International Journal of Emerging Science and Engineering (IJESE)
ISSN: 2319–6378 (Online), Volume-12 Issue-5, April 2024

Methods of Improving Thermal Performance of Vapour Compression Based Refrigeration System Through Eco Friendly Refrigerants to Reduce Their Environmental Impact

R.S. Mishra, Ansh Agarwal, Jayant Dixit, Samruddhi Kadam

Abstract: ***Tetrafluoroethane (CF3CH2F), an HFC refrigerant, is also known as R134a. It is safe for normal handling because it is neither poisonous, flammable, nor corrosive. Following the recent discovery that R-134a contributes to global warming, the European Union banned its use in new automobiles starting in 2011. Worked on a vapour compression-based refrigeration system, utilised hydrocarbon (HC) refrigerants, which were examined for their energetic and exergetic performance. In this investigation, pure Tetrafluoroethane (CF3CH2F) from the R134a family of HFCs was used for a theoretical analysis, along with other refrigerants which were eco-friendly and had a lower environmental impact(low Global Warming Potential and Ozone Depletion Potential):trans-1,3,3,3-Tetrafluoroprop -1-ene(R1234 ze (Z), R1234ze (E), (Z)-1-Chloro-2,3,3,3-Tetrafluoropropane (R1224YD (Z)), Fluoroethene (R1141),3,3,3-Trifluoroprop-1-ene (R1243 ZF). The thermodynamic equations of the refrigerants were solved for analysis using the Engineering Equation Solver application. It was concluded that R1234ZE (Z) is the most effective refrigerant.***

Key Words: Thermal Performance analysis, Refrigeration System, Refrigerants, Eco-friendly.

I. INTRODUCTION

An upgraded version of the air refrigeration cycle used in general refrigeration and commercial applications is the vapour compression cycle.. It involves four operations: compression, condensation, expansion, and vaporisation. The thermodynamic cycle is a process in which a liquid refrigerant is condensed into a saturated liquid and stored inthe liquid receiver.

The low-pressure refrigerant vapour expands before entering the evaporator or refrigerator, where it absorbs heat and creates refrigeration. At point 5, the cold and partially vaporised refrigerant moves towards point 1, passing through the evaporator coils/tubes. Warm air isintroduced through the coil or tubes by a fan. The generatedrefrigerant vapour then flows back to point 1, the compressor inlet. The vapour compression cycle, which involves compression, condensation, throttling, and evaporation, has been the focus of scientists' attention. EES is a commercial software package used to solve systems of simultaneous nonlinear equations, store thermodynamic properties, and perform iterative problemsolving. Code can be input in any order.

II. LITERATURE REVIEW

R.S. Mishra et al. (2013) [1] Employed several evaporators, compressors, expansion valves, intercoolers, and flash chambers to enhance the vapour compression refrigeration system's thermal efficiency. Results revealed a 22% improvement in first- and second-law effectiveness.

R.S Mishra et al. (2020) [2] found that raising evaporator load or decreasing high-grade energy can both increase the thermal performance(COP) of a Vapour compression-based refrigeration system utilising eco-friendly refrigerants.

S C Kaushik et al. (2008) [3] performed a conceptual study of a vapour compression-based refrigeration system using R502,R600, R404A, and R507A [4]. R507A was concluded to be a better replacement for R502 than R404A, with minor issues related to the liquid-vapour heat exchanger efficiency and minor condenser issues.

Akhilesh Arora and SC Kaushik et al. (2008) conducted a study to identify the appropriate interstage pressure and temperature of a Refrigeration system with two stages utilising HCFC22, R410A, and R717 refrigerants.

Conclusion: R717 is a more suitable replacement for HCFC-22 refrigerant than R410A.

S K Tyagi et al. (2012) [5] found that the system's overall exergy destruction is highest at 100% charge and lowest at 25% charge.

Kapil Chopra, V. Sahni et al. (2015) [6] compared the refrigerants used in two-stage vapour compression refrigeration systems. At -50°C for evaporation and 45°C for condensation, R134a had 8.97% and 5.38% less energyand exergy efficiency than R152a and R600.

Manuscript received on 10 May 2023 | Revised Manuscript received on 05 May 2023 | Manuscript Accepted on 15 April 2024 | Manuscript published on 30 May 2024.
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Vaibhav Jain et al. (2011) conducted a performance comparison research of R22, R134a, R410A, R407C, and M20-based vapour compression refrigeration systems.

R407C can be a viable HFC refrigerant replacement withthe least expense and work.

Huang et. al. (2017) [7] studied the energetic and exergetic performance of a mini air-cooled heat exchanger.

Naushad Ahmad Ansari, Akhilesh Arora, Samsher, and K. Manjunath et al. (2019) investigated the functioning of a vapour compression-based refrigeration system with customised mechanical subcooling and the Effect of Green Refrigerants. It was found that R1233zd(E), a low GWP refrigerant, performed better than R134a in terms of COP and energy efficiency.

Jeyaraj Thavamani & Ramalingam Senthil et al. (2020) had conducted a study on the effectiveness of retrofitting hydrocarbon-based household vapour compression refrigeration systems [8][9]. Separate tests using HC mix and R134a refrigerants were conducted under no-load conditions. Due to the high latent heat, it was found that the temperature of the HC mix is 3 °C lower.

Bolaji, B.O. et al. (2011) [10] chose environmentally friendly refrigerants from methane derivatives and ethane derivativesbased on flammability, toxicity, chemical stability, and atmospheric lifespan.

Neeraj Agrawal, Shriganesh Patil, Prasant Nanda et al. (2017) [11] used R290/R600a Zeotropic Blends to determine theideal charge for a residential refrigerator, with a 60 g charge and -3.5°C as the lowest temperature.

Piyanut Saengsikhiao, Juntakan Taweekun, Somchai Sae-ung, Thanasak et al. (2020) [12] conducted research tocreate an energy-efficient and ecologically friendly refrigerant for medium temperature refrigeration systems. The end product is a nontoxic refrigerant with low GWP,0% ODP, high capacity, and low operating pressure.

Kazm Kumaş, Ali Akyüz et al. (2020) [13] conducted a performance investigation of the R450A refrigerant in a vapour compression cooling system. The energy characteristics of R450A and R134a refrigerants were theoretically and ecologically examined. It was determined that R450A has a larger mass flow rate than R134a, as it cools more slowly. R134a has a greater COP.

Alptug Yataganbaba, Ali Kilicarslan, Irfan Kurtbas et al. (2015) [14] found that R1234yf and R1234ze are good alternatives to R134a in terms of their environmental friendliness.

Mr. Sandip P. Chavhan, Prof. S. D. Mahajan et al. (2015) [15] conducted a study on the experimental performance assessment of R152a as a potential R134a replacement. R152a has an average refrigerating effect that is 57% higher than that of R134a. It is the most energy-efficient refrigerant since it uses the least amount of electricity per tonne of refrigeration of the two refrigerants under study and has the lowest GWP(Global Warming Potential (120)) and ODP (Ozone Depleting Potential (0)) values.

Lalit Mishra, Asst. Prof. Sunil Kumar, Prof. Abhishek Bhandari et al (2019) [16] analysed the performance of an ice plantusing R-134a eco-friendly refrigerant. Three refrigerants, R32, R152a, and R245a were combined in a particular ratio toreplace R134a. The global warming potential of all three refrigerants was lower than that of R134a. Based on their thermal performance in the given conditions and environmental impact, the refrigerant mixes were evaluated.

A L Tarish, J Al Douri, and V Apostol et al.(2020) [17] examined effectiveness and efficiency for a vapour compression-based refrigeration system (VCRS) employing R1234ze and R1234ze, two ecologically friendly refrigerants. Studied how performance and energy destruction were affected by subcooling temperature in all VCRS components. The thermodynamic properties of the refrigerant were obtained using the Engineering Equation Solver (EES) software programme. The findings showed that R1234yf demonstrated the most significant COP gain (16.7%) as a result of subcooling, followed by R1234ze (14%) and R134a (12.8%).

Uma Shankar Prasad, R.S Mishra, R.K Das et al. (2020) [18] investigated the thermal performance of a vapour compression based refrigeration system utilising R134a refrigerant with nanofluids and an Al2O3 base. They concluded that nanoparticles with R134a refrigerant can improve heat transfer qualities.

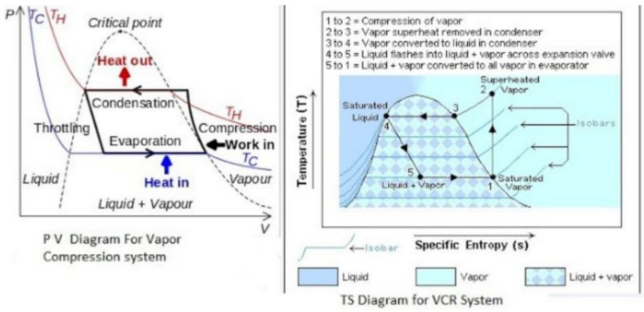

Figure 1: PV And TS Diagram for Vapour Compression System

III. ADVANTAGES AND DISADVANTAGES

Benefits of a vapour compression system include its smaller size and cheaper running costs for a given refrigeration capacity. It may be used in a wide variety of temperatures. The vapour compression system offers the following benefits: It is smaller in size for the same refrigeration capacity, and it costs less to operate. Disadvantages of the Vapour Compression System: The system's primary difficulty lies in controlling refrigerant leakage, and the initial cost is relatively high. Moving Parts cause more wear and tear and noise. Liquid droplets in the suction line could be harmed.

A. System description

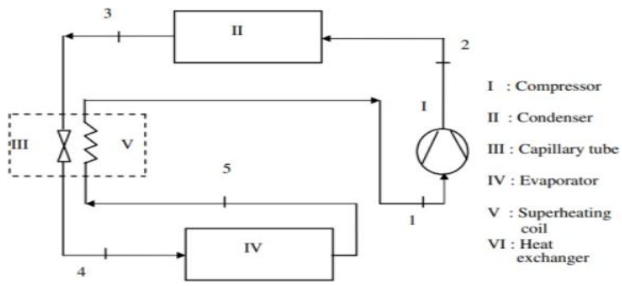

Figure 2: System Description

I: Compressor: To maintain a constant flow of refrigerant throughout the system, compressors pull refrigerant vapour from the evaporator and increase its temperature and pressure, causing it to condense.

II: Condenser: It is a heat exchanger device used for condensation, employing a cooling medium to transfer heat from the refrigerant. The cooling system of the apparatus generally utilises atmospheric air or water as the medium which receives the system's rejected heat. The cooling medium ultimately releases the heat into the universe or the surrounding atmosphere. The heat rejected in the condenser is equivalent to the heat required for the compressor work and the heat absorbed by the evaporator. Due to heat transfer, the refrigerant going through the condenser is first desuperheated, then condensed, and occasionally somewhat sub-cooled.

III: Capillary Tube: Since the capillary tube is not adjustable and cannot alter the flow of the refrigerant, it is designed for specific environmental conditions. However, if correctly chosen, it can perform pretty effectively under a variety of scenarios. Because of the capillary's short diameter, the pressure of the refrigerant decreases.

IV: Evaporator: The evaporator also serves as a heat exchanger in a typical refrigeration circuit, in addition to the condenser. It functions at the "business end" of the refrigeration cycle. The evaporator's fins absorb heat from the air as it is forced past them, cooling the air by transferring heat from the surrounding space. Since it transfers heat from the objects in the cold room to the refrigerant, it is the central part of the refrigeration system.

Superheating: The process of converting saturated or wet steam into superheated or dry steam, which is subsequently used in steam turbines, steam engines, and processes like steam reforming, is known as superheating. Before the liquid reaches the evaporator coil, it evaporates, absorbing heat that is then released as superheated vapour. The operational superheat controls the amount of the evaporator used.

VI: Heat Exchanger: Heat is transferred from one flowing substance to another that is flowing and has a lower initial temperature using a heat exchanger. Heat exchangers are employed as evaporators and condensers in refrigeration engineering, where the refrigerant undergoes a phase change. As a counter-flow heat exchanger, the capillary tube and suction line transport refrigerant vapour from the evaporator to the condenser, maintaining its condensed state throughout the process. Throughout the procedure, which employs a non-adiabatic throttling technique, heat is transferred from the capillary tube to the suction line, thereby keeping it separate from the evaporator. The thermal performance of this system is boosted due to heat transfer.

IV. MATERIALS AND METHODS

The mentioned numerical values were employed for the numerical calculation to verify the thermal model: Reference temperature (T_0) = 298.15 Kelvin

Reference pressure (P_0) = 110 kilo Pascal Refrigeration capacity (Q_{evap}) = 10 kilo Watt

Evaporator temperature range (T_{evap}) = 250–273.15 Kelvin Condenser temperature range ($T_{condenser}$) = 313–333.15 Kelvin

Subcooling temperature (DTSC) = 0 Kelvin Superheating temperature (DTSH) = 3 Kelvin Compressor isentropic efficiency = 80% Electric motor efficiency = 90%

Mass flow rate range of refrigerants:

R134a = 0.06905 kg s-1 R600 = 0.0042 kg s-1 R600a = 0.0050 kg s-1

A. Energy and Exergy Analysis

For the simple vapour compression refrigeration cycle, energy and exergy analyses require some mathematical formulations. The compressor receives external energy (power), and the evaporator adds heat to the system while the condenser rejects heat. The energy efficiency of refrigerants changes in response to variations in heat rejection and heat addition for different refrigerants. The various components of the system experience different exergy losses. T0 and P0 represent the surrounding ambient temperature and pressure. Exergy is consumed or destroyed as a result of the entropy generated by the associated processes.

Second law efficiency (Exergy):

$\Psi = (h - h_0) - T_0 (s - s_0)$ -------- [1]

For Evaporator: Heat addition in evaporator $Q_{ev} = m (h_1 - h_4)$----------------------------------- [2]

Exergetic losses:

$I_{ev} = m (\psi_4 - \psi_1) + Q_{ev} (1 - T_0 / T_{evap})$

$= m[(h_4 - h_1) - T_0(s_4 - s_1)] + Q (1 - T_0 / T_{evap})$ --- [3]

For Vapour Compressor:

Exergetic losses:

$I_{compressor} = m (\psi_1 - \psi_2) + W_{el}$

$= m[(h_1 - h_2) - T_0 (s_1 - s_2)] + W_{el}$ ------------------ [4]

For Condenser:

$Q_{condenser} = m (h_2 - h_3)$--------------- [5]

Exergetic losses:

$I_{condensor} = m (\psi_2 - \psi_3) - Q_{condenser} (1 - T_0 / T_{condenser})$

$= m[(h_2 - h_3) - T_0 (s_2 - s_3)] – Q_{condenser} (1 - T_0 /Condenser)$ - - - - - - - [6]

For expanding through a valve, cooling the condensed refrigerant

Exergetic destruction:

$I_{exp} = m (\psi_4 - \psi_3)$

$= m (s_4 - s_3)$

[Throttling, $h_4 = h_3$] ------------- [7]

For thermal efficiency: coefficient of performance $COP = Q_{ev} / W_{el}$ -------------------------------- [8]

aggregate system destruction:

total = $I_{condenser} + I_{exp} + I_{compressor} + I_{ev}$ ----------------- [9]

Exergetic efficiency (2nd law efficiency):

$\eta_x = (\Psi_1 - \Psi_4)/W_{el}$

B. EES:

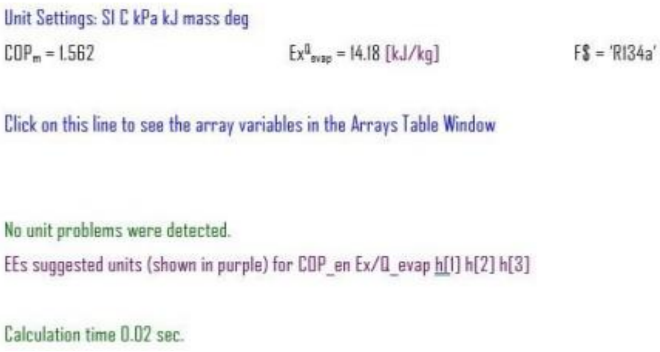

Figure 3: Settings of EES Code

V. RESULTS AND DISCUSSIONS

A. R134a:

Table 1(a): Variation of Evaporating Temperature with Thermal Performance for R134a

Temp Evap (deg C)	-20	-15	-10	-5	0
COP	2.10	2.36	2.68	3.06	3.54
Efficiency	0.3	0.29	0.27	0.26	0.23
Q(cond)	14.66	14.46	14.28	14.12	13.96
W(comp)	4.25	3.8	3.38	2.97	2.58
Exergy Product	1.85	1.65	1.45	1.25	1.04
Q(evap)	10.41	10.66	10.9	11.14	11.37
EDR(sys)	2.28	2.4	2.57	2.83	3.2

Table 1(b): Variation of Condensing Temperature with Thermal Performance for R134a

Temp Cond (deg C)	60	55	50	45	40
COP	1.89	2.16	2.46	2.81	3.22
Efficiency	0.16	0.18	0.21	0.24	0.28
Q(cond)	12.85	13.24	13.61	13.96	14.28
W(comp)	7.44	4.19	3.93	3.66	3.38
Exergy Product	1.12	1.2	1.29	1.37	1.45
Q(evap)	8.41	9.05	9.68	10.3	10.9
EDR(sys)	5.18	4.41	3.73	3.13	2.57

B. R1234ze (Z):

Table 2(a): Variation of Evaporating Temperature with Thermal Performance for R1234ze(Z)

Temp Evap (deg C)	-20	-15	-10	-5	0
COP	2.61	3.01	3.32	3.72	4.33
Efficiency	0.29	0.27	0.26	0.24	0.24
Q(cond)	12.82	13.14	13.57	13.84	14.55
W(comp)	4.12	3.84	3.67	3.39	2.99
Exergy Product	1.91	1.83	1.8	1.7	1.62
Q(evap)	10.77	11.57	12.2	12.61	12.93
EDR(sys)	2.34	2.48	2.6	2.94	3.31

Table 2(b): Variation of Condensing Temperature with Thermal Performance for R1234ze(Z)

Temp Cond (deg C)	60	55	50	45	40
COP	1.99	2.26	2.67	2.92	3.34
Efficiency	0.26	0.28	0.31	0.34	0.38
Q(cond)	12.98	13.41	13.82	13.96	14.32
W(comp)	7.74	4.28	3.93	3.56	3.23
Exergy Product	1.42	1.61	1.7	1.47	1.58
Q(evap)	8.61	9.15	9.88	10.45	10.92
EDR(sys)	5.38	4.81	3.48	3.22	2.87

C. R1234ze (E):

Table 3(a): Variation of Evaporating Temperature with Thermal Performance for R1234ze(E)

Temp Evap (deg C)	-20	-15	-10	-5	0
COP	2.42	2.872	3.325	3.67	4.322
Efficiency	0.311	0.28	0.27	0.2611	0.23
Q(cond)	14.86	14.61	14.2	14.13	14
W(comp)	4.29	3.884	3.31	2.88	2.56
Exergy Product	1.9	1.711	1.46	1.23	1.11
Q(evap)	10.38	11.15	11.01	10.61	11.08
EDR(sys)	2.25	2.42	2.6	2.84	3.211

Table 3(b): Variation of Condensing Temperature with Thermal Performance for R1234ze(E)

Temp Cond(deg C)	60	55	50	45	40
COP	1.887	2.17	2.47	2.82	3.23
Efficiency	0.1623	0.187	0.2112	0.2431	0.2981
Q(cond)	12.82	13.31	13.65	13.98	14.35
W(comp)	7.5	4.13	3.97	3.65	3.33
Exergy Product	1.18	1.2	1.27	1.34	1.52
Q(evap)	8.4	9.05	9.633	10.32	10.8
EDR(sys)	5.232	4.41	3.78	3.445	2.456

D. R1224YD (Z):

Table 4(a): Variation of Evaporating Temperature with Thermal Performance for R1224YD

Temp Evap (deg C)	-20	-15	-10	-5	0
COP	2.41	2.85	3.34	3.69	4.29
Efficiency	0.3	0.29	0.28	0.27	0.23
Q(cond)	14.81	14.59	14.23	14.05	13.91
W(comp)	4.22	3.88	3.31	2.8	2.59
Exergy Product	1.91	1.76	1.76	1.72	1.7
Q(evap)	10.17	11.05	11.08	10.32	11.1
EDR(sys)	2.23	2.44	2.53	2.85	3.12

Table 4(b): Variation of Condensing Temperature with Thermal Performance for R1224YD

Temp Cond (deg C)	60	55	50	45	40
COP	1.86	2.14	2.56	2.9	3.25
Efficiency	0.16	0.19	0.21	0.24	0.3
Q(cond)	12.86	13.57	13.79	13.98	14.56
W(comp)	7.46	4.13	3.96	3.64	3.33
Exergy Product	1.14	1.23	1.28	1.38	1.67
Q(evap)	8.45	9.08	9.69	10.56	10.78
EDR(sys)	5.28	4.48	3.78	3.42	2.43

E. R1141:

Table 5(a): Variation of Evaporating Temperature with Thermal Performance for R1141

Temp Evap (deg C)	-20	-15	-10	-5	0
COP	2.61	3.01	3.32	3.72	4.33
Efficiency	0.29	0.27	0.26	0.24	0.24
Q(cond)	12.82	13.14	13.57	13.84	14.55
W(comp)	4.12	3.84	3.67	3.39	2.99
Exergy Product	1.91	1.83	1.8	1.7	1.62
Q(evap)	10.77	11.57	12.2	12.61	12.93
EDR(sys)	2.34	2.48	2.6	2.94	3.31

Retrieval Number: 100.1/ijese.F95690512623
DOI: 10.35940/ijese.F9569.12050424
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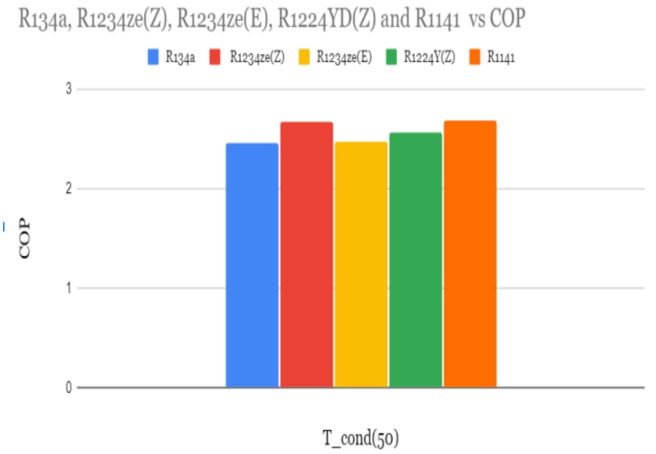
Table 5(b): Variation of Condensing Temperature with Thermal Performance for R1141

Temp Cond (deg C)	60	55	50	45	40
COP	1.99	2.28	2.68	2.96	3.36
Efficiency	0.26	0.29	0.31	0.34	0.38
Q(cond)	12.93	13.56	13.93	13.99	14.48
W(comp)	7.77	4.28	3.98	3.84	3.27
Exergy Product	1.46	1.68	1.7	1.45	1.55
Q(evap)	8.63	9.17	9.89	10.59	10.97
EDR(sys)	5.38	4.82	3.46	3.23	2.84

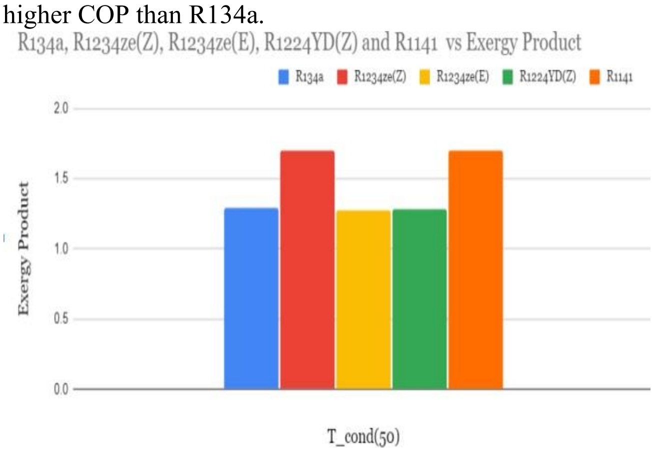
F. Comparison Between Refrigerants:

Table 6(a): Comparison Between Refrigerants at Tcond(50)

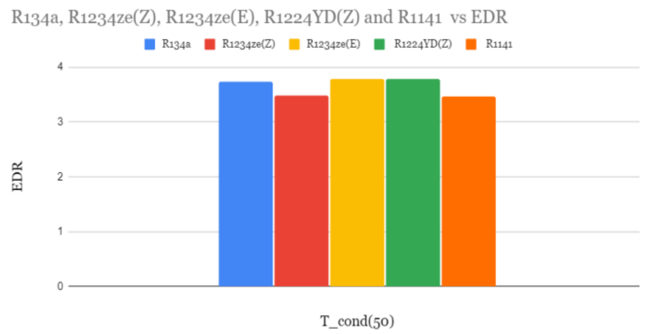
T_cond(50)	COP	Exergy Product	EDR	Q(cond)	Comp Work	Q(evap)	Efficiency
R134a	2.46	1.29	3.73	13.61	3.93	9.68	0.21
R1234ze(Z)	2.67	1.7	3.48	13.82	3.93	9.88	0.31
R1234ze(E)	2.47	1.27	3.78	13.65	3.99	9.633	0.2112
R1224YD(Z)	2.56	1.28	3.78	13.79	3.96	9.69	0.21
R1141	2.68	1.7	3.46	13.93	3.98	9.89	0.31



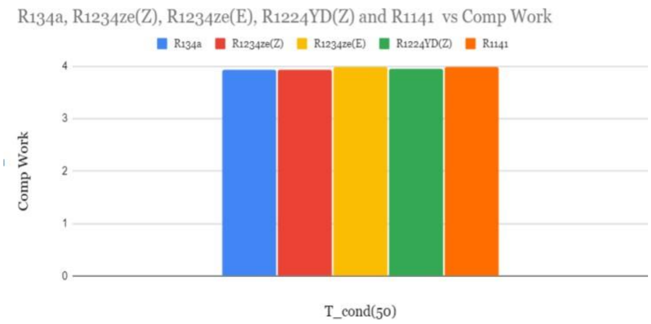
Graph 1: The graph compares the refrigerants based on their COP at T_cond(50). The results demonstrate that R1234ze(Z), R1234ze(E), R1224YD(Z), and R1141 have higher COP than R134a.



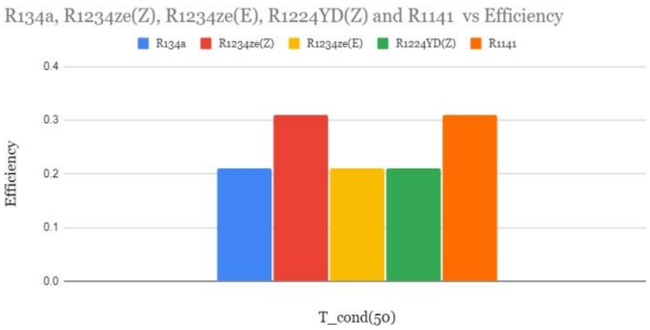
Graph 2: The graph compares the refrigerants based on their Exergy Product at T_cond(50). The results demonstrate that R1234ze(Z) and R1141 have a higher Exergy Product than R134a, whereas R1234ze(E) and R1224YD(Z) have a lower Exergy Product than R134a.



Graph 3: The graph compares the refrigerants based on their EDR at T_cond(50). The results demonstrate that R1234ze(Z) and R1141 have lower EDR than R134a, whereas R1234ze(E) and R1224YD(Z) have higher EDR than R134a.



Graph 4: The graph compares the refrigerants based on their coefficient of performance (COP) at T_cond = 50 °C. The results demonstrate that R1234ze(E), R1224YD(Z), and R1141 have higher Compression work than R134a, whereas R1234ze(Z) has the same Compression work as R134a.



Graph 5: The graph compares the refrigerants based on their Efficiency at T_cond(50). The results demonstrate that R1234ze(Z) and R1141 have higher Efficiency than R134a, whereas R1234ze(E) and R1224YD(Z) have the same efficiency as R134a.

Table 6(b): Comparison Between Refrigerants at Tevap(0)

T_evap(0)	COP	Exergy Product	EDR	Q(evap)	Comp Work	Q(cond)	Efficiency
R134a	3.54	1.04	3.2	11.37	2.58	13.96	0.23
R1234ze(Z)	4.33	1.62	3.31	12.93	2.99	14.55	0.24
R1234ze(E)	4.322	1.11	3.211	11.08	2.56	14	0.23
R1224YD(Z)	4.29	1.7	3.12	11.1	2.59	13.91	0.23
R1141	4.33	1.62	3.31	12.93	2.99	14.55	0.24

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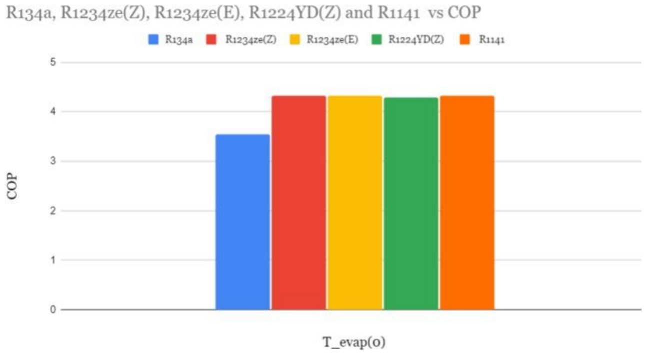
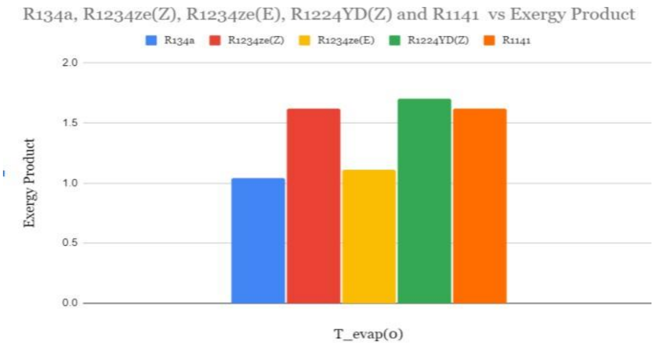
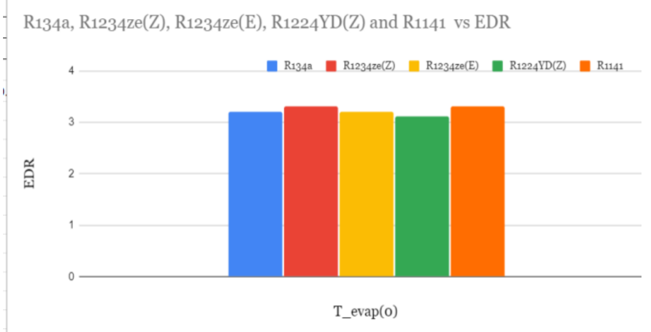


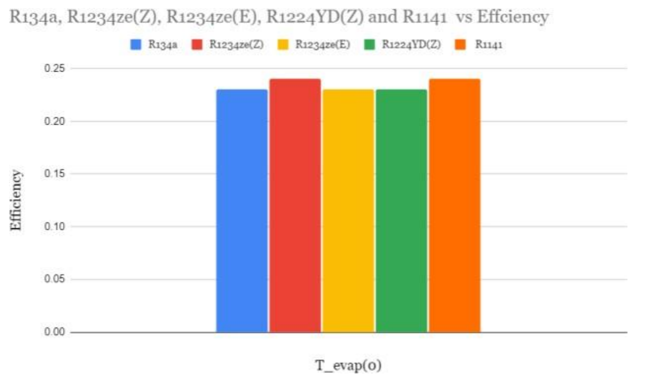
Graph 6: The graph compares the refrigerants based on their COP at T_evap(0). The results demonstrate that R1234ze(Z), R1234ze(E), R1224YD(Z), and R1141have higher COP than R134a.



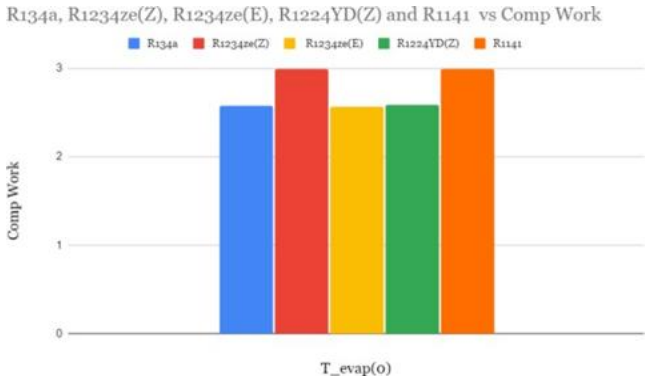
Graph 7: The graph compares the refrigerants based on their Exergy Product at T_evap(0). The results demonstrate that R1234ze(Z), R1234ze(E), R1224YD(Z), and R1141 have higher Exergy Product than R134a.



Graph 8: The graph compares the refrigerants based on their EDR at T_evap(0). The results demonstrate that R1234ze(Z), R1234ze(E), and R1141 have higher EDR than R134a, whereas R1224YD(Z) has lower EDR than R134a.



Graph 9: The graph compares the refrigerants based on their Efficiency at T_evap(0). The results demonstrate that R1234ze(Z) and R1141 have higher Efficiency than R134a, whereas R1234ze(E) and R1224YD(Z) have the same efficiency as R134a.



Graph 10: The graph compares the refrigerants basedon their coefficient of performance (COP) at T_evap(0). The results demonstrate that R1234ze(Z), R1224YD(Z), and R1141 have higher Comp Work than R134a, whereasR1234ze(E) have lesser Comp Work than R134a. Based on a comprehensive investigation and comparison, it has been demonstrated that R1234ze (Z) andR1141 are the most efficient refrigerants when compared to R134a.

VI. CONCLUSION

To improve the overall performance of the vapour compression system, the temperature differential betweenthe evaporator and condenser must be reduced. To enhance the compressor's performance, it is necessary to improve both the motor's efficiency and thelubrication system. Operating the system at low condensing and high evaporating temperature ranges willresult in a high coefficient of performance (COP) and minimal energy loss. The following findings were reached as a result of the current investigation:

1. R1234ZE(Z) is the most efficient refrigerant.
2. Exergy, also known as availability, is the most significant amount of work that a fluid stream may do during a cyclic mechanism before achieving thermal equilibrium with its surroundings. Second law analysis evaluates the effectiveness of a thermodynamic system. Unlike energy, exergy is not conserved and may be destroyed. Energy efficiency declines as evaporator temperature rises. The increased irreversibility of the components contributes to this as the evaporator temperature rises.
3. Eco-friendly refrigerants exhibit better thermodynamic properties than traditional refrigerants, leading to improved energy efficiency. This means that the system will require less energy to operate, resulting in lower operating costs and energy bills over time.
4. Improved energy efficiency, reduced maintenance costs, and compliance with regulations can lead to significant cost savings and enhanced profitability over time. Additionally, the environmental benefits of using eco-friendly refrigerants can also result in positive social and economic impacts that are difficult to quantify but are nonetheless valuable.

Retrieval Number: 100.1/ijese.F95690512623
DOI: 10.35940/ijese.F9569.12050424
Journal Website: www.ijese.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

ACKNOWLEDGEMENT

We express our sincere gratitude to Prof. S.K. Garg (HOD), Mechanical Department, Delhi Technological University, for giving us the motivation to strive for the stars and the opportunity to complete the project. They helped us accomplish our project, and we owe them a great deal for their motivating leadership, supportive guidance, and gracious monitoring. We would especially want to thank PROF. R.S. MISHRA for all the time and effort he put into this semester as our supervisor. We sincerely appreciatethe suggestions and counsel you provided while we workedon the project. You have our eternal gratitude for this. Not least among all of these sources of inspiration are our parents. With all due respect, I say. We would like to thank them for their assistance.

DECLARATION STATEMENT

Funding	No, I did not receive.
Conflicts of Interest	No conflicts of interest to the best of our knowledge.
Ethical Approval and Consent to Participate	No, the article does not require ethical approval or consent to participate, as it presents evidence.
Availability of Data and Materials	Not relevant.
Authors Contributions	All authors have equal contributions to this article.

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