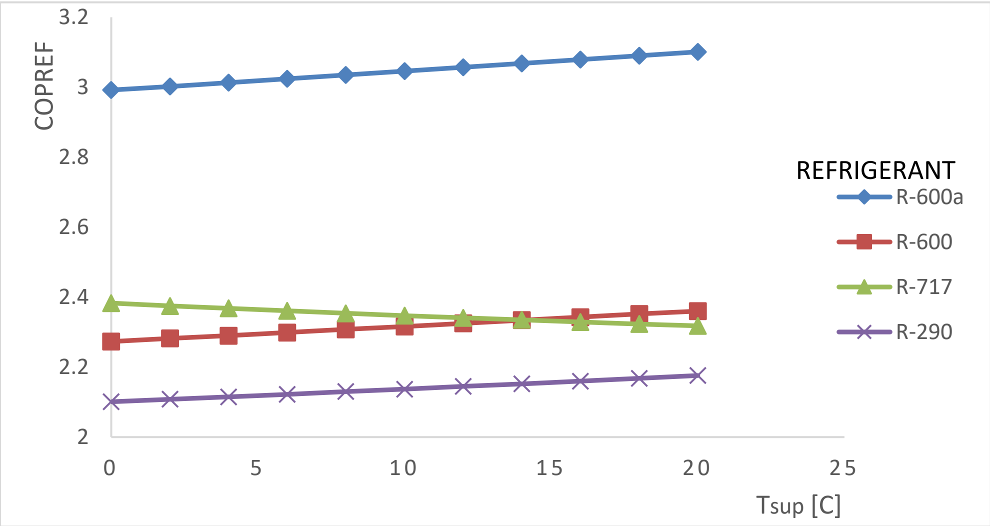

Figure 6: Effect of Superheating Temperature (T_{sup}) on the Coefficient of Performance (COP_{REF}) Using Natural Refrigerant.

3.4 Effect of Degree of sub-cooling (T_{sub})

Figure 7 shows the effect of sub cooling on the COP of single stage vapour compression systems. From the figure, it can be seen that the COP of all the four natural refrigerants in ths study increased with increase in the degree of sub cooling. This is due to the fact that sub cooling only increases the refrigeration effect without affecting the compressor work thereby increasing the COP of the refrigerating system. This figure shows that R-717 has the highest COP value of 2.321 at T_{sub} of 0°C and the lowest COP value of 2.555 at T_{sub} of 20°C compared with other three natural refrigerant in this study using the same T_{sub}. This indicate that T_{sub} has marginal efeect on the COP value of R-717 but it has greater effect on COP value of other three refrigerants. R-600 has the highest overall COP value of 2.669 compared with othe three refrigerant at T_{sub} of 20°C.

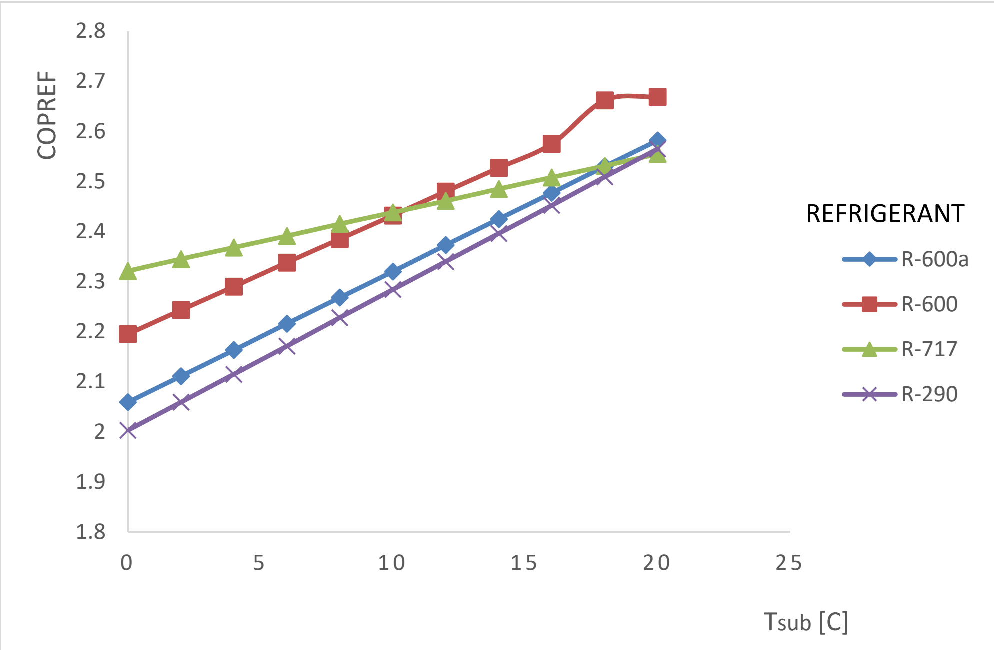

Figure 7: Effect of Evaporating Temperature (T_{sub}) on the Coefficient of Performance (COP_{REF}) Using Natural Refrigerant.

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

Figure 8 shows the effect of refrigerant mass flow rate on the COP of single stage vapour compression systems. From this figue, it can be seen that COP value of all the four refrigerants are nearly 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 2.368 while R-290 has the lowest constant value of 2.115.

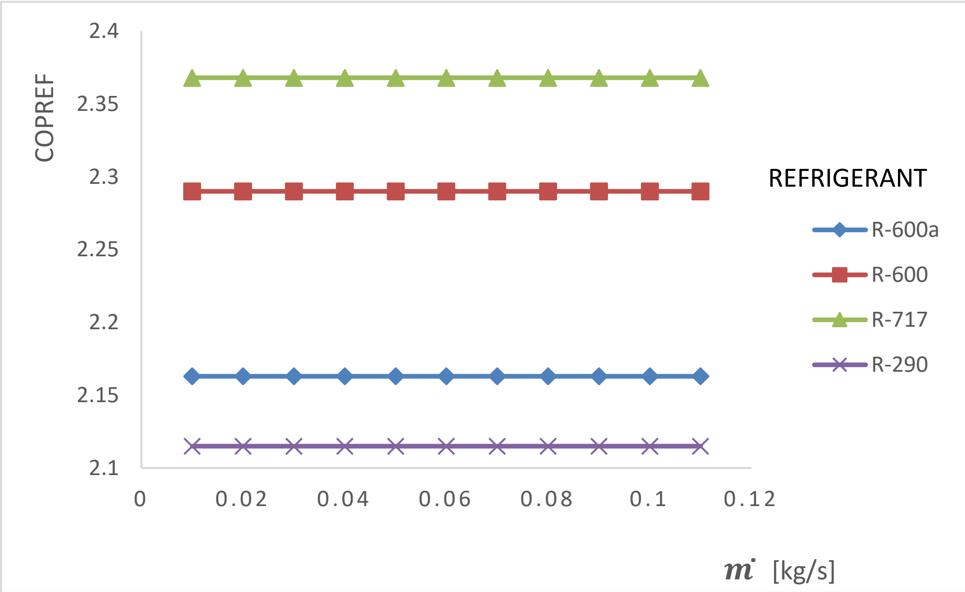

Figure 8: Effect of Refrigerant Mass Flow Rate ($\dot{m}$) on the Coefficient of Performance (COPREF) Using Natural Refrigerant

4 Conclusion

The following conclusions are therefore deduced from the thermodynamic analysis:

i. R-717 gave the best result when used in a single-stage vapour compression system.
ii. When T_C is increased, COP of the system decreased for the single-stage vapour compression system.
iii. A single-stage vapour compression system is not very effective for a low-temperature system below -40 ^{o}C.
iv. COP increased as the degree of sub-cooling increases.
v. COP increased as the degree of superheating increases except for R-717.
vi. $\dot{m}$ has marginal effect on the COP of a single-stage vapour compression system.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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