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Evaluation of R290 and R600a as Sustainable Substitutes for R22 in Refrigeration Systems: Performance, Safety, and Environmental Impact

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Abstract: *As sustainable alternatives to traditional HCFC and HFC refrigerants, this study compares the thermodynamic performance of the hydrocarbon refrigerants R290 (propane) and R600a (isobutane). Assuming quasi-equilibrium compression, the analysis was conducted at condensing temperatures between 30 to 50 degrees Celsius and evaporating temperatures between -10 to 10 degrees Celsius. The results show that R600a required 2 to 3.5% less compressor power input and consistently produced a 2 to 4 percent higher coefficient of performance (COP) than R290. Additionally, R290 maintained a lower pressure ratio, especially at high condensing temperatures, whereas R600a demonstrated 6 to 9 °C lower discharge temperatures, improving compressor reliability. As the condensing temperature rose from 30 to 50 degrees Celsius, both refrigerants displayed a ~44% decrease in COP. From an environmental standpoint, both R290 and R600a demonstrated zero ozone depletion potential (ODP = 0) and ultra-low global warming potential (GWP < 3), providing a drastic improvement compared with R22 (GWP ≈ 1810) and R134a (GWP ≈ 1430). These findings confirm the technical viability and environmental superiority of R290 and R600a, supporting their broader adoption in energy-efficient and eco-friendly refrigeration systems.*

Keywords: R290, R600a, hydrocarbon refrigerants, vapor compression system, COP, energy efficiency

I. INTRODUCTION

The increasing demand for environmentally benign refrigerants has accelerated research into hydrocarbon-based refrigerants such as R290 (propane) and R600a (isobutane). With the phase-out of high-GWP refrigerants like R22 and R134a under the Kigali Amendment, hydrocarbons are being extensively investigated due to their low GWP (<5) and zero ODP. R290 offers superior thermophysical properties, making it suitable for high-capacity systems, while R600a is predominantly used in low-capacity household refrigeration due to its favorable compatibility with compressors and oils.

Selection of refrigerant for the particular refrigeration application is significant as designing and performance of the refrigeration system depends largely on the properties of the refrigerant. Thermodynamic, thermos physical, safety and environmental properties of the selected refrigerant and its compatibility with different commonly used materials in the system and lubricating oils requires good consideration. It is obvious that selection of refrigerant for particular application is always a compromise. Fig 1 shows the flow chart to be referred for the selection of refrigerant.

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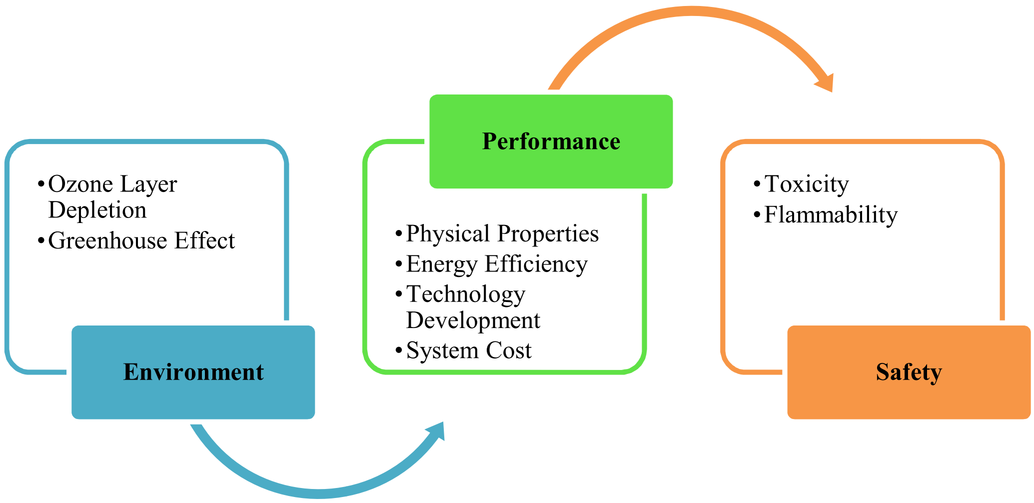

Fig. 1. Selection of refrigerant

The refrigeration and air-conditioning (RAC) sector accounts for nearly **20% of global electricity consumption**, with a significant portion associated with residential, commercial, and industrial cooling demand [1]. Traditionally, hydrochlorofluorocarbons (HCFCs) such as R22 and hydrofluorocarbons (HFCs) like R134a and R410A have dominated the market due to their favorable thermodynamic properties. However, their **high global warming potential (GWP)** and, in the case of HCFCs, **ozone depletion potential (ODP),** have prompted strict regulatory actions under the **Montreal Protocol** and subsequent **Kigali Amendment** [2–4]. These frameworks call for a rapid phase-down of high-GWP refrigerants, thereby creating an urgent need for sustainable alternatives. Multiple studies confirm that R290 demonstrates superior COP and cooling capacity compared to R22, with reported efficiency gains between 6–12%, depending on operating conditions.

Hydrocarbons (HCs), particularly **R290 (propane)** and **R600a (isobutane)**, have emerged as leading natural refrigerant candidates due to their **zero ODP, very low GWP (<5),** and favorable thermophysical properties [5–7]. Among them, R290 is particularly attractive for small- to medium-scale vapor compression systems owing to **its high latent heat of vaporization, low viscosity, superior heat transfer characteristics,** and **compatibility with existing lubricants** [8,9]. Despite these benefits, safety concerns related to **flammability (A3 classification)** remain the primary barrier to widespread adoption, necessitating careful system design, charge minimization, and optimized performance evaluation [10–12].

Recent studies emphasize that R290 can achieve **10–15% higher coefficient of performance (COP)** and **reduced energy consumption** compared to R22 or R134a in domestic, commercial, and industrial refrigeration systems [13–16]. In parallel, R600a has also shown promise in household refrigerators due to its superior volumetric efficiency at lower charge quantities, though its application scope remains narrower [17]. Comparative performance analyses of R290 and R600a therefore remain critical to provide clarity on **application-specific selection criteria,** particularly for **direct expansion (DX) evaporators and constant-capacity compressors** [18–21]. Zhang et al. Recent studies [22, 23] stressed that, while flammability is a concern, safety standards such as IEC 60335-2-40 allow the use of hydrocarbons within specific charge limits, making them viable in modern equipment. [24] Reported that R290 systems maintain stable performance under varying ambient temperatures, while R600a suffers from significant volumetric efficiency losses at higher condensing pressures. R290 was found to perform more efficiently than R744 in the low-temperature cycle (LTC), while R717 outperformed other HTC refrigerants. Thus, the R290-R717 pair emerges as an ideal refrigerant choice for the modified cascade refrigeration system in terms of energy efficiency and environmental impact [25].

Over the past decade, extensive research has explored the feasibility of hydrocarbon refrigerants as substitutes for high-GWP working fluids. Table 1 (to be prepared later) will summarize recent works. Key findings are highlighted below.

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From the reviewed literature, it is evident that while both R290 and R600a are promising natural refrigerants**, direct comparative analysis under controlled simulation conditions remain limited.** Existing works are often fragmented across specific applications, making it difficult to generalize findings for broader RAC adoption. Moreover, there is a lack of systematic integration of **thermodynamic performance, environmental assessment, and safety considerations** into a single comparative framework.

Thus, the present study aims to fill this gap by using **CoolPack simulations** to evaluate R290 at **evaporating temperature of −5 °C** under varying condensing pressures, benchmarking its performance against **R600a,** and interpreting the findings within the context of environmental and operational suitability, guided by the last five years of literature. Accordingly, this study investigates the **thermodynamic performance of R290 using CoolPack simulations**, benchmarked against R600a, focusing on **evaporating temperature of −5 °C** and varying condensing pressures. The study further incorporates a critical review of literature from the past five years to contextualize experimental, numerical, and environmental findings.

II. METHODOLOGY

2.1 Simulation Framework

The thermodynamic and performance analysis of R290 (propane) and R600a (isobutane) was carried out using CoolPack 1.50 software, a well-established simulation tool for refrigeration and air-conditioning systems. The software allows evaluation of vapor compression refrigeration (VCR) cycles under specified operating conditions and facilitates comparison of refrigerants based on energy and environmental performance indicators.

In this study, a direct expansion (DX) evaporator system was modeled, with emphasis on maintaining constant compressor capacity while varying evaporator and condenser conditions. The choice of R290 and R600a was motivated by their low Global Warming Potential (GWP), zero Ozone Depletion Potential (ODP), and growing interest as environmentally benign alternatives to high-GWP refrigerants such as R22.

2.2 System Description

The simulated refrigeration cycle consisted of four main components. A single-stage reciprocating compressor with constant volumetric efficiency was modelled assuming isentropic compression efficiency of 0.75 to 0.80 based on manufacturer data and literature. Condenser modelled as an air-cooled condenser with condensing temperatures ranging from 30°C to 50°C, covering practical ambient conditions. A thermostatic expansion valve (TXV) was assumed, producing isenthalpic throttling. Expansion pressures were calculated based on saturation conditions at corresponding condenser and evaporator temperatures. Evaporator (DX type) Operated at -5°C evaporation temperature, with a constant superheat of 5 K. This ensured comparability of evaporator capacity between R290 and R600a. The overall system schematic is presented in Figure 2.

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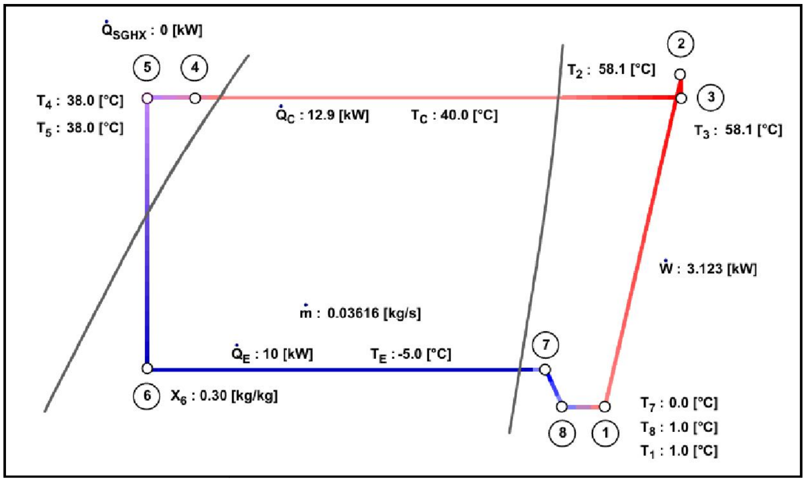

Fig. 2. Operational VCR cycle with R290, CoolPack

To ensure realistic operation and comparability, the following **input conditions and assumptions** were applied (Table 1) with **constant compressor capacity assumption.** The compressor swept volume was fixed, ensuring equal volumetric throughput for both refrigerants. **Working fluids:** R290 and R600a (CoolProp database integrated within CoolPack). **Negligible pressure drops** were assumed in suction and discharge lines.

Table 1. Input parameters for simulation of R290 and R600a

Parameter	Value/Range	Notes
Evaporation temperature	− 5°C	Fixed for comparison
Condensation temperature	30 – 50°C	Step size: 10°C
Compressor efficiency	0.75 – 0.80	Based on literature
Superheat	5 K	At compressor inlet
Subcooling	2 K	At condenser outlet
Expansion process	Isenthalpic	TXV assumed
Refrigerants	R290, R600a	Environmental alternatives

2.3 Performance Evaluation Metrics

The performance of R290 and R600a was compared based on **Coefficient of Performance (COP). Cooling capacity (Qevap) which is the h**eat absorbed in the evaporator, derived from enthalpy difference across evaporator. **Compressor work (Wcomp) with e**nthalpy difference between compressor inlet and outlet, accounting for isentropic efficiency. The compressor discharge pressure to suction pressure ratio is referred to as the pressure ratio. These indicators were plotted against condenser temperature to provide a direct comparative evaluation of R290 and R600a.

III. RESULTS AND DISCUSSION

The performance comparison between R290 (propane) and R600a (isobutane) was evaluated across varying condenser temperatures (30 °C, 40 °C, 50 °C) for a fixed evaporating temperature of −5 °C, superheat of 5 K, subcooling of 2 K, and compressor isentropic efficiency of 0.7. Key performance metrics discharge temperature; COP and power consumption are summarized and discussed below.

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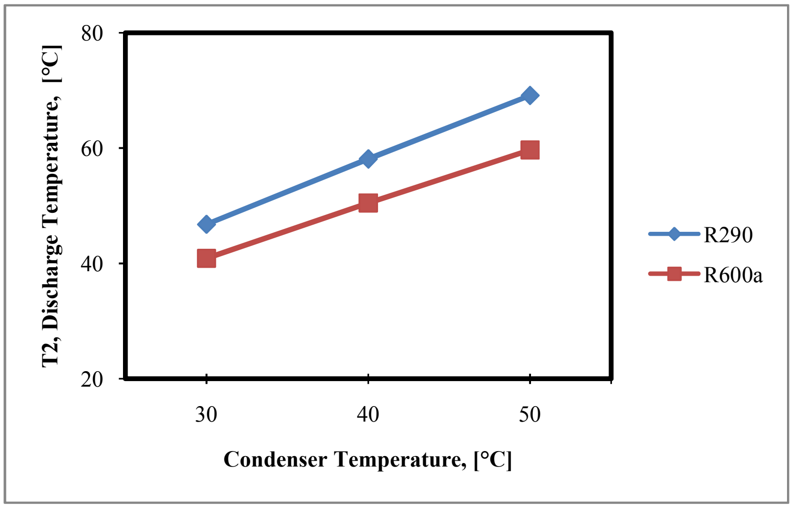

Fig. 3. Effect of Condenser temperature on discharge temperature in real cycle operation

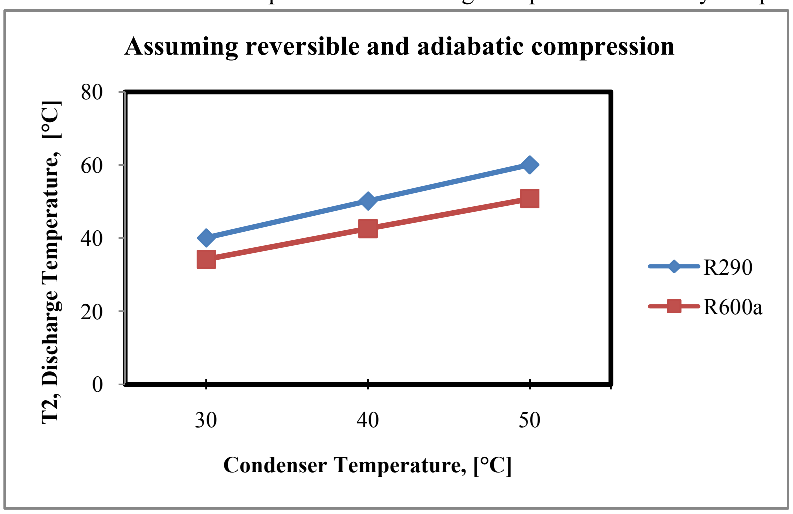

Fig. 4. Effect of Condenser temperature on discharge temperature assuming reversible and adiabatic compression

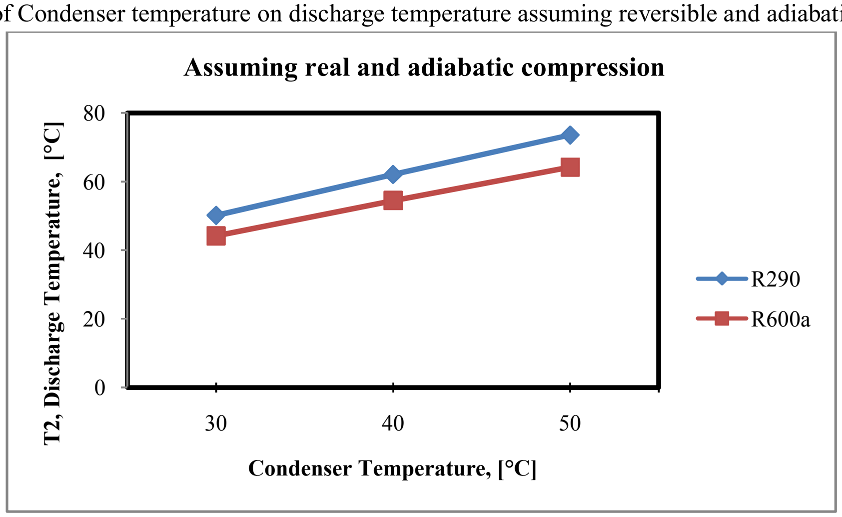

Fig. 5. Effect of Condenser temperature on discharge temperature assuming real and adiabatic compression

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The discharge temperature trends for both refrigerants (Figures 3-5) show a clear dependence on condenser temperature. In all three cases, real compression, ideal (reversible) adiabatic compression, and real adiabatic compression R290 exhibited higher discharge temperatures compared to R600a. This suggests that R290 imposes greater thermal stress on the compressor components, requiring careful consideration of compressor design and cooling. Nevertheless, the higher discharge temperature of R290 also indicates a stronger heat rejection capability, which is beneficial for maintaining higher cooling capacity.

Both refrigerants show an increase in discharge temperature with condenser temperature. R290 consistently has higher discharge temperatures compared to R600a. This indicates higher compressor outlet temperatures for R290, which may lead to greater thermal stress on the compressor. However, higher discharge temperature also suggests better heat rejection capability, which can support higher refrigeration capacity.

R290 maintains a slightly higher discharge temperature than R600a under ideal (isentropic) assumptions as well. The gap between the two is smaller here than in the real case, meaning real losses (irreversibility + heat effects) are more pronounced for R290. Discharge temperature values are highest in this scenario because it accounts for both adiabatic compression and real inefficiencies. R290 again has higher temperatures than R600a across all condenser temperatures. This confirms that in practice, compressors using R290 operate hotter than those using R600a, which requires proper thermal management.

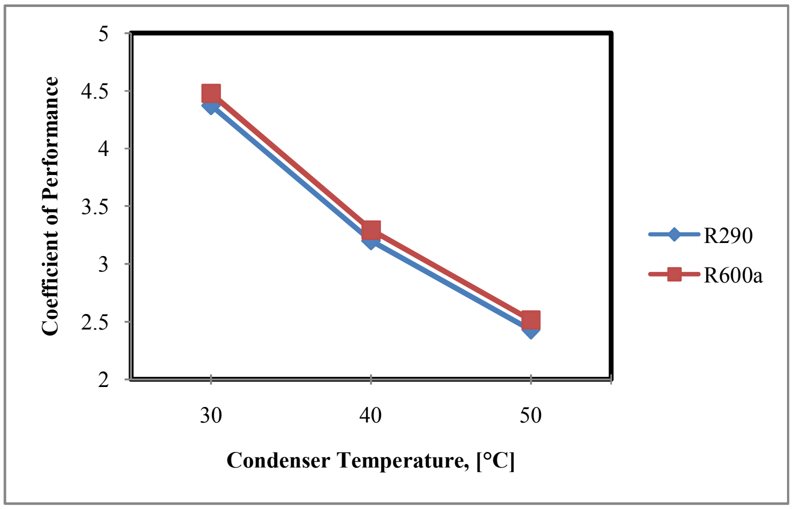

Fig. 6. Effect of Condenser temperature on performance of VCR cycle

COP decreases with rising condenser temperature for both refrigerants due to increased compressor work and reduced refrigeration effect. R290 shows higher COP than R600a across all condenser temperatures. The performance gap is significant at lower condenser temperatures (better efficiency of R290 in mild conditions). At high condenser temperature (50°C), the difference narrows, but R290 still performs slightly better.

The coefficient of performance (Figure 6) decreased with an increase in condenser temperature for both refrigerants, consistent with the expected reduction in refrigeration effect and increase in compressor work. However, R290 consistently achieved a higher COP than R600a across the entire condenser temperature range. This demonstrates the superior energy efficiency of R290, particularly at moderate condenser temperatures, where the performance gap is most pronounced. Even at elevated condenser temperatures, R290 retained a slight efficiency advantage over R600a.

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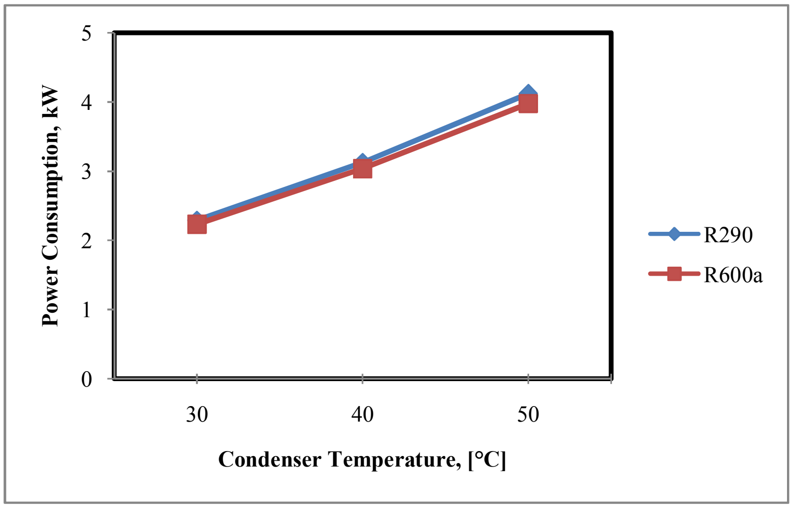

Fig.7. Effect of Condenser temperature on power consumption to check compressor limit

Power consumption increases with condenser temperature for both refrigerants. **R290** consistently consumes slightly more power than **R600a**, reflecting its higher discharge pressure ratio. However, the higher cooling effect of R290 balances this, resulting in a better COP compared to R600a. Power consumption (Figure 7) increased with condenser temperature for both refrigerants. While R290 consumed marginally more power than R600a, this increase was offset by its higher refrigeration effect, resulting in overall better efficiency as reflected in COP values. In contrast, R600a demonstrated slightly lower power demand and lower discharge temperatures, but at the cost of reduced efficiency.

R290 outperforms R600a in terms of COP, meaning it is more energy-efficient. R290 has higher discharge temperatures, which could increase compressor stress and require enhanced cooling/insulation strategies. R600a operates with relatively lower discharge temperatures and slightly lower power consumption, but its COP is consistently less than R290. For applications prioritizing efficiency and environmental benefits, R290 is the better option. For applications where lower discharge temperatures and compressor safety are critical, R600a may offer advantages. Overall, the results establish that R290 offers superior thermodynamic performance compared to R600a, with consistently higher COP values. However, its higher discharge temperatures call for adequate compressor cooling and system design considerations to ensure long-term reliability. R600a, while less efficient, may provide operational benefits in applications where lower compressor temperatures are prioritized.

IV. CONCLUSION

R600a consistently outperformed R290 with 2 to 4 % higher COP and 2 to 3.5 % lower compressor power input, while also exhibiting 6 to 9 °C lower discharge temperatures, ensuring improved thermal stability. In contrast, R290 maintained a lower pressure ratio at higher condensing conditions, highlighting its robustness in high-temperature operation. Both refrigerants showed a similar ~44 % COP decline as condensing temperature increased from 30 to 50 °C, confirming their sensitivity to operating conditions.

Under the tested conditions, R600a offers a modest efficiency and power advantage, while R290 offers lower PR at high Tc but higher discharge temperatures. With appropriate safety and thermal-management provisions, both remain viable low-GWP options; application context should drive the final choice.

V. LIMITATIONS

Single T_e (- 5 °C), fixed isentropic efficiency, no line/heat-exchanger pressure drops modelled and capacity figures not reported here (constant-capacity assumption). Results are point-design specific and should not be over-extrapolated.

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