Faculty of Natural and Applied Sciences Journal of Applied and Physical Sciences
Print ISSN: 3026-9857
www.fnasjournals.com
Volume 3; Issue 1; March 2026; Page No. 44-56.
DOI: https://doi.org/10.63561/japs.v3i1.1182

Performance Analysis of a Vapour Compression Cooling Box Using Refrigerants R134a, R290 and R600a for Outdoor Activities

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Abstract

The increasing participation in outdoor recreational activities has intensified the demand for effective food and beverage preservation under elevated ambient temperature conditions. However, this demand raises concerns regarding the environmental implications of conventional cooling technologies. This study evaluates the performance of a sustainable and energy-efficient 500 L outdoor cooling box, with particular emphasis on the coupled effects of ambient temperature variations and refrigerant thermophysical properties on overall refrigeration performance. The study analysed the performance of the three refrigerants across varying ambient temperatures, representative of different locations, mainly Lagos, Jos and Mambilla Plateau in Nigeria. Results indicate a decline in COP, mass flow rate, cooling capacity and increasing power consumption with rising condensing temperature for all refrigerants at the evaporating temperature of -50C. At the evaporating temperature of -50C, it was observed that at the lowest condensing temperature of 300C, the COP is highest in the three refrigerants but the reverse is the case at 600C. At -5°C evaporating temperature and 30°C condensing temperature, R600a has the highest COP (3.7), followed by R134a (3.3) and R290 (2.9). R290 demonstrates the highest cooling capacity (0.57 kW) at -5°C, followed by R134a (0.55 kW) and R600a (0.52 kW). Despite requiring higher condensing temperatures of 60oC for optimal COP, R600a exhibits the lowest power consumption (0.19 kW/kW of refrigeration), likewise R290, compared to R134a (0.24 kW/kW) power consumption R134a's high mass flow rate (12.3 kg/h) implies larger compressors and possible higher energy use in hot conditions, compared to R600a (6.7 kg/h) and R290 (6.6 kg/h). The study highlights the importance of considering ambient temperature when designing and selecting refrigerants for outdoor cooling applications. It study reveals how high ambient temperature results in decreasing performance (COP, mass flow rate and cooling capacity) as it is difficult to achieve lower condensing temperatures at this condition. In hotter climates, R600a's efficiency at moderate condensing temperatures might be advantageous. However, R290's robust cooling capacity could be more valuable in regions with extreme heat fluctuations.

Keywords: Cooling box, COP, Refrigerants, Modelling, Small-Scale Cooling, Vapour Compression

Introduction

A cooling box is a mini refrigerating system that is used to keep food, beverages and drinks at low temperatures. These boxes, compared to their refrigerator counterpart, are good choices for outdoor activities such as picnics, camping and many others because of their portability, off-grid capabilities andease of transportation. It is designed to be cost-effective and used at places where energy supply is inefficient. Refrigeration of food is accomplished by various methods such as vapour compression refrigeration, vapour absorption refrigeration and thermo-electric or Peltier refrigeration (Bansal and Martin, 2000). Of these three, most refrigerating appliances globally use the vapour compression cycle. The vapour compression system has the lowest cost and is the most efficient refrigeration technology currently available for these appliances. This system operates on the principle of compression and condensation of an organic fluid (refrigerant). The refrigerant absorbs heat from a desired space, which makes it evaporate, and then the refrigerant is compressed and the absorbed heat released elsewhere. This cycle is crucial for maintaining low temperatures in refrigerated spaces and is employed in various applications,including household refrigerators, air conditioners, and industrial cooling systems. The efficiency of a refrigerator is closely tied to its ability to transfer heat from the inside to theoutside. Refrigeration appliances are estimated to consume as much as 6% of global electricity, which improving their efficiencies are important especially with respect to future climate change mitigation. It is imperative that the development of suitable energy policies to reduce energy consumption should begin with an understanding of key drivers of energy consumption. (Harrington *et. al*., 2018) Ambient temperatures, which refers to the surrounding environmental temperatures, are critical to the performance of refrigeration systems and directly influences the cooling process. Both high and low ambient temperatures have significant impact on the efficiency of refrigeration systems and performance (Ben Taher *et. al*., 2022). High ambient temperatures can negatively affect the efficiency of the refrigeration systems. When the ambient temperature is high, the performance of the condensing unit reduces and becomes harder dissipating heat into the environment. As a result, the condenser operates at a higher pressure, increasing the workload on the compressor, power consumption increases and the cooling capacity reduces.

The ambient temperature influences the amount of energy consumed by a cooling system as noted. The energy consumption of household refrigerating appliances is largely understood to be influenced by room temperature. However, there is paucity of data or analysis into the effects that changes in room temperature have on the energy consumption of these appliances. Moreover, earlier research into refrigerator energy consumption identified that ambient temperature was an important driver of energy consumption. (Harrington *et al*., 2018) The growing popularity of outdoor activities is met with the challenge of keeping food and beverages cool in increasingly hot ambient temperatures. This creates a conflict between enjoying these activities and the environmental impact of current cooling methods. Traditional coolants, like ice packs with chemical refrigerants, contribute to plastic waste, potential toxicity concerns and environmental pollution. Meanwhile, conventional refrigeration systems using HFC refrigerants like R134a, while prevalent, contribute to global warming. Finding sustainable and efficient cooling solutions for outdoor refreshment necessitates investigating alternative refrigerants with low environmental impact, like hydrocarbons R290 and R600a, while considering the influence of rising ambient temperatures on their performance and system efficiency.

Outdoor environments expose cooling boxes to varying ambient temperatures, directly affecting their performance. Studies show a clear correlation between higher ambient temperatures and COP reduction and increased condensing temperatures within the system. (Nicoletti *et al*., 2024; Hischier *et al*., 2020) hence, the ability of the box to extract heat and maintain low internal temperatures diminishes. This signifies the system requires more energy input to achieve the desired cooling capacity under hotter conditions. As ambient temperature rises, the system's cooling capacity generally decreases (Szyszka *et al*., 2020; Ghadiri and Rasti, 2014). This can lead to insufficientcooling, especially in critical applications. Higher ambient temperatures can cause the compressor to work harder, potentially leading to increased wear and tear and reduced lifespan (Fensel *et al*., 2017).

Refrigerants operate according to a specific pressure-temperature relationship (McLinden and Huber, 2020). Refrigerants work by extracting heat from the space to be cooled and releasing it to the environment through phase changes. They operate within specific temperature ranges, and variations can impact efficiency. Refrigerant properties change with temperature fluctuations, affecting boiling points and heat absorption. Higher ambient temperatures lead to increased refrigerant pressure, reducing its abilityto absorb heat and impacting the overall system efficiency (Nicoletti *et al*., 2024). Increased ambient temperatures can elevate the refrigerant's boiling point, hindering its ability to readily absorb heat fromthe cold space (Sharma *et al*., 2025). This can decrease cooling capacity and increase compressor workload. Higher ambient temperatures can also affect the refrigerant's viscosity, impacting its flow characteristics within the system (Ogbonnaya *et al*., 2023). This can lead to pressure drop variations and potential inefficiencies. Different refrigerants exhibit varying sensitivity to ambient

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temperature changes. Exploring alternative refrigerants like R290 and R600a might offer advantages in specific operating conditions (Ibrahim*et al*., 2024).

The investigation conducted by Saidur, *et al.* (2002) on two frost-free household refrigerator-freezers of the same capacity revealed that energy consumed by the Refrigerator-freezers is greatly affected by room temperature, door opening and thermostat setting position. Their results reveal that ambient temperature has a higher effect on energy consumption followed by door opening then thermostat setting.

The study investigates and assesses how ambient temperature as well as refrigerant properties both influences the efficiency of cooling boxes. The expectation is that cooling boxes should exhibit minimal energy consumption while achieving optimal cooling and the approach to this analysis is simulation. The temperature conditions of Lagos, Jos and Mambilla Plateau in Nigeria were considered.

Methodology

This study used the conditions of three geographically diverse locations in Nigeria: Lagos, Jos, and Mambilla Plateau. Lagos, with its coastal influence, experiences tropical maritime conditions, while Jos, situated at a higher elevation, encounters a more temperate climate. The Mambilla Plateau, known for its elevated terrain, introduces cooler temperatures, adding complexity to the analysis.

Figure 1: Average Temperature Distribution of Lagos

Figure 2: Average Temperature Distribution of Jos

Figure 3: Average Temperature Distribution of Mambilla

The graphs (Figure 1, Figure 2, and Figure 3) show the average temperature distribution of each location, (Lagos, Jos and Mambilla respectively) over the year 2023. The average temperature range in Lagos is between 75°F and 91°F (23℃ - 33℃). Jos, situated at a higher elevation, has a more temperate climate, with temperatures ranging from around 53℉to 92°F (11°C to 34°C). Mambilla Plateau, known for its elevated terrain, encounters cooler temperatures, ranging from approximately 53℉ - 82℉(11℃- 27℃) over the course of a year.

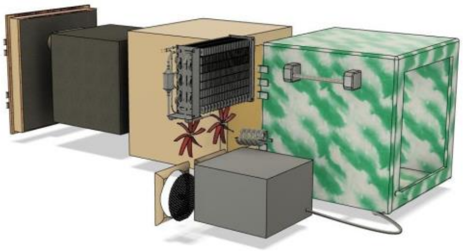

Figure 4: CAD Drawing of the Cooling Box

Selection of Refrigerants for the Design

Based on the following properties, toxicity, flammability, ODP and GWP, the three refrigerants selected for the design analysis are propane (R290), 1,1,1,2-tetrafluoroethane (R134a) and Isobutane R600a especially because they have the least GWP and zero ODP. Some other refrigerants like carbon dioxide (R744) and ammonia (R717) also have these qualities but they are not suitable for small applications like domestic refrigerators because they operate at high pressure. Ammonia is usually used in the vapour absorption refrigeration cycle. Though, it satisfies most of the required refrigerant properties, it is toxic, irritant and may catch fire. A comparison of the properties of the selected refrigerant is shown in Table 1.

The Table 1 shows the comparison between the properties of the three refrigerants of study. It is important to note that COP values can vary depending on operating conditions and equipment used. The refrigerants under scrutiny exhibit distinct temperature ranges and thermodynamic characteristics. R290, a hydrocarbon, R134a, a fluorocarbon, and R600a, an isobutane, each present unique boiling points and heat transfer capabilities crucial to the efficiency of the cooling box

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Table 1: Relationship between R290, R134a and R600a

Refrigerant	R290 (Propane)	R134a (Tetrafluoroethane)	R600a (Isobutane)
Application	Portable cooling boxes, commercial refrigeration	Household refrigerators, air conditioners	Portable cooling boxes, domestic refrigerators
Operating Pressure (High/Low)	5.2 MPa / 0.2 MPa	1.2 MPa / 0.1 MPa	1.0 MPa / 0.2 MPa
COP (Coefficient of Performance)	4.5 (High)	3.0 (Moderate)	3.5 (Moderate)
Latent Heat of Vaporization (kJ/kg)	426 (High)	243 (Moderate)	365 (Moderate)
Critical Pressure (MPa)	4.2 (High)	3.4 (Moderate)	3.7 (Moderate)
Thermal Conductivity (W/m·K)	0.19 (Moderate)	0.12 (Low)	0.16 (Moderate)
Global Warming Potential (GWP)	3 (Lowest)	1300 (High)	3 (Lowest)
Flammability	High	Low	Highly Flammable
Boiling Point	-42.1	-26.1	-11.7

Simulation

The simulation used the data from the design of the cooling box to analyse the impact and relationship between ambient temperature and the thermodynamic properties of three key refrigerants: R290, R134a, and R600a. The simulation was carried out to reveal the relationship between ambient temperature, refrigerant properties, and the optimal design of a cooling box tailored for outdoor activities, offering insights into the challenges posed by diverse climatic conditions.

The simulation was carried out using Danfoss cool selector software from the ambient temperature condition of 15℃ to 40℃. The condensing temperature is gotten by adding 15℃ to the ambient temperature. The evaporating temperature (-5℃) remains constant through the simulation because we want to achieve thesame desired cooling temperature of 0℃ at the various temperatures. The results revealed the interaction between the ambient temperature, the different refrigerants and the performance parameters of the refrigeration (COP, mass flow rate, energy consumption and cooling capacity).

Results and Discussion

The design results (Tables 2 to 4) and proposed adaptations provided a foundation for developing a cooling box capable of achieving 417W cooling capacity. Carefully selecting the materials and optimising the design parameters such as the lengths and diameters of the condenser, evaporators and capillary tube, the desired cooling capacity can be achieved.

Table 2: Design parameters of Cooling Box Design

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Mass Flow Rate	COP	Cooling Capacity	Power input to compressor
0.00345kg/s	3.38	0.42kW	0.13kW

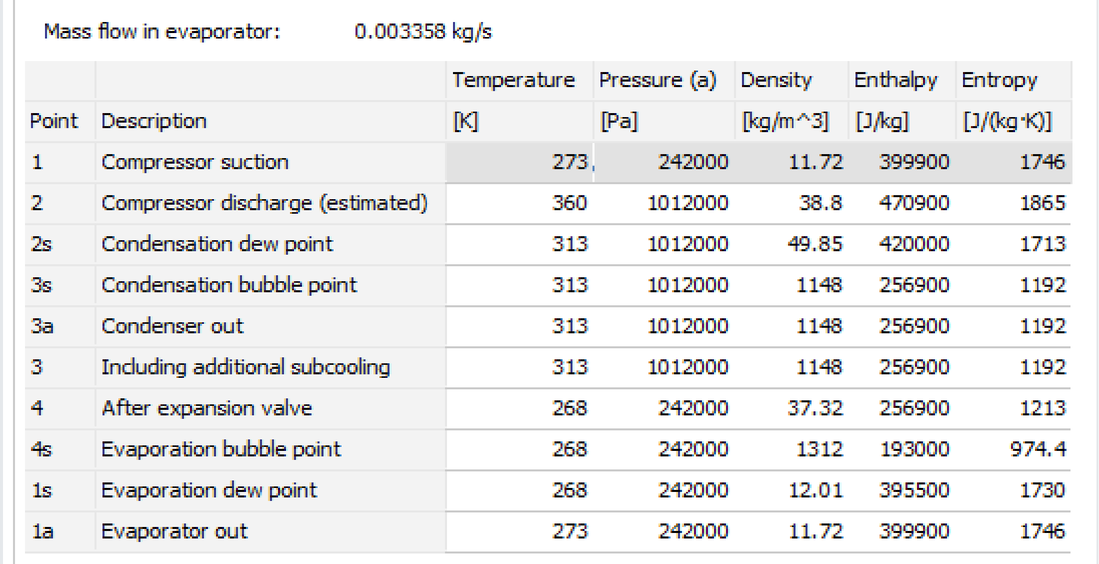
Table 3: Theoretical Cooling Box Design Results using refrigerant 134a

Process	*Point*	*Temperature T (^0C)*	*Pressure P (Kpa)*	*Enthalpy H (kJ/kg)*	*Entropy, S (kJ/kg.K)*	*Specific Vol. v (m^3/kg)*
Evaporation	1	-5	243.34	395.7	1.73	0.08280
Comp. Discharge	2	45.24	1168.8	436.88	1.73	0.00008
Condensation	2’	40	1016.6	419.43	1.711	0.01997
Throttling	3	40	1016.6	256.41	1.1905	0.0009
After Throttling	4	-5	243.34	256.41	1.21	0.0264

Simulations Result Using Cool Selector Software

Below are the tables and graphs that show the results of the simulation of the vapour compression cycle usingrefrigerant R134a.

Table 4: Result of thermodynamic property of refrigerant 134a from simulation



Mass flow in evaporator: 0.003358 kg/s

		Temperature	Pressure (a)	Density	Enthalpy	Entropy
Point	Description	[K]	[Pa]	[kg/m^3]	[J/kg]	[J/(kg·K)]
1	Compressor suction	273	242000	11.72	399900	1746
2	Compressor discharge (estimated)	360	1012000	38.8	470900	1865
2s	Condensation dew point	313	1012000	49.85	420000	1713
3s	Condensation bubble point	313	1012000	1148	256900	1192
3a	Condenser out	313	1012000	1148	256900	1192
3	Including additional subcooling	313	1012000	1148	256900	1192
4	After expansion valve	268	242000	37.32	256900	1213
4s	Evaporation bubble point	268	242000	1312	193000	974.4
1s	Evaporation dew point	268	242000	12.01	395500	1730
1a	Evaporator out	273	242000	11.72	399900	1746

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Figure 5: Cycle Diagram from simulation

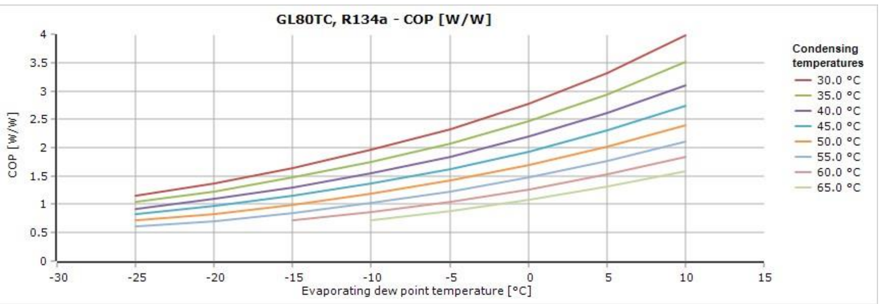


Figure 6: Graph of COP versus Evaporating and Condensation Temperature for Refrigerant R134a

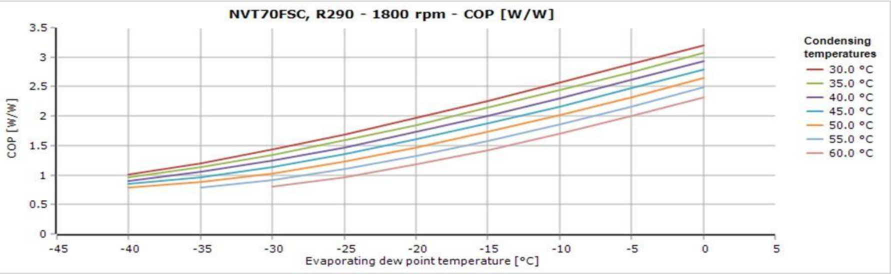


Figure 7: Graph of COP versus Evaporating and Condensation Temperature for Refrigerant R290

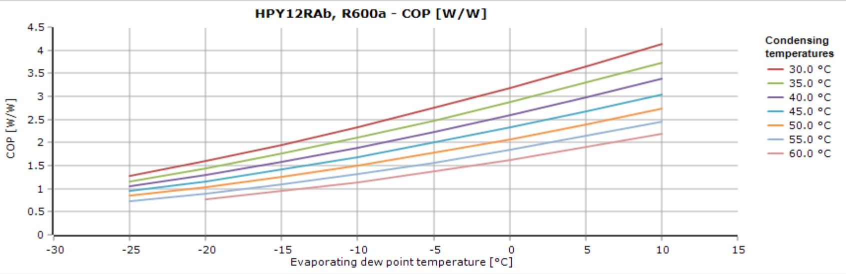


Figure 8: Graph of COP versus Evaporating and Condensation Temperature for Refrigerant R600a

Figures 6 to 8 show the graph of COP vs. evaporating temperature. The different line colours depict different condensing temperatures ranging from 30°C-60°C. At evaporating temperature of -5°C, it was observed that the lowest condensing temperature, 30^0C, has the highest COP in the three Refrigerants, with similar COP results of about 2.7 in both R134a and R600a, while

R290 has a COP of 2.9. It was revealed that the COP reduces with an increase in condensing temperatures. However, at 5°C, the COP of R600a was 3.7, while R134a has a COP of 3.35.

The simulations revealed that lower condensing temperatures lead to higher COP for all three refrigerants. In hotter environments like Lagos, achieving lower condensing temperatures might require larger or more efficient condensers, impacting size and cost. It can be observed that R600a exhibits the highest overall COP, particularly at lower condensing temperatures (30°C), making it potentially suitable for moderate Nigerian climates like Jos. At condensing temperatures beyond 40°C, R290 offers competitive COPs. R134a consistently shows the lowest COP across all tested conditions. This can be compared to Gardenghi *et al*., (2021), who, in their work, presented two transient mathematical models for simulating a vapour compression refrigeration system of a domestic refrigerator using R134a and discovered that ambient temperature augmentation by 18°C decreases refrigerator COP without thermal load in 10% and 16% for pull-down and on/off operations, respectively. Likewise, the experimental study of refrigerant mixing (Mohanraj *et al*., 2009) as a drop-in substitute for R134a. Mohammed and Theeb (2023) observed that the mixture of R600a and R290 (60:40% by weight) resulted in 16% higher coefficient of performance than R134a. The finding also aligns with the results of Yunus *et al*., (2016) as the COP of the system decreased when compressor speed increased because more work was used to compress refrigerant in the compressor.

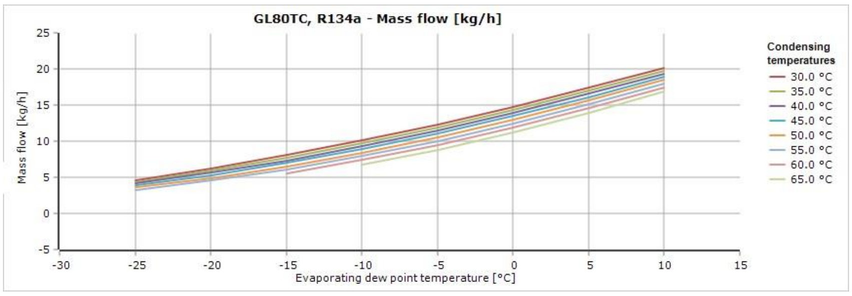


Figure 9: Graph of mass flow rate versus Evaporating and Condensing Temperature for

refrigerantsR134a

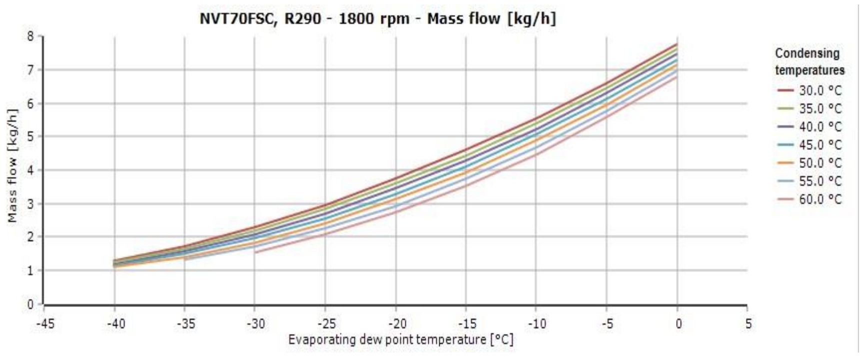


Figure 10: Graph of mass flow rate versus Evaporating and Condensing Temperature for refrigerantsR290

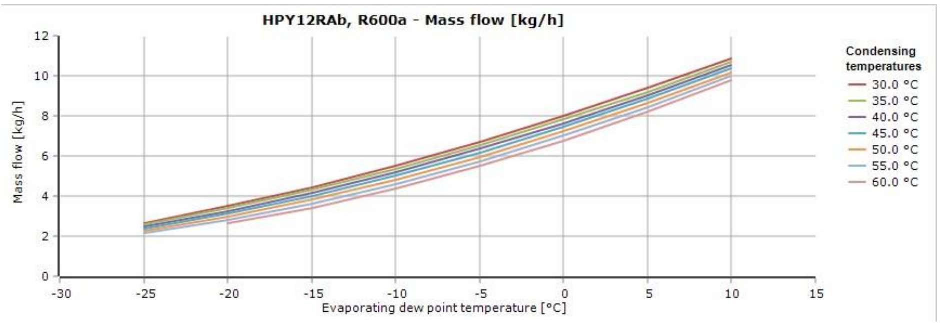


Figure 11: Graph of mass flow rate versus Evaporating and Condensing Temperature for refrigerantR600a

Figures 9, 10 and 11 present graphs of mass flow rate vs. evaporating temperature. It has been observed that at the lowest condensing temperature of 30^0C, the mass flow rate is highest in the three refrigerants. The mass flow rate for R134a is 12.3kg/h, for R600a is 6.7kg/h, and the flow rate is 6.6kg/h for R290 at the evaporating temperature of -5°C. R134a requires the highest mass flow rate, implying larger compressor size and potential energy consumption, particularly in hotter environments. R600a and R290 demand lower mass flow rates, suggestingpotential for smaller, more efficient compressors. It is observed that the rising evaporating temperature leads to an increase in the refrigerant mass flow rate supplied by the compressor, negating the condenser's reduction in specific heat rejected (Ariyo *et al*. 2017). In the comparison of cooling parameters of R134a and R290/R600a for a refrigeration cycle operating between temperature limits of 25^0C (evaporator temperature) and 42^0C (condenser temperature) Flow rate of R134a is higher than that of R290/R600a, which indicates its low evaporative specific heat.

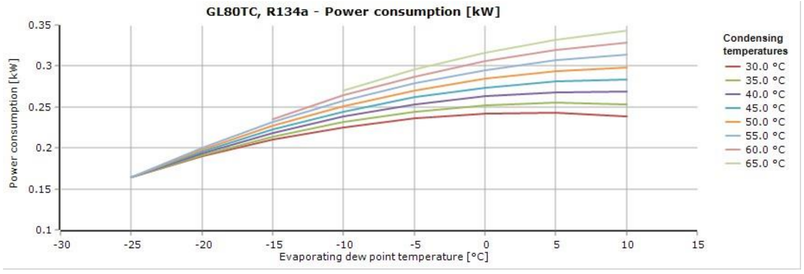
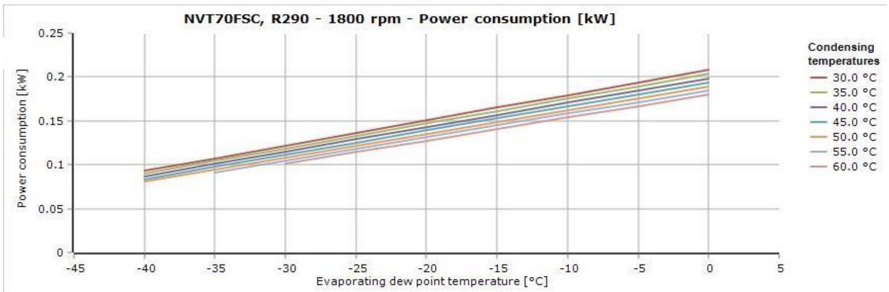


Figure 12: Graph of power consumption versus Evaporating and Condensing



Temperature forrefrigerants R134a

Figure 13: Graph of power consumption versus Evaporating and Condensing Temperature for refrigerants R290

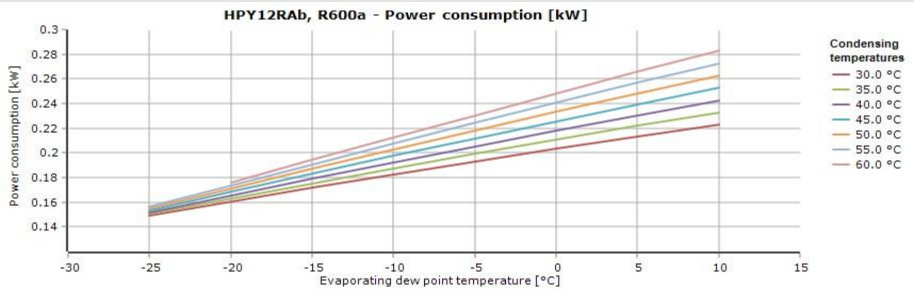
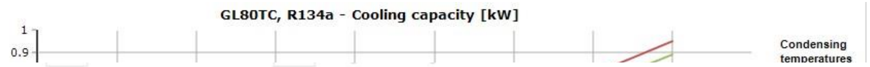


Figure 14: Graph of power consumption versus Evaporating and Condensing Temperature forrefrigerants R600a

Figures 12, 13 and 14 show the graph of power consumption vs evaporating temperature. For all the refrigerants power consumption increases with increasing condensing temperature. Despite requiring higher condensing temperatures for optimal COP, R600a exhibits the lowest power consumption of 0.19 per kw of refrigeration as well as R290 at evaporating temperature of $-5^{0}C\ and\ condensing\ temperature\ of\ 60^{o}C$ compared to R134a which consumed 0.24kW of power. This result can be compared to the experimental study of refrigerant mixing as a drop in substitute for r134a revealed that the mixture of R600a and R290 (60:40% by weight) resulted in25.8% lower power consumption than R134a n the same refrigerator at the same operating conditions (Mohammed & Theeb, 2023).

Figure 11: Graph of Cooling Capacity versus Evaporating and Condensing Temperature forrefrigerants R134a



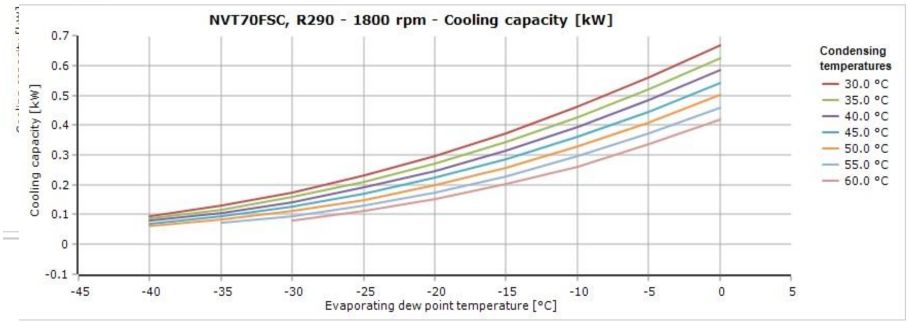


Figure 12: Graph of Cooling Capacity versus Evaporating and Condensing Temperature forrefrigerants R290

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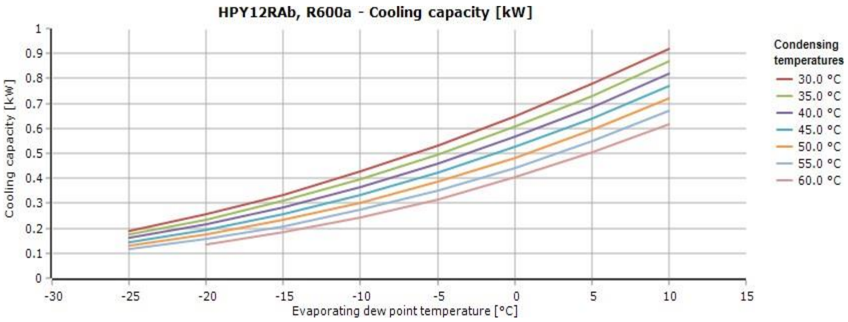

Figure 13: Graph of cooling capacity versus Evaporating and Condensing Temperature refrigerantsR600a

From the figures above, showing the graph of COP vs. evaporating temperature. The different colours ofline depict different condensing temperature ranging from 30^0C-60^0C. At evaporating temperature of -5^0C, it can be seen that at lowest condensing temperature 30^0C, the cooling capacity is highest in the three refrigerants, but reverse is the case at 60^0C. The cooling capacity was highest in R290 with avalue of 0.57KW followed by R134a with the cooling capacity of 0.55KW and the least is R600a with cooling the capacity of 0.52KW. At constant condensing temperature and evaporating temperature, the cooling capacity of the three refrigerants (R134a, R600a and R290) varies.

R290 delivers the highest overall cooling capacity, especially at lower condensing temperatures. R134aoffers slightly lower cooling capacity than R290 but surpasses R600a at higher condensing temperatures. This result compared to that of performance comparison of conventional vapour compression refrigeration system (VCRS) using various refrigerants such as R134a, R152a, R600a andR290 at evaporator temperature range of -30 °C to 10 °C and the condenser temperature range of 40 °Cto 45 °C. In this performance analysis it is seen that R290 shows favourable properties and can serve asbest refrigerant among all in the group.

Conclusion

This study represents a significant step forward in picnic cooling box offers a convenient and reliable solution for preserving food and maintaining optimal temperatures during outdoor activities. The analysis and proposed adaptations provide a solid foundation for developing a cooling box capable of achieving 420W of cooling capacity.The results showed the achievable mass flow rates, COP and cooling capacity of the design usingthe same parameters in both theoretical model and simulation. The simulated results were observed to slightly lower than the theoretical design predicted COP (3.38) and cooling capacity (0.42 kW) in comparison to the simulated results (COP: 3.3, Cooling capacity: 0.4 kW). This small discrepancy is likely due tosimplifying assumptions made in the theoretical calculations compared to the more complex thermodynamic model used in the software. Variations in refrigerant property data and simulation settings could also contribute. The overall trends across theoretical and simulated results remain consistent, providing confidence in the general conclusions drawn from your analysis. Considering the diverse locations which this research focuses on, as for Lagos, R600a might be a suitable choice due to its high COP at moderate condensing temperatures and potentially lower energy consumption. However, achieving lower condensing temperatures in high ambient conditions might require careful design considerations. As for Jos, R600a or R290 could be viable options depending onspecific needs. R600a's high COP at moderate temperatures and R290's lower power consumption offer different advantages. For Mambilla Plateau, R290's high cooling capacity and lower power consumption in cooler conditions make it a potential candidate. However, its flammability necessitatesadherence to safety regulations.

This study also revealed the comparative performance of R134a, R600a, and R290 refrigerants in the context of an outdoor cooling box. The findings align well with established knowledge and highlight the potential advantages of R600a and R290, particularly in terms of energy efficiency, compact design, and lower power consumption at specific operating conditions. This analysis suggeststhat R600a and R290 appear promising alternatives to R134a, offering improved COP, lower power consumption, and comparable or even higher cooling capacity in certain operating ranges. However, their flammability necessitates careful safety considerations and design adaptations. Furthermore,trade-offs exist between COP, cooling capacity, and operating temperatures, warranting careful consideration when selecting the optimal refrigerant for your specific design goals and priorities.

Finally, Future research should explore the integration of renewable energy sources, such as solar panels, to further enhance energy efficiency and achieve off-grid operation. Energy-efficient components like brushless DC motors for fans and compressors can also be used to minimize power consumption and maximize the impact of renewable energy sources.

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Cite this article as:
Layeni, A.T., Oresanwo, O.T., Nwaokocha, C.N., Olumomi, E.A., Poheto, D.J., & Sogbaike, S.O.(2026) Performance analysis of a vapour compression cooling box using refrigerants r134a, r290 and r600a for outdoor activities. *FNAS Journal of Applied and Physical Sciences*, 3(1), 44-56. https://doi.org/10.63561/japs.v3i1.1182