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Experimental assessment of bio-nanolubricants on the performance characteristics of a developed refrigeration system using R600a

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Abstract. This study involved synthesizing biodegradable nanomaterials to formulate nanofluids for a vapour compression refrigeration system. The importance of the refrigeration system for household appliances cannot be overemphasized due to the preservation of perishable items such as vaccines, food, and beverages and the comfort it delivers in both developed and underdeveloped countries. Its high level of energy consumption has led to the optimization of the system using various techniques, such as increasing the surface area of the heat exchanger, utilizing low global warming potential (GWP) and zero ozone depletion potential (ODP) refrigerants, and applying heat transfer enhancers like nanofluids derived from organic waste to enhance the heat transfer properties of the working fluid (R600a) in order to improve the performance of the system by increasing the coefficient of performance (COP) and reducing energy consumed. Isobutane (R600a) was selected due to its ODP = 0 and GWP < 5. The energy consumption rate by the compressor during experimental evaluation is reduced, with an increased COP and a drop in the evaporator temperature. The results show that the COP of the refrigeration system using a concentration of 0.5 wt% bio-nanofluid performed excellently compared to the control and 0.1 and 1.0 wt%, with an increase of 61.7%, 24.3%, and 13.1%, respectively, while the lowest evaporator temperature (ET) was achieved in 120 minutes.

1 Introduction

The significance of the refrigeration system across the world today is critical due to its flexibility and multiple applications, and it contains four essential components, including the compressor, condenser, evaporator, and capillary tube (expansion valve). Qc represents the heat dissipated from the condenser, while Qe is the latent heat absorbed at the evaporator, which is generated from the substances to be cooled inside the evaporator chamber as indicated in Figure 1.

The high rise in energy consumption by the existing vapour compressor refrigeration system has demanded an energy-efficient system that serves as a substitute [1]. The working fluid contributed to the energy consumption rate due to operating pressure, heat transfer coefficient, and thermodynamic efficiency as shown in Table 1. In an attempt to secure a solution to the lower performance of vapour compression systems, the emergence of domestic refrigerators has, over the years, centered on the selection of different refrigerants [2]. This has solved the issue of nonperformance and unseemly energy consumption by the refrigeration system.

However, some refrigerants are not green, which poses havoc to the immediate environment. They have good thermodynamic properties but with a high global warming potential that negatively impacts the ozone layer [3]. Hydrofluorocarbons (HFCs) were discovered in the 1990s and became a substitute for conventional refrigerants such as chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC), with high GWPs of 8000 and 1500, respectively. Due to the excellent thermodynamic properties of HFC, it has become the predominant refrigerant used in most refrigeration systems in a few developed nations and developing countries. In 2019 and 2024, HFC refrigerants will be phased down in the refrigeration system in developed and developing nations, respectively, due to high global warming potential, which has risen to 1430 [4].

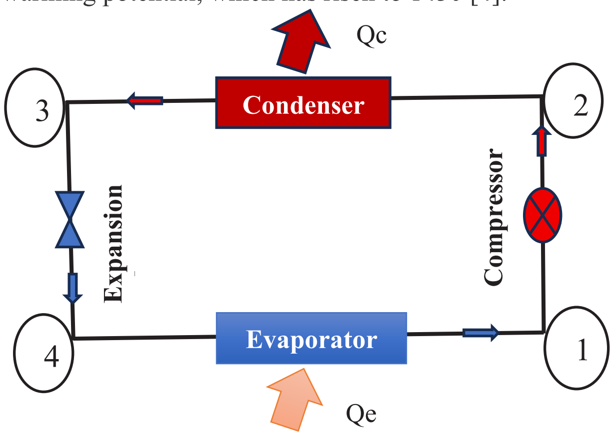

Fig. 1: A refrigeration cycle diagram

Natural refrigerants are serving as a substitute for halocarbon refrigerants, and this is due to the fact that hydrocarbon refrigerants (HCRs) are numbered among working fluids with zero ozone depletion potential and negligible global warming potential; they have high energy efficiency and are miscible with mineral oil, which enhances the performance of the compressor [5]. These characteristics make the hydrocarbon refrigerant preferred over halocarbon refrigerants such as HFC, CFC, and HCFC, which have high GWP and ODP, as shown in Table 1.

Due to the threat that halocarbon refrigerants pose to the climate, an agreement was made in 2016 under the Montreal Protocol framework pioneered by the United Nations Environment Programme (UNEP) for countries to adopt the Kigali Amendment to phase down working fluids with high GWP and ODP. The actual success of hydrocarbon refrigerants is the ability to use them in completely sealed systems of relatively low mass charge. HCR began to gain popularity in the mid-1990s and has different applications, such as domestic refrigerators, heat pumps, water heaters, and portable air conditioning, among others [6]. Subsequently, the refrigeration system requires further energy reduction, and this is obtainable using a heat-enhancing substance such as nanoparticles, which is suspended in a base fluid to form mixed substances known as nanofluids [7]. Inelastic technological development has prompted the immediate need for progress in nanoscience.

The concept of nanotechnology was first used by a scientist known as Norio Taniguchi in 1974. Consequently, in 1995, scientist Choi of Argonne Laboratory was the first individual to formulate nanofluids. Since this discovery, the research work in nanotechnology has increased significantly within the last decade, as the desire for energy savings and system efficiency is paramount [8, 9].

Nanofluids are the suspension of nanosized particles ranging from 1 to 100 nm in a base fluid such as polyol ester. Nanoparticles enhance the nanofluid's thermophysical properties, that is, thermal emissivity, viscosity, thermal diffusivity, thermal conductivity, and convective heat transfer coefficient. [10, 11].

The study enables the determination of the system's performance and enhancement of the heat transfer capacity of nanofluids in vapour compression refrigeration systems by involving organic nanoparticles derived from waste materials for stage-wise application and focuses on the enhancement of the vapour compression refrigeration system.

Table 1: Refrigerant performance [12]

Refrigerant Type	Energy Efficiency	GWP	ODP	Heat transfer capacity
R600a	Very High	3	0	Excellent
R134a	Moderate	1430	0	Good
R744	Variable	1	0	High
R410A	High	2088	0	Very Good
R290	Very high	3	0	Excellent
R32	High	675	0	Excellent
R717	Highest	0	0	Excellent
R12	Very high	10,900	1	Excellent
R22	Very good	1810	0.055	Good

2 Methodology

A developed experimental test rig was used to analyze the influence of synthesized bio-nanoparticles and refrigerant-600a on the energy performance of a refrigeration system. The materials for the system were locally sourced, as shown in Table 2. The nanoparticles were prepared from nanomaterial (mango peel) due to low cost and availability. They were washed with distilled water to reduce the chances of contamination with dust and dirt.

A two-step method was employed in synthesizing the nanoparticles by thermal decomposition of metal compounds. The rinsed organic materials were shade-dried for 30 days without direct contact with the sunlight. After the peels were absolutely dry, the materials were crushed into fine particulate matter using a mechanical grinder to enlarge the material surface area and improve extraction and dispersion of the nanoparticle. A liter of distilled water was added to 200 grams of each ground sample of mango peels, and the mixtures were boiled for one hour and thirty minutes on the hot plate to form an aqueous extract. The mixtures were sieved to separate the boiled mango peels from the aqueous solution.

Thereafter, 250 ml of the aluminium sulphate solution was poured into the extracts, and it was stirred at an interval of 1 hour to allow proper reaction with the organic matter, which enabled the bioactive compound to release electrons to the metal ions, resulting in a stable formation of solid nanoparticles, where the mango peel serves as a reducing agent to form metal nanoparticles. The reaction mixture was poured into centrifuge tubes and inserted into the centrifuge cup inside the centrifuge machine, and the operating speed was set to 4000 revolutions per minute for 30 minutes, which enabled the nanoparticles to separate from the supernatant. The nanoparticles were dried using a muffle furnace that operates at 75°C for 24 hours to remove moisture.

The synthesized nanoparticles were dispersed into the base fluid to form a homogeneous substance known as a ‘bio-nanofluid’ using an ultrasonic probe sonicator. The nanolubricant was observed for 30 days to discover if there is a separation between the nanoparticles and the base fluid. Since it was homogenized, the nanolubricant was charged into the compressor at different concentrations, and a refrigerant mass charge of 15 g of R600a was charged into the refrigeration system.

The performance of the system was evaluated by using various mechanical devices, such as a wattmeter and digital data logger, to determine the refrigerant temperatures at the condenser, evaporator, compressor, and capillary tube, while the wattmeter measured the energy intake by the compressor. Likewise, the digital manifold pressure gauge measured the suction and the discharge pressures of the compressor, and a vacuum pump was consistently used after each experiment to clean up the interior of the system before charging the same gram of refrigerant into the system for a separate concentration of bio-nanofluid. The use of a halogen leakage detector enables detection of leakages along the refrigeration cycle, as shown in Figure 2.

The thermophysical properties of the nanofluids were determined with equipment such as a pH meter and viscometer. The pH and viscosity of the bio-nanolubricant were 7.5 and 36 centipoises, respectively, which are within the range of a standard bio-nanolubricant. The performance metrics, including cooling capacity, compressor work, and coefficient of performance, were determined using the collected data during the experiment under an ambient temperature of 28 degrees Celsius.

The experiment was run repeatedly for three consecutive times for each concentration to evaluate the consistency of the system, and the average values were finally used for the system analysis. The performance characteristics were analyzed using equations 1 to 5 [13].

Fig. 2: Experimental test rig

2.1 Thermodynamic Analysis

In this experimental analysis, thermodynamic parameters were measured and evaluated on the vapour compression system under steady-state conditions.

2.1.1 Coefficient of performance (COP)

The coefficient of performance is the fraction of enthalpy change in the evaporator to the enthalpy change in the compressor, using the following thermodynamic analysis [14].

$$COP = \frac{\dot{m}(he_1 - he_4)}{\dot{m}(hc_2 - hc_1)} \quad (1)$$

Enthalpies are measured in (kJ/kg)
he_1 = enthalpy of the evaporator outlet
he_4 = enthalpy of the evaporator inlet
hc_2 = enthalpy of the compressor outlet
hc_1 = enthalpy of the compressor inlet
$\dot{m}$ = refrigerant mass flow rate (kg/s)

2.1.2 Evaporator refrigerating effect

The refrigerating effect is the difference between the outlet and inlet specific enthalpies of the evaporator.

$$RE = he_1 - he_4 \quad (2)$$

2.1.3 Compressor work input

Work input to the compressor is the product of the mass flow of the refrigerant and the specific enthalpy changes in the compressor.

$$hcomp = \dot{m}(hc_2 - hc_1) \quad (3)$$

Table 2: Materials for the development of VCRS

S/No	Description	Material Type
1	Cooler	Thermoplastic
2	Condenser	Steel tubing
3	Evaporator	Copper pipe
4	R600a Compressor	Composite
5	Capillary tube	Copper
6	Dryer	Copper
7	Huameiflex	Elastomeric nitrile rubber foam/Leather
8	Marine Board	Waterproof board
9	Charging Valve	Copper
10	Digital manifold pressure gauge	Composite
11	Digital data logger	Composite
12	Wattmeter	Composite

2.1.4 Condenser heat transfer rate

Heat rejected by the condenser is the product of the mass flow rate of the refrigerant and specific enthalpy changes in the condenser.

$$hc = \dot{m}(hc_2 - hc_3) \quad (4)$$

hc_2 = enthalpy of the condenser inlet
hc_3 = enthalpy of the condenser outlet

2.1.5 Mass flow rate of the refrigerant

The mass flow rate of the refrigerant is the fraction of the cooling load to the enthalpy change of the evaporator.

$$\dot{m} = \frac{Cooling\ load}{he_1 - he_4} \text{ (kg/s)} \quad (5)$$

2.1.6 Volume fraction of the bio-nanofluid

The volume fraction of the bio-nanofluid is the fraction of the volume of the dispersed component to the total volume of the mixture, as shown in equation 6 [15].

$$\phi = \frac{\frac{m_p}{\rho_p}}{\frac{m_p}{\rho_p} + \frac{m_f}{\rho_f}} \quad (6)$$

$\O$ = volume fraction
$m\rho$ = mass of the prepared nanoparticles
ρp = density of the prepared nanoparticles
mf = mass of the polyol ester
ρf = density of the polyol ester

3 Experimental Results

Fig. 3 shows the variation in the coefficient of performance of the vapour compression refrigeration system operating with the base fluid, also known as the control, and the synthesized different concentrations of bio-nanofluid extracted from mango peel *(Mangifera indica) using* an inorganic salt (aluminium sulphate). The comparative evaluation was conducted under the same ambient temperature of 28 ºC and a significant improvement was discovered when the bio-nanofluid was used as an alternative to the base fluid. 0.5 wt.% aluminium oxide nanoparticles dispersed in polyol ester performed excellently with an increase of 61.7, 24.3, and 13.1% COP compared to the base fluid, Al_2O_3/0.1 wt.% (M_P), and Al_2O_3/1.0 wt.% (MP), respectively. This performance enhancement of the system is based on the rate of heat transfer within the system. The results revealed that the application of a 0.5 wt.% concentration of bio-nanoparticles improves the performance of the vapour compression refrigeration system compared to the base fluid.

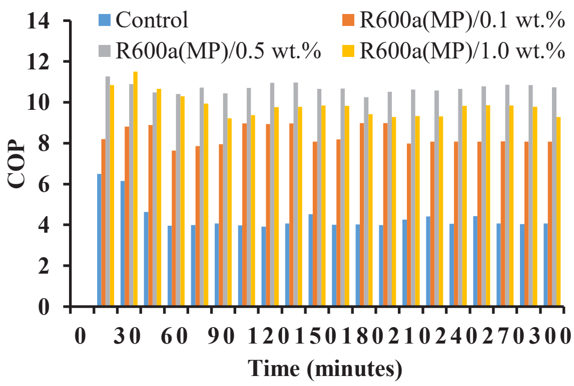

Fig. 3: Coefficient of performance with time

The effect of the synthesized bio-nanoparticles on the performance of the vapour compression system was significant, as shown in Fig. 4. The experiment was conducted using the base fluid and 0.1 wt%, 0.5 wt%, and 1.0 wt% concentrations of the bio-nanolubricant, and the system temperatures for the condenser, evaporator, capillary tube, and compressor were examined for a period of five hours using a digital data logger to monitor the accuracy of the values. The results show that the system operating with a 0.5 wt.% concentration of aluminium oxide nanoparticle performed better at 78.3, 43.5, and 21.7% compared to the base fluid, Al_2O_3/0.1 wt.% (M_P), and Al_2O_3/1.0 wt.% (MP), respectively. The refrigeration system attained a minimum evaporator temperature of -23 °C within 2 hours of operation.

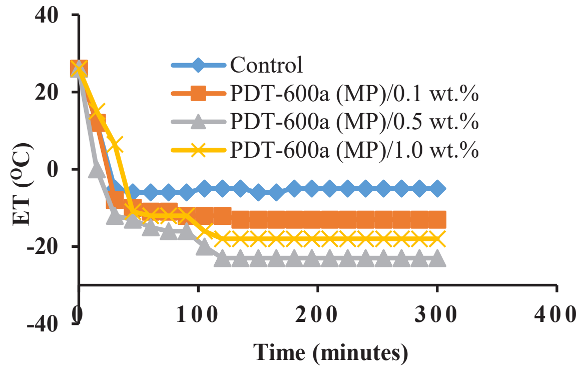

Fig. 4: Evaporator temperature with time

The compressor is referred to as the heart of a vapour compression refrigeration system, being a pivot to the entire system that pumps refrigerant across the system. The energy consumed by the refrigeration system absolutely depends on the power rating of the compressor and the refrigerant type. During the experimental analysis, the power consumed by the system was recorded when it worked with the base fluid and at different concentrations of bio-nanofluids, as shown in Fig. 5. It was observed that a 0.5 wt.% concentration of aluminium oxide nanoparticles (M_P), synthesized from mango peel, significantly caused a reduction in power consumption by the compressor compared to the base fluid, Al_2O_3/0.1 wt.% (M_P), and Al_2O_3/1.0 wt.% (M_P) at 17.9, 12.7, and 14.3%, respectively. This proffers a solution to the high energy consumption rate in existing refrigeration systems.

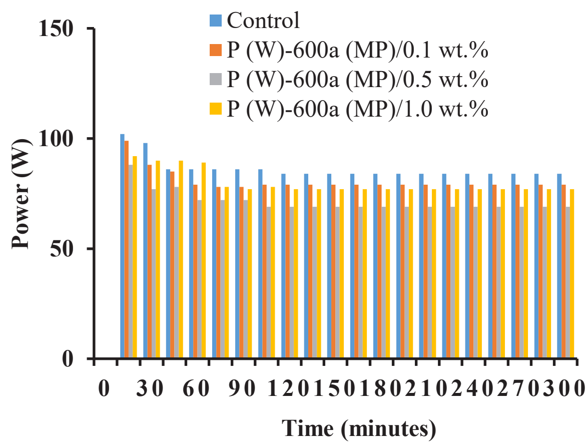

Fig. 5: Energy consumed by VCRS with time

4 Conclusion

This research work tends to solve the existing problems in the refrigeration systems by reducing the energy consumption rate by the compressor through the enhancement of the heat transfer rate within the refrigeration cycle with an additive of nanoparticles to a base fluid, which increases the thermal conductivity of the flowing fluids. More so, improving the performance characteristics of the system, such as coefficient of performance and cooling capacity. Likewise, the application of biological nanoparticles caused a reduction in energy consumption, which resulted in a reduction of greenhouse emissions that come from the power generation. The energy reduced significantly when the system operated with a concentration of 0.5 wt% of bio-nanofluid compared to the base fluid, 0.1 wt%, and 1.0 wt% of the bio-nanofluid, with an energy drop of 17.9%, 12.8%, and 10.4%, respectively. This becomes a platform for creating employment for the younger generation through large production and exploring various areas of application. Conclusively, it is clear that bio-nanofluid has an influence on the overall performance of the vapour compression refrigeration system.

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