Experimental Study on the Performance of a Vapor Compression Refrigeration System Using Alternative Refrigerants

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***Abstract*—This study experimentally examines the performance of a vapor compression refrigeration (VCR) system charged with four refrigerants R134a, R600a, R290, and R1234yf with a dual focus on thermodynamic performance and environmental impact. The investigation covers key indicators such as coefficient of performance (COP), cooling capacity, compressor power consumption, and discharge temperature, along with comparative assessments of volumetric cooling capacity, compressor displacement, and Life Cycle Climate Performance (LCCP). Experimental outcomes indicate that the hydrocarbon options, R600a and R290, provide up to 15% higher COP than R134a while maintaining a markedly lower global warming potential (GWP). Although R1234yf delivers slightly reduced efficiency (about 5–10% lower), it stands out as a viable replacement refrigerant owing to its extremely low GWP (<1) and compliance with current environmental regulations. Overall, the results highlight the trade-offs between efficiency, safety, and sustainability, offering guidance for system designers and policymakers aiming to align refrigeration practices with the Kigali Amendment.**

Keywords— Vapor Compression Refrigeration System (VCRS), Refrigerant Alternatives, Thermodynamic Performance, Global Warming Potential (GWP)

I. INTRODUCTION

Refrigeration systems are essential in modern life, supporting applications ranging from food preservation to air conditioning. Among the various technologies available, the vapor compression refrigeration (VCR) system is the most widely adopted due to its simplicity and efficiency. However, the use of conventional refrigerants with high ozone depletion potential (ODP) and global warming potential (GWP) has raised environmental concerns, prompting the search for more sustainable alternatives. This study explores and compares the performance of a standard VCR system using a range of refrigerants to identify suitable replacements for high-GWP refrigerants such as R134a. Usman A. et al. [1] reviewed recent developments in refrigerant technology and emphasized the potential of Hydrofluoroolefins (HFOs) as future refrigerants, owing to their favorable environmental and performance characteristics. Refrigerants like CO_2 (R744), R170, R1132a, and R41 also show potential, particularly for ultra-low temperature applications. Kadhim S. A. et al. [2] carried out an extensive energy, exergy, and environmental assessment of low-GWP HFOs, identifying R1234yf as a drop-in replacement for R134a and R1234ze(E) as a promising option with some compressor modifications. In contrast, R1336mzz(Z) was deemed unsuitable for domestic refrigeration due to suboptimal thermal and environmental characteristics. Chaturvedi S. et al. [3] conducted an exergy analysis of a VCR system utilizing R134a, R600a, and R125, highlighting how temperature variations influence exergy destruction, overall system efficiency, and performance. Their findings support the optimization of refrigeration system design through comparative studies and MATLAB-based modeling. Kumar N. et al. [4] investigated the retrofitting of HFC-based VCR systems with environmentally friendly R600a. Their results demonstrated a reduction in refrigerant charge and compressor pressure, along with an increase in COP—over 11% in retrofitted systems and up to 26% when paired with hydrocarbon compressors. R600a also improved the refrigeration effect and energy efficiency, reinforcing its potential for sustainable applications.

Bhatkar V. W. et al. [5] designed a versatile VCR setup equipped with an aluminum minichannel condenser to test alternative refrigerants to R134a. Their study found that R152a, R600a, and R1234ze improved the COP, with R600a exhibiting the highest exergy loss among the tested options. The research offers comprehensive guidance on refrigerant selection based on performance parameters and compressor compatibility. Hussain Z. et al. [6] conducted simulations on six low-GWP refrigerants as potential drop-in substitutes for R134a. R152a, R450a, and R516a emerged as strong candidates due to their comparable performance and lower environmental impact. Among them, R1234ze(E) delivered the highest energy efficiency and total equivalent warming impact (TEWI) reduction, while R152a provided higher cooling capacity at the expense of increased annual energy consumption. Wu J. et al. [7] developed a mathematical model to compare the performance of compressors using R290 and R32. Although R290 demonstrated similar COP and lower discharge temperatures, it had reduced cooling capacity and volumetric efficiency due to design constraints. The study recommended optimizing R290 compressors by minimizing clearance volume and using thinner discharge valve plates. Ragavendiran R. et al. [8] performed experimental evaluations of hydrocarbon refrigerant blends as substitutes for R134a. Blends of R290/R600a/R1270 in 10/20/70 and 20/20/60 weight ratios outperformed R134a in terms of both environmental and thermodynamic performance, indicating their promise as eco-friendly alternatives. Ozsipahi M. et al. [9] experimentally analyzed the performance of R290/R600a blends in variable-speed hermetic compressors. Increasing R290 concentration improved mass flow rate and COP, although it also raised power consumption. Optimal performance, with COP enhancements ranging from 10–20% over R600a, was achieved at around 2100 rpm, depending on blend composition and operating conditions. Patel A. K. et al. [10] explored the impact of nanoparticle additives in R-152a on the performance of a VCR system. The inclusion of nanoparticles enhanced heat transfer and system efficiency due to improved thermo physical properties. Their study, conducted using a computerized test rig, assessed energy and exergy performance across various nanoparticle concentrations and operating conditions.

II. EXPERIMENTAL SETUP AND METHODOLOGY

A. System Description

The experimental setup comprises a standard VCR system with the following components:

TABLE I. COMPONENTS OF VCRS

Component	**Description**
Capacity	500 W at rated test conditions
Refrigerant	R134a, R600a, R290, and R1234yf
Compressor	Hermetically sealed
Condenser	Copper tubes, aluminum fins, forced convection air cooled
Condenser fan motor	Axial flow induction type
Drier / filter	Molecular sieve type
Expansion device	Capillary tube
Refrigerant flow measurement	Glass tube rotameter
Hp/Lp cutout	Provided
Pressure indication	Pressure gauges, 2nos. provided
Energy meter	Jaipur make, 2 nos.
Heater	500W
Temperature control of the calorimeter	Automatic by digital temperature controller
Evaporator for refrigeration test rig	Direct expansion, shell & coil type. Refrigerant through pipe, water around the coil
Temperature indication	Digital led
Insulation for water tank	Nitrile foam
Supply	230 V, 50Hz, 1 phase, Ac.
Construction	Main body: 18 g crca, powder coated. Calorimeter: ss 304

B. Principle of Operation

The refrigeration test rig functions based on the vapor compression cycle to maintain a space at a temperature below the ambient level. A specific refrigerant circulates continuously through the system, undergoing evaporation at low pressure and temperature and condensation at high pressure and temperature. The compressor increases the pressure of the refrigerant vapor coming from the evaporator and directs it to the condenser, where it releases heat and condenses into a liquid. The liquid refrigerant then passes through a drier/filter and an expansion device, which lowers its pressure and temperature before it enters the evaporator. In the evaporator, the refrigerant absorbs heat and evaporates once again, repeating the cycle. The system is equipped with instrumentation such as pressure gauges, temperature sensors, an energy meter, a heater, and a flow meter to monitor and evaluate its performance effectively.

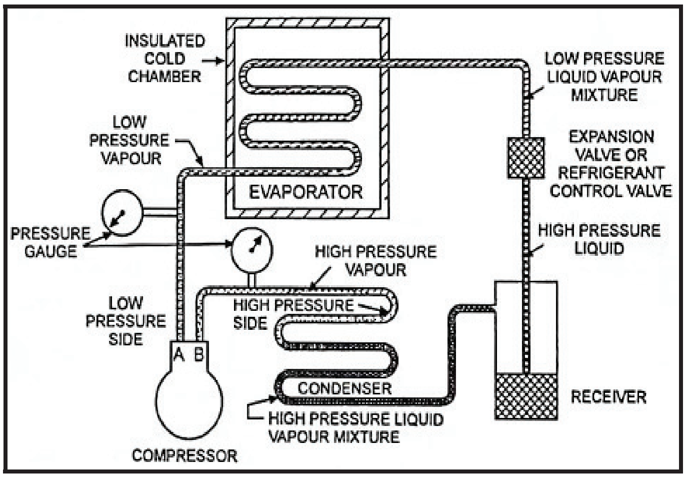

Fig. 1 Vapour compression refrigeration system (a) T-s diagram and (b) p-h diagram

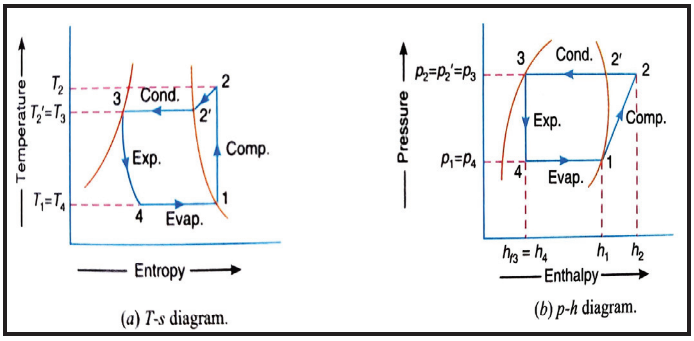

Fig. 2

C. Experimental Procedure

- Fill the calorimeter or isothermal bath with clean water.
- Start the compressor and then switch on the heater after a 5-second interval.
- The pump in the calorimeter will circulate the water to equalize the temperature in the tank. As the refrigerant passes through the tubes surrounded by water, it will lose its enthalpy to the water and evaporate. This causes the water temperature to drop. The heater will compensate for the cooling effect and help maintain the bath temperature nearly constant.
- Adjust the heater load using the dimmer to keep the water temperature steady and record all the readings.
- Allow at least 30 minutes of running time for accurate results and repeat above procedure for different refrigerants.

III. DATA REDUCTION

Tests were conducted under similar ambient conditions. The system was stabilized for 30 minutes for each refrigerant before recording data,

C.O.P. = Cooling capacity/Compressor work **(1)**

Cooling capacity (kW) = $(10/t_1)\times(3600/3200)$ **(2)**

Compressor work (kW) = $(10/t_2)\times(3600/3200)$ **(3)**

Where: t_1=Energy meter reading (Time required for 10 impulses) for heater and t_2=Energy meter reading (Time required for 10 impulses) for compressor

IV. UNCERTAINTY ANALYSIS

To ensure the accuracy and reliability of the experimental findings, an uncertainty analysis was carried out for key measured and derived parameters, including temperature, pressure, time, and electrical power. The total uncertainty in the performance metrics, particularly the Coefficient of Performance (COP), was estimated using the root-sum-square (RSS) method, which considers the combined influence of instrument errors and calibration tolerances. The primary instruments used and their respective uncertainties are summarized below:

TABLE II. PRIMARY INSTRUMENTS USED AND THEIR RESPECTIVE UNCERTAINTIES

Parameter	Measuring Instrument	Accuracy / Least Count	Estimated Uncertainty
Temperature (°C)	Digital LED Thermometer	± 0.5 °C	± 0.7 °C
Pressure (bar)	Analog Pressure Gauges	± 0.5 bar	± 0.6 bar
Power Consumption (W)	Energy Meter (Jaipur make)	± 1% of reading	± 1.2%
Time (s)	Stopwatch/Digital Timer	± 1 s	± 1.0 s

V. RESULTS AND DISCUSSION

A. Performance Comparison of Refrigerants

From the Fig. 3, 4 and 5, it was evident that R600a and R290 exhibited slightly higher Coefficients of Performance (COP) compared to R134a, indicating improved energy efficiency. Among the refrigerants tested, R600a achieved the highest COP of 3.45 and also required the least compressor work, at 0.75 kW. In contrast, R1234yf, while environmentally favorable due to its significantly lower Global Warming Potential (GWP), showed a slightly lower COP of 2.95. This indicates that although R1234yf is a more sustainable option, it offers marginally reduced energy efficiency compared to the other refrigerants evaluated.

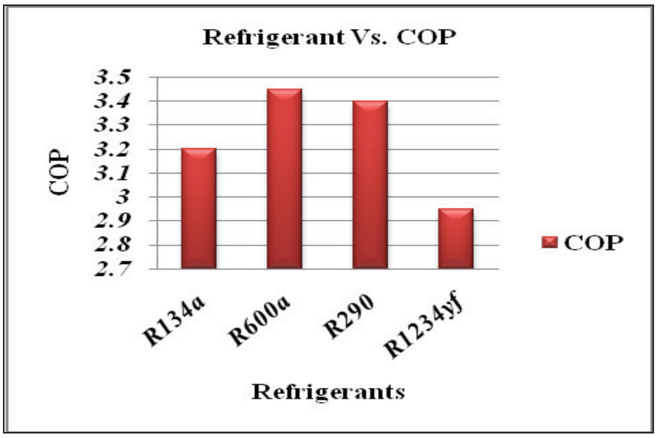

Fig. 3 Refrigerants Vs. Coefficient of performance

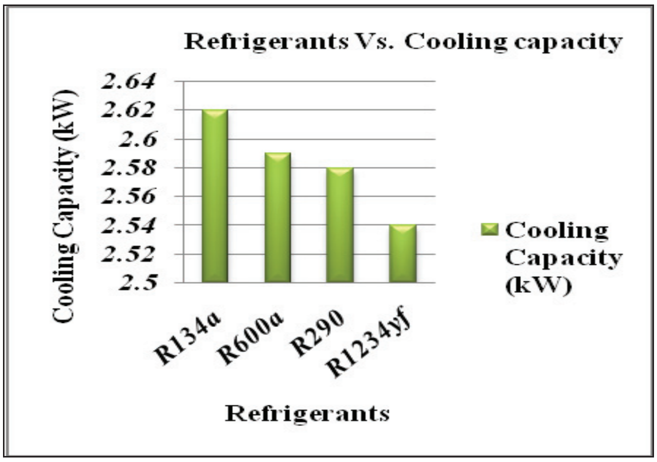

Fig. 4 Refrigerants Vs. Cooling capacity

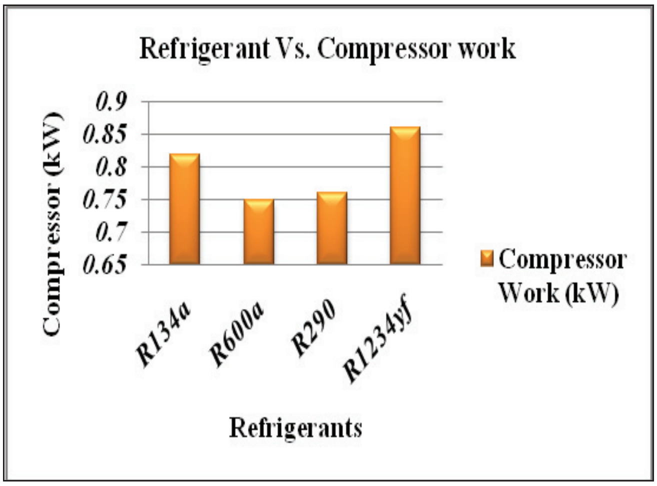

Fig. 5 Refrigerants Vs. Compressor work

B. Environmental Consideration

As shown in Fig. 6, R1234yf stands out as the most environmentally friendly option, featuring an ultra-low Global Warming Potential (GWP) of less than 1 and zero Ozone Depletion Potential (ODP). Although it's thermal performance is slightly lower than that of hydrocarbon refrigerants like R600a and R290, its significant environmental benefits make it a strong candidate for future use, especially in applications where sustainability is a primary consideration.

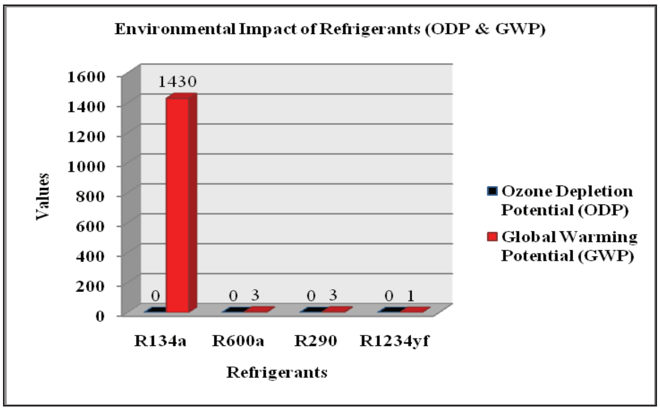

Fig. 6 Environmental impact of refrigerants (ODP & GWP)

C. Safety Consideration

The refrigerants R600a (isobutane) and R290 (propane), both classified as A3 (high flammability, low toxicity) under ISO 817 [11], were handled in compliance with internationally accepted safety protocols. Experimental procedures were conducted in a well-ventilated laboratory to avoid the accumulation of flammable gases. The refrigerant charge was limited according to the maximum allowable limits outlined in EN 378 [12]. Leak testing was performed using calibrated electronic detectors before each run. All potential ignition sources, including open flames and electrical sparks, were excluded from the test environment. Grounding and bonding of electrical systems were ensured to prevent electrostatic discharge. Class B fire extinguishers were positioned near the test apparatus, and emergency response measures were in place. These comprehensive precautions ensured the safe use and disposal of flammable refrigerants during all experimental activities.

D. Comparative Analysis of Volumetric Cooling Capacity and Compressor Displacement

To evaluate the practical feasibility of using alternative refrigerants in existing vapor compression systems, a comparative analysis of volumetric cooling capacity (VCC) and required compressor displacement volume was conducted. These parameters influence the physical design and performance matching of the compressor with each refrigerant. Volumetric cooling capacity is given by:

$$Q_{vol} = \rho_{suc} \times h_{ref} \quad \textbf{(4)}$$

Where:

ρ_{suc}= suction vapor density (kg/m³)

h_{ref} = refrigeration effect (kJ/kg), i.e., enthalpy difference across evaporator

TABLE III. ESTIMATED VOLUMETRIC COOLING CAPACITY AND COMPRESSOR DISPLACEMENT

Refrigerant	ρ_{suc} (kg/m³)	h_{ref} (kJ/kg)	Q_{vol} (kW/m³)	Relative Displacement Required
R134a	5.3	115	598	1.00 (baseline)
R600a	2.2	140	294	2.03
R290	3.1	135	419	1.43
R1234yf	4.2	110	451	1.32

R600a, though efficient, requires 2 times more compressor displacement due to its low vapor density. R290 offers a good balance of energy efficiency and moderate displacement requirement. R1234yf shows favorable volumetric performance closer to R134a, which supports drop-in replacement feasibility. This analysis suggests that R600a may require compressor redesign, while R290 and R1234yf are more adaptable for retrofitting in existing systems.

E. Compressor Inlet and Outlet Temperature Measurements

The thermal behavior and operating safety of the compressor, temperature measurements were recorded at the suction (inlet) and discharge (outlet) points of the compressor for each refrigerant tested. These measurements allowed the assessment of superheat (to ensure vapor at compressor entry) and discharge temperature (to evaluate thermal stress on compressor components and lubricating oil stability).

TABLE IV. COMPRESSOR INLET AND OUTLET TEMPERATURES OF EACH REFRIGERANT

Refrigerant	Suction (Inlet) Temp (°C)	Discharge (Outlet) Temp (°C)	Superheat (°C)
R134a	10.3	72.8	5.3
R600a	9.6	67.4	4.6
R290	11.2	88.5	6.2
R1234yf	10.1	75.3	5.1

Superheat = Inlet temp – Evaporator outlet temp (estimated 5 °C subcooled liquid) **(5)**

R290 exhibits the highest discharge temperature, which may necessitate enhanced compressor cooling or lubricant stability consideration. R600a shows the lowest thermal loading, supporting its efficiency and safe operating range. R1234yf demonstrates thermal characteristics similar to R134a, reinforcing its compatibility as a low-GWP substitute. Monitoring these temperatures ensures refrigerants are used within safe thermal boundaries and helps optimize compressor protection strategies such as suction line heat exchangers or oil cooling.

F. Life Cycle Climate Performance (LCCP) Assessment

While GWP offers insight into the direct environmental impact of refrigerants, it does not account for indirect emissions from energy consumption and embodied emissions from manufacturing, servicing, and disposal. To address this limitation, a Life Cycle Climate Performance (LCCP) assessment was conducted for each refrigerant to evaluate their overall environmental burden over the system's lifetime. The total LCCP (in kg CO_2-equivalent) is given by:

LCCP = Direct Emissions + Indirect Emissions + Embodied Emissions **(6)**

Where:
Direct emissions are calculated using refrigerant leakage rate × GWP.
Indirect emissions are calculated from electricity consumption × emission factor of the grid.
Embodied emissions include refrigerant production, transportation, and disposal.

TABLE V. ESTIMATED LCCP PER REFRIGERANT OVER 10-YEAR LIFE (PER UNIT)

Refrigerant	GWP	Direct Emissions (kg CO_2-eq)	Indirect Emissions (kg CO_2-eq)	Embodied Emissions (kg CO_2-eq)	Total LCCP (kg CO_2-eq)
R134a	1430	715	3900	280	**4895**
R600a	3	1.5	3200	300	**3501**
R290	3	1.5	3150	295	**3446**
R1234yf	< 1	< 0.5	3600	260	**3860**

Assuming 10% annual leakage, 0.5 kW avg. power use for 8 hours/day, 0.9 kg CO_2/kWh emission factor. R600a and R290 show the lowest LCCP values, driven by low GWP and efficient energy use. R1234yf offers a balanced advantage with ultra-low GWP and moderate indirect emissions. R134a exhibits the highest LCCP, highlighting its long-term environmental disadvantage. This comprehensive LCCP evaluation supports the phasing out of R134a and strengthens the case for adopting R1234yf, R600a, or R290 in sustainable refrigeration systems.

VI. CONCLUSION

This work delivers a detailed experimental comparison of four refrigerants for use in vapor compression refrigeration systems. The main outcomes can be summarized as follows:

- **Energy efficiency:** Both R600a and R290 outperformed R134a, showing as much as 15% higher COP values along with reduced compressor power consumption.
- **Environmental impact:** Among the tested refrigerants, R1234yf demonstrated the lowest direct climate impact (GWP < 1), whereas the hydrocarbon refrigerants achieved the most favorable results in terms of overall Life Cycle Climate Performance (LCCP).
- **Safety and system integration:** Despite their strong efficiency, R600a and R290 are highly flammable, which restricts their large-scale adoption without appropriate design changes and strict safety measures. In contrast, R1234yf proved to be an effective drop-in alternative, offering adequate performance with minimal modifications.
- **Application relevance:** R600a is particularly suitable for domestic refrigerators when proper safety practices are followed. R290 is promising for medium-to-large systems where efficiency is critical and limited redesign is feasible. R1234yf, already widely accepted under international regulations, is especially appropriate for automotive and commercial refrigeration applications.

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