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PERFORMANCE ANALYSIS OF A R134A REFRIGERATION SYSTEM USING R513A AS A DIRECT REPLACEMENT

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ABSTRACT
This work investigates the feasibility of replacing R134a, a refrigerant with high Global Warming Potential (GWP), with R513a in a vapor compression refrigeration system without modifications. The experiment analyzes the system's performance, including refrigeration effect, work input, and coefficient of performance (COP) with R513a. The results demonstrate the system's safe operation with R513a without modifications and provide valuable observations for further research.

Keywords:
R134a replacement, Low GWP refrigerant, R513a, Vapour compression refrigeration (VCR), Coefficient of performance (COP)

I. Introduction
The roots of refrigeration systems can be traced back to the 19th century. Early refrigerants, the working fluids in these systems, were ethers like dimethylether (E170) and ethyl ether (R610). Due to their hazardous properties, a quest for safer alternatives began alongside their initial use. Soon, the first generation of safer refrigerants emerged, including ammonia (R717), carbon dioxide (R744), and air (R729). These dominated the field until the 1930s, when the use of synthetic chlorofluorocarbons (CFCs) became widespread. Initially lauded for their chemical stability and lack of toxicity, chlorofluorocarbons (CFCs) were once believed to be environmentally benign. However, research revealed a troubling interaction between CFCs and ozone in the stratosphere, the Earth's upper atmosphere. This reaction led to the conversion of ozone molecules into oxygen molecules. The alarming discovery of this chain reaction, causing ozone layer depletion, spurred authorities to take action. As a result, a continuous effort to develop and adopt alternative refrigerants in refrigeration applications began, a process that persists to this day.
The refrigerants used in vapor compression refrigeration systems (VCRSs) have undergone a significant shift due to international agreements on climate change spearheaded by the United Nations (UN). The United Nations Environment Programme (UNEP) first raised the alarm about ozone depletion in 1976. Under UNEP's leadership, ongoing assessments of ozone depletion continued, leading to the first international discussions on curbing ozone-depleting substances (ODS) in 1981. This culminated in the Montreal Protocol of 1987, a landmark treaty adopted by 196 countries that phases out the use of refrigerants with high ozone depletion potential (ODP) [1].
The Montreal Protocol, a landmark international agreement, curbed the use of chlorofluorocarbons (CFCs) due to their high ozone depletion potential (ODP). Hydrochlorofluorocarbons (HCFCs) were introduced as replacements, offering a lower ODP compared to CFCs but intended as a temporary solution. Subsequently, hydrofluorocarbons (HFCs) with zero ODP gained favor in VCRSs. However, HFCs presented a new challenge: their high global warming potential (GWP) contributing to climate change. The Kyoto Protocol, another international treaty adopted in 1997, addressed this concern by restricting HFCs due to their high GWP, prompting the ongoing search for more environmentally friendly refrigerants [2]. The Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report identifies R134a, a commonly used refrigerant in refrigeration, air conditioning, and heat pump applications, as having a 1300 GWP (Global Warming Potential) over a 100-year period [3]. The widespread use of R134a in refrigeration systems prompted rapid exploration of alternative

refrigerants [4]. This focus on alternatives gained further momentum with the 2016 Kigali Amendment to the Montreal Protocol, which addressed refrigerant use [5]. The amendment introduced changes aimed at reducing the environmental impact of refrigerants. The Kigali Amendment mandates a phase-down of HFC refrigerants based on both Global Warming Potential (GWP) and refrigerant charge amount. For instance, commercially available refrigerators and freezers containing HFCs with a GWP exceeding 2500 will be banned by January 1st, 2025, with a stricter limit of 150 GWP taking effect in 2029. Similarly, single-split air conditioners with a GWP above 750 and exceeding a 3 kg charge of fluorinated greenhouse gases will be phased out by 2025, alongside portable room air conditioners exceeding a 150 GWP and any amount of fluorinated greenhouse gases. This dual focus on GWP and charge highlights the need for alternative refrigerants with not only low GWP but also minimal charge requirements. Research efforts have since shifted towards R513A as a potential transitional refrigerant with a moderate GWP, along with exploring refrigerant blends as replacements for R134a [6-8].
Hydrofluoroolefins (HFOs) serve as GWP-reducing components in refrigerant blends. R513A, a blend containing HFOs, is considered a promising transitional refrigerant. Studies by Mota-Babiloni et al. ([9], [10]) explored R513A as a replacement for R134a in a refrigeration system. Their findings suggest that R513A can be a suitable substitute, requiring only a thermostatic expansion valve adjustment for optimal performance and potentially achieving higher cooling capacity. Furthermore, they reported that R513A aligns well with the system's second-law thermodynamics, with the compressor experiencing the highest exergy destruction rate [10]. Similarly, Yang et al. [8] observed improved freezing capacity in a domestic refrigerator using R513A compared to R134a. Additionally, Saadoon and Aljubury's [11] research investigated R513A as a replacement for R134a in car air conditioning systems.
Several studies have evaluated R513A as a potential replacement for R134a in various cooling systems, with mixed results regarding performance. Mota-Babiloni et al. [9, 10] observed promising results for R513A in a refrigeration system, suggesting its suitability with minimal modifications and potentially achieving higher cooling capacity. However, other studies reported lower Coefficient of Performance (COP) or Energy Efficiency Ratio (EER) for R513A compared to R134a under similar operating conditions [7, 13, 14, 15]. Notably, Meng et al. [15] proposed R513A as a transitional option for automotive air conditioning despite its lower COP. While these studies primarily focused on GWP reduction, Makhnatch et al. [12] highlighted R513A's favorable pressure ratio, discharge temperature, and mass flow for a small capacity cooling system, indicating potential benefits beyond just GWP. Research on R513A as an alternative continues, with Mendez-Mendez et al. [16] finding it to have a higher volumetric cooling capacity in a refrigeration system.
Building on existing research on R513A as a replacement for R134a, Belman-Flores [17] identified a 28% reduction in COP when using R513A in a refrigeration system. While ongoing studies primarily focus on energetic and exergetic performance, highlighting R513A's potential as a transitional option [14, 15], the Kigali Amendment emphasizes both GWP and refrigerant charge. This necessitates considering factors like existing system compatibility and leakage management, which are heavily influenced by refrigerant amount. Modifications being expensive and time-consuming, Belman-Flores' study [17] presents a novel approach. It analyzes refrigerant mass flow in relation to energetic and exergetic performance parameters during the R513A substitution process. This focus on both GWP and refrigerant amount, along with the correlation between performance and mass flow, addresses the new criteria introduced by the Kigali Amendment. This research aims to assist researchers lacking the resources to test refrigerant amount-related performance parameters, ultimately contributing to a smoother transition under the Kigali Amendment.

II. Experimental Setup

Refrigeration test rig is available in the Thermal Engineering Laboratory at Al-Ameen Engineering College, Erode, Tamilnadu, India. This setup was assembled by Mech-Lab Equipments, located in Coimbatore, Tamilnadu, India. A refrigeration test rig is a self-contained experimental setup used to study and demonstrate the principles of refrigeration, typically focusing on the vapour compression cycle.

Figure 2.1 . VCR Refrigeration Test Rig

This experimental rig is designed to both demonstrate and analyze the refrigeration cycle. Users can observe the refrigerant go through all four stages: compression, condensation, expansion, and evaporation. By measuring temperatures and pressures at key points in the cycle, students or researchers can calculate the Coefficient of Performance (COP). This COP value serves as an indicator of the efficiency of the refrigeration system, allowing users to assess its overall performance.

Table 2.1. Description of Component

S.No.	Component	Description
1	Compressor	The Emerson Climate Technologies India Ltd. KCE444HAG.V334H rotary compressor is designed for R-134a refrigerant and uses 10.5POE lubrication oil. It operates on a single phase with a voltage range of 220-230 volts.
2	Condenser	A forced convection air cooled compact condenser utilizes a single phase induction motor with a voltage range of 220-230 volts for its condenser fan motor.
3	Expansion Device	Danfoss Thermal Expansion valve fits all VCR applications (from 2.75 to 34.7 TR)
4	Evaporator	A natural convection water-cooled evaporator utilizes a spiral-type coil for heat transfer.
5	Temperature Sensor	Range: -25°C to 125°C, Accuracy : ± 0.2°C
6	Energy Meter	The Techno Energy Meter is Class -1, 240V, 50Hz, Type -124.
7	Water Tank	A 20-liter water tank houses an evaporator coil.

III. Working Fluid

R134a, also known as 1,1,1,2-tetrafluoroethane, is a widely used hydrofluorocarbon (HFC) refrigerant found in various applications like domestic refrigerators and freezers, mobile air conditioning systems, and some commercial freezers and display coolers. Despite its advantages of being non-toxic, non-flammable, non-corrosive, having a low boiling point for efficient cooling, and zero ozone depletion potential (ODP), its high global warming potential (GWP) of around 1430 raises environmental concerns. This has led to regulations phasing out R134a, potentially increasing its cost due to future scarcity.

R513a is emerging as a more environmentally friendly alternative to the widely used R134a refrigerant in various vapor compression refrigeration systems (VCRs) like refrigerators and air conditioners. As an azeotrope blend, it maintains consistent properties throughout the crucial evaporation and

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condensation stages. While its molecular weight is slightly higher than R134a, the critical pressure is marginally lower and the critical temperature is somewhat similar. Most importantly, R513a boasts a significantly lower Global Warming Potential (GWP) compared to R134a, making it a more sustainable choice. This eco-friendly benefit comes with the added advantage of offering similar performance characteristics to R134a in terms of cooling capacity.

Table 3.1. Comparison of Important Properties of R134a and R513a

S.No.	Property	R134a	R513a
1	Molecular Weight (g/mol)	102.03	108.4
2	Critical Pressure (kPa)	4059	3770
3	Critical Temperature (°C)	101.06	96.5
4	Global Warming Potential (GWP) [3]	1300+	573
5	Flammability	Non-flammable	Non-flammable

3.1 Similarities between R134a and R513a

Both R134a and R513a possess relatively close molecular weights (102.03 g/mol for R134a and 108.4 g/mol for R513A). Their critical pressures and temperatures also exhibit some similarity, suggesting comparable behavior around the phase change point from liquid to gas. For instance, R134a has a critical pressure of 4059 kPa and a critical temperature of 101.06 °C, while R513A's critical pressure is 3770 kPa and critical temperature is 96.5 °C. Furthermore, both refrigerants demonstrate comparable latent heats of condensation and evaporation, signifying that they absorb and release similar amounts of heat during phase changes.

3.2 Differences between R134a and R513a

While R134a and R513a share similar molecular weights, critical properties, and latent heat, a crucial difference lies in their environmental impact. R134a's high Global Warming Potential (GWP) exceeding 1300 makes it a significant contributor to global warming if leaked. In contrast, R513a boasts a much lower GWP, offering a more environmentally friendly alternative. However, a slight difference exists in system compatibility. R134a allows charging in either liquid or vapor state, whereas R513a, being an azeotrope blend, requires charging only in the liquid phase.

IV. Thermodynamic Concepts on the Experimental Setup

To evaluate the thermodynamic performance of the vapour compression refrigeration system (VCRS), experiments were conducted under steady-state conditions. Individual thermodynamic relations were established for each of the four key components: compressor, condenser, expansion valve, and evaporator. The following assumptions were incorporated into the system's thermodynamic analysis:

- Steady-state, steady-flow processes occur within the system components.
- Heat transfer between the system components and the surrounding environment is negligible.
- Kinetic and potential energy changes are considered insignificant.

4.1. Compressor

The compressor in a vapor compression refrigeration system raises the pressure of the refrigerant by decreasing its volume. This compression process also increases the refrigerant's temperature and, consequently, its enthalpy. We can use the following relation for Work Input (W_{comp}).

W_{comp} = mass flow rate ($\dot{m}$) * enthalpy change ($h_2 - h_1$)

Where

- $\dot{m}$: mass flow rate of the refrigerant (kg/s)
- h_1: Specific enthalpy of the refrigerant at the compressor inlet (kJ/kg)
- h_2: Specific enthalpy of the refrigerant at the compressor outlet (kJ/kg)

4.2. Condenser

In the condenser, the refrigerant rejects heat to the surrounding environment at nearly constant pressure (P_2). We can use the following relation for heat rejection (Qc)

$Qc = m * (h_2 - h_3)$

Where:

- Qc: Heat rejected by the condenser (kW)
- m: Mass flow rate of the refrigerant (kg/s)
- h_2: Specific enthalpy of the refrigerant at the condenser inlet (kJ/kg)
- h_3: Specific enthalpy of the refrigerant at the condenser outlet (kJ/kg)

4.3. Expansion Valve

The expansion valve is an throttling device where the refrigerant undergoes a pressure drop with a significant decrease in temperature (due to the Joule-Thomson effect) but negligible change in enthalpy (isentropic process). Ideally:

$h_4 = h_3$

Where: $h_3=h_4$: Specific enthalpy of the refrigerant at the evaporator inlet (kJ/kg)

4.4. Evaporator

Similar to the condenser, the evaporator absorbs heat (Qe) from the cooled space at nearly constant pressure (P_1). We can use the following relation for heat absorption:

$Qe = m * (h_4 - h_1)$

Where:

- Qe: Heat absorbed by the evaporator (kW)
- $h_3=h_4$: Specific enthalpy of the refrigerant at the evaporator inlet (kJ/kg)
- h_1: Specific enthalpy of the refrigerant at the compressor inlet (kJ/kg)

4.5. Refrigeration Effect

The refrigeration effect is another term for the heat removed from the cooled space (identical to Qe in the evaporator relation): RE = Qe, but we need to calculate the actual refrigeration effect

Actual refrigeration effect = $RE = m_w * cp_w * (T_{wi} - T_{wf})$

where:

- RE: Actual refrigeration effect (in Joules or kJ)
- m_w: Mass of the substance being cooled (kg)
- cp_w: Specific heat capacity of the water (J/kg·K)
- T_{wi}: Initial temperature of the water (K or °C)
- T_{wf}: Final temperature of the water (K or °C)

4.6. Work Supplied

The work supplied (W) represents the energy input to the compressor, often obtained from the compressor's electrical power consumption. Actual Work Supplied = $W_s = (E_f - E_i) *3600$ (in KJ)

Where:

- E_f: Final energy meter reading (KWh)
- E_1: Initial energy meter reading (KWh)

4.7. Coefficient of Performance (COP)

Theoretical COP (COP_{th}):

The theoretical COP represents the ideal performance limit of a refrigeration system under perfect operating conditions. It tells you the maximum amount of cooling you could achieve for a given amount of work input. It's calculated using the formula: $COP_{th} = Q_e / W_{comp}$

where:

- Q_e: Heat absorbed by the evaporator (KJ)
- W_{comp}: Work input to the compressor (kJ)

Actual COP (COP_a):

The actual COP reflects the real-world performance of a refrigeration system, taking into account various inefficiencies that occur during operation. It tells you the actual amount of cooling achieved for the work input. It's calculated using the formula: $COP_a = R.E / W_s$

where:

- R.E: Actual refrigeration effect
- Ws: Actual Work Supplied

There are two main reasons why we need to calculate the actual COP instead of relying solely on the theoretical COP in a vapour compression refrigeration system:

i. Real-world Inefficiencies: The theoretical COP represents an ideal scenario where the system operates perfectly with no internal losses. However, real-world systems experience various inefficiencies that reduce performance. These inefficiencies can include:

- Friction: Friction between moving parts in the compressor and other components generates heat, which reduces the overall cooling effect.
- Pressure drops: Pressure drops occur in the refrigerant lines due to friction and inefficiencies in valves. This reduces the pressure difference across the compressor, impacting its work output.
- Heat transfer with surroundings: There is always some heat transfer between the system components and the surrounding environment. This can reduce the effectiveness of the cooling process.

ii. Practical System Design: The theoretical COP is calculated under specific assumptions that might not be achievable in practical applications. For example, the theoretical COP might assume:

- Isentropic compression: This is a perfectly reversible compression process with no internal irreversibility like friction, which is not achievable in reality.
- No heat transfer with surroundings: In real systems, some heat transfer with the environment is unavoidable.

By calculating the actual COP, we get a more realistic picture of how efficiently the system is performing in real-world conditions. This information is crucial for:

- System Optimization: Identifying areas for improvement by comparing the actual COP to the theoretical COP. This helps engineers focus on reducing inefficiencies in the system design or operation.
- Performance Evaluation: Comparing the actual COP of different systems or under different operating conditions allows for a more accurate assessment of their effectiveness.
- Energy Efficiency Ratings: Actual COP is often used in energy efficiency ratings for appliances like refrigerators and air conditioners. This helps consumers compare the energy consumption of different models.

In wrapping up, while the theoretical COP serves as a benchmark for ideal performance, the actual COP offers a more practical understanding of a vapor compression refrigeration system's real-world efficiency. Therefore, this project focused on calculating the actual COP to provide data on the system's actual performance. Instead of solely relying on the theoretical COP, we meticulously documented the temperature and pressure of the refrigerant at key points within the system to ensure its proper operation.

V. Observations and Calculations

5.1. Readings and Calculations VCR with R134a

Test duration: 30 minutes; Initial energy meter reading E_i = 09.00 kwh; Final energy meter reading E_f = 09.15 kwh; Initial temperature of water T_{wi} = 30°C; Initial temperature of water T_{wf} = 22°C; Mass of water m_w = 20 kg = 20 liters; Suction pressure = 25 psi; Delivery pressure = 135 psi.

Temperature of the Refrigerant during process: T1 - After Evaporation / Before Compression; T2 - After Compression / Before Condensation ; T3 - After Condensation / Before Expansion; T4 - After Expansion

Table 5.1. Temperature of R134a during the process

Duration	T_1	T_2	T_3	T_4
1 min	33°C	37°C	30°C	15°C

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5 min	33°C	37°C	30°C	15°C
10 min	33°C	38°C	28°C	12°C
15 min	32°C	40°C	28°C	11°C
20 min	32°C	42°C	27°C	9°C
25 min	32°C	43°C	27°C	8°C
30 min	32°C	43°C	27°C	8°C

(i) Actual refrigeration effect = RE = $m_w * cp_w * (T_{wi} - T_{wf})$ = 20 * 4.186 * (30-22) = 669.76KJ
(ii) Actual work supplied = $W_s = (E_f – E_i)$ *3600 = (09.15 – 09.00) *3600 = 540 KJ
(iii) Actual COP = R.E / W_s= 669.76 / 540 = 1.24

5.2. Readings and Calculations VCR with R513a

Test duration: 30 minutes; Initial energy meter reading E_i = 14.00 kwh; Final energy meter reading E_f = 14.15 kwh; Initial temperature of water T_{wi} = 30°C; Initial temperature of water T_{wf} = 23°C; Mass of water m_w = 20 kg = 20 liters; Suction pressure = 25 psi; Delivery pressure = 130 psi.
Temperature of the Refrigerant during process: T1 - After Evaporation / Before Compression; T2 - After Compression / Before Condensation ; T3 - After Condensation / Before Expansion; T4 - After Expansion

Table 5.2. Temperature of R513a during the process

Duration	T_1	T_2	T_3	T_4
1 min	33°C	37°C	30°C	16°C
5 min	34°C	37°C	30°C	16°C
10 min	34°C	38°C	30°C	14°C
15 min	35°C	40°C	30°C	14°C
20 min	35°C	40°C	30°C	12°C
25 min	35°C	40°C	30°C	10°C
30 min	35°C	40°C	29°C	10°C

(i) Actual refrigeration effect = RE = $m_w * cp_w * (T_{wi} - T_{wf})$ = 20 * 4.186 * (30-23) = 586.04 KJ
(ii) Actual work supplied = $W_s = (E_f – E_i)$ *3600 = (14.15 – 14.00) *3600 = 540 KJ
(iii) Actual COP = R.E / W_s = 586.04 / 540= 0.974
(iv) Percentage of drop in COP due to refrigerant change = (1.24-0.974) /1.24 *100 = 21.45%

VI. Results and Discussion

To assess the viability of R513A as a replacement for R134a, this study compares system performance metrics obtained during tests with both refrigerants under near-identical operating conditions. The only difference between the test setups was the type of refrigerant used.

Figure 6.1 Temperature of the R135a during testing

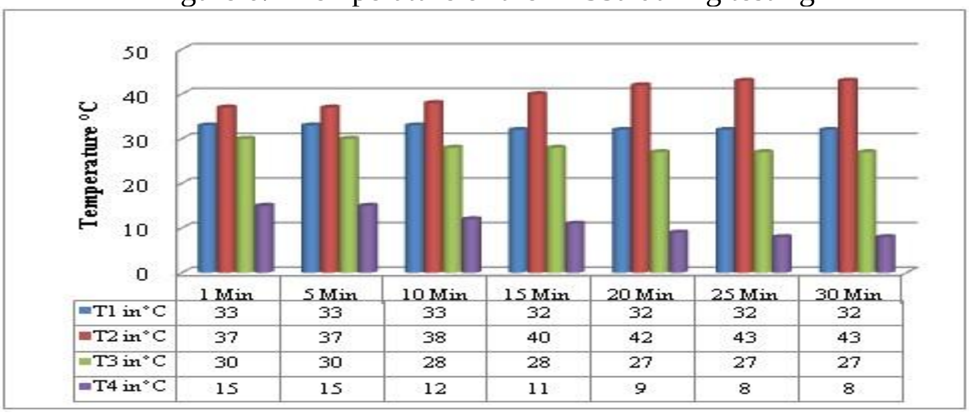

Figure 6.2 Temperature of the R513a during testing

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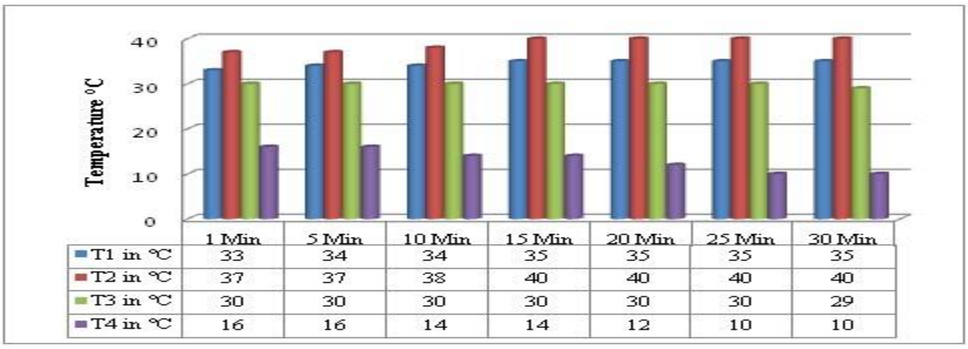


Throughout the entire test, the suction and delivery pressures of refrigerant R513a remained steady, similar to R135a, before and after compression. This absence of fluctuation in delivery pressure indicates the compressor's compatibility with R513a. The change in temperature of refrigerant R513a throughout the process (Figure 6.2) closely resembles that of R135a (Figure 6.1), indicating proper operation of the vapor compression refrigeration system with R513a. However, differences in temperature and pressure between R135a and R513a can influence system performance. To determine the exact performance impact, we need to analyze the refrigerant effect, the actual work input, and the system's COP. Figure 7.3 presents both the work input and discharge pressure for the system. Interestingly, at comparable operating conditions, the alternative refrigerant, R513A, exhibits similar power consumption to R134a. However, a notable drawback is the 3.7% decrease in discharge pressure, which can negatively impact overall system performance.

Figure 6.3 presents both the work input and discharge pressure for the system. Interestingly, at comparable operating conditions, the alternative refrigerant, R513A, exhibits similar power consumption to R134a. However, a notable drawback is the 3.7% decrease in discharge pressure, which can negatively impact overall system performance.

Figure 6.3 Work supplied and delivery pressure

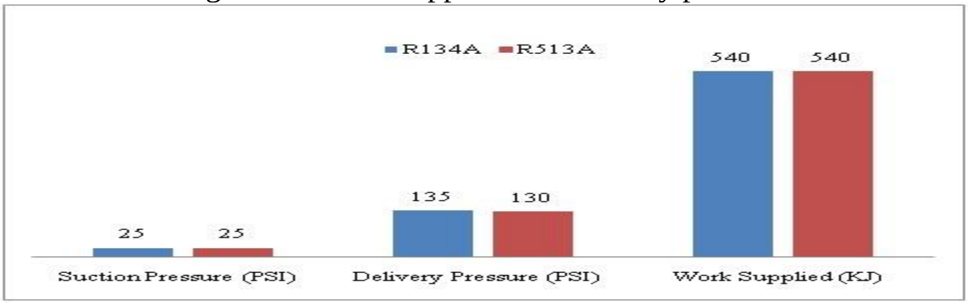
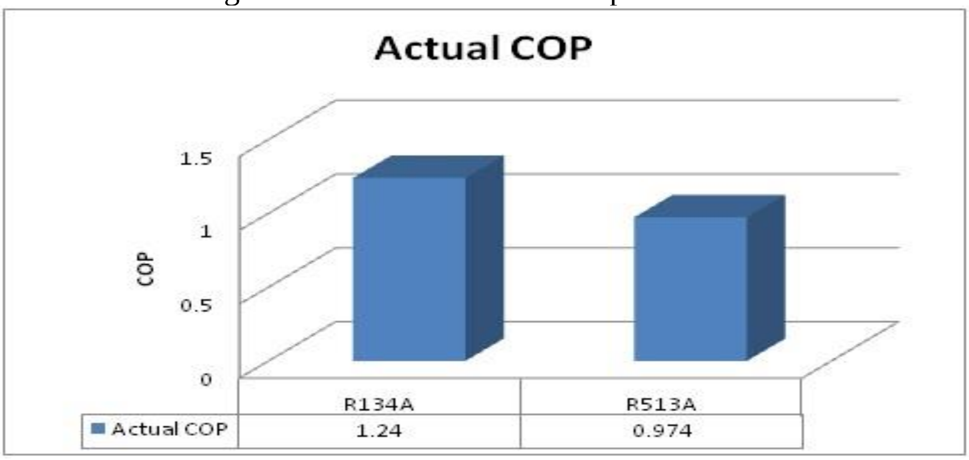


Figure 6.4 Actual coefficient of performance



Figures 6.4 illustrate the coefficient of performance (COP) of the VCR system, notably, the COP decreases by 21.45% due to a decline in refrigeration effect, even with the same work input.

VII. Conclusion

This project experimentally investigates R513A as a potential replacement for R134a in a vapor compression refrigeration system. Key parameters including refrigerant pressure and temperature changes, refrigerant effect, actual work input, and system COP were evaluated. The following findings summarize the results.

- Replacing R134a with R513a in the vapor compression refrigeration system did not require any modifications and ensured safe compressor operation. However, a 3.7% reduction in R513a's delivery pressure compared to R134a negatively impacts system performance.
- Both refrigerants functioned safely in the expansion valve. However, the heat transfer rate in the condenser and evaporator was lower with R513a compared to the R134a system, resulting in a 12.5% reduction in refrigerant effect.
- The system's COP (coefficient of performance) exhibited a decrease of roughly 24.45% when using R513a compared to R134a.

In conclusion, the study revealed a performance trade-off when replacing R134a with R513a in a vapor compression refrigeration system. While R513a functioned safely without requiring system modifications, its lower delivery pressure and heat transfer rates resulted in a decrease in refrigerant effect and COP compared to R134a. This highlights the importance of considering refrigerant charge optimization alongside GWP (Global Warming Potential) when selecting alternatives. Despite the performance reduction, R513a's compatibility with existing systems suggests its potential as a transitional refrigerant, particularly in small-capacity applications. However, caution is advised for large-capacity cooling systems, where the balance between GWP and required refrigerant amount becomes more critical. Future research on alternative refrigerants should encompass both GWP and optimal charge determination.

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References

[1]UNEP: United Nations Environment Programme, Montreal Protocol on Substances that Deplete the Ozone Layer, Final Act. United Nations, New York, 1987.
[2]GCRP: Global Environmental Change Report. A brief analysis kyoto protocol, vol. IX, p. 24. 1997.
[3]IPCC: Intergovernmental Panel on Climate Change, in: T.F. Stocker, D. Qin, G.- K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley (Eds.), The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
[4]B.O. Bolaji, Z. Huan, “Performance investigation of some hydro-fluorocarbon refrigerants with low global warming as substitutes to R134a in refrigeration systems”, J. Eng. Thermophys. 23 (2) (2014) 148–157, https://doi.org/10.1134/ S1810232814020076.
[5]UNEP: United Nations Environment Programme, Twenty-eighth meeting of the parties to the Montreal Protocol on substances that deplete the ozone layer, Decision XXVIII/Further Amendment Montreal Protocol (2016) 1–9.
[6]P. Makhnatch, A. Mota-Babiloni, R. Knodabandeh, “Experimental study of R450A drop-in performance in an R134a small capacity refrigeration unit”, Int. J. Refrigerat. 84 (2017) 26–35, https://doi.org/10.1016/j.ijrefrig.2017.08.010.

[7]J. Sun, W. Li, B. Cui, "Energy and exergy analyses of R513a as a R134a drop-in replacement in a vapor compression refrigeration system", Int. J. Refrigerat. 112 (2020) 348–356, https://doi.org/10.1016/j.ijrefrig.2019.12.014.
[8]M. Yang, H. Zhamg, Z. Meng, Y. Qin, "Experimental study on R1234yf/R134A mixture (R513A) as R134a replacement in a domestic refrigerator", Appl. Therm. Eng 146 (2019) 540–547, https://doi.org/10.1016/j.applthermaleng.2018.09.122.
[9]A. Mota-Babiloni, P. Makhnatch, R. Khodabandeh, J. Navarro-Esbri, "Experimental assessment of R134a and its lower GWP alternative R513A", Int. J. Refrigerat. 74 (2017) 682–688, https://doi.org/10.1016/j.ijrefrig.2016.11.021.
[10] A. Mota-Babiloni, J.M. Belman-Flores, P. Makhnatch, J. Navarro-Esbri, J. M. Barroso-Maldonado, "Experimental exergy analysis of R513A to replace R134a in a small capacity refrigeration system", Energy 162 (2018) 99–110, https://doi.org/ 10.1016/j.energy.2018.08.028.
[11] Y.G. Saadoon, I.M. Aljubury, "Experimental analysis of mobile air conditioning system using R513A as alternative refrigerants to R134a", J. Mech. Continua Math. Sci. 14 (6) (2019) 450–469, https://doi.org/10.26782/jmcms.2019.12.00031.
[12] P. Makhnatch, A. Mota-Babiloni, A. Lopez-Belchi, R. Khodabandeh, "R450A and R513A as lower GWP mixtures for high ambient temperature countries: experimental comparison with R134a", Energy 166 (2019) 223–235, https://doi. org/10.1016/j.energy.2018.09.001.
[13] F.J.S. Velasco, F. Illan-Gomez, J.R. Garcia-Cascales, "Energy efficiency evaluation of the use of R513A as a drop-in replacement for R134a in a water chiller with a minichannel condenser for air-conditioning applications", Appl. Therm. Eng. 182 (2021), https://doi.org/10.1016/j.applthermaleng.2020.115915.
[14] J.M. Belman-Flores, Y. Heredia-Aricapa, D. Pardo-Cely, D.A. Rodriguez- Valderrama, M. De Alba-Rosano, J.C. Silva-Romero, "Experimental evaluation of R513A as a low GWP refrigerant to replace R134a in a domestic refrigerator", Int. J. Refrigerat. 142 (2022) 148–155, https://doi.org/10.1016/j.ijrefrig.2022.06.019.
[15] Z.F. Meng, X.N. Cui, Y. Liu, S. Wang, C.Y. Du, R.S. Hu, "Performance of R1234yf and R513A as alternatives to R134a in automotive air conditioning systems in winter", Thermal Sci. 27 (3A) (2023) 1937–1946, https://doi.org/10.2298/ TSCI2303937M.
[16] Mendez-Mendez, D., Perez-Garcia, V., Morales-Fuentes., "Experimental energy evaluation of R516A and R513A as replacement of R134a in refrigeration and air conditioning modes", Int. J. Refrigerat., 154, 73–83. 10.1016/j.ijrefrig.2023.06.00 3.
[17] J.M. Belman-Flores, Y. Heredia-Aricapa, J.J. Garcia-Pabon, V. Perez-Garcia, C. G. Perez-Reguera, "Drop-in replacement of R134a in a household refrigerator with low-GWP refrigerants R513A, R516A, and R1234ze(E)", Energies. (Basel) 16 (8) (2023), https://doi.org/10.3390/en16083422.
[18] https://www.venturezero.co.uk/post/journey-to-net-zero