

PERFORMANCE INVESTIGATION OF FOUR ECO-FRIENDLY REFRIGERANTS AS RETROFITS FOR DOMESTIC REFRIGERATORS

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Abstract

This paper examines eco-friendly hydrocarbon refrigerants as substitutes for R134a in vapour compression refrigeration systems. It details the retrofitting of an existing system for R134a with modifications including a copper capillary tube, filter drier, refrigerant charge adjustment kit for hydrocarbons, and a sub-cooling coil to improve cooling capacity and energy efficiency while minimizing environmental impact. It explores retrofitted systems using Liquefied Petroleum Gas (LPG), Propane (R290), Iso-butane (R600a), and Carbon dioxide (R744), comparing their effectiveness to R134a through experimental analysis. R290 refrigerant outperforms others in pull down times, achieving cooling in 15 minutes at -10°C evaporator and 40°C condenser temperatures, followed by R600a, LPG, and R744. R134a is the least energy efficient at 850W and has the longest pull-down time of 22 minutes. LPG, propane, and iso-butane are more efficient and eco-friendly alternatives to R134a, consuming 644W to 805W with better pull-down time, power consumption, and lower pressure ratios. LPG exhibits a refrigerating effect of 150 kJ/kg with a COP of 3.50 and 78.7% efficiency. R290 has a superior effect at 240 kJ/kg, COP of 3.45, and 76.7% efficiency, followed by R600a at 230 kJ/kg, COP of 3.42, and 76.3% efficiency. R744, however, shows the lowest refrigerating effect at 140 kJ/kg, COP of 2.30, and 66.5% efficiency, while R134a, despite its low cooling capacity, achieves 78.1% efficiency. Hydrocarbon refrigerants are eco-friendly alternatives to R134a, with R600a being the most effective. R290 and LPG are also suitable substitutes for domestic refrigerators during phase-out, as they help reduce energy consumption.

Keywords

Hydrocarbon refrigerants, retrofitting system, mass charges, suitable substitutes, energy efficiency.

1. INTRODUCTION

Refrigeration is crucial for socio-economic development and sustainability, providing global comfort. It finds applications in oil management, gas and liquid separation, subcooling, superheating, and refrigerant flow to maintain and reduce temperatures. The field encompasses both natural and artificial cooling methods, with cryogenics specializing in very low temperature attainment [1]. To mitigate environmental impacts and energy use, it is essential to decrease refrigerant consumption and leakage. The growing demand for refrigeration and air conditioning, influenced by urbanization and lifestyle changes, highlights the concerns regarding conventional refrigerants, which significantly contribute to ozone depletion and global warming [2]. The refrigerants, essential for cycles that vaporize and condense, must possess specific chemical, physical, and thermodynamic properties to ensure safety and cost-effectiveness. Their significance is heightened due to environmental concerns, as conventional refrigerants contribute to ozone depletion. Primary applications include air conditioning and refrigeration systems [3]. The ideal refrigerant is characterized as safe, noncorrosive, and thermodynamically efficient. Eco-friendly refrigerants provide multiple benefits, including zero ozone depletion potential (ODP), very low global warming potential (GWP), high energy efficiency compared to synthetic refrigerants, low cost with wide availability (especially hydrocarbons), and suitability for small, portable refrigeration systems [4].

The evaluation of refrigerants indicates that R290, while having a slightly lower COP than R134a, offers better thermodynamic properties for automotive applications. R290 systems require less refrigerant mass flow than those using R22, with energy assessments showing energy savings for low-GWP alternatives,

while R1234yf increases energy use. Mixtures of R290 and R600a exhibit favorable COP and GWP for refrigeration retrofitting, supported by experimental evaluations using Design Expert software [5].

[6] research indicates that refrigerants R1234ze(E) and R1234yf consume more power and have lower coefficients of performance (COPs) and cooling capacities compared to R134a. A [7] found that a frost-free refrigerator with R1234yf achieved 3% energy savings over 24 hours versus R134a. [8] study assessed a home refrigerator using R290/R600a, attaining a refrigeration effect of 35% and a COP of about 47%, showing improved performance under varied conditions. Investigations into HFC/HC mixtures for low global warming potential (GWP) compliance revealed that a 1:1 ratio of R290/R600a provided increased capacity and lower energy consumption, with the replacement of R134a by the R290/R600a blend leading to higher COP and reduced refrigerant charge [9] - [12].

Traditional refrigerants (R-22, R-134a, R-404A) pose environmental risks, including ozone depletion and global warming. Sustainable alternatives, such as hydrocarbons and CO₂, offer zero ODP and low GWP but come with challenges, including flammability and the need for high-pressure systems. Hydrocarbons like propane and isobutane, along with abundant and inexpensive CO₂, are positioned to reduce refrigeration costs across various sectors. The goal is to identify refrigerants that effectively balance performance, safety, and environmental sustainability for retrofitting. The study evaluates six eco-friendly refrigerants: propane, propene, butane, isobutane, LPG, and CO₂, as substitutes for harmful refrigerants with high Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). It examines their physical and thermodynamic properties, environmental impacts, safety issues, retrofitting compatibility, and application recommendations. The findings suggest that hydrocarbons are ideal for smaller applications due to their low charge requirements, whereas CO₂ is preferable for larger systems like supermarkets, emphasizing the importance of portability in refrigerant selection for retrofitting [13].

[14] assessed six low GWP alternatives to R404A in refrigeration (R407C, R448A, R454C, R468A, R290, and R1270). Under controlled low evaporation conditions, the evaluation focused on energy usage, exertion, and environmental impacts. R290 was identified as the most effective refrigerant, with performance values nearly matching those of R1270. [15] examined the use of a propane and iso-butane blend as an alternative to R134a in domestic refrigerators, revealing a higher coefficient of performance (COP) under the same conditions. The research underscores concern regarding the toxicity of hydrofluorolefins and the declining use of high-global warming potential (GWP) hydrofluorocarbons (HFCs), emphasizing the necessity for further investigation into environmentally friendly refrigerants. A numerical model of a vapour compression refrigeration system [16] report indicated that R290 outperforms R134a in environmental performance. The study involved different refrigerants, and simulation parameters were chosen for comparison, confirming that the results align with previous research within acceptable ranges using a valid analytical approach and design.

Several alternatives to hydrocarbons and CO₂ exist, including ammonia (R-717), which is efficient but toxic and limited to industrial settings [17]. Hydrofluoroolefins (HFOs) are costly synthetic refrigerants with low global warming potential but lack long-term validation. Absorption systems using heat instead of electricity are available but rarely used for residential refrigeration. Hydrocarbon (HC) blends have the potential to reduce environmental impacts and global warming while effectively replacing halogenated refrigerants and enhancing the coefficient of performance [18].

Hydrocarbon refrigerants such as propane, propene, butane, and isobutane are efficient and environmentally friendly. Propane and isobutane are common in household refrigerators, while LPG offers a cost-effective, variable composition alternative. Carbon dioxide (CO₂) is becoming popular as a sustainable refrigerant due to its non-flammable, non-toxic properties at low concentrations, cost-effectiveness, and a global warming potential of 1 [19].

This study examined four eco-friendly hydrocarbon refrigerants: LPG, Propane (R290), Iso-butane (R600a), and Carbon dioxide (R744) as substitutes for R134a in residential vapor compression refrigeration systems. The study involved modifying an existing R134a system to enhance cooling capacity and energy efficiency while reducing environmental impact. Experiments were conducted to compare the effectiveness of these hydrocarbon refrigerants against R134a.

2. MATERIALS AND METHOD

An existing vapour compression refrigeration system was retrofitted for R134a by modifying a 4-meter copper capillary tube (0.50 mm diameter) and adding a sub-cooling coil to enhance cooling capacity. Adjustments were made to the existing filter drier for proper operation and a refrigerant charge adjustment kit was utilized to ensure efficient use of hydrocarbon refrigerants. The retrofit aimed to enhance energy efficiency and reduce environmental impact. Four eco-friendly refrigerants; LPG, Propane (R290), Iso-butane (R600a), and CO₂ (R744) were used and assessed based on their thermodynamic properties, environmental impact, safety, suitability for retrofitting, and economic factors. The analysis included

evaluations of thermodynamic performance (COP, cooling capacity, efficiency), environmental properties (ODP, GWP), and safety concerns (flammability, toxicity) to determine the appropriateness of these refrigerants for existing systems.

2.1. Experimental Analysis

The domestic vapour compression refrigeration system was retrofitted for R134a by modifying a 4-meter copper capillary tube, adding a sub-cooling coil, and adjusting the existing filter drier. A refrigerant charge adjustment kit was utilized, with 60 g of R134a charged into the compressor, which operated for 50 minutes. Based on the refrigerant minimum evaporating temperature and refrigerant maximum condensing temperature and with the aid of REFPROP software where refrigerant transport properties were taken, refrigerating system performance characteristics such as Refrigerating Effect (RE), Mass Flow Rate (MFR), Evaporator Cooling Capacity (ECC), Compressor Capacity (CC), Ideal Coefficient of Performance (COP ideal), Actual Coefficient of Performance (COP actual) and System Efficiency (SE) were determined using equations. The procedures were repeated for varying masses charges 20g, 30g, 40g, and 50g of LPG, Propane (R290), Iso-butane (R600a), and CO₂ (R744) in a simple vapour compressor refrigerating system, with an evaporator temperature of -10°C, a condenser temperature of approximately 40°C and ambient temperature is 25°C.

The refrigerating effect (Re) was calculated using REFPROP Software version 10.0, as indicated by equation 1 [20].

$$R_e = h_1 - h_4 \quad (1)$$

Where $(h_1 - h_4)$ is represents the enthalpy difference at the evaporator and condenser temperatures, respectively.

The refrigerant mass flow rate was estimated using ASHRAE's equation 2, and the evaporator cooling capacity (Ec) was estimated using equation 3.

$$m_r = \frac{T_l}{R_e} \quad (2)$$

$$E_c = m(h_1 - h_4) \quad (3)$$

The work done by a compressor is defined by equation 4, while the compressor capacity for refrigerant is defined by equation 5.

$$C_c = m(h_2 - h_1) \quad (4)$$

$$W_c = h_2 - h_1 \quad (5)$$

The Coefficient of Performance (COP_a) for actual refrigerant is estimated by equation 6, while the Ideal Coefficient of Performance (COP_i) is determined using equation 7.

$$COP_a = \frac{R_e}{W_c} \quad (6)$$

$$COP_i = \frac{E_t}{C_t - E_t} \quad (7)$$

The system efficiency is calculated using equation 8.

$$S_e = \frac{COP_a}{COP_i} \times 100 \quad (8)$$

3. RESULTS AND DISCUSSION

3.1. Refrigerating Effect and Pull-Down Time

Table 1 indicates that R134a, the baseline refrigerant, consumed the most energy at 850W, while the hydrocarbon refrigerants (LPG, Propane, Iso-butane, and Carbon dioxide) had lower energy consumption ranging from 644W to 805W. Additionally, R134a had the longest pull-down time at 22 minutes, compared to R290, which had the shortest pull-down time of 15 minutes. Overall, tested hydrocarbon refrigerants demonstrated better performance in terms of pull-down time, power consumption, and pressure ratio, highlighting their potential as alternatives to R134a.

Refrigerant pull down times indicate that at -10°C evaporator and 40°C condenser temperatures, R290 provides the fastest cooling, followed by R600a, LPG, and R744. In contrast, R134a requires more time and energy to achieve the same cooling capacity. Thus, the selected refrigerants are preferable substitutes for R134a due to their superior cooling rates and eco-friendliness.

Table 1: Pressure and temperature data for selected refrigerants

Refrigerant	Suction pressure (bar)	Discharge pressure (bar)	Pressure ratio	Evaporator temperature (°C)	Condenser temperature (°C)	Power (w)	Pull down Time (min)
LPG	2.5	11.2	4.48	- 10	40	644	18
R290	3.6	13.6	3.78	- 10	40	552	15
R600a	1.2	5.7	4.75	- 10	40	506	16
R744	26.1	100.0	3.83	- 10	40	805	20
R134a	2.1	10.0	4.76	-10	40	850	22

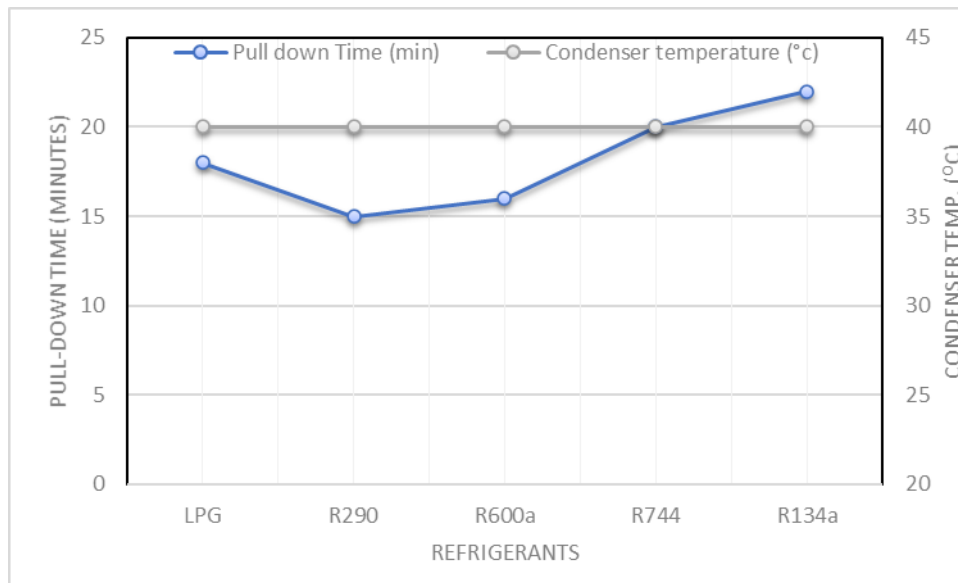


Figure 1: Condenser temperature and pull-down time

3.2. Coefficient of Performance and System Efficiency

At -10°C, LPG shows a refrigerating effect of 150 kJ/kg and a COP of 3.50 with 78.7% efficiency. R290 performs better with 240 kJ/kg, COP of 3.45, and 76.7% efficiency. R600a has 230 kJ/kg, COP of 3.42, and 76.3% efficiency (Table 2). R744 has the lowest refrigerating effect at 140 kJ/kg, COP of 2.30, and 66.5% efficiency. R134a, while having the lowest cooling capacity, achieves 78.1% efficiency. Hydrocarbon refrigerants are highlighted as potential eco-friendly alternatives to R134a in agreement with [20].

Table 2: Performance metrics of various refrigerants at an evaporator air temperature at -10°C

Refrigerant	Evaporator air temperature °C	Refrigerating effect (KJ/kg)	Compressor Work (KJ/kg)	COPa	COPi	System Efficiency (%)
LPG	-10	150	25	3.50	4.45	78.7
R290	-10	240	35	3.45	4.50	76.7
R600a	-10	230	30	3.42	4.48	76.3
R744	-10	140	50	2.30	3.46	66.5
R134a (baseline)	-10	135	26	3.49	4.47	78.1

Refrigerants exhibit varying performance levels, with R290 demonstrating the highest refrigerating effect of 240 kJ/kg and the lowest compressor work at 35 kJ/kg, followed by R600a at 230 kJ/kg (Figure 2). In comparison, R744 has the highest compressor work at 50 kJ/kg, while R134a, serving as the baseline, has a refrigerating effect of 135 kJ/kg with 26 kJ/kg compressor work. These results advocate for the adoption of

hydrocarbon refrigerants as substitutes for R134a due to their reduced global warming potential and lower energy consumption as opined by [22].

Refrigerant efficiency data indicates that LPG has a COP of 3.5 with 78.7% efficiency, making it the most efficient alternative to R134a, which has a COP of 3.49 and 78.1% efficiency (Figure 3). R290 follows closely with a COP of 3.45 and 76.7% efficiency, while R600a shows the lowest COP at 3.42 and 76.3% efficiency. R744 reported a COP of 2.30 and 66.5% efficiency. Overall, R600a has the least COP but moderate efficiency, whereas LPG demonstrates the highest efficiency performance.

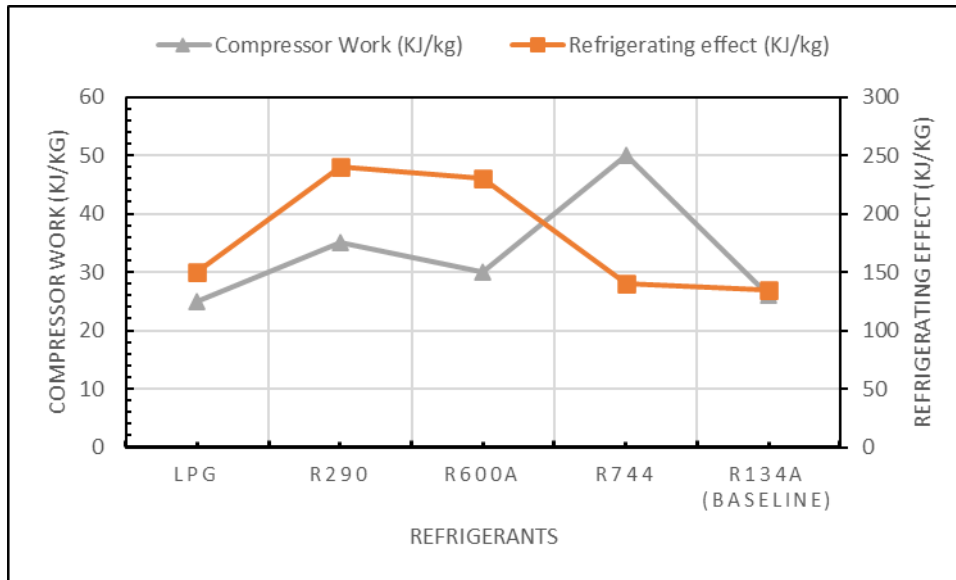


Figure 2: Refrigerants performance on compressor work and refrigerating effect

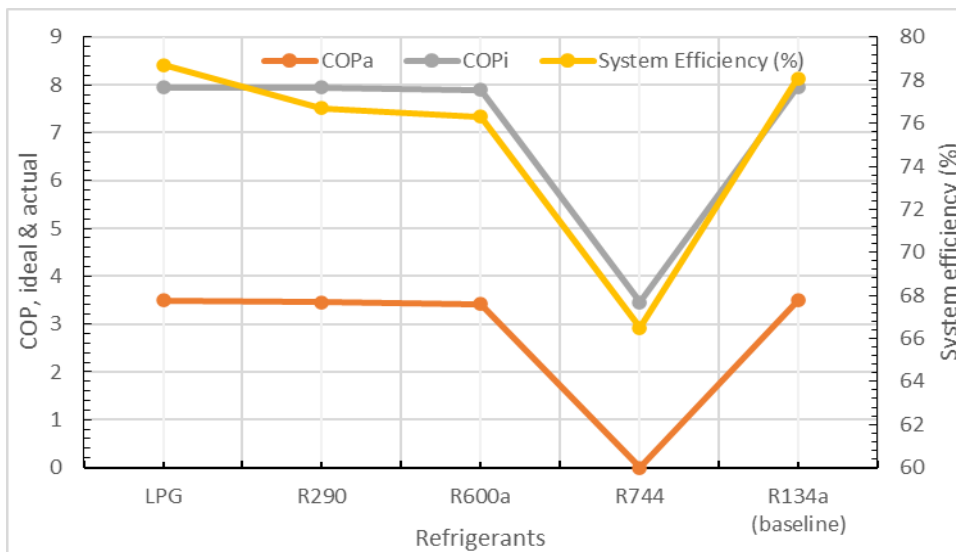


Figure 3: Refrigerants performance on system COP and efficiency

3.3. Environmental and Safety Comparison

Refrigerants have distinct properties as stated in Table 3. LPG and R290 have an ODP of 0, low GWP (~5 for LPG and ~3 for R290), high flammability, and medium operating pressure. R600a also has an ODP of 0 and GWP of ~3, with moderate flammability and low operating pressure. R744, with ODP of 0 and a GWP of 1, is non-flammable and operates at very high pressure.

3.4 Thermodynamics Performance

3.4.1 Liquefied petroleum gas (LPG)

The performance of Liquefied Petroleum Gas (LPG) as a refrigerant improved, with its refrigerating effect rising from 140 kJ/kg to 144 kJ/kg for charges between 20g and 50g, while the baseline R134a at 60g displayed lower efficiency at 135 kJ/kg (Table 4).

Table 3: Environmental and safety of selected refrigerants

Refrigerant	ODP	GWP	Flammability	Operating pressure
LPG	0	3	High	Medium
R290	0	3	High	Medium
R600a	0	3	Moderate	Low
R744	0	1	Non flammable	Very high
R134a	0	1430	Non- flammable	Medium to high

Table 4: Thermodynamic properties of LPG (liquified petroleum gas)

Mass (g)	P _{in} (bar)	P _{out} (bar)	S _t (°C)	E _t (°C)	R _e (kJ/kg)	W _c (kJ/kg)	C.O.P	M _r (kg/s)	P _c (kW)
20	2.2	8.5	9	-1	140	23	6.09	0.00714	0.164
30	2.9	11	4	-7	146	24	6.08	0.00685	0.164
40	3.3	13	1	-11	150	25	6.00	0.00667	0.167
50	3.7	14.5	3	-9	144	27	5.33	0.00694	0.187
60	4.1	16	6	-6	135	29	4.66	0.00741	0.215

The Coefficient of Performance (COP) for LPG decreased from 6.09 to 5.33, aligning with R134a's COP at 60g. LPG's energy consumption ranged from 0.164 kg/s to 0.187 kg/s, which is lower than R134a's consumption of 0.215 kg/s at larger charges. Hence, LPG is a viable alternative to R134a for domestic refrigerators, offering reduced energy consumption as R134a is phased out. Refrigerants exhibit varying efficiency and cooling effects (Figure 4). LPG is the most efficient at 150 kJ/kg with 78.7% efficiency, while R290 offers a strong cooling effect (240 kJ/kg) but lower efficiency (76.7%). R600a also has a good refrigerating effect (230 kJ/kg) and slightly reduced efficiency (76.3%). R744 has the weakest refrigerating effect (140 kJ/kg), highest compressor work (50 kJ/kg), and lowest efficiency (66.5%). R134a serves as a baseline with the weakest refrigerating effect (135 kJ/kg) but improved efficiency (78.1%). Overall, LPG stands out for efficiency, whereas R600a is notable for cooling capacity.

Refrigerants were evaluated for Coefficient of Performance (COP) under both actual (COP_a) and ideal (COP_i) conditions, indicating their system efficiency (Figure 5). LPG had the highest COP_a at 3.5 with 78.7% efficiency, followed by R290 at 3.45 (76.7% efficiency) and R600a at 3.42 (76.3% efficiency). R744 demonstrated a lower COP_a of 2.30 with 66.5% efficiency, while R134a, the baseline refrigerant, showed a COP_a of 3.49 and 78.1% efficiency. Although R134a is efficient, the examined refrigerants are preferred alternatives due to their favorable thermodynamic properties and low global warming potential in line with [21].

Mass values ranging from 20 to 60 grams align with energy values of 23 to 29 kJ/kg, while power consumption increases from 0.164 kW to 0.215 kW as mass rises (Figure 6). This highlights a notable shift in the relationship between compressor work and power. The findings suggest that hydrocarbon refrigerants demonstrate lower energy consumption at reduced mass charges, positioning them as more efficient alternatives to R134a, which has the highest energy consumption.

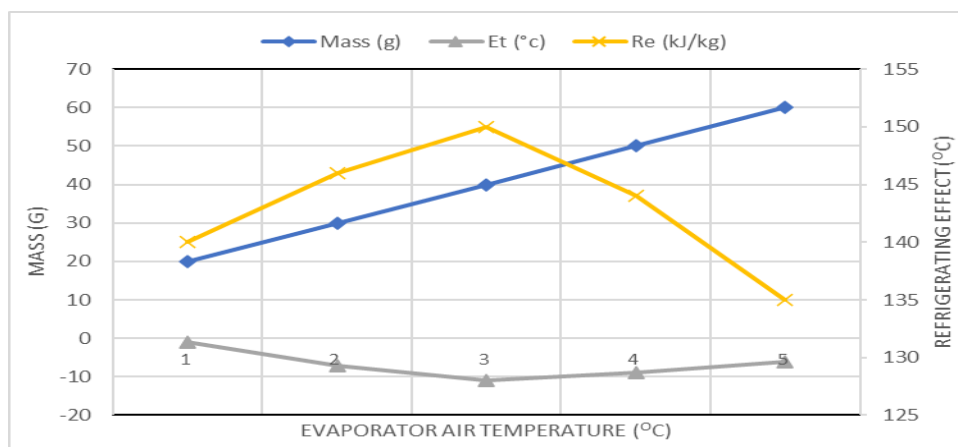


Figure 4: Performance of LPG with refrigerating effect, evaporator temperature and mass charges

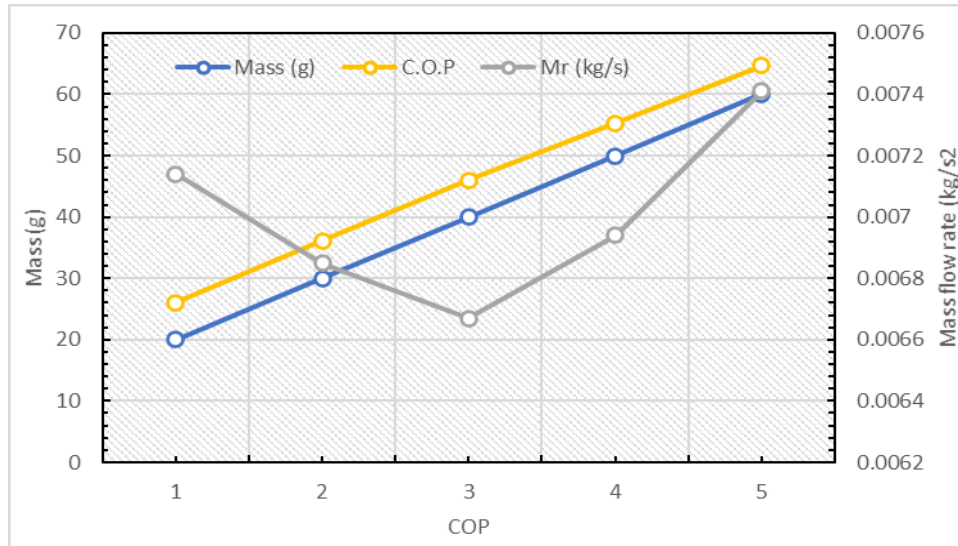


Figure 5: Coefficient of Performance, mass flow rate and charges

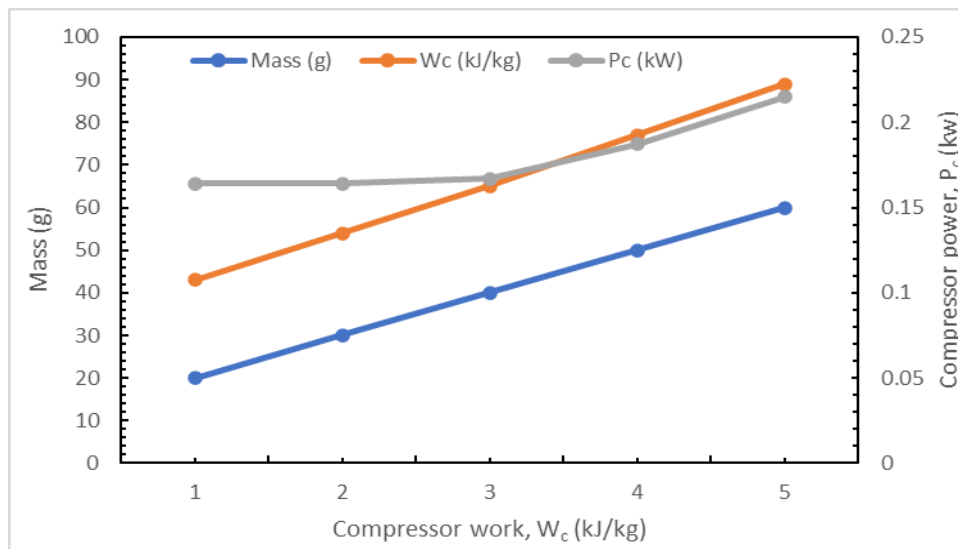


Figure 6: Variation of mass charges with compressor work and power

3.4.2 Propane (R290)

The performance of Propane (R290) as a refrigerant shows improvement, with its refrigerating effect increasing from 142 kJ/kg to 144 kJ/kg for 20g to 50g charges, while R134a at 60g has lower efficiency at 136 kJ/kg (Table 5). The Coefficient of Performance (COP) for Propane decreased from 6.17 to 5.33, compared to R134a's COP of 4.69. Energy consumption for Propane ranged from 0.162 kW to 0.187 kW, lower than R134a's 0.213 kW. Therefore, Propane is a viable alternative to R134a in domestic refrigerators, providing reduced energy consumption as R134a is phased out [21].

Figure 7 presents the relationship between mass (in grams), specific energy (Re in kJ/kg), and coefficient of performance (C.O.P) for various values of mass. The findings indicate that as mass increases from 20g to 60g, the refrigerating effect (Re) initially rises to a peak at 50g before declining, while the C.O.P shows a decreasing trend from 6.17 to 4.69.

Results in Figure 9 indicates the correlation among mass, Coefficient of Performance, and mass flow rate (Mr) across several mass values. Result indicates that using 20g to 50g of hydrocarbon refrigerant yields a coefficient of performance (C.O.P) ranging from 6.17 to 5.33 as mass charges increase, compared to a C.O.P of 4.69 with R134a, highlighting the hydrocarbon's potential as a substitute for R134a.

3.4.3 Iso-butane (R600a)

The evaluation of Iso-butane (R600a) as a refrigerant indicates enhanced performance, with its refrigerating effect increasing from 145 kJ/kg to 148 kJ/kg for 20g to 50g charges, while R134a shows lower efficiency at 140 kJ/kg for a 60g charge.

Table 5: R290 (Propane) performance metrics

Mass (g)	P _{in} (bar)	P _{out} (bar)	S _i (°C)	E _t (°C)	R _e (kJ/kg)	W _c (kJ/kg)	C.O.P	M _r (kg/s)	P _c (kW)
20	2.8	9.5	7	-3	142	23	6.17	0.00704	0.162
30	3.4	11.5	4	-7	148	24	6.17	0.00676	0.162
40	3.9	13.5	1	-11	150	25	6.00	0.00667	0.167
50	4.3	14.8	3	-9	144	27	5.33	0.00694	0.187
60	4.7	16.0	6	-6	136	29	4.69	0.00735	0.213

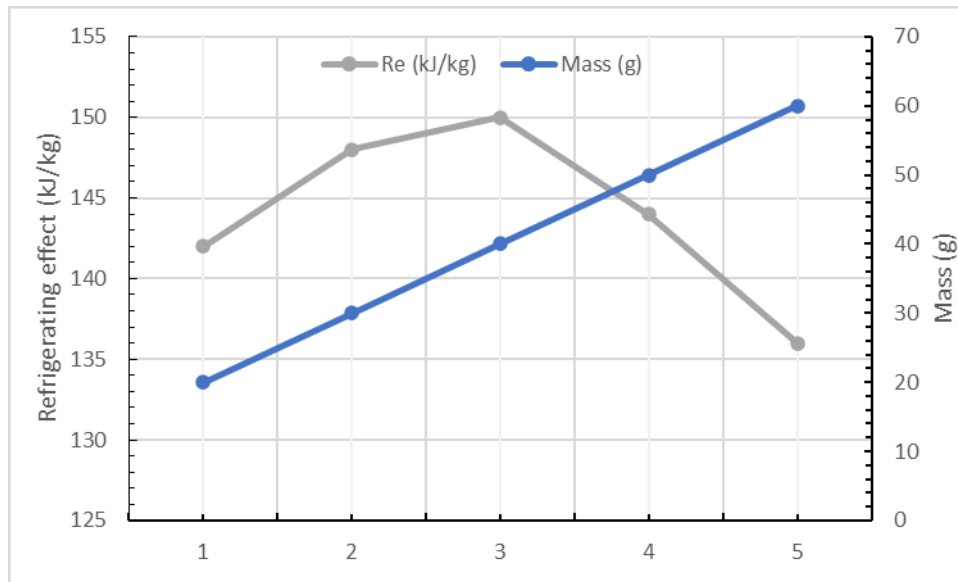


Figure 7: Refrigerating effect and mass charges of R290 (Propane)

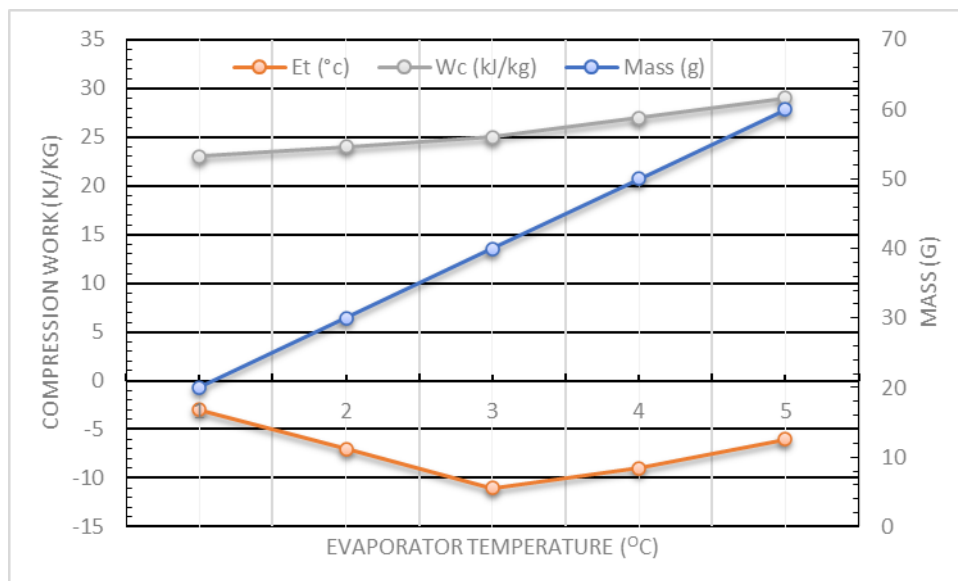


Figure 8: Evaporator temperature, compressor work and mass charges of R290 (Propane)

The Coefficient of Performance (COP) for R600a decreased from 6.30 to 5.48, compared to R134a's COP of 4.83. Additionally, the energy consumption for R600a ranged from 0.159 kW to 0.183 kW, which is lower than R134a's 0.207 kW. Thus, R600a presents a viable alternative to R134a in domestic refrigerators, with decreased energy usage as R134a is phased out in support of [21].

Table 6 shows a correlation between temperature and energy consumption, with the refrigerating effect increasing as temperature decreases. Power consumption declines, but it increases in R134a, leading to a rise in the coefficient of performance (C.O.P). The results indicate that the tested hydrocarbon is more energy-efficient than R134a, positioning it as a viable alternative.

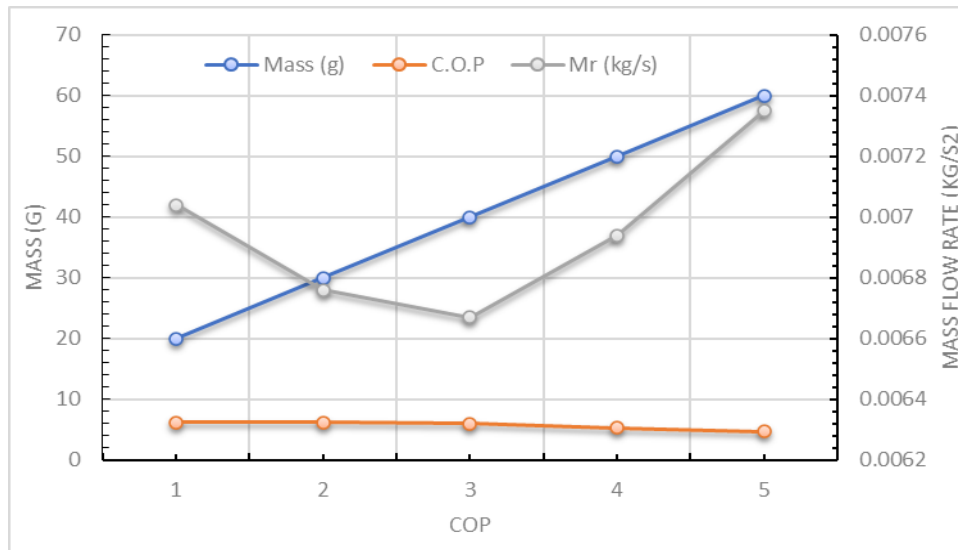


Figure 9: Relation between COP, mass flow rate and charges of R290 (Propane)

Table 6: Performance metrics of R600a Iso-butane)

Mass (g)	P _{in} (bar)	P _{out} (bar)	S _t (°C)	E _t (°C)	R _e (kJ/kg)	W _c (kJ/kg)	C.O.P	M _r (kg/s)	P _c (kW)
20	1.2	4.5	10	0	145	23	6.30	0.00690	0.159
30	1.6	6.0	6	- 5	150	24	6.25	0.00667	0.160
40	1.9	7.8	2	- 12	155	25	6.20	0.00645	0.161
50	2.2	8.5	4	- 9	148	27	5.48	0.00676	0.183
60	2.5	9.5	6	- 6	140	29	4.83	0.00714	0.207

3.4.4 Carbon Dioxide (CO₂) - R744

Evaluation of Carbon dioxide (R744) as a refrigerant demonstrates its superior performance compared to R134a. The refrigerating effect for R744 improved from 105 kJ/kg to 108 kJ/kg, while R134a remains at 100 kJ/kg (Table 7). Although R744's Coefficient of Performance (COP) decreased from 2.63 to 2.25, it still outperforms R134a's COP of 1.92. Additionally, R744 consumes less energy, ranging from 0.381 kW to 0.444 kW, compared to R134a's 0.520 kW. Thus, R744 is a viable alternative for domestic refrigerators, promising reduced energy consumption as R134a usage declines.

The data presented in Table 7 indicates that the evaporating temperatures range from -8 to 2 °C, with refrigerating effects between 100 to 115 kJ/kg, power consumption from 40 to 52 kJ/kg, and coefficient of performance (C.O.P) values from 1.92 to 2.63. The findings suggest that the tested hydrocarbon is more energy-efficient than the baseline R134a, making it a viable alternative.

Table 7: Performance metrics of R744 (CO₂)

Mass (g)	P _{in} (bar)	P _{out} (bar)	S _t (°C)	E _t (°C)	R _e (kJ/kg)	W _c (kJ/kg)	C.O.P	M _r (kg/s)	P _c (kW)
20	20	65	12	2	105	40	2.63	0.00952	0.381
30	25	75	6	- 1	110	43	2.56	0.00909	0.391
40	30	90	2	- 8	115	45	2.56	0.00870	0.392
50	35	100	5	- 6	108	48	2.25	0.00926	0.444
60	40	110	8	- 3	100	52	1.92	0.01000	0.520

3.5 Analysis of Selected Refrigerants

3.5.1 Propane (R-290)

Propane (R-290) is an environmentally friendly refrigerant with an ODP of 0 and a GWP of approximately 3. It has a boiling point of -42.1°C and demonstrates high efficiency due to its excellent thermodynamic performance. Although it is widely available and inexpensive, propane is highly flammable, necessitating leak-proofing, spark-free components, and safety valves for retrofitting. While it is a strong candidate for replacing R-134a in small to medium refrigeration and AC systems, safety concerns remain a significant issue.

3.5.2 Isobutane (R-600a)

Isobutane (R-600a) is an efficient refrigerant with a boiling point of -11.7°C, zero ozone depletion potential (ODP), and a low global warming potential (GWP) of approximately 3. It performs excellently at medium to

low temperatures but is flammable. Retrofitting systems for isobutane requires a small refrigerant charge and some modifications. It is commonly used in household refrigerators and freezers, making it a popular choice for domestic applications due to its efficiency and low environmental impact.

3.5.3 Liquefied Petroleum Gas (LPG)

Liquefied Petroleum Gas (LPG) has an Ozone Depletion Potential (ODP) of 0 and a Global Warming Potential (GWP) of approximately 5. Its boiling point is variable due to its composition of propane and butane. LPG's efficiency is comparable to R-12 and R-134a refrigerants, but it is highly flammable, necessitating safety precautions. Retrofitting for LPG requires similar measures to other hydrocarbons, and it is both inexpensive and widely available.

3.5.4 Carbon Dioxide (R-744)

Carbon Dioxide (R-744) has an ODP of 0 and a GWP of 1. Its boiling point is -78.5°C , exhibiting lower efficiency (COP) compared to hydrocarbons, particularly in hot climates. It is non-flammable and non-toxic, but operates under very high pressure. Retrofitting systems for R-744 requires significant redesign, making it unsuitable as a drop-in replacement. Despite being affordable and readily available, it is best suited for commercial, industrial systems, and heat pumps, rather than low-pressure systems.

4. CONCLUSION

This paper analyzes four eco-friendly refrigerants as alternatives to R134a, examining their thermodynamic performance, environmental impact, safety, and retrofit compatibility. Experimental tests on refrigerants LPG, Propane (R290), Iso-butane (R600a), and CO_2 (R744) in a vapor compressor system at -10°C evaporator and 40°C condenser showed that R600a had the highest coefficient of performance (COP), followed by R290 and LPG; R134a and R744 followed. In refrigerating effect, R600a was again the most effective, with R290, R134a, LPG, and R744 trailing. R744 exhibited the highest energy consumption and mass flow rate, outperforming R134a, R290, and LPG in compressor work, while R600a demonstrated generally good performance with low energy consumption.

Hydrocarbons (propane, propene, butane, isobutane, LPG) are efficient refrigerants with zero ozone depletion potential (ODP), though flammability poses a risk. Carbon dioxide (CO_2) is safe and non-flammable but necessitates expensive high-pressure systems. Isobutane (R-600a) is recommended for domestic use, while propane and CO_2 are preferable in commercial and industrial settings. All studied refrigerants have zero ODP, with hydrocarbons featuring very low global warming potential ($\text{GWP} < 5$) and CO_2 having the lowest GWP of 1. Selecting a refrigerant depends on the application, requiring safety standards and system modifications to minimize environmental impact while maintaining energy efficiency.

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