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Performance Analysis of R600a as a Replacement for R134a in a Household Refrigeration System

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Abstract--*This study evaluates the performance of a 50-liter mini refrigerator using R600a as an alternative to the factory-default refrigerant, R134a. The experimental setup included pressure gauges and digital thermometers to measure key parameters such as temperature and pressure at critical points in the refrigeration cycle. Tests were conducted under two scenarios: no-load and a 4 kg chicken meat load. Initially, the system operated with R134a at 16 bar and 20 g charge before being evacuated and recharged with R600a at the same pressure. Data was collected over 10 minutes under stable conditions and analyzed using a P-h (Pressure-Enthalpy) diagram to determine enthalpy, refrigeration effect, compressor work, and coefficient of performance (COP). The effect of using R600a was that efficiency increased by 4% without load and 7% with load operation compared to the R134a system. Meanwhile, the actual COP has increased by 5% and 10%, respectively. The results indicate that R600a offers comparable performance to R134a while presenting potential advantages in terms of energy efficiency and environmental impact. These findings contribute to the ongoing evaluation of R600a as a sustainable replacement for R134a in household refrigeration applications.*

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1. INTRODUCTION

Household refrigeration (HR), commercial refrigeration (CR), and automobile air conditioning (AAC) systems play a crucial role in transferring heat from low-temperature enclosed spaces to higher-temperature surroundings [1], [2]. The most commonly used method for this process is the single-stage vapor compression refrigeration (VCR) system, which is widely implemented in food and beverage storage to maintain freshness [3]. R134a has been the dominant refrigerant in domestic refrigerators due to its favorable thermodynamic properties [4]. However, it is being phased out under the Kyoto Protocol due to its high global warming potential (GWP) [5], [6], [7], [8], [9]. As a result, the transition to R600a (isobutane) is driven by environmental concerns, energy efficiency, and performance advantages [10]. As a natural refrigerant with a GWP of zero, R600a presents a sustainable alternative with minimal impact on ozone depletion and global warming [5], [11], [12].

Refrigerators are among the most energy-consuming household appliances [13]. Research has shown that hydrocarbon-based refrigerants, such as propane (R290) and isobutane (R600a), offer energy-efficient and environmentally friendly alternatives to traditional refrigerants [6], [14]. Various studies have demonstrated that R600a significantly reduces GWP compared to conventional refrigerants like R134a and R410A [15]. Moreover, R600a has been reported to lower power consumption in refrigeration systems, enhancing energy efficiency [16], [17]. Experimental investigations also indicate that refrigeration systems using R600a achieve a higher coefficient of performance (COP) than those using R134a, confirming its superior thermodynamic performance [18], [19].

Several studies have examined the performance of R600a in comparison to R134a [20]. For instance, Katoch et al. and Irwansyah et al. found that incorporating SiO_2, ZnO, and TiO_2 nanoparticles into R600a enhances domestic refrigerator performance, demonstrating its effectiveness with a safe refrigerant charge while improving system efficiency [21], [22]. Similarly, Bull et al. confirmed that R600a is a viable replacement for R134a, yielding promising results in energy consumption and cooling efficiency [23]. Experimental analyses further show that R600a can improve refrigerating power by 28.6% to 87.2% over R134a, highlighting its efficiency [24]. Additionally, Ajayi observed that bio-based nanoparticles combined with R600a enhance thermal performance and reduce energy consumption in vapor compression refrigeration systems [25]. Madyira's research further supports this by demonstrating that using nanolubricants with R600a increases refrigeration capacity and reduces compressor power consumption, making it ideal for household applications [26]. Furthermore, Hmood et al. emphasized that R600a can replace R134a with minimal system modifications, addressing safety concerns associated with its flammability [27], [28].

Many consumers use their household refrigerators for extended periods, often requiring maintenance and overhauls due to wear and tear [29]. Replacing R134a with the more environmentally friendly R600a during these maintenance procedures can help reduce accidental refrigerant leakage into the environment.

In this experiment, a household refrigerator was tested by replacing its existing R134a refrigerant with R600a, and the system's performance was systematically evaluated. The findings aim to contribute to the growing database on R600a's compatibility as a direct substitute for R134a in existing refrigeration systems. Additionally, this study seeks to give consumers greater confidence in the feasibility and efficiency of using R600a in retrofitted household refrigerators.

2. METHODOLOGY

The research was conducted to evaluate the performance of a mini refrigerator using R600a compared to the factory-default refrigerant, R134a. A Polytron mini refrigerator with a 50-liter capacity was selected for the study. Initially, the refrigerator operated with R134a and was charged with 20 g of refrigerant at a pressure of 16 bar. The unit was powered by a 220 V, 50 Hz electrical supply.

Table 1. Properties of R134a and R600a used in household applications

Refrigerant Properties	***R134a***	***R600a***
Name	TetraFluro-Ethane	Isobutane
Formula	CH_3CH_2F	C_4H_{10}
Critical Temp. ^oC	101	135
Molecular W in kg/mol	102	58.1
Normal boil point	-26.5	-11.6
Pressure at -25 ^oC in bar (absolute)	1.07	0.58
Liquid density kg/l	1.37	0.6
Vapor density kg/m^3	4.4	1.3
Volumetric capacity kJ/m^3	658	373

The refrigerator was equipped with monitoring instruments to facilitate performance measurements, including two pressure gauges and four digital thermometers with NTC 10k 3435 sensors, as shown in Figure 1. The pressure gauges were installed at the compressor inlet and outlet (P_2 and P_1, respectively). At the same time, the thermometers were positioned to measure temperatures at the condenser inlet and outlet (T_2 and T_3, respectively), as well as the evaporator inlet and outlet (T_4 and T_1, respectively). These measurements were essential for evaluating key performance parameters such as the Coefficient of Performance (COP) and overall system efficiency [30].

The experimental testing was conducted under two different scenarios. In the first scenario, the refrigerator was operated from room temperature with an empty compartment (no cooling load). The compartment was loaded with 4 kg of chicken meat in the second scenario, starting from room temperature. The experiment was conducted at an average ambient temperature of 32 ^oC.

Following the initial tests with R134a, the vacuum pump removed the refrigerant from the system entirely. The system was then recharged with R600a until it reached 16 bar, ensuring consistency with the no-load pressure of R134a. The same measurement procedures were applied to the new refrigerant, allowing for a direct comparison of performance parameters. Once the system reached stable operating conditions, data was collected over 10 minutes under both no-load and load conditions. The recorded values were plotted on a P-h (Pressure-Enthalpy) diagram, enabling a detailed analysis of the thermodynamic performance of both refrigerants.

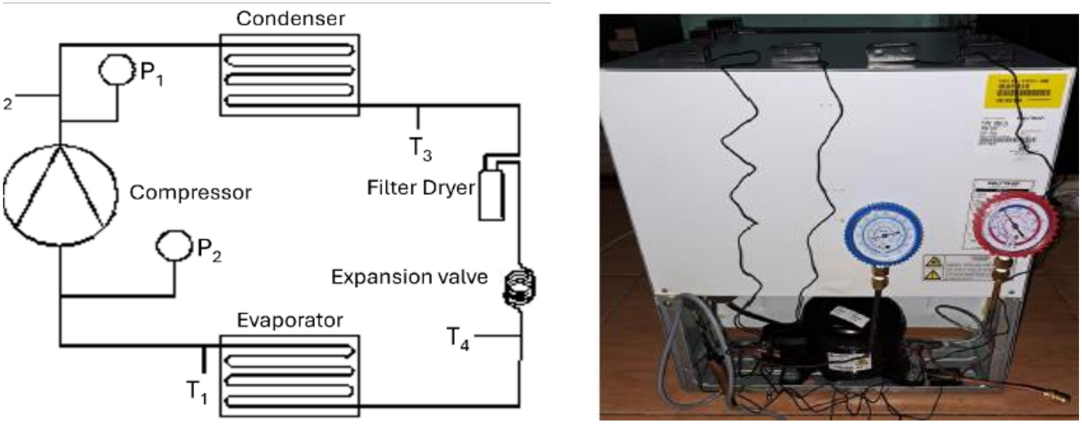


Figure 1. Schematic figures of the experimental setup

2.1 Performance parameters of the refrigeration system

The collected data is processed and analyzed using thermodynamic equations and performance indicators. Data analysis is performed on all the collected parameters to determine the actual performance of the condenser. This analysis includes the calculation of compressor work and refrigeration effect. Additionally, the actual and ideal COP and the overall system efficiency are calculated and compared to assess the system's performance on both refrigerants. The key parameters related to condenser performance measured during the data collection phase are described below [31].

Compressor work (q_w) refers to the amount of heat the refrigerant absorbs per unit mass during the refrigeration process. It is calculated by determining the difference in enthalpy between the compressor's inlet and outlet. The formula for calculating compressor work is:

$$q_w = h_2 - h_1 \qquad (1)$$

h_1 is the enthalpy at the compressor inlet, and h_2 is the enthalpy at the compressor outlet, measured in kJ/kg.

The refrigeration effect is the heat the refrigerant absorbs from the environment or product being cooled. It can be calculated by determining the difference in enthalpy between the outlet and inlet of the evaporator. The equation is:

$$q_e = h_1 - h_4 \qquad (2)$$

h_1 is the enthalpy at the evaporator outlet, and h_4 is the enthalpy at the evaporator inlet, both in kJ/kg.

The actual Coefficient of Performance (COP_{actual}) measures a cooling machine's efficiency. It is calculated as the ratio of the refrigeration effect to the compressor work. The formula is:

$$COP_{actual}: \frac{q_e}{q_w} = \frac{h_1 - h_4}{h_2 - h_1} \qquad (3)$$

This helps to quantify how efficiently the system uses energy to transfer heat. Similarly, the ideal Coefficient of Performance (COP_{ideal}) represents the theoretical maximum efficiency of the refrigeration system. It is calculated as the ratio of the evaporator temperature to the temperature difference between the condenser and evaporator. This can be expressed as

$$COP_{ideal} : T_e/(T_c - T_e) \qquad (4)$$

$_{He}$ is the evaporator inlet temperature, and T_c is the condenser inlet temperature.

The efficiency of the refrigeration machine is evaluated by comparing the actual COP to the ideal COP. It provides insight into how closely the system operates to its theoretical maximum efficiency. The formula used for this calculation is:

$$\eta = (COP_{actual}/COP_{ideal}) \times 100\% \qquad (5)$$

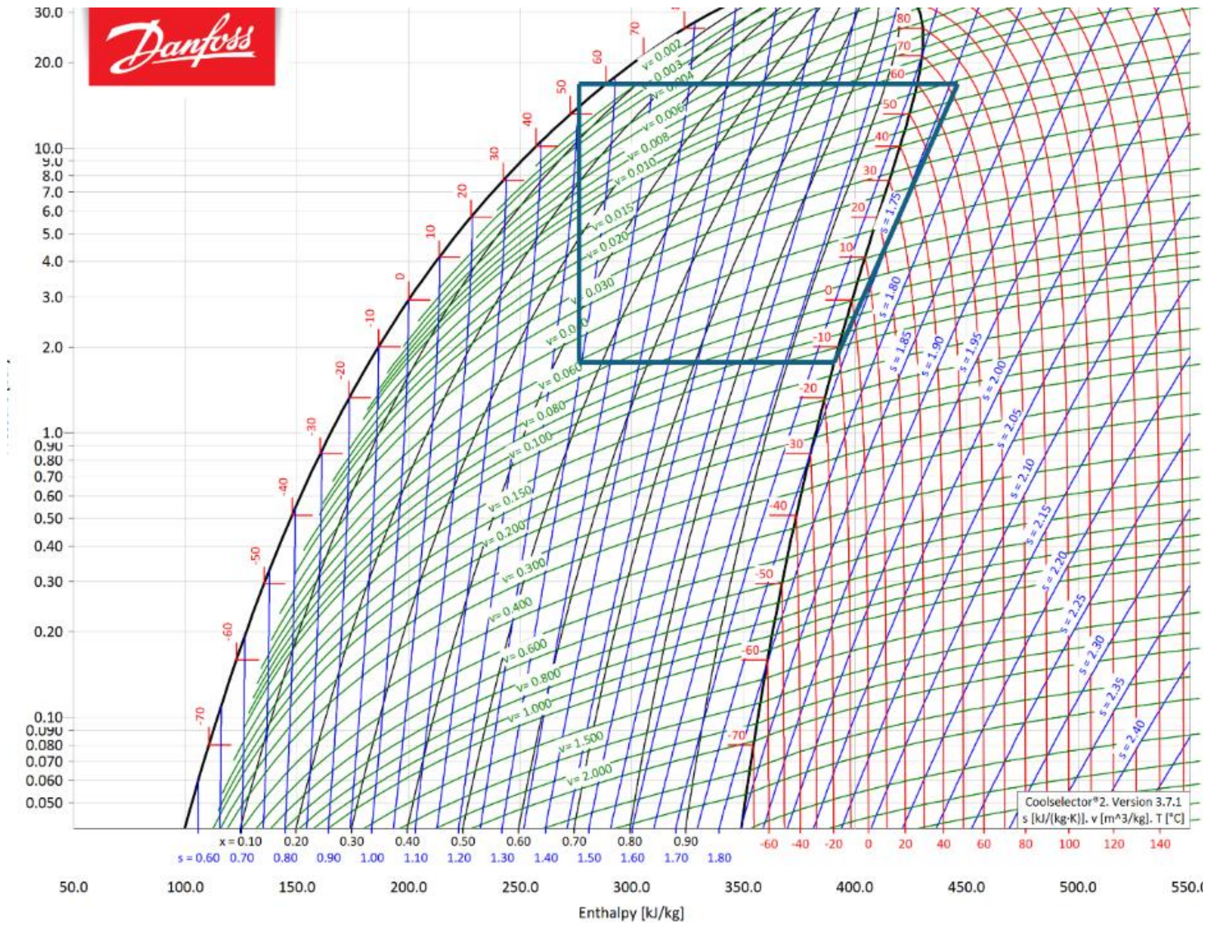
The research concludes with a comprehensive report summarizing the findings, performance comparisons, and recommendations for refrigerant selection in household refrigeration applications.

3. RESULT AND DISCUSSION

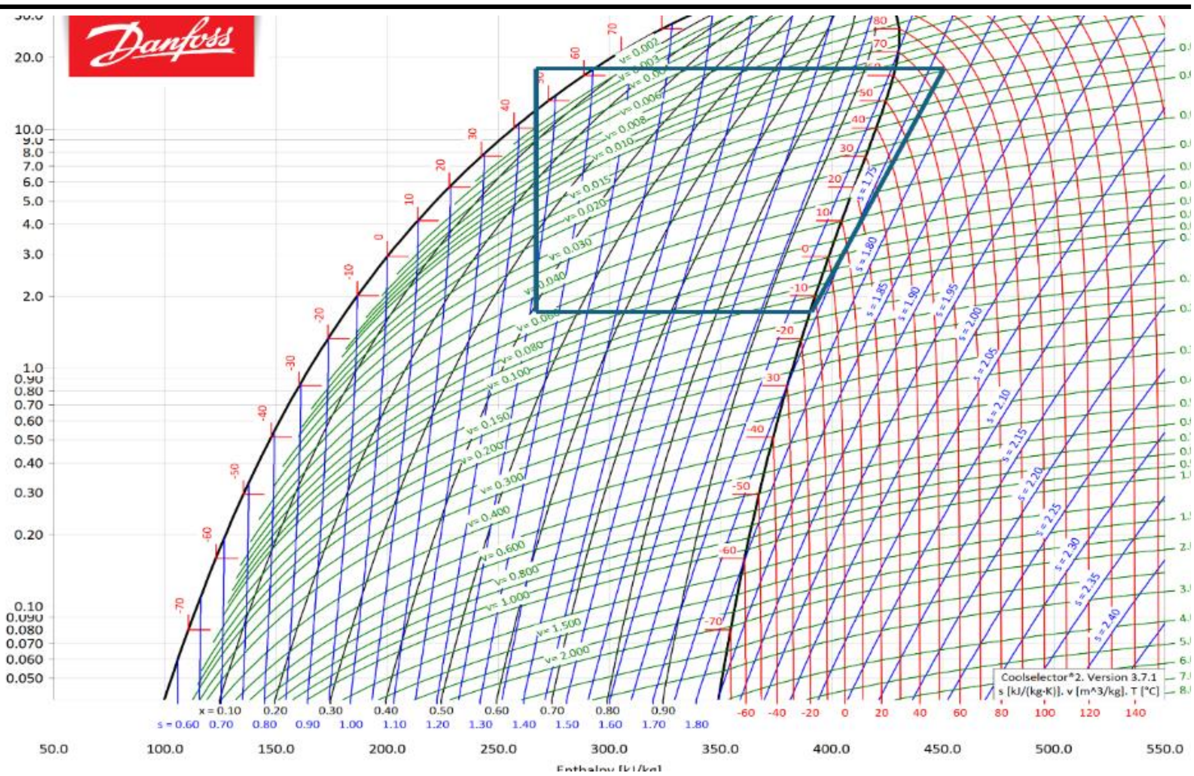
Observations were conducted on the refrigeration system for household use of R134a and R600a as working fluids. During the operation, data was collected on key parameters, including temperature variations at different phases of the cycle compression, condensation, expansion, and evaporation as well as the high and low pressures of the compressor. The recorded data, as shown in Table 2, was then analyzed to assess the performance of each refrigerant under operational conditions, providing insights into their efficiency and overall effectiveness in the system. The data, as shown in Table 2, was then plotted on a P-h diagram to determine the enthalpy at each stage of the refrigeration cycle, as shown in Figure 2. Afterward, the results were presented and discussed in this section.

Table 2. Measurements result of the experiment

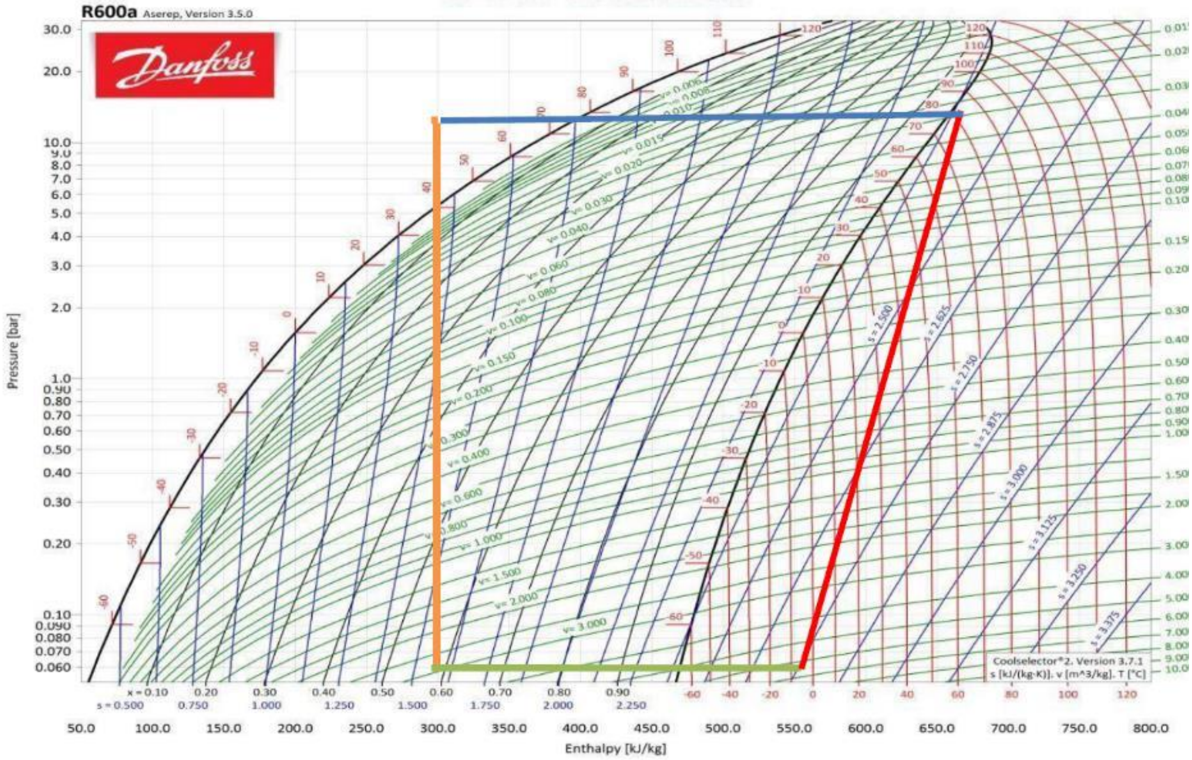
Parameters	Unit	R134a		R600a	
		Without Load	With Load	Without Load	With Load
P_1	Bar	16	17	16	17
P_2	Bar	1.71	1.57	0.06	0.1
T_1	°C	-6	-6	-2	-4
T_2	°C	75	81	83	90
T_3	°C	42	42.5	41.5	41.5
T_4	°C	-14	-16	-13	-15



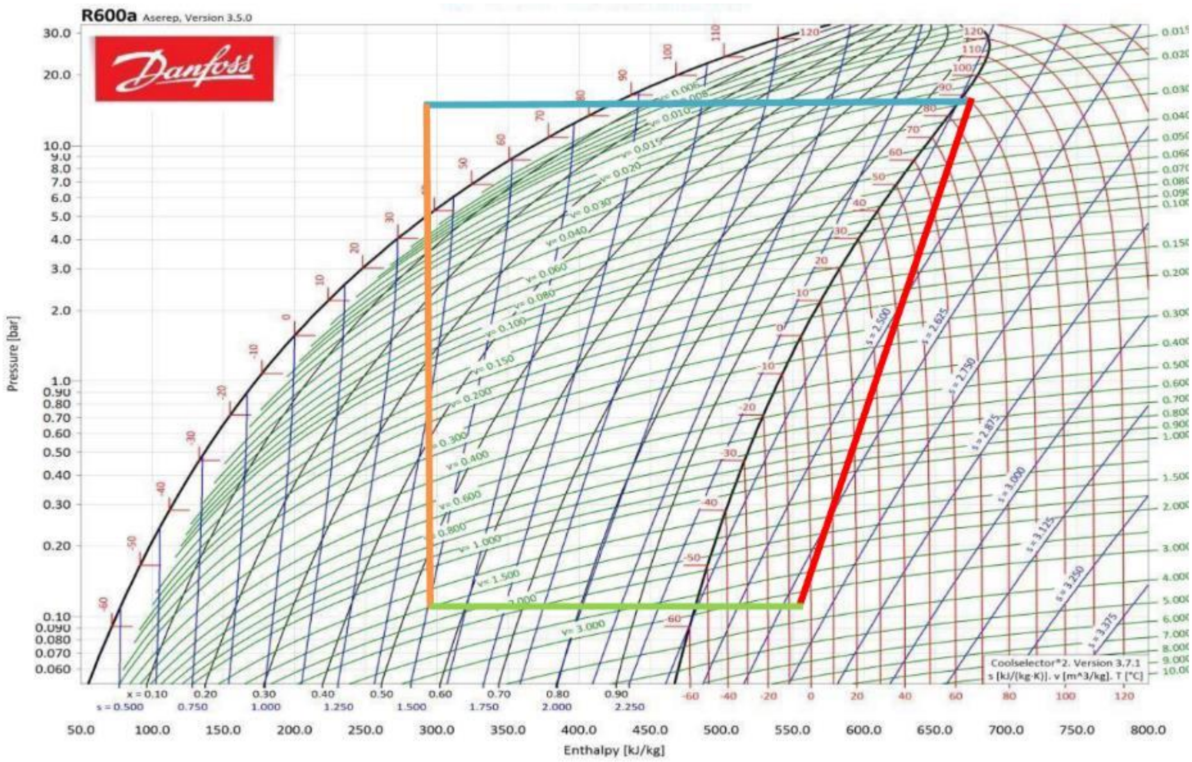
(a) R134a refrigeration cycle without load



(b) R134a refrigeration cycle with a 4 kg chicken meat load



(c) R600a refrigeration cycle without load

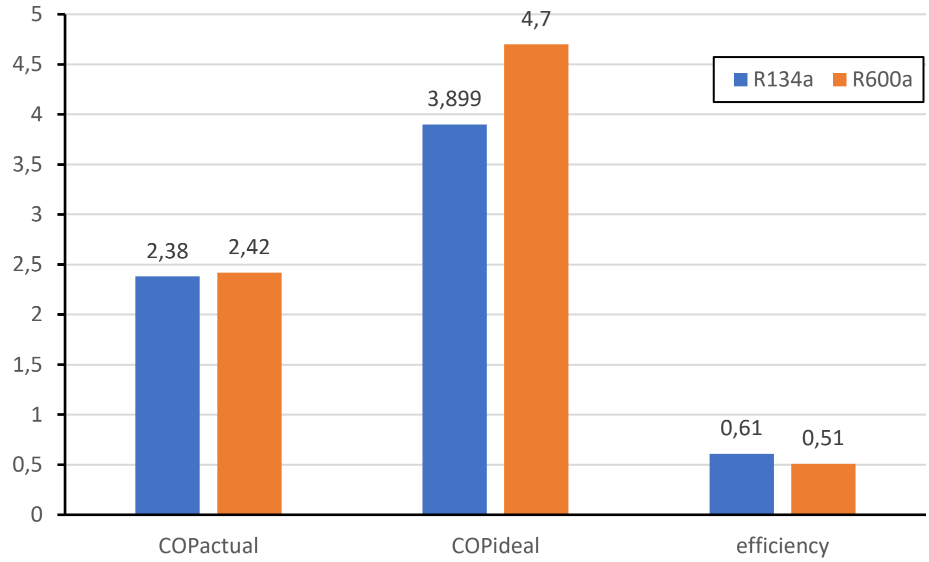


(d) R600a refrigeration cycle with a 4 kg chicken meat load

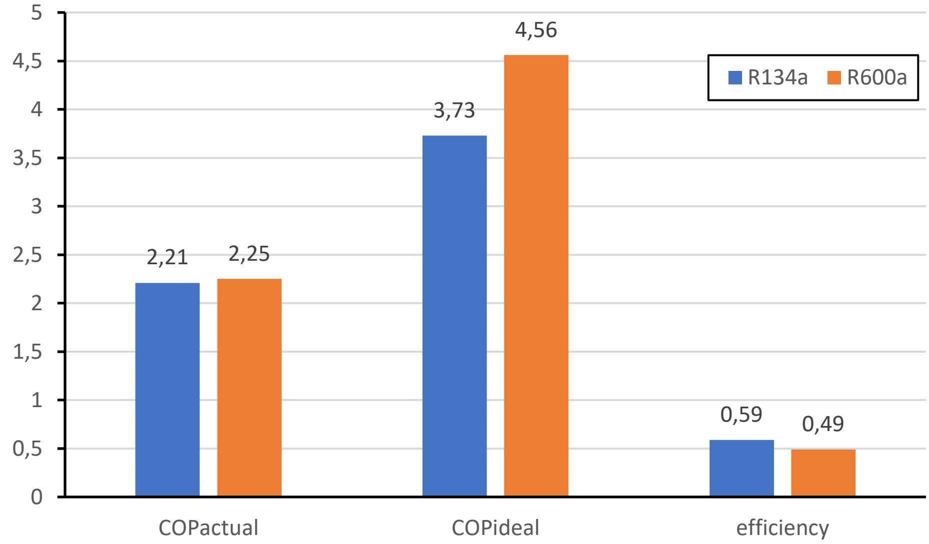
Figure 2. P-h diagram of the refrigeration cycle for R134a and R600a under different operating scenarios.

Figure 2 presents the experimental measurement results for R134a and R600a under both no-load and load conditions, illustrating their behavior regarding pressure (y-axis) and enthalpy (x-axis). The pressure-enthalpy diagrams indicate that refrigeration systems with a minor enthalpy difference between the evaporator and condenser typically exhibit lower efficiency [32]. The analysis reveals that R600a has a larger enthalpy difference across the evaporator, leading to a higher refrigeration effect and improved cooling performance.

Furthermore, refrigerant pressure levels influence system efficiency, as higher pressures may indicate increased refrigerant temperatures or less effective heat transfer. Compared to R134a, R600a generally operates at a lower pressure for similar enthalpy values, suggesting reduced compressor workload and better overall thermodynamic efficiency. Additionally, R600a has a higher critical temperature and pressure than R134a, which can enhance its performance under specific operating conditions. Since the coefficient of performance (CoP) is directly related to the refrigeration effect and inversely related to compressor work, a refrigerant with a higher CoP is considered more energy efficient. The results suggest that R600a offers superior thermodynamic performance, making it a more efficient alternative to R134a in household refrigeration applications.



(a) Without load



(b) With load

Figure 3. Comparison of R134a and R600a parameter conditions under different operating scenarios.

Figure 3 illustrates that the ideal Coefficient of Performance (COP) is significantly higher for refrigerants under no-load conditions, with R134a at 3.899 and R600a at 4.7. R600a demonstrates superior performance, suggesting its higher efficiency in ideal conditions. However, the efficiency values are relatively close, with R134a at 0.61 and R600a at 0.51, indicating that both refrigerants have similar efficiency levels, though R134a appears slightly more efficient in the no-load scenario.

Despite R134a exhibiting slightly better efficiency without load, R600a outperforms R134a in actual and ideal COP across all operating conditions. This suggests that R600a offers better overall thermodynamic performance. The efficiency reduction under load for both refrigerants highlights the impact of operational conditions on system performance, with R134a experiencing a smaller efficiency drop. Using R600a resulted in a 4% increase in efficiency under no-load conditions and a 7% increase under load compared to R134a. Similarly, the actual COP of R600a increased by 5% and 10%, respectively, in the same conditions. The COP of R600a was found to be 40.86%–46.54% higher than that of R134a, further reinforcing its superior performance. Additionally, using R600a led to a 3%

reduction in compressor energy consumption compared to a standard R134a domestic refrigeration system [33].
The results also indicate that the test conditions for R134a may have been overcharged. Compared to the study by Qureshi and Bhatt, where evaporator temperatures reached -25°C for R134a and -28°C for R600a, the current study recorded lower temperatures of -16°C and -15°C, respectively. Overcharging can cause excessive refrigerant accumulation, increasing discharge pressure and elevated condenser temperatures. This negatively affects heat rejection, reducing the condenser's effectiveness and decreasing system performance.

4. CONCLUSION

A comparative study was conducted on household refrigeration systems using R134a and R600a as working fluids under two operational conditions: no load and a cooling load inside the refrigerator compartment. The analysis of pressure-enthalpy diagrams revealed that R600a exhibits a larger enthalpy difference across the evaporator, resulting in a higher refrigeration effect. Furthermore, the lower operating pressure of R600a reduces compressor work, leading to an improved coefficient of performance (CoP), indicating that R600a is a more energy-efficient refrigerant than R134a. For future work, actual electricity consumption should be measured using a power meter to assess real-world energy efficiency, and the effect of varying refrigerant charge amounts should be investigated to determine the optimal operating parameters.

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