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Article

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Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Babarinde, T. O.; Akinlabi, S. A.; Madyira, D. M.; Ekundayo, F. M. (2020) : Enhancing the energy efficiency of vapour compression refrigerator system using R600a with graphene nanolubricant, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 2, pp. 1-10,
<https://doi.org/10.1016/j.egy.2019.11.031>

This Version is available at:

<https://hdl.handle.net/10419/243850>

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The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019),
20–23 September 2019, Okinawa, Japan

Enhancing the energy efficiency of vapour compression refrigerator system using R600a with graphene nanolubricant

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Received 4 October 2019; accepted 22 November 2019

Abstract

The use of graphene nanolubricant to enhance the performance of eco-friendly refrigerant (R600a) in a vapour compression system was investigated. The graphene nanoparticles were dispersed in the base lubricant and prepared for three different samples of graphene nanolubricant concentration of 0.2, 0.4 and 0.6 g/L, the nanolubricant concentrations were investigated in 50, 60 and 70g of R600a refrigerant each. The performances were compared with the base lubricant (mineral oil). The result showed that R600a performed better in graphene nanolubricant compared to the base lubricant in terms of pull-down time, COP, power consumption, cooling capacity. Therefore, graphene nanolubricant can be used as a drop-in replacement for pure mineral oil in the vapour compression system.

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: GWP; ODP; COP; Power consumption; Graphene nanolubricant

1. Introduction

Natural refrigerants have been adopted as a substitute for hydrofluorocarbon (HFC) refrigerants in vapour compression system (VCRS) and R600a is one of them due to its lower Global Warming Potentials (GWP's) and zero The use of CFC refrigerants have been banned in domestic refrigerator worldwide due to its high GWP and ODP and replace with HFC refrigerants. R134a and HFC refrigerant as adopted to replace R12 in the domestic refrigerator due to its zero ODP. However, the GWP of R134a is still very high. According to the Montréal and Kyoto protocol Mota-Babiloni et al. [1] and UNEP [2] HFC refrigerants were listed among the chemicals that contribute to global warming. Consequently, a treaty was signed by the United Nation members to limit the use of

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Nomenclature

VCRS	Vapour compression refrigeration system
COP	Coefficient of performance
Q_{evap}	Cooling capacity (kW)
W_C	Compressor power input (kW)
h	Enthalpy (kJ/kg)
T	Temperature ($^{\circ}C$)
\dot{m}	mass flow rate (kg/s)

Subscripts

1	Compressor inlet
2	Compressor outlet
3	Condenser outlet
4	Evaporator outlet

HFCs and phase out HFCs by developed countries in 2020 and completely phase out HFCs in 2030 worldwide. Currently, the use of HFCs in domestic VCRS has been phased out completely in Europe. Since then, an effort has been geared towards the use of natural refrigerants in the refrigeration system. Hydrocarbon refrigerants have been adopted as of the refrigerants and Isobutene (R600a) is one of them. Numerous researchers have made effort to replace and improve the performance of hydrocarbon refrigerant in VCRS Agrawal et al. [3], Kasaieian et al. [4] and Oyedepo et al. [5] they all concluded that hydrocarbon refrigerants can serve as substitutes to R12 and 134a in vapour compression system.

The energy demand associated with refrigeration systems has made researchers think about new technology to enhance the energy efficiency of the refrigeration system Di Battista and Cipollone [6] through the introduction of nanotechnology. The two popular methods of introducing nanoparticles in refrigeration systems: one is by dispersing it in the base refrigerant while the other is by dispersing the nanoparticles in the base lubricant, this result into nanolubricant which eventually mix with the refrigerant in refrigeration system in operation. The application of nanotechnology in refrigeration systems is new and has started gaining attention. Dispersion of nanoparticles into the base lubricant general increase the transport properties of the refrigerant and subsequently efficiency of the vapour compression system. Apart from this, some nanoparticles are capable of improving lubricity and reducing wear in a system. Currently, R600a refrigerant is the most widely used refrigerant in domestic refrigerators. Therefore, there is a need for performance improvement of R600a in VCRS. Graphene nanolubricant can be a better improvement in this direction. The use of graphene nanoparticles has been renewed recently due to its characteristics like good mechanical strength, weak sliding forces that exist between graphene nanoparticles layers Rasheed et al. [7]. Graphene is capable of reducing friction energy consumption and also have good anti-wear properties when being used either as additives in lubricants Gupta et al. [8] and Mao et al. Zhao et al. [9]. The use of graphene nanoparticles as additives in the lubricant is gaining swift attention from researchers. However, the properties of nanoparticles that affect the performance refrigerant in refrigeration system depend on chemical and physical properties such as nanoparticles size, shape and concentration of the nanoparticles in the base lubricant.

Some researchers have reported on the use of nanoparticles as additives in lubricating oil. In the work of Wang et al. [10]. They conducted an experiment on fullerene (170) and NiFe₂O₄ nanolubricant and compared it with based lubricant in an air-conditioning system, the result showed a 23% increases in the COP of the system with a reduction in the wear and coefficient of friction Kumar et al. also studied the performance of Al₂O₃ in R600a. They reported improvement in the cooling capacity and also a decrease in the power consumption in the system compared to the based fluid. In the experiment of Melnyk [11] Al₂O₃ and TiO₂ nanoparticles were introduced into a mineral oil in a VCRS working with R600a. The result showed that Al₂O₃ and TiO₂ nanolubricant performed better in terms of thermal conductivity and viscosity in the system. Ghorbani et al. [12] also investigated CuO in polyester oil (POE) used in the refrigeration system. The CuO nanoparticle and POE mass percentage were varying from 0.5% to 1.5%. The resulting output was compared with the base lubricant, the result showed that the introduction of CuO

nanoparticles as additive to the POE yielded increase in heat transfer coefficient from the range of 4.1% to 13.7%. However, 1.5% mass percentage of CuO/POE offered the best heat transfer coefficient performance. Martorana et al. [13] carried out a study carbon nanofiber and graphene as additives in ethanol solution in order to improve the efficiency of gear operating on hydraulic circuit. The result showed that carbon nanofiber and graphene yielded a better pumping efficiency within 195–1500 ppm concentration range compared to pure ethanol solution. Miura and Ishikawa [14] also used graphene nanoparticles as an additive in grease in order to achieve improved lubricating performance compared to the based grease. The result showed a decrease in friction and wear in the experiment than the based grease. They conclude that the improvement was due to the antiwear and friction properties of the graphene present in the based grease. Zhang et al. [15] used oleic acid to modify liquid phase exfoliated graphene in lubricating oil. The result showed enhancement of 17 and 14% in the friction coefficient and wear respectively. Kinoshita [16] carried out an experiment of water base and graphene oxide nanoparticles-based coolant over a 60 000 cycle. It was found that surface wear was reduced and the coefficient of friction also decreased by 0.05.

Presently, there is more literature on the use of nanoparticles as additives in halogenated refrigerants which are not eco-friendly and also will soon be banned worldwide in the near future. However, this study considers the application of nanotechnology to enhance the performance of domestic refrigerator working with hydrocarbon refrigerants. Graphene nanoparticles have been selected for this present study. The use of graphene as additives in lubricant gives advantages such as stability, larger surface area, lower corrosion, clogging, and lower demand pumping power Sadeghinezhad et al. [17,18]. Also, R600a refrigerant has been chosen because of its most widely used refrigerant in the domestic refrigerator today. R600a is a clean refrigerant and for safety purpose, a maximum mass charge of 150 g has been recommended for use in a large domestic refrigerator. Different from existing literature, the graphene nanolubricant concentrations were varied and tested in various mass charge of R600a. This was done in order to reach a reasonable conclusion about the potency of graphene nanolubricant in enhancing the energy efficiency of a vapour compression system.

2. Experimental procedures

The experimental test rig used for this experiment is a domestic refrigerator primarily designed to work with 100 g R134a refrigerant. The system was evacuated and properly flushed with vacuum flusher. In this experiment, R600a refrigerant is considered because of its physical properties such as zero ODP and very low GWP. The maximum allowable mass charge for hydrocarbon refrigerants is 150 g due to its flammability. Because the refrigerator compressor was designed to work with 100 g of R134a. Therefore, the R600a refrigerant mass charges were varied within the range 50 g–70 g, this is due to the lower density of R600a compared to R134a. The base lubricant used for this experiment is 1 litre of mineral oil, the mineral oil was selected because of its compatibility with R600a and the refrigerator component materials. Graphene nanoparticles are used because of has larger contact area, high stiffness and aspect ratio which makes it have more outstanding thermal conductivity than other nanoparticles. The graphene nanoparticles used are 99.9% pure and 2 nm - 8 nm size as stated by the manufacturer (Aldrich) in Table 2.

In the preparation of the nanolubricant 1 litre of mineral oil was used to prepare three different samples of nanolubricant concentration of 0.2, 0.4 and 0.6 g/L. A digital charging scale was used to measure each of the nanoparticles. The nanoparticles were dispersed into the mineral oil. The graphene nanolubricants were stirred with the aid of magnetic stirrer for 45 min. An ultrasonic homogeniser was used to homogenised the nanolubricant mixture together for 3 h within the temperature range of 15 °C–20 °C according to Mahbulul et al. [19] when preparing Al₂O₃ nanolubricant for R134a refrigerant. Each graphene nanolubricant was tested in 50 g, 60 g, and 70 g mass charge of R600a. Fig. 2. shows the preparation flow chart of the nanolubricant while Table 3 shows the properties of the mineral oil used for the experiment.

The R600a refrigerant was charged into the system with the digital charging system. The inlet and outlet temperatures of each component (compressor, evaporator, condenser and capillary tube) of the system were taken. K-type digital thermocouples were employed to measure the temperature at each component inlet and outlet of the refrigerator components. Two pressure gauges (Bourdon gauge) were connected to measure the suction and discharge pressure of the compressor. Also, a digital Watt metre was used to measure the power consumed by the refrigerator compressor. The uncertainty of the measuring instruments used is shown in Table 1. The schematic of the experimental setup and condition are shown in Fig. 1 and Table 3. The power, pressure and temperature readings were recorded and repeated for five times at intervals of 30 min for a period 300 min. The temperature and pressure readings recorded were used to determine the performance of the system using the Ref-prop, version 9.0. These

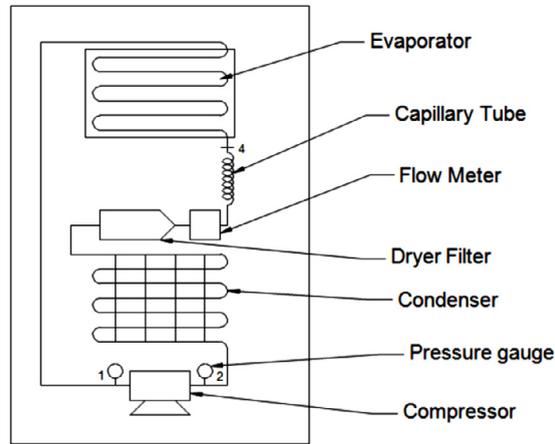


Fig. 1. Experimental setup.

Table 1. Measuring instrument and uncertainty.

S/N	Parameter	Specification	Range	Uncertainty
1	Temperature	Digital Thermocouple K	−50 °C–700 °C	±3 °C
2	Pressure	Bourdon gauge	0–2000 kPa	±1%
3	Power consumption	Digital Watt/Watt-h-metre	1–2000 W (0.0001–999.9 kWh)	±1%

Table 2. Nanoparticles information.

S/N	Type	Specification	Manufacturer
1	Graphene	2 nm–8 nm	Aldrich

results were analysed and compared with performance R600a refrigerant in the base lubricant in the system using Eqs. (1)–(3).

The system performance of the system was evaluated using Eqs. (1)–(3)

Cooling capacity (Q_{evap}) is capacity given by

$$Q_{evap} = \dot{m}(h_4 - h_1) \quad (\text{kW}) \quad (1)$$

The compressor power input is given by

$$W_C = \dot{m}(h_2 - h_1) \quad (\text{kW}) \quad (2)$$

Coefficient of performance

$$COP = \frac{Q_{evap}}{w_C} \quad (3)$$

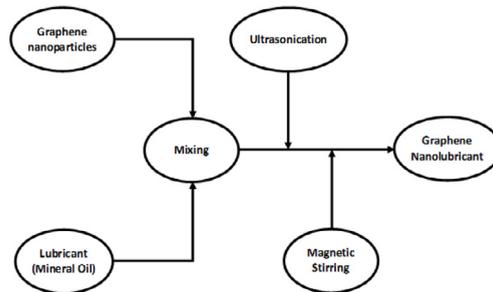
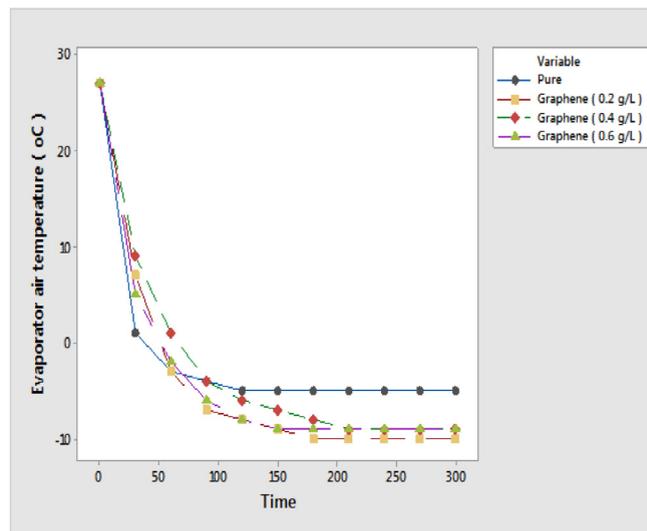
The uncertainty analysis

The uncertainties of the experiment were calculated using Eq. (4) where R is the desired parameter, U_R is denoting the total uncertainty, U_{vi} represents uncertainty the each independent and n represents the total number of the variables. The experimental uncertainty for T_1 , T_2 , T_3 , P_1 , P_2 and watt-matter are 0.2, 0.3, 0.3, 2.0, 4.0 and 0.4 respectively.

$$U_R = \left[\sum_{i=1}^n \left(\frac{\partial R}{\partial v_i} U_{vi} \right)^2 \right]^{\frac{1}{2}} \quad (4)$$

Table 3. Experimental conditions.

S/N	Parameters	Experimental range
1	Refrigerant mass charge	50 g, 60 g and 70 g
2	Refrigerant	R600a
3	Compressor lubricant	Pure lubricant, Graphene Nano lubricants
4	Graphene Nanoparticles	2 nm–8 nm
5	Nano-lubricant concentration	0.2 , 0.4 , 0.6 g/L
6	Test ambient temperature	27 °C
7	Capillary length	1.5 m
8	Condenser	Air-cooled
9	Evaporator capacity	70 L
10	Lubricant	Mineral oil
11	Density at 15 °C	0.914
12	Kinematic viscosity at 40 °C	32cSt

**Fig. 2.** Graphene nanolubricant preparation flow chart.**Fig. 3.** Effect of graphene nanolubricant on the pull-down time of 50 g R600a in the system.

3. Results and discussion

The comparison of the performance of the system at steady at states are discussed below: Figs. 3–5 and Table 4 depict the results of the pull-down time of the R600a in the base lubricant and graphene nanolubricant concentration. The pull-down time of a refrigerator system is the time required for the evaporator air temperature to achieve the desired steady state. The Figs. 3–5 shows that for 50, 60, and 70 g of R600a 0.2 g/L of graphene nanolubricant offer

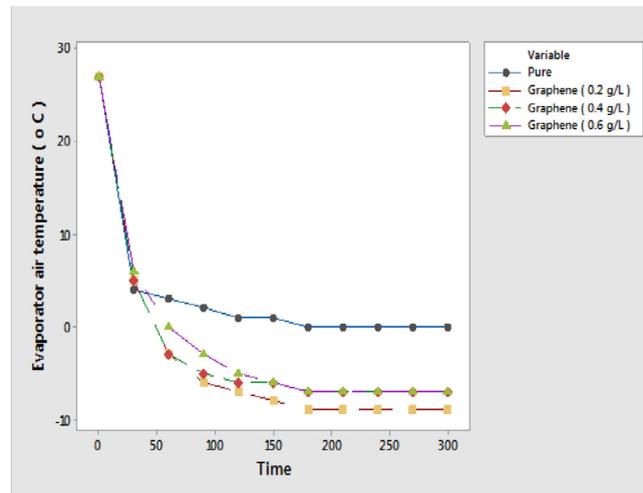


Fig. 4. Effect of graphene nanolubricant on the pull-down of 60 g R600a in the system.

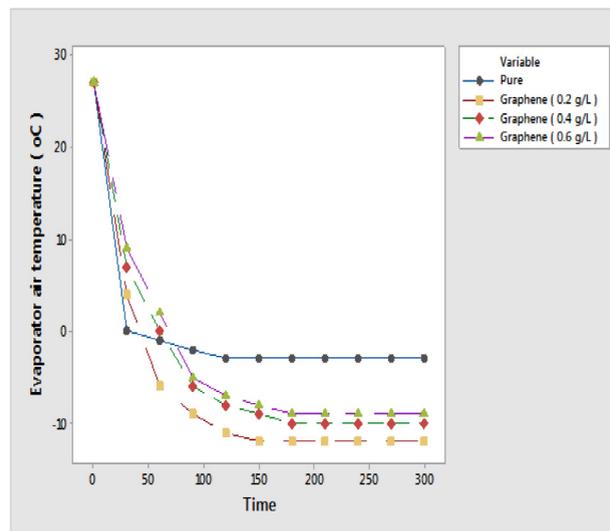


Fig. 5. Effect of graphene nanolubricant on the pull-down of 60 g R600a in the system.

the lowest pull-down time of 120, 150, and 180 min at -5 , -13 , and -9 °C. However, for every mass charge of R600a, graphene nanolubricant concentration offers a lower evaporator air temperature with a shorter pull-down time compared to the base lubricant. This result conforms to the results of Malvandi et al. [20] that cooling temperature is being enhanced with nanofluid compared to the base fluid in the cooling system. Also, this is as a result of enhancement in heat transfer and increase in critical heat flux of graphene nanoparticles in the lubricant compared to the base lubricant.

Fig. 6 shows the cooling capacity of the system at steady state. The cooling capacity of the graphene nanolubricant is higher than the base lubricant for every mass charge of R600a in the system. The cooling capacity of 50, 60 and 70 g of R600a in 0.2, 0.4 and 0.6 g/L of graphene nanolubricant concentrations increases within the range of 3.9%–8.5%, 5.1%–22.5% and 25.7%–33.4% respectively. The 50, 60 and 70 g mass charge of R600a in 0.2 g/L graphene nanolubricant offers the highest cooling capacity of 0, 1891, 0.2054 and 0.1887 kW in the system for every mass charge of R600a. Fig. 6 also shows that a very small amount of graphene nanoparticles is required in the base lubricant for effective cooling capacity in the system. Even at higher graphene nanolubricant concentration graphene nanolubricant still poses a higher cooling capacity compared to the base lubricant. The increase in the

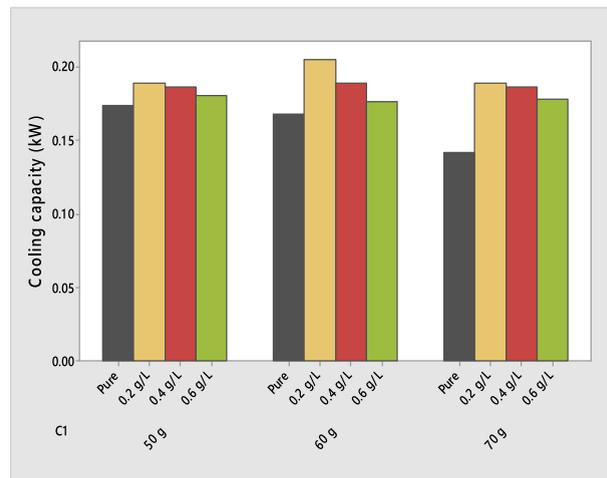


Fig. 6. Effect of graphene nanolubricant on cooling capacity the system.

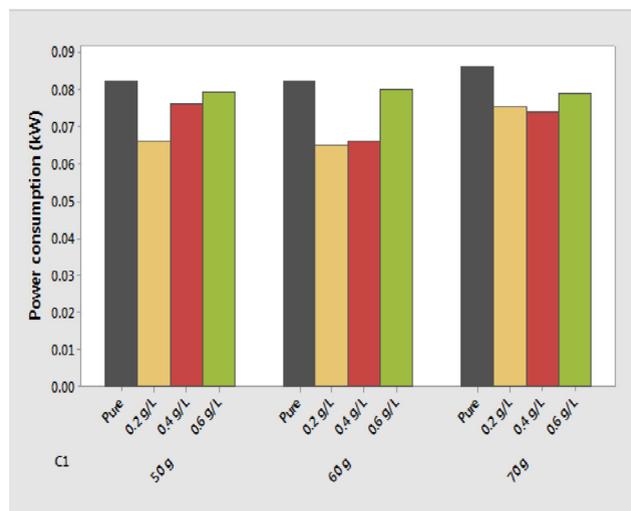


Fig. 7. Effect of graphene nanolubricant on power system.

cooling capacity is due to the higher thermal conductivity of the graphene nanoparticles, therefore increase in the heat absorbed by the system Sharif et al. [21].

Fig. 7 illustrate the effect of graphene nanolubricant on the power consumption of the system at steady state. For every mass charge of R600a in graphene nanolubricant concentration, the power consumption reduces until it reaches the optimal graphene nano concentration for each mass charge of R600a refrigerant in the system. The power consumption of 50, 60 and 70 g of R600a in 0.2, 0.4 and 0.6 g/L of graphene nanolubricant concentrations increases within the range of 3.1%–19.4%, 1.2%–20.7% and 1.2%–13.8% respectively with 60 g of R600a in 0.2 g/L graphene nanolubricant concentration offering the lowest power consumption of 0.0653 kW in the system. The result can be attributed to a reduction in pumping power compared to the base lubricant to achieve the same and better heat transfer Ahamed et al. [22]. The reduction in pumping power is also attributed to the tribological characteristic of the graphene nanoparticles.

Fig. 8 depicts the COP of the system. Graphene nanolubricant presents higher COP than the base lubricant. The COP of 50, 60, 70 g mass charge of R600a in graphene nanolubricant is higher and ranges from 2.3–2.9, 2.2–3.2 and 2.3–2.5 respectively compared to R600a in the base lubricant. The maximum COP enhancement of 3.2 was achieved at 0.2 g/L graphene nanolubricant concentration. The increase in the COP of the system is a result of

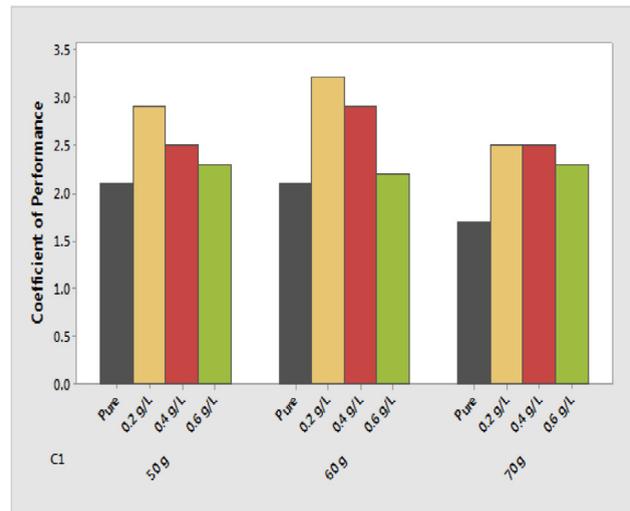


Fig. 8. Effect of graphene of nanolubricant on COP of the consumption of the system.

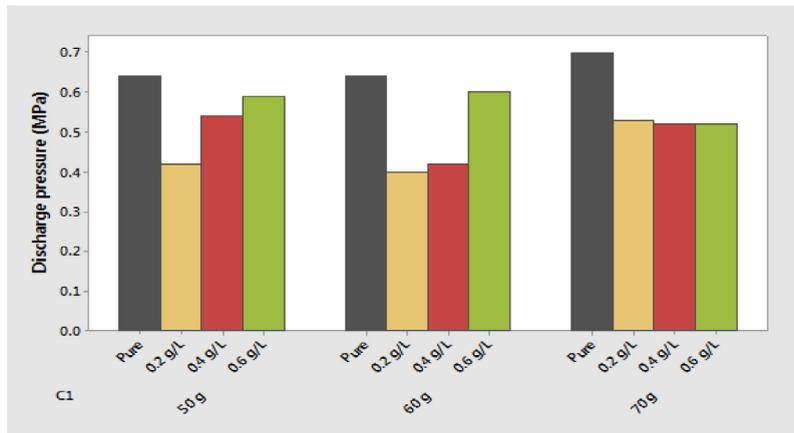


Fig. 9. Effect of graphene nanolubricant on the discharge pressure of the system.

a reduction in the power consumption and increase in the cooling capacity of the graphene nanolubricant in the system.

Fig. 9 depicts the discharge pressure of the system. The discharge pressure of the base lubricant is higher than the graphene nanolubricant. 0.2 g/L of graphene nanolubricant has the lowest discharge pressure in 50 g and 60 g of R600a. But a decrease in discharge pressure was experienced as the nanolubricant concentration increases for 70 g of R600a. This shows that the optimal graphene nanolubricant concentration for 50 g and 60 g of R600a is 0.2 g/L while the optimal graphene nanolubricant concentration for 70 g of R600a is within 0.4 g/L and 0.6 g/L nanolubricant. The discharge pressure of 50, 60 and 70 g of R600a in 0.2, 0.4 and 0.6 g/L of graphene nanolubricant concentrations decrease within the range of 7.8%–34.4%, 6.3%–34.4% and 24.3%–34.6% respectively compared to the base lubricant in the system. This can be linked to the antiwear and friction reduction properties of graphene in the compressor of the refrigerator system.

4. Conclusion

In this experimental investigation, the performance of graphene nanolubricant was evaluated and compared with base lubricant in a domestic refrigerator system through the cooling capacity, power consumption, and coefficient

Table 4. Summary of the experimental result of graphene nanolubricant in the system.

S/N	Refrigerant mass charge (g)	Nanolubricant concentration (g/L)	Pull downtime (minutes)	Evaporator temp. (°C)	COP	Power consumption (kW)	Cooling capacity (kW)	Mass flow rate kg/s	Discharge pressure (MPa)
1		Pure	120	−5	2.1	0.0821	0.1742	0.00075	0.64
2		0.2	180	−10	2.9	0.0662	0.1891	0.00071	0.42
3	50	0.4	210	−9	2.5	0.0762	0.1869	0.00077	0.54
4		0.6	210	−9	2.3	0.0791	0.1809	0.00077	0.59
5		Pure	120	−3	2.1	0.0821	0.1677	0.00071	0.64
6		0.2	150	−13	3.2	0.0651	0.2054	0.00077	0.40
7	60	0.4	180	−10	2.9	0.0661	0.1887	0.00071	0.42
8		0.6	210	−9	2.2	0.0801	0.1762	0.00075	0.60
9		Pure	180	0	1.7	0.0860	0.1415	0.00062	0.70
10		0.2	180	−9	2.5	0.0752	0.1887	0.00077	0.53
11	70	0.4	180	−7	2.5	0.0741	0.1868	0.00074	0.52
12		0.6	210	−7	2.3	0.0790	0.1779	0.00071	0.52

of performance (COP). The different mass charge of R600a refrigerant (50, 60, 70 g) was tested in different graphene nanolubricant concentration of 0.2, 0.4 and 0.6 g/L. Based on the experimental performance of the vapour compression system, the following conclusions were made for the use of graphene nanolubricant concentration in vapour compression:

- The graphene nanolubricants have the highest COP, with lower evaporator temperature than the base lubricant throughout in the refrigerator system which meets the ISO 8187 standard temperature of -3°C at 180 min. The power consumption is the lowest compared to based lubricant other graphene nanolubricant concentrations.
- The graphene nanolubricant concentrations of 0.2, 0.4 and 0.6 g/L offer lower evaporator air temperature and power consumption throughout the experiment. Therefore, it is considered as a substitute for pure mineral oil in the refrigeration system working with R600a
- Since graphene nanolubricant works efficiently in terms of COP, power consumption, cooling capacity and pull-down time in the domestic refrigerator it can be used as a substitute for base lubricant in vapour compression refrigerator working with R600a.

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