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Research article

Performance assessment of a refrigeration system with an integrated condenser under different environmental conditions

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a workable vapour compression system (VCS) for evaluating the performance of a refrigeration system with an integrated condenser that uses a long-term alternative refrigerant to halocarbon as a heat transfer medium (R600a). India's refrigeration system uses halocarbon refrigerants due to their excellent thermophysical and thermodynamic properties. Greenhouse gas emissions from halocarbon refrigerants and fossil fuel combustion contribute to global warming that engenders climate change and the deterioration of the ecosystem. The halocarbon refrigerant was discontinued based on high global warming potential. The system was investigated under various ambient temperatures of 16, 20, 24, and 28 °C (^{o}C). The performance of the VCS was analyzed using the parameters of coefficient performance, compressor work, and pull-down time (PDT). The experimental result shows that the vapour compression system obtained its best PDT, enhanced coefficient of performance, and energy reduction when the ambient temperature was 20 °C.

1. Introduction

The emission of greenhouse gases has created an unsafe environment, which poses a threat to the climate. A few decades ago, the domestic refrigeration system used conventional refrigerants, such as chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants, which were reported to have high global warming potential (GWP) and ozone depletion potential (ODP) [1,2]. The presence of chlorine and fluorine atoms in the emitted halocarbon refrigerant from a refrigeration system impacts the ozone layer and causes degradation of the climate. The compressors designed for CFC and HCFC refrigerants have a high volumetric capacity and the ability to consume an enormous amount of electricity compared to hydrocarbon refrigerants [3–6]. In the early 1990s, a new refrigerant was discovered with the promise of serving as an alternative to the existing conventional refrigerants. The refrigerant has a high GWP of 1430 while having minimal ozone depletion, a low boiling point, and good thermodynamic qualities. This constraint has led researchers worldwide to refocus their attention on alternatives to hydrofluorocarbons (HFCs). Researchers have recently been able to locate refrigerants that work better, allowing the heating, ventilation, and air conditioning (HVAC) industry to systematically employ refrigerants such as propane, carbon dioxide, butane, propylene, and isobutane. The regulatory agencies have stipulated

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deadlines for conventional refrigerants to go extinct. In most industrialized countries nowadays, hydrocarbon refrigerants are regarded as suitable substitutes for traditional refrigerants [7–10]. Extended heat transfer surface (EHTS) increases the heat transfer rate, which enhances the overall performance of the refrigeration system in addition to the refrigerant's remarkable impact. Three types of EHTS with layers of tubes joined by fins to aid in heat transfer include water-cooled, air-cooled, and evaporative. For the purposes of this study, a conventional refrigerator with an air-cooled condenser was utilized [11] investigated the effects of retrofitting a refrigeration system to accept various extended heat transfer surfaces. Using a liquefied petroleum gas (LPG) mixture of 17.2% isobutane, 56.4% butane, and 24.4% propane as the refrigerant, the diameter of the fin spacing was varied from 2, 4 and 6 mm. The refrigeration system performance was enhanced with the fin spacing of 2 mm by 28.8% and 39.5%, respectively, compared with when the system operated with 4 and 6 mm fin spacing. The system with the fin spacing of 2 mm had energy reduction of 16.4% and 18.7%, compared to 4 and 6 mm fin spacings [12]. a theoretical approach was used to access a domestic refrigerator in order to replace hydrofluorocarbon (R134a) refrigerant due to the system's combined features, which include the same specific volume characteristics, low global warming, and zero ozone depletion. The rate of heat transfer increased because the refrigerant mixtures had higher latent heat contents than R134a. The findings demonstrate that R440a and R451a blends, which are alternative refrigerants, perform better than R134a by 14 and 5%, respectively [13]. did a study on a designed refrigeration and air-conditioning system by comparing aluminum alloy and copper materials using the conventional refrigerant R134a. The heat transfer rate and condenser performance were evaluated with Ansys software, and the results showed copper material performed excellently compared to aluminum alloy but became disadvantageous due to its weight [14]. studied three different kinds of condensers: air-cooled, evaporative, and water-cooled. There was a decrease in the pressure of the system when an evaporative condenser was employed, and this was due to the use of a spray approach to increase heat rejection. Energy savings and coefficient of performance were improved when the refrigeration system was operated using an evaporative condenser [15]. carried out tests on a conventional refrigeration system that was retrofitted to accommodate isobutane (R600a). The findings showed that the hydrocarbon refrigerant performed better than conventional refrigerant in terms of rate of heat transfer, energy consumption, coefficient of performance (COP) and pull-down time that is the time required for the refrigeration system to attain its lowest temperature. The COP increased by 32.2% and had energy reduction of 4.5% using hydrocarbon refrigerant (R600a).

[16] did a review of the development of variable refrigerant flow systems which was published in 2019. Further research reveals the need for energy efficiency and control strategies, as well as alternate refrigerants, uses, design, optimization, and problem detection and diagnosis. Due to their simplicity of maintenance, installation, control, and improved part-load performance, variable refrigerant flow systems have gained acceptance in both residential and commercial applications. Conversely, the performance was hard to understand because of its inflexible framework. Consequently, policymakers, academics in the field, and product creators may find a solution in the study's conclusions. Because hydrofluorocarbon refrigerant has a large GWP and damages the ozone layer [17], studied the performance of a refrigeration system that employs a combination of new and synthetic pure chemicals as a drop-in for hydrofluorocarbon refrigerant because of its high propensity to cause global warming, which is detrimental to the ozone layer [18]. did a study on the effect of a thermostat as a regulator to control the cooling effect of a domestic refrigerator as a food-preservative household appliance. Consequently, an inappropriate temperature condition enhances the rate of food-borne outbreaks. The test revealed that the thermostat setting, not the load, type, or age of a refrigerator, is the most important factor for the cooling effect. It creates the conditions for food contamination during the food chain experiment [19]. evaluated a refrigeration system's performance employing an air-cooled condenser using an experimental assessment and mathematical model. The investigation was performed in both forced and natural settings in order to allow the condenser to reject heat. An axial fan with a maximum speed of 4.6 m/s was used, and the result shows that the heat transfer rate from the condenser and coefficient of performance were increased by 36.5 and 33.43%.

This work focused on investigating the use of a domestic refrigerator with an integrated condenser that uses a hydrocarbon refrigerant (R-600a) as its working fluid in different environmental conditions. The configuration of the system used for this study does

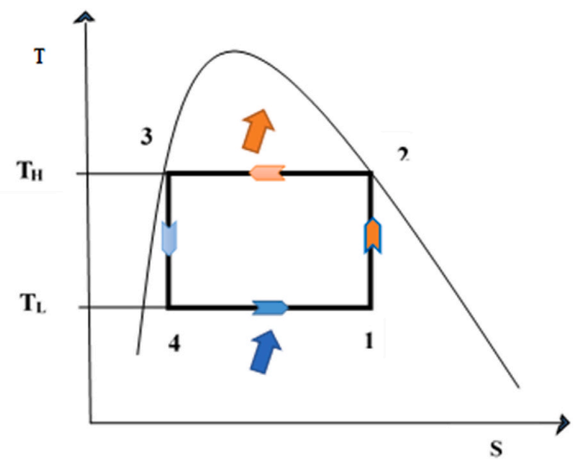

Fig. 1. T-S diagram for a refrigeration system.

not require external factors such as an axial fan to operate; it works using natural convection, which helps avoid excessive energy consumption. Moreover, the system requires a lower refrigerant mass charge of 20 g to operate compared to other systems that use a conventional refrigerant as their heat transfer medium. Heat transfer within the refrigeration system could be improved by introducing heat enhancers such as nanoparticles and increasing the extended heat transfer surfaces to further investigate the system's performance at the same ambient temperatures. Thus, the heat transfer processes are represented by the temperature-entropy (T-S) diagram as shown in Fig. 1. The four processes are required to attain the stabled performance of a vapour compression refrigeration system, and the governing equations are (1) to (5) [20].

1.1. Isobaric heat absorption at the evaporator

From Fig. 1, stage 4 to 1 is the evaporation region and isobaric heat absorption, the low pressure and temperature refrigerant turns vapour due to the latent heat absorbed (LH) at the evaporator chamber at constant temperature and pressure. Equation (1) shows the LH absorbed in the evaporator by the refrigerant. The phase change from stage 4 to 1 is due to the work done on the refrigerant.

1.2. Isentropic compression at the compressor

The vapourized refrigerant from the evaporator undergone isentropic compression from stage 1–2 using reciprocating compressor. Equation (2) describes the work done on the refrigerant as well as the rate of heat transfer that results to stage 2, which is the superheated state.

1.3. Isobaric heat rejection at the condenser

The stage 2–3 is condensation region and an isobaric heat rejection process that is heat emitted to the surrounding due to condensation, which occurs due to the inter-phase of the surrounding air and the refrigerant that passes through the heat exchanger (condenser). And this provide access for the working fluid to attain stage 3, which is the sub-cool state, The heat loss is established by equation (3).

1.4. Isenthalpic expansion at the capillary tube

The isenthalpic process (stage 3–4) is assumed to be adiabatic process, that is refrigerant is assumed not loss or gain heat, where the enthalpy at the condenser exit is the same as the enthalpy of the evaporator inlet ($h_3 = h_4$). At this expansion region, pressure reduces drastically as the refrigerant moves from stage 3–4 due to the expansion of the gas.

Heat absorbed in the evaporator:

$$Q_e = \dot{m}(he_1 - he_4)\ \text{kW} \tag{1}$$

Compressor work:

$$W_c = \dot{m}(hc_2 - hc_1)\ \text{kW} \tag{2}$$

Heat rejected at the condenser:

$$hcond = \dot{m}(hc_2 - hc_3)\ \text{kW} \tag{3}$$

where,

W_c is work done by the compressor
Q_c is heat rejected at the condenser
hc_2 is enthalpy of a vapourized refrigerant leaving the compressor and entering the condenser (kJ/kg).
hc_3 is enthalpy of condensed refrigerant leaving the condenser and entering the capillary tube (kJ/kg).
$\dot{m}$ is refrigerant mass flow rate (kg/s).
Q_e is latent heat absorbed at the evaporator
he_1 is enthalpy of vapourized refrigerant leaving the evaporator and entering the compressor (kJ/kg).
he_4 is enthalpy of the low pressured refrigerant leaving capillary tube and entering the evaporator (kJ/kg).
COP is coefficient of performance
R.E is refrigerating effect

1.5. Experimental details

A vapour compression system with a volume capacity of 69 L was set up as a test rig in a standard room size of 6.71 by 8.53 ft. The refrigeration system operates with 20 g of a hydrocarbon refrigerant, and the choice of the refrigerant was due to its miscibility with mineral oil, which enhances the performance of the system and also possesses a low global warming potential of less than five with zero ozone depletion potential. The thermophysical properties of the refrigerant, which enable the determination of the workability of the refrigeration system, as shown in Table 1. There are four primary components associated with the domestic refrigerator: a compressor, a condenser, an evaporator and a capillary tube. The ambient temperatures were conditioned after each experiment with the use of a 1.5-hp split air-conditioning system as the environmental control device, and systematically, the refrigeration system's performance was evaluated. Each of the experiments was carried out at a three-day interval to determine its average temperature at different ambient temperatures. The research system includes an inbuilt condenser and various mechanical instruments, such as a suction pump, which was used to clear the system and prevent clogging. The pressure at the compressor's suction and discharge points was measured using a manifold pressure gauge, and the amount of refrigerant that needed to be charged into the refrigeration system was calculated using a digital weighing scale. The energy meter was employed to gauge the compressor's power input. As seen in Fig. 2, K-type thermocouples were affixed to every component in order to monitor and document their temperatures. The mechanical devices' values were recorded every 15 min throughout the 5 h while the experiment was conducted.

2. Results and discussion

The coefficient of performance (COP) under various operating environments is shown in Fig. 3. When operating at 20 °C ambient temperature, the system's COP increased by 4.9%, 6.8%, and 15.9% in comparison to operating at 16 °C, 24 °C, and 28 °C ambient temperature, respectively. Equation (4) was used to determine the COP [11].

$$COP = \frac{he1 - he4}{hc2 - hc1} \tag{4}$$

Fig. 4 shows the variation of power consumed by the compressor while the vapour compression system works under different environmental conditions, using an eco-friendly refrigerant as the working fluid. The ambient temperature was conditioned and the system has its best performance at 20 °C with a corresponding reduction in energy of 2.6%, 6.3%, and 14.8% compared to when the ambient temperatures were at 16, 24, and 28 °C respectively. The compressor power input was determined using equation (5) [20].

$$Wc = \frac{R.E}{COP} \tag{5}$$

The time it takes the evaporator to reach its lowest temperature (ET) under various environmental circumstances is known as the pull-down time of the vapour compression system (VCS), as shown in Fig. 5. Based on this "pull-down" study, the refrigeration system will take a certain amount of time to reach its optimum cooling impact. At 20 °C, the system reached its optimal PDT.

A scientific method was used to examine the performance of a vapour compression system that was subjected to varying ambient temperatures. The findings demonstrate optimal evaporator temperatures at a 20 °C ambient temperature, which improved the VCS's pull-down time, COP, and compressor work. The performance of the refrigeration system significantly decreased at 16, 24, and 28 °C, indicating the impact of environmental factors on the vapour compression system's performance characteristics. Furthermore, to illustrate the impact of power on the refrigeration system's cooling capability, many mechanical charts of compressor power input (CPI) versus evaporator temperatures (ET) were plotted.

Fig. 6 depicts the thermodynamic profile of a refrigerating system as the compressor's takeoff power is relatively high because more energy is required to actuate the compressor from an idle state, and as the system gradually works, the power decreases with little irregularity due to the surrounding air temperature of 16 °C, while the cooling effect steadily increases compared to when the system operates at 24, and 28 °C.

Fig. 7 reveals a similar increase in the compressor's takeoff power but with a power output trend that favours the refrigeration system when working at an ambient temperature of 20 °C and a progressive reduction in energy consumed by the compressor as the evaporator temperature was enhanced compared to when the system operates at an ambient temperature of 16, 24, and 28 °C.

Fig. 8 displays the effect of compressor power input on evaporator temperature at a surrounding air temperature of 24 °C. The ET consistently improved, but there was little or no significant reduction in energy due to the environmental control, which made it less efficient compared to when the refrigeration system worked at 16 and 20 °C.

Fig. 9 shows the downward trend in the operation of the refrigeration system as the evaporator temperature decreases due to the interphase of environmental conditions on the refrigeration system at an ambient temperature of 28 °C and no significant energy reduction during the system's operation.

Table 1
Thermophysical properties of refrigerants [21,22].

Refrigerant	R600a	R134	R12
Name	Isobutane	Hydrofluorocarbon	Dichloro-di-fluoro-methane
Formula	$(CH_3)_3CH$	CF_3–CH_2F	CCl_2F_2
Critical temperature	135	101	112
Normal boiling point	−11.6	−26.5	−29.8
Molecular weight in kg/k mol	58.2	102	120.9
Liquid density (kg/I)	0.60	1.37	1.47
Pressure at −25 °C in bar (absolute)	0.58	1.07	1.24
Vapour density at 25/+32 °C in kg/m^3	1.3	4.4	6.0
Volumetric capacity at 25/55/+32 °C	373	658	727
Enthalpy of vaporization ion at −25 °C (KJ/kg)_	376	216	163
Pressure at +20 °C (bar)	3.0	5.7	5.7

Fig. 2. Experimental set up of the refrigeration system.

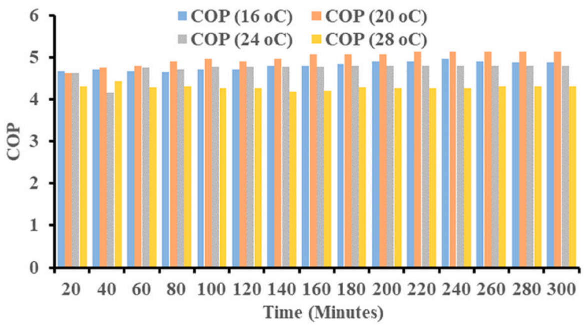

Fig. 3. COPs at four cases of ambient temperature.

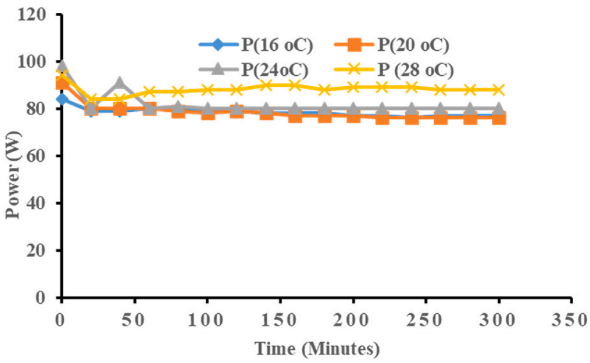

Fig. 4. Compressor power at four different ambient temperatures.

3. Conclusion

The effectiveness of a vapour compression system with an integrated condenser using hydrocarbon refrigerant (R600a) as the working fluid under various environmental conditions was assessed in this study. The objective is to increase the coefficient of performance relative to the amount of energy consumed by the refrigeration system. The ambient temperature is important for having the most efficient and best-performing refrigeration system. Results obtained with experimental analysis were captured and compared at different ambient temperatures, including 16, 20, 24, and 28 °C. The refrigeration cycle performed excellently when the ambient temperature was 20 °C. For further experimental work, the rate of heat transfer within the system can be enhanced by some additives, such as nanoparticles, either chemically or biologically. Conclusively, the effect of the surrounding air temperature is significant for the

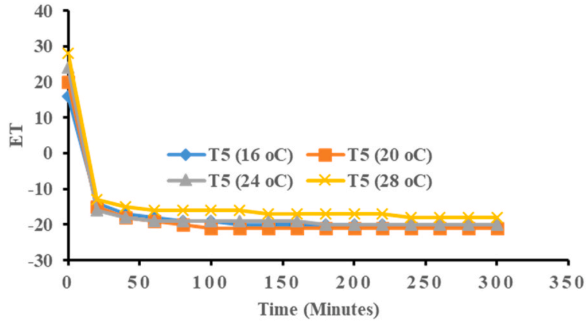

Fig. 5. Pull down time at four different cases of ambient temperature.

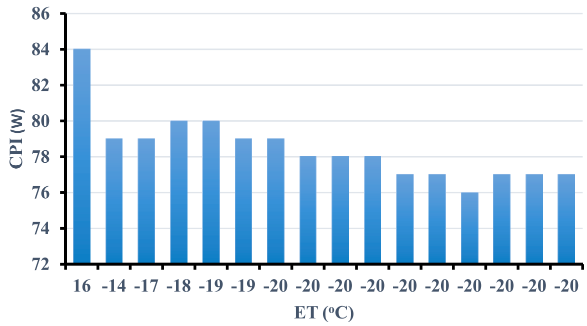

Fig. 6. Effect of power input on ET at 16 °C ambient temperature.

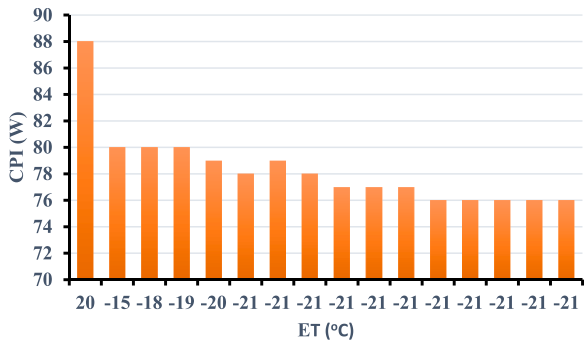

Fig. 7. Effect of power input on ET at 20 °C ambient temperature.

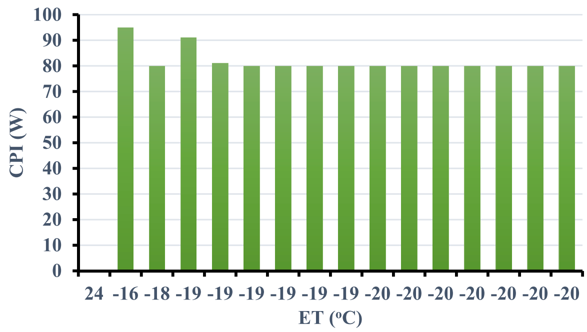

Fig. 8. Effect of power input on ET at 24 °C ambient temperature.

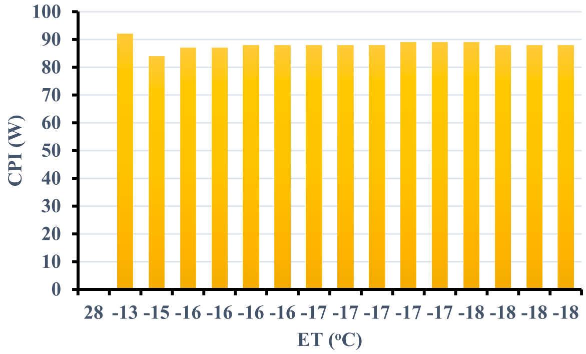

Fig. 9. Effect of power input on ET at 28 °C ambient temperature.

performance of a refrigeration system.

Data availability statement

The authors solemnly decided not to make the data available due to some logistics and further research work related to the manuscript. We sincerely regret any impact the decision may have.

CRediT authorship contribution statement

S.O. Banjo: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **B.O. Bolaji:** Supervision. **O.A. Oyelaran:** Validation. **P.O. Babalola:** Investigation. **A.S. Afolalu:** Software. **E.Y. Salawu:** Project administration. **M.E. Emetere:** Data curation.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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