Performance Analysis of Vapour Compression Refrigeration System Using R600a/R134a Mixture

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***Abstract*—In response to increasing environmental concerns regarding high-GWP refrigerants, this study presents a performance analysis of a vapour compression refrigeration system using mixtures of R600a (Isobutane) and R134a (1,1,1,2-Tetrafluoroethane). The experimental investigation evaluates blend ratios of 60:40, 70:30, and 80:20 (R600a: R134a by mass) to assess thermodynamic efficiency, particularly the Coefficient of Performance (COP), along with energy consumption and environmental impact. The findings reveal that the 80:20 mixture offers an optimal balance between efficiency, safety, and reduced global warming potential. Compared to pure R134a, the blend improves COP by up to 24%, while significantly lowering GWP. The study confirms that R600a/R134a mixtures are viable drop-in alternatives in existing domestic refrigeration systems, supporting the transition toward sustainable and eco-friendly cooling technologies in line with international environmental protocols.**

***Index Terms*—Vapour Compression Refrigeration System, R600a, R134a, Refrigerant Mixture, COP, GWP, Eco-Friendly Refrigerants**

1. INTRODUCTION

Refrigeration systems are essential in modern society for applications such as food preservation, air conditioning, and industrial cooling. The Vapour Compression Refrigeration System (VCRS) remains the most commonly used refrigeration technology due to its simplicity and reliability. Traditionally, refrigerants such as R134a (tetrafluoroethane), a hydrofluorocarbon (HFC), have been widely used in VCR systems owing to their favorable thermodynamic properties and chemical stability. However, R134a poses a serious environmental threat due to its high Global Warming Potential (GWP ≈ 1430), prompting a global shift toward low-GWP alternatives in accordance with international protocols such as the Kyoto Protocol and Kigali Amendment., hydrocarbon refrigerants like R600a (isobutane) are gaining attention due to their negligible GWP (~3), zero Ozone Depletion Potential (ODP), and superior energy efficiency. Despite these benefits, R600a is highly flammable, posing challenges in terms of safety and limiting its widespread adoption in larger systems.

This study explores the potential of using R600a/R134a binary mixtures in various proportions as eco-friendly alternatives to conventional refrigerants. By blending R600a with R134a, it is possible to reduce the overall GWP while maintaining system safety and performance. The study investigates the performance of these mixtures in a standard VCR system, focusing on parameters such as the Coefficient of Performance (COP), energy consumption, and environmental impact. The goal is to identify an optimal blend ratio that balances efficiency, environmental compliance, and operational safety, thereby offering a sustainable refrigeration solution.

2. MATERIALS

The experimental setup for this study was designed to analyze the performance of a Vapour Compression Refrigeration System (VCRS) using R600a, R134a, and their mixtures.

2.1 Refrigerants:

R134a (1,1,1,2-Tetrafluoroethane): A widely used hydrofluorocarbon with good thermodynamic properties but high GWP.

R600a (Isobutane): A hydrocarbon refrigerant with very low GWP and high energy efficiency, but flammable.

R600a/R134a Mixtures: Prepared in 60:40, 70:30, and 80:20 ratios by mass to evaluate performance variation.

2.2 VCRS Components:

Compressor: Hermetically sealed reciprocating compressor suitable for domestic refrigeration applications.

Condenser: Air-cooled, finned-tube type used to reject heat from the refrigerant.

Capillary Tube: Copper tubing used for refrigerant expansion and pressure drop.

Evaporator: Finned-tube evaporator used to absorb heat from the surrounding medium.

2.3Measuring Instruments:

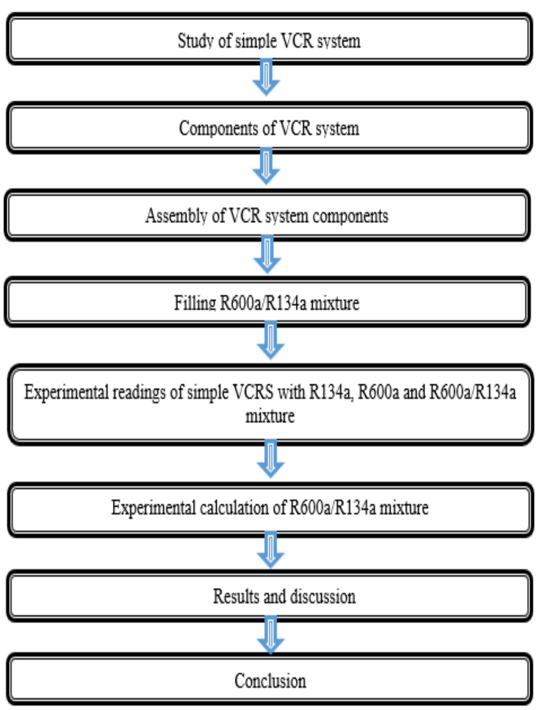
Energy Meter: For measuring power input to the compressor in kilowatt-hours (kWh).

Temperature Sensors (RTDs/Thermocouples): For accurate temperature measurement at various state points.

Pressure Gauges: To measure suction and discharge pressures of the refrigerant.

Digital Temperature Indicator (Multi-channel): For real-time display of temperature readings.

3.METHODOLOGY



4.SELECTION OF REFRIGERANTS

The selection of an appropriate refrigerant is a critical step in the design and operation of vapour compression refrigeration systems. It significantly impacts system efficiency, environmental sustainability, safety, and cost-effectiveness. Key factors that influence refrigerant selection include thermodynamic properties, environmental impact, safety classification, and economic feasibility.

4.1 Criteria for Selection

A suitable refrigerant should meet the following criteria:

- Thermodynamic Properties: High latent heat of vaporization, appropriate boiling and critical temperatures, and high refrigerating effect to ensure energy efficiency.
- Chemical Stability: Non-corrosive and chemically inert to prevent system degradation.
- Environmental Considerations: Low or zero Ozone Depletion Potential (ODP) and Global Warming Potential (GWP).
- Safety Aspects: Low toxicity and flammability, as classified by ASHRAE standards.
- Compatibility: Should be compatible with existing system materials and lubricants.
- Cost and Availability: Economical and easily available in the market.

4.2 Conventional vs Alternative Refrigerants

Synthetic refrigerants such as R11, R12, R22, and R502 were widely used due to their desirable thermophysical properties. However, these refrigerants are now being phased out due to their high ODP and GWP. R134a (1,1,1,2-Tetrafluoroethane), an HFC refrigerant, emerged as a popular substitute with zero ODP but still possesses a high GWP (~1430).

Natural refrigerants like R600a (Isobutane) are gaining attention due to their negligible GWP (~3) and zero ODP. Despite their excellent thermodynamic performance, hydrocarbons like R600a are classified under ASHRAE safety group A3 due to their flammability, restricting their use in large-charge systems.

4.3 Rationale for Using R600a/R134a Mixtures

Blending R600a with R134a offers a strategic balance between environmental benefits and operational safety. The mixture reduces the overall GWP while maintaining system performance and ensuring compatibility with standard system components. By optimizing the mixing ratio, the flammability risk can be mitigated while achieving a higher Coefficient of Performance (COP). This study evaluates mixtures in the ratios of 60:40, 70:30, and 80:20 (R600a: R134a by mass), analyzing their thermodynamic behavior, energy efficiency, and environmental impact to determine their viability as drop-in alternatives.

4.4 Comparison on R134a, R600a and R600a/R134a Mixture:

Properties	Unit	R134a	R600a	R600a/ R134a	R600a/ R134a	R600a/ R134a
Chemical Name	-	1,1,1,2-Tetrafluoroethane	Isobutane	(80:20 by mass) Refrigerant Mixture	(70:30 by mass) Refrigerant Mixture	(60:40 by mass) Refrigerant Mixture
GWP	-	1430	3	287	431.1	573.8
ODP	-	0	0	0	0	0
Molecular Mass	g/mol	102.03	58.12	66.902	71.29	75.68
Triple point	ºC	-103.3	-159.6	-160	-142.71	-137.08
Boiling point	ºC	-26.1	-11.7	-14.5	-16.02	-17.46
Critical Temperature	ºC	101.1	134.7	127.5	124.62	121.26
Critical Pressure	Bar	40.6	36.5	38	37.73	38.14

5.WORKING PRINCIPLE OF VAPOUR COMPRESSION REFRIGERATION SYSTEM

The Vapour Compression Refrigeration System (VCRS) is a widely adopted refrigeration technology used in domestic and industrial applications. It operates on a thermodynamic cycle involving phase changes of a refrigerant to achieve cooling by absorbing and rejecting heat.

5.1 Basic Components

The primary components of a VCRS include:

- Compressor: Increases the pressure and temperature of the refrigerant vapor.
- Condenser: Condenses the high-pressure vapor into liquid by rejecting heat to the surroundings.
- Capillary Tube (Expansion Device): Reduces the pressure of the liquid refrigerant before it enters the evaporator.
- Evaporator: Absorbs heat from the space to be cooled, causing the refrigerant to evaporate.

5.2 Ideal Cycle Processes

The ideal VCR cycle consists of four thermodynamic processes:

- Process 1–2: Isentropic Compression

The low-pressure, low-temperature vapor from the evaporator is compressed adiabatically in the compressor to high pressure and high temperature. Entropy remains constant.

- Process 2–3: Isobaric Heat Rejection (Condensation)

The high-pressure vapor flows through the condenser, where it releases latent heat to the surroundings and condenses into a high-pressure liquid.

- Process 3–4: Isenthalpic Expansion

The liquid refrigerant undergoes throttling through a capillary tube, resulting in a pressure drop and partial evaporation. Enthalpy remains constant during this process.

- Process 4–1: Isobaric Heat Absorption (Evaporation)

In the evaporator, the refrigerant absorbs heat from the refrigerated space, completing the cycle by converting into low-pressure vapor.

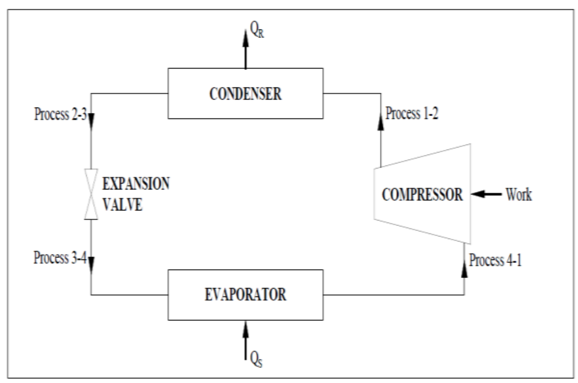


Fig.1 Vapour Compression Refrigeration system

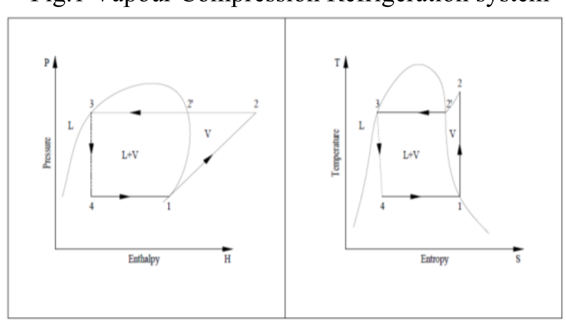


Fig.2 Pressure vs Enthalpy & Temperature vs Entropy

6.CALCULATIONS AND RESULTS

6.1 Formula Used

Net Refrigeration Effect (NRE)

$Q = M * Cp * (\Delta T/ \Delta t)$

Work done by the compressor (W)

$W = (5/t) * (3600/x) * 0.9$

Experimental COP (COPexp)

$COPexp = Q/W$

6.2 Result and Discussion

S. No	Refrigerant	Net Refrigeration Effect (NRE)	Work Done by Compressor	Coefficient of Performance (COP)
1	R134a	Low	Moderate	Lowest
2	R600a	Highest	Moderate	Highest
3	R600a/R134a (80:20) mixture	High	Slightly Lower	High
4	R600a/R134a (70:30) mixture	Moderate	Similar	Moderate
5	R600a/R134a (60:40) mixture	Lower	Similar	Lower

Fig.3 Results Comparison on the Performance of VCRS

The performance of the Vapour Compression Refrigeration System was analyzed for various refrigerants, including pure R134a, pure R600a, and their blends in different ratios. Among the refrigerants tested, R600a demonstrated the highest efficiency, reflected in its maximum Coefficient of Performance (COP) and Net Refrigeration Effect (NRE). The R600a/R134a (80:20) mixture offered an excellent compromise between high performance and improved safety, making it an ideal alternative to conventional refrigerants. As the proportion of R134a increased in the mixtures, both COP and NRE showed a gradual decline, indicating reduced system efficiency. R134a alone performed the least efficiently. Based on the comparison, the 80:20 mixture is identified as the most balanced and environmentally sustainable option.

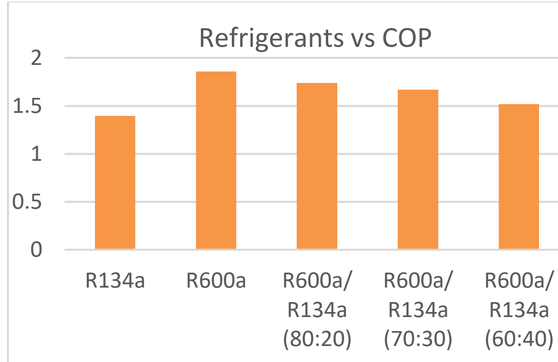


Fig.4 Comparison for Different Refrigerants of COP

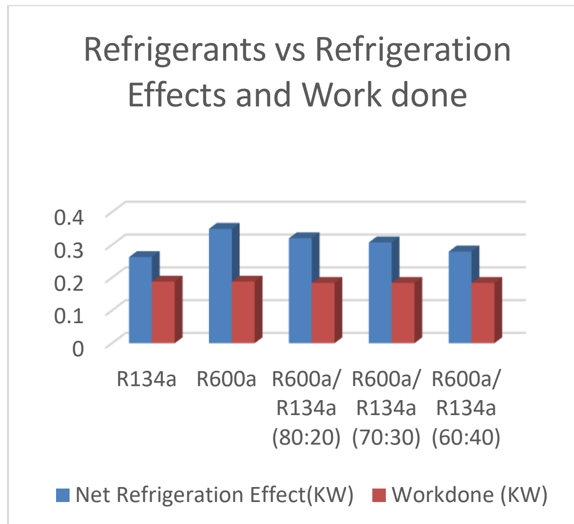


Fig.5 Comparison for Different Refrigerants of Net Refrigeration Effect and Work done

7.CONCLUSION

This study investigated the performance characteristics of a Vapour Compression Refrigeration System (VCRS) using environmentally friendly refrigerants—specifically, various blend ratios of R600a (Isobutane) and R134a (Tetrafluoroethane). The analysis was conducted based on experimental observations of key performance parameters such as Net Refrigeration Effect (NRE), Compressor Work, and Coefficient of Performance (COP).

The results demonstrate that:

- Pure R600a provided the highest energy efficiency, attributed to its superior thermodynamic properties and low Global Warming Potential (GWP).
- Among the tested blends, the R600a/R134a (80:20) mixture exhibited the most favorable

balance between performance and safety, achieving high COP values while maintaining a significantly lower environmental impact than pure R134a.

- As the proportion of R134a increased in the blends, a corresponding decrease in performance metrics was observed, highlighting the inverse relationship between R134a content and energy efficiency.
- All mixtures tested offered improved environmental sustainability compared to pure R134a, aligning with global mandates such as the Kigali Amendment and F-Gas regulations.
- The system operated safely and efficiently with all tested blends, indicating their feasibility as drop-in alternatives in existing refrigeration systems with minimal hardware modifications.

In conclusion, the R600a/R134a (80:20) blend is recommended as an optimal substitute for conventional refrigerants in domestic and light commercial refrigeration applications. It successfully combines environmental compliance, operational safety, and enhanced energy efficiency, supporting the transition toward sustainable cooling technologies.

REFERENCES

[1] Daniel Calleja-Anta, Manel Martínez-´Angeles, Laura Nebot-Andres, Daniel Sanchez, Rodrigo Llopis. "Optimizing R152a/R600 and R290/R600 mixtures for superior energy performance in vapor compression systems: Promising alternatives to Isobutane (R600a)". Applied Thermal Engineering 247 (2024) 123070

[2] T.O. Babarinde,S.A. Akinlabi, D.M. Madyira,O.S. Ohunakin, D.S. Adelekan "Comparative Analysis of The Exergetic Performance of a Household Refrigerator Using R134a and R600a". International Journal of Energy for a Clean Environment 19(1–2):37–48 (2018).

[3] Shalaka S. Hastak, Jagdeep M. Kshirsagar, "Comparative performance analysis of R600a and R436a as an alternative of R134a refrigerant in a domestic refrigerator". Materials Science and Engineering 377 (2018) 012047 doi:10.1088/1757-899X/377/1/012047.

[4] D. Sánchez, R. Cabello, R. Llopis, I. Arauzo, J. Catalán-Gil, E. Torrella, Energy performance evaluation of R1234yf, R1234ze(E), R600a, R290 and R152a as low-GWP R134a alternatives, International Journal of Refrigeration (2016), http://dx.doi.org/doi: 10.1016/j.ijrefrig.2016.09.020.

[5] Akintunde, M.A. "(Experimental Study of R134a, R406A and R600a Blends as Alternative to Freon)" 12 IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) Volume 7, Issue 1 (May. - Jun. 2013), PP 40.

[6] D. Calleja-Anta, L. Nebot-Andres, J. Catalan-Gil, D. S´anchez, R. Cabello, R. Llopis, Thermodynamic screening of alternative refrigerants for R290 and R600a, Results in Engineering (2020) 5.

[7] M. Rasti, S. Aghamiri, M.-S. Hatamipour, Energy efficiency enhancement of a domestic refrigerator using R436A and R600a as alternative refrigerants to R134a, Int. J. Therm. Sci. 74 (2013) 86–94.

[8] D. Calleja-Anta, L. Nebot-Andres, D. S´anchez, R. Cabello, R. Llopis, Drop-in substitutes for R-600a. Experimental evaluation and optimization of a commercial fridge, Appl. Therm. Eng. 211 (2022).

[9] D. Calleja-Anta, D. S´anchez, L. Nebot-Andr´es, R. Cabello, R. Llopis, Alternative mixtures to R-600a. theoretical assessment and experimental energy evaluation of binary mixtures in a commercial cooler, Int. J. Refrig 152 (2023) 83–92.

[10] Arora CP, Refrigeration and Air-Conditioning Third Edition, Tata-McGraw-Hill Publishing Company Limited, New Delhi

[11] Khurmi R.S., Gupta J.K., A Textbook of Refrigeration and Air Conditioning, S. CHAND.

[12] Mathur M.L., Mehta M.S. – Refrigerant and Psychrometric Properties (Tables and Charts), Publication - Jain Brothers (Year 2018).

[13] Neeraja Upodhya," To study the effect of sub-cooling and diffuser on the COP of vapour compression refrigeration system", International journal of research in aeronautical and mechanical EngineeringISSN:2321-3051 June 2014

[14] Adityaswaroop. "To Improve COP of a Refrigerator Using Diffuser", proceedings of 2017 4th International conference latest trends in

engineering, science, humanities and management. Indian federation of united nations association, Qutab institutional area, New Delhi 2017. Vaezi, M., Chua, C.K., "Layer thickness effects on mechanical properties in 3DP," Int. J. Adv. Manuf. Tech., 2011.