

Research Article

Access Energy and Exergy Analysis of R134A, R290 and R32 in Vapour Compression Refrigeration System with Liquid Vapour Heat Exchanger

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Received: 15/05/2025; Revised: 11/05/2025; Accepted: 18/06/2025; Published: 30/06/2025

DOI: <https://doi.org/10.69996/fmep.2025007>

Abstract: This study presents an energy and exergy analysis of R134A, R290, and R32 refrigerants in a vapor compression cycle to assess their environmental impacts and system performances. Factors such as the Coefficient of Performance (COP), exergy loss, exergetic efficiency, and deficiencies in system efficiency are considered. The analysis compares the refrigerants Ozone Depletion Potential (ODP) and Global Warming Potential (GWP), aiming to provide a comprehensive understanding of their performances. The study finds R290 to be a more suitable alternative to R134A than R32, showing higher exergetic efficiency and lower efficiency defects at condenser temperatures between 40°C and 55°C. The analytical framework employed in this study is constructed utilizing the Engineering Equation Solver (EES) software. This study offers an accurate assessment of the refrigerants environmental impacts while considering their effect on system performance.

Keywords: COP, Exergy, Efficiency, ODP, GWP.

1.Introduction

Refrigeration systems are essential in contemporary society; however, their effect on the environment must be acknowledged. The use of refrigerants, such as R22 and R115, has contributed significantly to ozone depletion, leading to the need for more environmentally friendly alternatives [1]. Researchers have proposed various substitutes for these refrigerants, and studies have primarily focused on their performance using the energy approach. Nevertheless, the energy approach fails to consider all the energy losses present in a refrigeration system. Exergy analysis, which considers both the First and Second Laws of thermodynamics, provides a more comprehensive understanding of the thermodynamic processes by quantifying the effect of irreversibility in the system [2].

Nomenclature

<i>COP</i>	Coefficient of Performance (non-dimensional)
<i>ED</i>	Exergy destruction Rate (<i>kW</i>)
<i>Ex</i>	Exergy rate of fluid (<i>kW</i>)
<i>h</i>	specific enthalpy (<i>kJ/kg</i>)
<i>m</i>	mass flow rate (<i>kg/s</i>)
<i>Q</i>	Rate of heat transfer (<i>kW</i>)
<i>s</i>	specific entropy (<i>kJ/kgkW</i>)
<i>T</i>	Temperature (<i>K</i>)
<i>W</i>	Work rate (<i>kW</i>)



Subscript

<i>comp</i>	Compressor
<i>cond</i>	Condenser
<i>evap</i>	Evaporator
<i>exp</i>	Expansion Valve
<i>r</i>	Refrigerant
<i>rr</i>	Reversible refrigerator
<i>vcr</i>	VCRS system
<i>o</i>	dead state

Greek symbols

η	efficiency (non-dimensional)
δ	efficiency defect (non-dimensional)

According to a study conducted by Akhilesh Arora et al, R507A is a more suitable alternative to R502 compared to R404A. In another study Naushad A. Ansari et al suggests that HFO-1234yt and HFO-1234ze may serve as effective substitutes for R134A. In this study, we examine the performance of R134A and its alternatives, R290 and R32, using both the energy and exergy approaches. In one of the recent study, Miranda et al. [3] experimentally tested HFC-161 mixture (HFC-161, HFC-125 and HFC-143a (10/45/45 wt.%)) as an alternative refrigerant to R502. Their results substantiated that this new refrigerant can achieve a high level of COP than R404A and R507 and can be considered as a promising retrofit refrigerant to R502. Naushad A. Ansari et al compares their Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) while considering their impact on the system performance. Additionally, we compute various parameters, including COP, exergy destruction, exergetic efficiency, and efficiency defects in the system, to provide a thorough understanding of the effects of degree of subcooling, decreases in pressure within the evaporator and condenser, along with the temperature at the dead state. From Reference [4] the authors analyze the system's performance using both energy and exergy approaches, we aim to provide a more accurate assessment of the refrigerant's environmental impact while also considering their impact on system performance.

Table 1: Physical and Environmental Characteristics of Refrigerants

Refrigerants	Formulae	ODP	GWP	Molar Mass (g/mol)	NBP (K)	Critical Pressure [MPa]	Critical temp [K]	Remarks
R134A	CH ₂ F CF ₃	0	1430	102	246.93	4.06	374.06	CFC-22 alternative for mobile air conditioner

R290	CH ₃ C H ₂ CH 3	0	3	44.1	230.9	4.25	369.8	Natural refrigerant, but flammable
R32	CH ₂ F ₂	0	675	52.0234	221.5	5.785	351.26	Low GWP and high performance, but flammable

2. Exergy Analysis

The vapor compression refrigeration cycle encompasses a liquid-vapor heat exchanger that incorporates superheating and subcooling processes within the evaporator and condenser, as illustrated in the Fig. 1(a) and (b) [5].

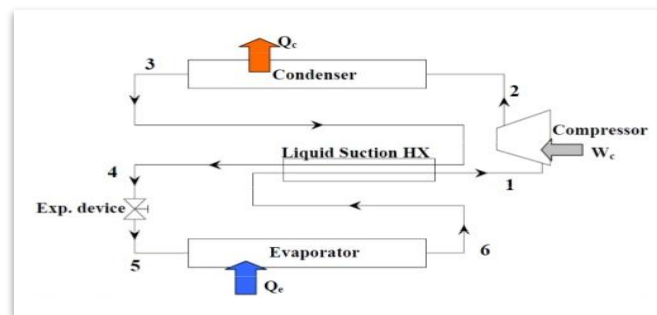
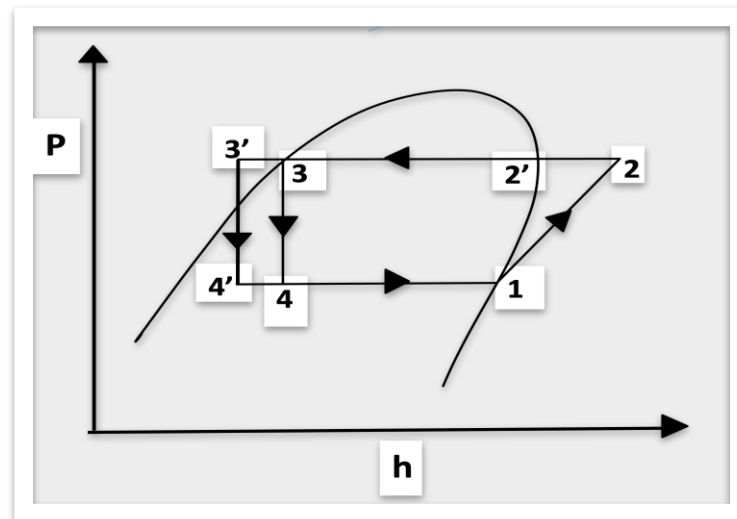


Figure 1: (a) Vapour Compression Refrigeration Cycle with Liquid Vapour Heat Exchanger



(b) Pressure – Enthalpy diagram of Vapour Compression Refrigeration Cycle with LVHE

The cycle's performance is measured using the Coefficient of Performance (COP), which is determined by the First Law of thermodynamics. The COP represents the amount of refrigeration effect (the desired outcome) produced for every unit of work required to operate the cycle. In simpler terms, the COP measures how effective the cycle is at producing the desired cooling effect Q_{evap} in relation to the amount of energy W_{comp} required to power it [6].

$$COP = \frac{Q_{evap}}{W_{comp}}$$

Exergy refers to the utmost potential work that can be extracted from a material stream as it transits from its initial state to a state of equilibrium with the surrounding environment. The exergy balance resembles an energy balance; however, the key distinction lies in the fact that the energy balance illustrates the conservation of energy, whereas exergy reflects the degradation of energy [7]. In essence, exergy assesses the quality of energy and the extent of useful work that can be extracted from it, while the energy balance accounts for the total energy present before and after a process. The Second Law of thermodynamics introduces the notion of exergy and elucidates its importance in evaluating energy usage.

$$ED = \sum (Ex)_{in} - \sum (Ex)_{out} + \sum Q \left(1 - \frac{T_o}{T}\right) + \sum W \quad (1)$$

Exergy in any state is given by

$$Ex = m_r [(h - h_o) - T_o (s - s_o)] \quad (2)$$

The equation presented in the passage illustrates how the rate of Exergy Destruction (ED) is influenced by several factors within a process. On the right side of the equation, four elements are present. The initial two elements represent the exergy associated with the inflow and outflow streams of the control volume. The subsequent terms, third and fourth, illustrate the exergy related to heat transfer (Q) from a source that is kept at a constant temperature (T). This exergy represents the work generated by a Carnot engine operating between the temperatures (T) and (T_o), signifying the utmost reversible work that can be obtained from thermal energy. The concluding term denotes the mechanical work that is either supplied to or removed from the control volume. Essentially, the equation clarifies the conversion and loss of energy during a process, with the first two terms illustrating energy input and output, while the third and fourth terms indicate energy lost as heat, and the last term pertains to the mechanical work involved.

According to study conducted by Paula et al, some equations are given

2.1 Exergy destruction in the system component

Evaporator

$$\begin{aligned} (ED)_{evap} &= (Ex)_4 + Q_{evap} \left(1 - \frac{T_o}{T_r}\right) - (Ex)_1 \\ &= m_r (h_4 - T_o s_4) + Q_{evap} \left(1 - \frac{T_o}{T_r}\right) - m_r (h_1 - T_o s_1) \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Compressor } (ED)_{comp} &= (Ex)_1 + W_{comp} - (Ex)_2 \\ &= m_r (T_o (s_2 - s_1)) \end{aligned} \quad (4)$$

Condenser

$$\begin{aligned}\left(\dot{ED}\right)_{cond} &= \left(\dot{Ex}\right)_2 - \left(\dot{Ex}\right)_3 \\ &= \dot{m}_r(h_2 - T_0 s_2) - \dot{m}_r(h_3 - T_0 s_3)\end{aligned}\quad (5)$$

Expansion valve

$$\begin{aligned}\left(\dot{ED}\right)_{exp} &= \left(\dot{Ex}\right)_3 - \left(\dot{Ex}\right)_4 \\ &= \dot{m}_r(T_0(s_3 - s_4))\end{aligned}\quad (6)$$

2.2 Total Exergy Destruction

Total exergy destruction in a system is the combination of the exergy destruction that occurs in each of the individual components of the system. In other words, the exergy destruction in each part of the system contributes to the overall loss of exergy [8].

$$\left(\dot{ED}\right)_{Total} = \left(\dot{ED}\right)_{comp} + \left(\dot{ED}\right)_{cond} + \left(\dot{ED}\right)_{evap}\quad (7)$$

2.3 Exergetic Efficiency (η_{exergy})

$$\eta_{exergy} = \frac{\text{potentially useful(exergy) output}}{\text{potentially useful(exergy) input}}\quad (8)$$

The potential useful (exergy) output is defined as the exergy of the heat absorbed into the evaporator from the space being cooled at a particular temperature (T_r). This indicates the highest quantity of beneficial work that can be derived from the cooling process. On the other hand, the potential useful (exergy) input is the actual work input required to operate the compressor $[(W)_{comp}]$. In simpler terms, the potential useful output represents the maximum amount of useful energy that can be obtained from the cooling process, while the potential useful input represents the actual energy required to power the process [9].

Hence, the exergetic efficiency is given by

$$\eta_{exergy} = \frac{\dot{Q}_{evap}\left(1 - \frac{T_0}{T_r}\right)}{W_{comp}} = \frac{COP_{vcr}}{COP_{rr}}\quad (9)$$

In this context, $[COP]_{rr}$ denotes the Coefficient of Performance for an ideal reversible refrigerator functioning between the temperatures (T_o) and (T_r), while $[COP]_{vcr}$ signifies the actual Coefficient of Performance for a vapour compression refrigeration system [10-12].

2.4 Exergy Destruction Ratio (EDR)

The EDR is calculated as the ratio of the total amount of exergy during a given task or process to the minimum exergy required to accomplish the same task.

$$EDR = \frac{ED}{Q_{evap} \left(1 - \frac{T_0}{T_r}\right)} = \frac{COP_{rr}}{COP_{vcr}} - 1 \quad (10)$$

EDR can be written in terms of exergetic efficiency as

$$EDR = \frac{1}{\eta_{exergy}} - 1 \quad (11)$$

2.5 Efficiency Defect

The efficiency defect is the fraction of the input energy that is lost due to irreversibility within the system's components. It represents the proportion of exergy destruction rate to the compressor work rate.

$$\delta = \frac{ED}{W_{comp}} \quad (12)$$

3.Result and Discussion

An advanced mathematical model has been created to conduct energy and exergy analysis of the system utilizing Engineering Equation Solver software.

The input data assumed for the calculation of results shown in figures 2-9 are:

- Mass flow rate of refrigerant Evaporator temperature (T_o): 223K to 273K
- Evaporator temperature (T_o): 223K to 273K
- Condenser temperature (T_c): 313K
- Ambient state temperature (T_o): 298K
- Difference between space and evaporator temperature ($T_r - T_e$): 15K
- Isentropic efficiency of compressor (η_{comp}): 75%
- Effectiveness of Liquid Vapour Heat Exchanger (ϵ_{lvhe}): 0.8
- Degree of sub-cooling of liquid refrigerant in LVHE (ΔT_{sub}): 5K
- It is assumed that the pressure drop across the evaporator, condenser, and liquid vapor heat exchanger is minimal.

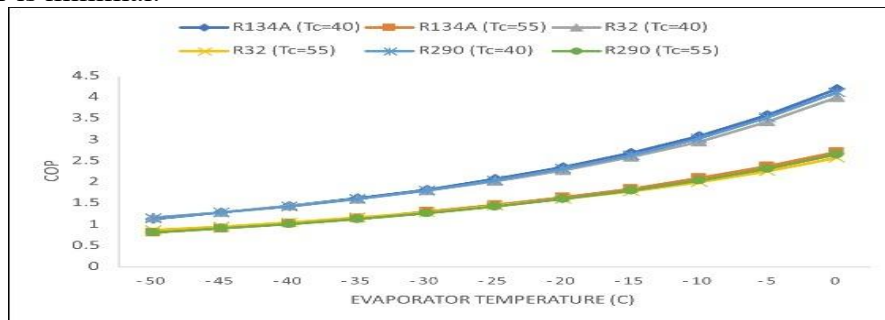


Figure 2: Variation of COP with Evaporator temperature

Figure 2 Shows variation of COP with Evaporator temperature, as the Evaporator temp increases the COP increases, the highest and lowest value of COP when Condenser temp is 55°C is 2.5 at 0°C and 0.8 at -50°C Evaporator temp respectively. The highest and lowest value of COP when Condenser temp is 40°C is 4.3 at 0°C and 1.2 at -50°C Evaporator temp respectively.

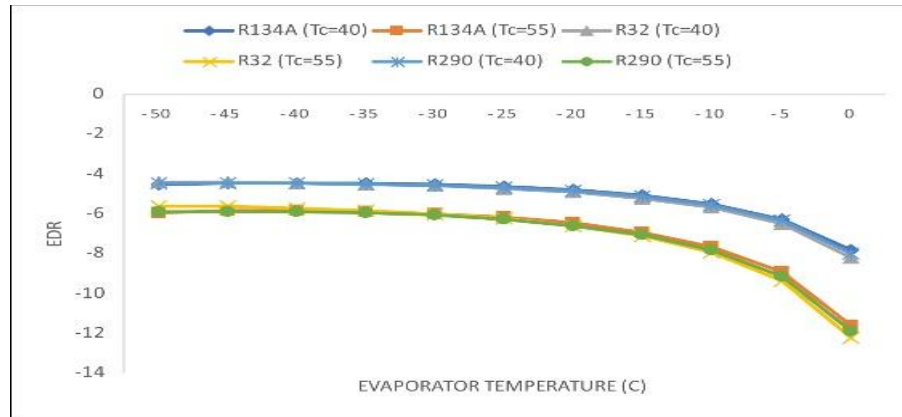


Figure 3: Variation of EDR with evaporator temperature

Figure 3 Shows Variation of EDR with Evaporator temperature, as the Evaporator temp increases the EDR decreases, the highest and lowest value of EDR when Condenser temp is 55°C is -6 at -50°C and -12 at 0°C Evaporator temp respectively. The highest and lowest value of COP when Condenser temp is 40°C is -4.2 at -50°C and -8 at 0°C Evaporator temp respectively.

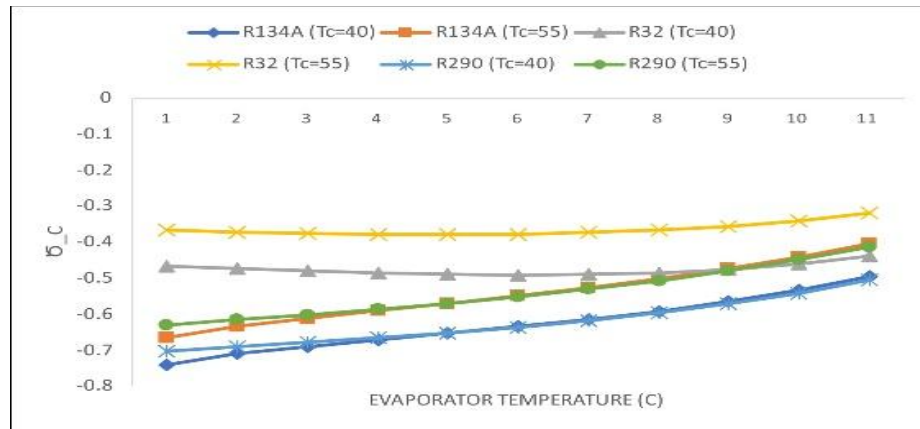


Figure 4: Variation of efficiency defect with evaporator temperature

Figure 4 Shows comparison of efficiency defect (condenser) with Evaporator temperature, all three refrigerant increases efficiency defect (Condenser) with increases in temp, but at Condenser temp 40°C, R-32 shows no defect with increase in Evaporator temp compared to other refrigerant.

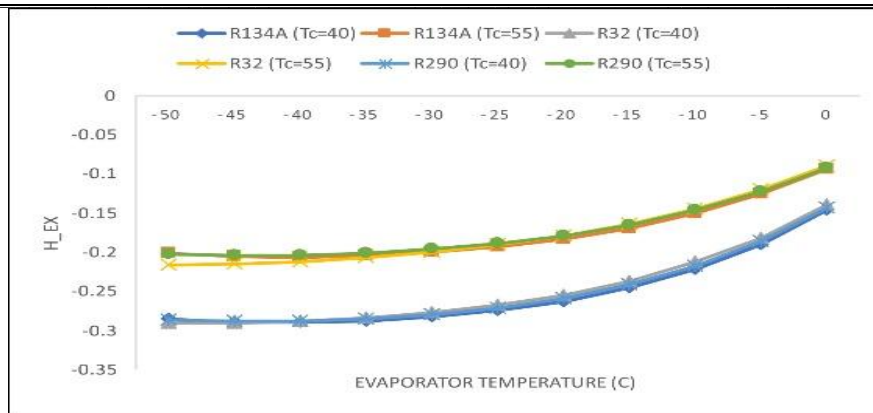


Figure 5: Variation of Exergetic efficiency with Evaporator temperature

Figure 5 Show the variation of Exergetic efficiency in relation to Evaporator temperature indicates that as the temperature of the evaporator rises, the Exergetic efficiency also increases, the highest and lowest Exergetic efficiency at Condenser temp 55°C is -0.12 at 0°C and -0.2 at -50°C Evaporator temp respectively. The highest and lowest Exergetic efficiency at Condenser temp 40°C is -0.15 at 0°C and -0.255 at -50°C Evaporator temp respectively.

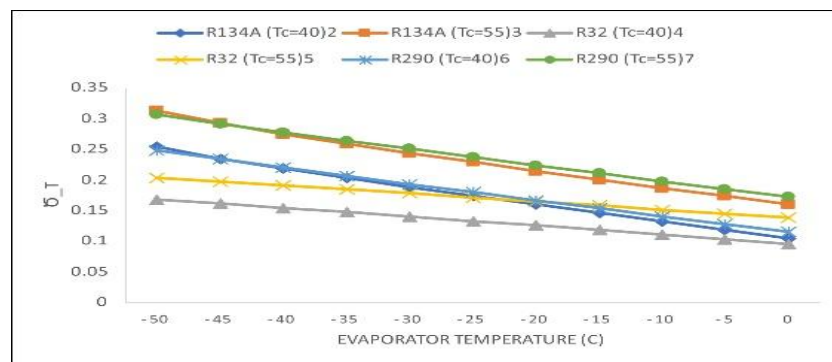


Figure 6: Variation of Throttling with Evaporator temperature

Figure 6 Shows comparison of Throttle valve with Evaporator temperature, as the Evaporator temp increases the Throttle valve decreases, the highest and lowest throttle valve at Condenser temp 50°C is 0.33 at -50°C and 0.14 at 0°C Evaporator temp respectively. The highest and lowest throttle valve at Condenser temp 40°C is 0.25 at -50°C and 0.11 at 0°C Evaporator temp respectively.

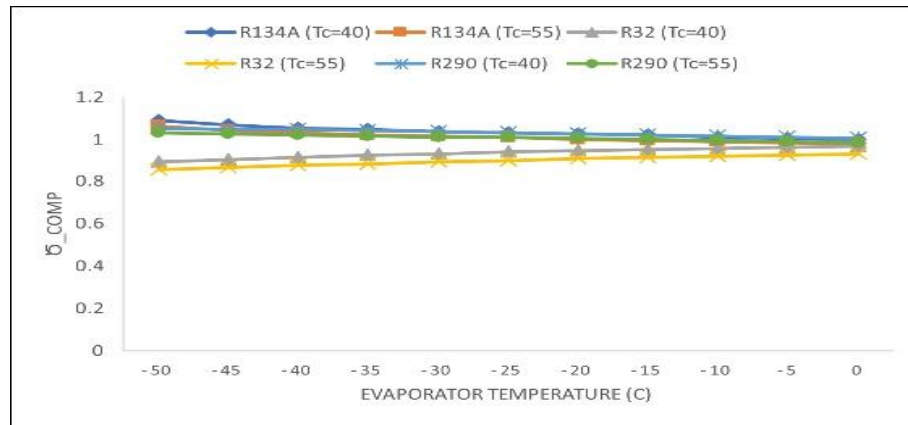


Figure 7: Variation of Efficiency defect with Evaporator temperature

Figure 7 Show comparison of efficiency defects in the compressor relative to Evaporator temperature, as the Evaporator temp increases, refrigerant like R-32 increases the efficiency defect in compressor but R-134A and R-290 shows decreases in Efficiency defect in compressor.

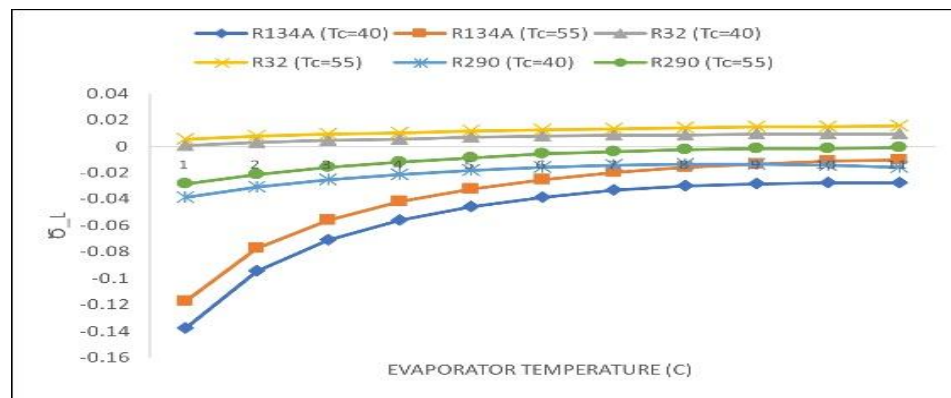


Figure 8: Variation of Efficiency defect in LVHE with Evaporator temperature.

Figure 8 Shows Efficiency defect in Liquid Vapour Heat Exchanger with Evaporator temperature. Only R-134A at Condenser Temp 40°C & 55°C shows a significant increase in efficiency defect with increase in the Evaporator Temp. The highest and lowest values of efficiency defect are 0.01 at Condenser Temp. 55°C and -0.14 at Condenser temp 40°C respectively.

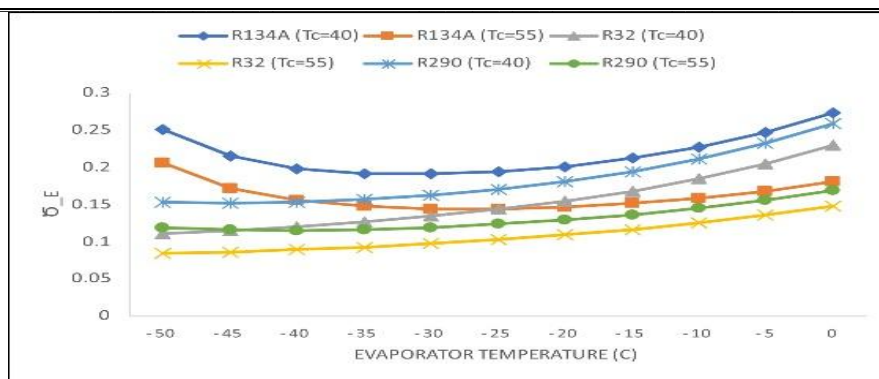


Figure 9: Variation of Efficiency defect in evaporator with Evaporator temperature

Figure 9 Shows Efficiency defect in evaporator with Evaporator temperature. The highest and lowest values of Efficiency defect are 0.275 at Condenser temp 40°C and 0.09 at Condenser temp.55°C.

4.Conclusions

This communication presents a comprehensive energy and exergy analysis of R123A, R32, and R290 within a real vapor compression cycle. The findings of this analysis are summarized below.

1. R290 outperforms R32 in terms of COP and exergetic efficiency when the condenser temperature is between 40°C and 55°C. The refrigerants can be ranked in descending order of EDR as R32, R290, and R134A.
2. The efficiency defects for R290 are lower than those for R32 when the condenser temperature is between 40°C and 55°C.
3. The increase in dead state temperature has a positive effect on Exergetic efficiency and EDR. R290 exhibits higher Exergetic efficiency than R32 when the condenser temperature is between 40°C and 55°C.

In light of the aforementioned conclusions, it can ultimately be asserted that R290 serves as a superior alternative to R134A when compared to R32.

Acknowledgement: Not Applicable.

Funding Statement: The author(s) received no specific funding for this study.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

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