Pull-Down Characteristics and Sustainable Cooling Performance of an Eco-Friendly R600a Vapour Compression Refrigeration System Using Graphene Oxide Nanolubricant

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Abstract
Pull-down time is a critical transient performance parameter for vapour compression refrigeration (VCR) systems with low Global Warming Potential (GWP) R600a refrigerant, representing the system's ability to rapidly achieve the desired cooling temperature. Faster pull-down time leads to reduced compressor operating duration, lower energy consumption and improved user comfort. This paper presents an experimental investigation on pull-down time and cooling effect of a VCR system operating with eco-friendly R600a refrigerant using graphene oxide (GO) based nano-lubricant. Graphene oxide nanoparticles were dispersed in polyolester (POE) oil at concentrations of 0.1 gram/L, 0.2 gram/L and 0.3 gram/L. Experiments were conducted at varying refrigerant mass charges of 40 gram, 50 gram and 60 gram. The cooling effect and transient pull-down characteristics were evaluated and compared. Results indicate a significant reduction in pull-down time and enhancement in cooling effect, reduction in power consumption and improvement in coefficient of performance with GO nano-lubrication compared to pure POE oil. An optimum performance was observed at 0.2 gram/L GO concentration with a 50 gram refrigerant charge. The findings demonstrate the potential of graphene oxide nano-lubricants to enhance transient cooling performance and improve energy efficiency in a vapour compression refrigeration system using low-GWP R600a refrigerant.

Keywords - Vapour compression refrigeration, Global Warming Potential , Graphene oxide, Nano-lubricant, R600a.

Introduction

n response to its dependability, portability, and comparatively high efficiency, vapor compression refrigeration (VCR) systems are widely utilized for home refrigeration. Enhancing refrigeration system performance has emerged as a top research priority due to growing global energy consumption and environmental concerns. While steady state measures such coefficient of performance (COP), cooling capacity, and compressor power consumption are the focus of traditional VCR system performance evaluation, transient performance characteristics have been growing in significance in recent years. Pull-down time is an essential measure of cooling system performance in transient measurements, especially in home applications. The pull-down time is the amount of time it takes a system for cooling to decrease the ambient temperature of the refrigeration compartment from its surroundings to a predefined fixed temperature after a startup or load disturbance. A shorter pull-down time indicates a faster conditioning reaction, lower compressor operating time, reduced cumulative energy usage, and improved user comfort. Pull-down time is a more reliable indicator of system efficiency than continuous state measures simply since residential refrigerators frequently meet door openings and erratic loading [1-2]. The refrigeration industry has also undergone significant changes as a result of stringent environmental rules such as the Kigali Amendment and the Montreal Protocol. These restrictions have accelerated the phase-out of high-potential climate change (GWP) refrigerants, while also encouraging the use of natural refrigerants. R600a (isobutane) has grown into a popular refrigerant for residential refrigeration equipment due to its favorable thermodynamic properties, low GWP, and low risk of ozone depletion [3-5]. When compared to typical refrigerants, a variety of experimental experiments have demonstrated that R600a can deliver competitive performance while significantly reducing environmental impact [6]. Despite its advantages, compressor lubrication on refrigerant charges, and thermal transfer properties have a significant effect on the performance of R600a-based cooling systems. Nanotechnology-based advancements, particularly the use of nano-lubricants, have received a great deal of interest in this respect. By adding nanoparticles to traditional compressor lubricating oils, nano-lubricants are created with enhanced tribological and thermophysical qualities. According to research, nano-lubricants can improve oil-refrigerant miscibility, lower friction and wear losses, and increase thermal conductivity, all of which can improve cooling system performance [7–9].

Numerous nanoparticles have been studied as lubricating additives in VCR systems, particularly Al_2O_3, TiO_2, CuO, SiO_2, ZnO, and carbon-based compounds. Although nanoparticles composed of metal oxide have been demonstrated to increase

COP and minimize compressor power consumption, their potential for improving performance is limited by their comparatively lower thermal conductivity when when compared to nanomaterials based on carbon [10–12]. On the other hand, carbon-based nanoparticles, including as carbon nanotubes, graphene, and graphene oxide, are very potential for refrigeration applications because of their very high heat conductivity and great lubricating properties [13–15]. Graphene oxide's two-dimensional structure, large surface area, and oxygen-containing functional groups have made it a very appealing nano lubricant addition. These functional groups in popular compressor oils, such as polyolester (POE), enhance dispersal stability, which is critical for long-term system reliability. Tribological and experimental testing have demonstrated that using graphene oxide as a lubrication ingredient greatly reduces rate of wear and friction coefficient [16-17]. Furthermore, GO-based nano-lubricants have demonstrated increased thermal transport properties, that may have a beneficial effect on compressor performances and evaporator thermal transfer [18-19].Many researchers have looked into whether nano-lubricating substances influence the steady-state performance of refrigeration systems. Systems using nano-lubricating substances and nano-refrigerant materials have been found to enhance cooling performance, COP, and energy use [20-22]. However, few studies have addressed transitory performance indicators, particularly pull-down time. Transient performance is inherently complex by the time-dependent interaction of gas flow, lubrication conductivity and heat transfer procedures, and compressor dynamics [23]. According to recent research, nano-lubricants can significantly decrease pull-down time by enhancing thermal transfer efficiency and reducing wear and tear in the compressor. Pull-down process time and energy usage in compression of vapour systems were significantly reduced when nanoparticles were added to compressor oil, according to Adelekan [24]. Similarly, Verma et al. [25] showed that, at optimal concentrations, graphene oxide nano-lubricating substances could significantly reduce pull-down duration in R600a refrigeration systems. The necessity of choosing the ideal nano-lubricant concentration is highlighted by the fact that inadequate nanoparticle loading may result in agglomeration, higher viscosity, and negative performance impacts [26]. However, there hasn't been a thorough investigation of the combined impact of refrigerant mass charge and graphene oxide nano-lubricant percentage on pull-down time.

Thus, the goal of this work is to experimentally examine the pull-down duration and cooling impact of a compression of vapour refrigeration system using graphene oxide-based nano-lubricant and environmentally benign R600a refrigerant. Experiments are carried out under various refrigerant mass charges and graphene oxide nanomaterials are distributed at various quantities in POE oil. Finding ideal operating conditions that reduce pull-down time and improve transient cooling performance is the main goal of this effort, which will aid in the creation of household refrigeration systems that are both environmentally friendly and energy-efficient.

1. Experimental

1.1 Experimental Setup

The experiment assessing the performance of refrigeration systems with nano additives offers a thorough framework for researching how nanofluids can influence system efficiency and efficacy. The chapter opens with a discussion of how nanofluids like GO are produced and dispersed into basic fluids such polyolester (POE) oil at various proportions utilizing varied mass concentrations of the natural refrigerant 600a. Nanoparticles are evenly and continuously spread across the base fluid utilizing advanced dispersion techniques such as magnetic stirring and ultrasonication. Figure 1 depicts the nanofluids being tested in a VCR system. The compressor is one of the system's major components that has been proven to give accurate performance evaluation. This included a condenser device, evaporating unit, and expansion device.

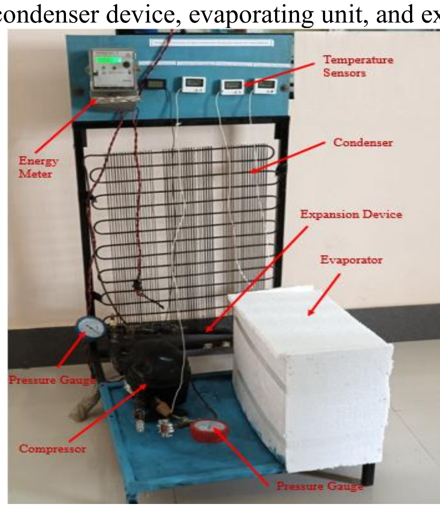

Fig. 1: Experimental Setup of Vapour Compression Refrigeration System

The technique's overall goal is to quantify improvements in cooling performance and thermal conductivity by measuring performance metrics such as COP, which shows the total effectiveness of the VCR cycle, and energy utilization, which is analyzed to determine the potential for lower operating costs. These measures include the COP, which shows the general efficacy of the VCR cycle, and energy consumption, which is used to calculate the possibility for lower running costs. The cooling capacity and heat transfer coefficients are also assessed in order to quantify advances in cooling capacity and thermal conductivity. The technique's overarching goal is to give a complete and systematic way to analyzing the pros and cons of employing nanoparticles in cooling systems, providing an understanding of how these new fluids can improve system efficiency and performance. The power consumption of the compressor was measured using a digital wattmeter, and the pressures of suction and discharge were recorded using pressure gauges. Similar experimental setups have been utilized in previous studies on nano-lubricant-based refrigeration [6], [11]. Previous studies on nano-lubricant-based refrigeration have commonly employed comparable experimental settings [6], [11].

1.2 Refrigerant and Nano-Lubricant Preparation

The eco-friendly qualities and adaptability of R600a refrigerant for home refrigeration applications led to its selection. There were three different refrigerant charge levels: 40, 50, and 60 grams. The base lubricant was made of polyolester oil. Using a two-step process that involved magnetic stirring and ultrasonication to achieve uniform dispersion and stability, the oxide of graphene nanomaterials were distributed into POE oil at levels of 0.1 gram/L, 0.2 gram/L, and 0.3 gram/L by weight. The preparation of lubrication with nanoparticles to create nano lubricants is the most crucial stage in research investigations. In the current study, nano lubricants were created by adding graphene oxide to polyolester oil. Ad-Nano Technologies Pvt. Ltd. supplied the 0.8–2 nanometer-sized graphene oxide nanoparticles. The graphene oxide nanopowder was examined using a SEM [18]. POE was mixed with graphene oxide nanoparticles in three distinct ratios: 0.1 gram/L, 0.2 gram/L, and 0.3 gram/L. Nano-lubricant can be prepared using both one-step and two-step processes. The two-step method used in this study to prepare the nano-lubricant is depicted in Fig.2.

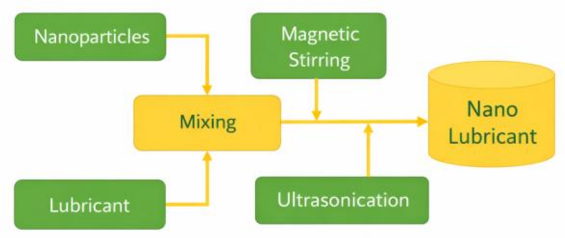

Fig. 2: Nano lubricant preparation process [32].

The produced GO nano-lubricants were mechanically agitated at atmospheric temperature for half an hour at a rotating speed of about 1000 rpm in order to ensure an even distribution of graphene oxide nanoparticle in the lubricant, as shown in Fig. 3.

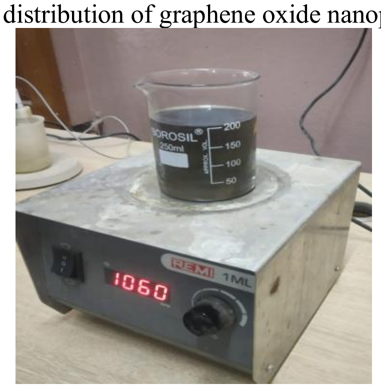

Fig. 3: Magnetic stirrer

Ultrasonication significantly improves the dispersion stability and thermophysical performance of the nano-lubricant, thereby making it suitable for refrigeration and other industrial applications [18].

Fig. 4: Ultra sonicator machine

In the present investigation, the nano-lubricant solution was subjected to ultrasonication for a duration of three hours at a maintained temperature range of 15–20 °C using an ultrasonic homogenizer is shown in Fig. 4.

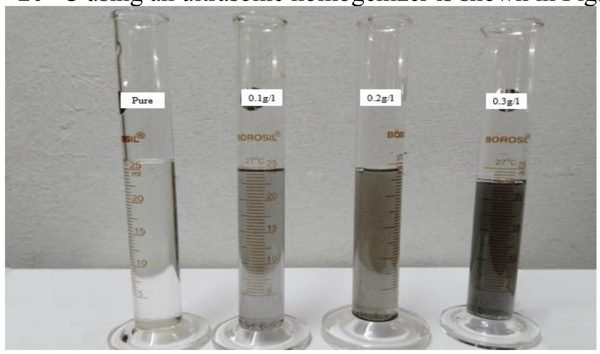

Fig.. 5: Nano-lubricant sample of pure POE oil, 0.1 gram/L, 0.2 gram/L and 0.3 gram/L of GO

A sedimentation test was used to verify the durability of the produced nanolubricant. Constant monitoring over a 5-day period demonstrated that the nanolubricant maintained visually stable, with no evidence of sedimentation, as seen in Fig. 5.

2. Results and Discussion

The temperature-time profiles revealed that the use of graphene oxide nano-lubricant significantly accelerates the cooling rate during the initial transient phase. Compared to pure POE oil, nano-lubricated cases exhibited steeper temperature reduction slopes, indicating faster heat extraction from the evaporator. Similar transient behavior has been reported in recent nano-lubricant based refrigeration studies [12], [16]. Pull-down time was defined as the time required for the evaporator temperature to decrease from ambient temperature to the desired set temperature under no-load conditions [6], [12]. Temperature-time data were recorded at regular intervals from system start-up until steady-state operation was achieved. Each investigation was conducted again to ensure that the findings were consistent and repeatable. This section investigates the effectiveness of graphene oxide, also known as GO, as a nano-lubricating material in a conventional compressing the vapor refrigeration system employing the refrigerant R600a. The mass charges of the refrigerant were 40g, 50g, and 60g, while the concentrations of nanoparticles were varied to 0.1, 0.2, and 0.3 gram/L. Key performance metrics including energy consumption, pressure characteristics, thermal performance and overall system efficiency are the main subjects of the study.

3.1 Pull-down time analysis for cooling effect with different graphene oxide nano lubricant concentration

The effect of adding graphene oxide nanoparticles POE oil at different concentrations (pure, 0.1 gram/L, 0.2 gram/L and 0.3 gram/L) is evaluated in terms of system refrigerating effect. The main aim is to determine the optimal concentration that enhances the thermodynamic performance of the vapor compression cycle at R600a mass charge of 40g, 50g and 60g.

3.1.1 Cooling effect at 0.1 gram/L GO with varying refrigerant mass charges

The study aims to provide important insights into how nano-lubricants can be integrated into refrigeration systems to increase efficiency by varying the refrigerant mass and keeping a constant nanoparticle concentration of 0.1 gram/L and vary refrigerant R600a mass charge 40g, 50g and 60g. By maximizing the concentration of nanoparticles and the volume of refrigerant, the results may improve system designs and operating tactics and yield better results.

a) Refrigerant Charge of 40g

With a 40g charge, the system's cooling capacity is limited, even with the improved heat transfer properties provided by the graphene oxide nano-lubricant. With 0.1 gram/L Go and 40g mass charges, the temperature of evaporator is decrease with pull down time as shown in Fig. 6.

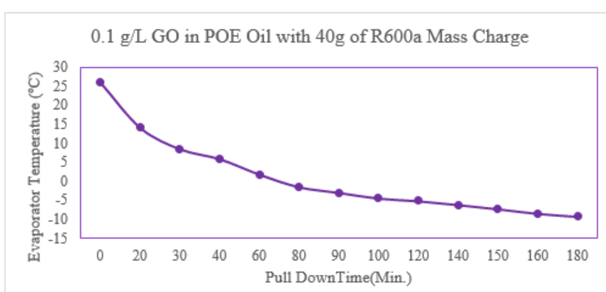

Fig. 6: 40g of R600a Mass Charge with 0.1 gram/L GO

b) Refrigerant Charge of 50g

With 0.1 gram/L GO and 50g mass charge for R600a were tested for the cooling effect with respective to the pull down time it is observed that cooling effect is improved with respective time shown in Fig. 7.

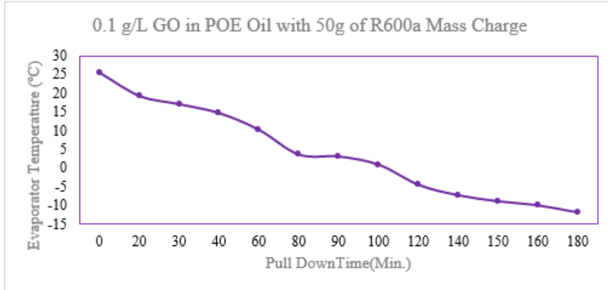

Fig. 7: 50g of R600a Mass Charge with 0.1 gram/L GO

The improved heat transfer efficiency increases the cooling capacity significantly, as the optimal refrigerant mass allows the system to make full use of the enhanced lubricant.

c) Refrigerant Charge of 60g

Even with the enhanced heat transfer characteristics offered by the graphene oxide nano-lubricant, the system's cooling capability is constrained with a 60g charge. As seen in Fig. 8 below, the temperature of the evaporator decreases with pull-down time when 60g mass charges and 0.1 gram/L GO are applied.

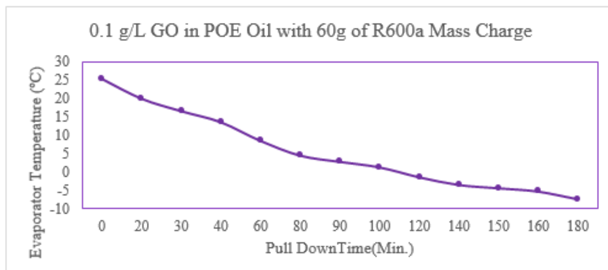

Fig. 8: 60g of R600a Mass Charge with 0.1 gram/L GO

Graphene oxide of 0.1 gram/L concentration for 40g, 50g and 60gregrigerant R600a was observed. With 50g evaporator temperature is significantly decrease, while refrigerant R600a mass charge 40g and 60g show less cooling effect as compare to 50g mass charges with respective to pull down time. At a 50g refrigerant charge, the system reaches its optimal balance between refrigerant mass and the 0.1 gram/L graphene oxide concentration. The cooling capacity shows a notable improvement because the refrigerant mass is sufficient to absorb and transfer the heat while the graphene oxide nanoparticles enhance the heat transfer between the refrigerant and the lubricant.

3.1.2 Cooling effect at 0.2 gram/L GO with Varying Refrigerant Mass Charges

By varying the refrigerant mass and maintaining a constant nanoparticle concentration of 0.2 gram/L, as well as the refrigerant R600a mass charge of 40g, 50g and 60g, the study seeks to offer significant insights into how nano-lubricants can be integrated into refrigeration systems to increase efficiency. By optimizing the concentration of nanoparticles and the volume of refrigerant, the results may improve system designs and operating tactics and yield better results.

a) Refrigerant Charge of 40g

Even with the enhanced heat transfer qualities offered by the graphene oxide nano-lubricant, the system's cooling capability is constrained with a 40g charge. The temperature of the evaporator decreases with pull-down time while using 40g mass charges and 0.2 gram/L Go, as indicated in Fig. 9 below.

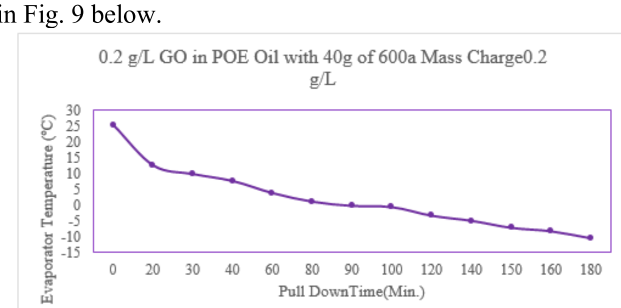

Fig. 9: 40g of R600a Mass Charge with 0.2 gram/L GO

b) Refrigerant Charge of 50g

It was found that the cooling effect improved with the pull-down time when the R600a was tested with a 50g mass charge and 0.2 gram/L GO in POE oil compare to 40g and 60g R600a mass charge shown in Fig. 10. The system achieves its ideal equilibrium between the refrigerant mass and the 0.2 gram/L concentration of graphene oxide at a 50g refrigerant charge. Since the refrigerant mass is adequate to absorb and transfer heat and the graphene oxide nanoparticles facilitate heat transfer between the refrigerant and the lubricant, the cooling capacity significantly improves.

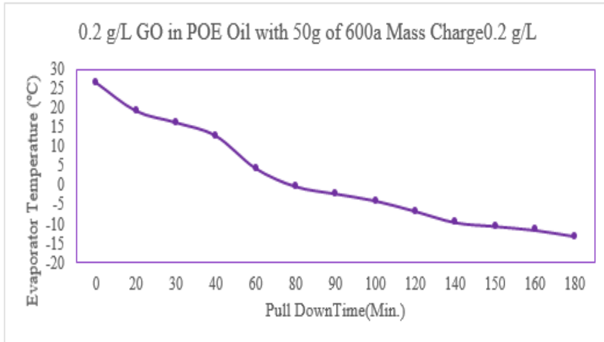

Fig. 10: 50g of R600a Mass Charge with 0.2 gram/L GO

c) Refrigerant Charge of 60g

The cooling capacity decreases slightly with 60g refrigerant charge over 50g, although overcharging symptoms appear in the system. It is found that cooling temperature decreases compared to 50g with respective time shown in Fig. 11.

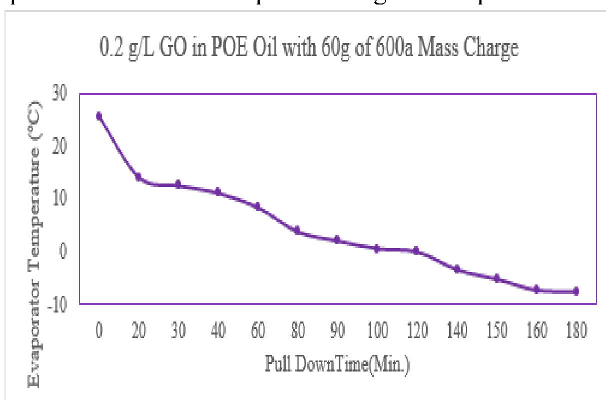

Fig. 11: 60g of R600a Mass Charge with 0.2 gram/L GO

3.1.3 Cooling effect at 0.3 gram/L GO with Varying Refrigerant Mass Charges

In order to maximize the concentration of nanoparticles and the volume of refrigerant, the results may improve system designs and operating tactics and yield better results. The study aims to provide important insights into how nano-lubricants can be integrated into refrigeration systems to find optimum results by varying the refrigerant mass and keeping a constant nanoparticle concentration of 0.3 gram/L and varying refrigerant R600a mass charge 40g, 50g & 60g.

a) Refrigerant Charge of 40g

The system's capacity to cool has constraints by a 40g charge, despite the graphene oxide nano-lubricant's improved heat transmission properties. As seen in the Fig. 12 below, the evaporator's temperature drops with pull-down time when 40g mass charges and 0.3 gram/L GO are used.

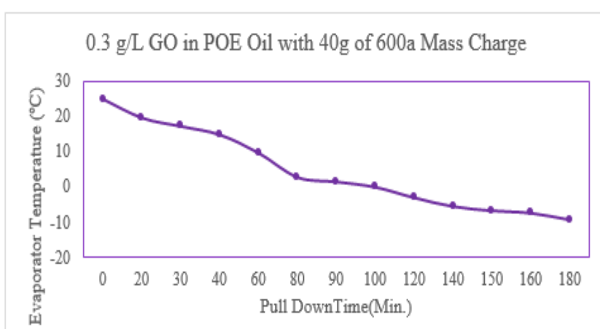

Fig. 12: 40g of R600a Mass Charge with 0.3 gram/L GO

b) Refrigerant Charge of 50g

When the R600a was tested with a 50g mass charge and 0.2 gram/L GO, as indicated in Fig. 13, it was discovered that the cooling effect improved with the pull-down time. At a 50g refrigerant charge, the system reaches its optimal balance between the refrigerant mass and the 0.3 gram/L concentration of graphene oxide.

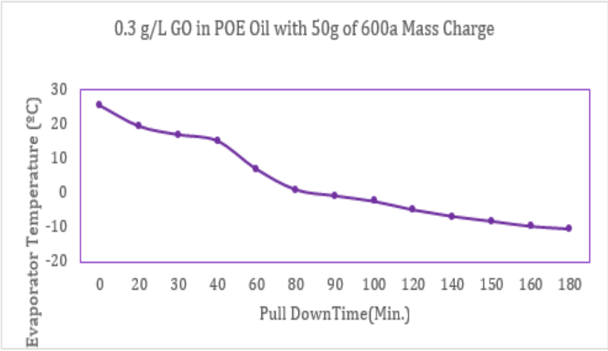

Fig. 13: 50g of R600a Mass Charge with 0.3 gram/L GO

c) Refrigerant Charge of 60g

The cooling capacity decrease marginally with 60g refrigerant charge over 50g, although overcharging symptoms appear in the system. It is found that cooling effect is decreases compared to 50g with respective time shown in Fig. 14.

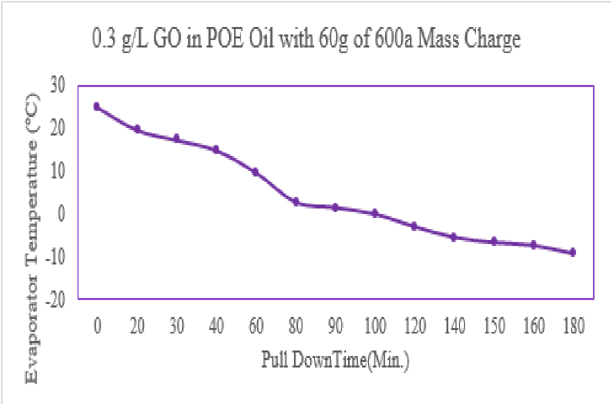

Fig. 14: 60g of R600a Mass Charge with 0.3 gram/L GO

The table 1 shows the comparative result for pull down time for analysing evaporator cooling temperature. It is observed that minimum temperature is achieved at 0.2 gram/L GO is -13.1 ºC while for pure POE oil, 0.1 gram/L and 0.3 gram/L GO in POE oil is -11.9 ºC and -11.5 ºC.

Table 1 – Comparative result for 50g R600a mass charge at different GO concentration

Pull down Time (Min.)	Evaporator Temperature ºC			
	Pure	0.1 gram/L	0.2 gram/L	0.3 gram/L
0	25.5	25.5	26.6	25.5
20	20	19.3	19.3	19.5
30	17.6	17.1	16.3	17
40	15.4	14.7	12.9	15.2
60	10.9	10.2	4.5	7
80	6.4	3.6	-0.2	1
90	4.1	3.1	-2.1	-0.8
100	0.7	0.9	-3.9	-2.4
120	-3.2	-4.5	-6.6	-4.9
140	-6.4	-7.3	-9.5	-6.8
150	-7.2	-8.9	-10.5	-8.2

160	-8.2	-10	-11.5	-9.7
180	-9.3	-11.9	-13.1	-10.5

Overall results indicate that graphene oxide nano-lubrication positively influences both transient and steady-state performance of the VCR system. Reduced pull-down time directly translates to lower compressor operating duration and energy savings, thereby improving system reliability and efficiency.

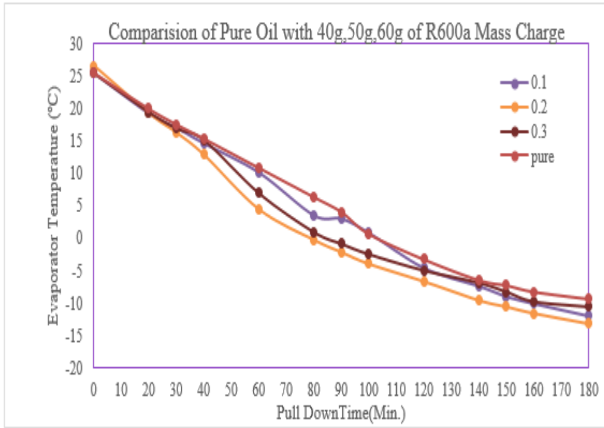

Fig. 15: Comparison of GO concentration for 50g of R600a Mass Charge

Result shows that by varying mass charge of 40g, 50g and 60g of R600a at different GO nanoparticle concentration in POE oil, the best possible results achieved for 50g for 0.1 gram/L, 0.2 gram/L and 0.3 gram/L of GO in POE oil shown in fig. The result shows that at 0.2 gram/L of GO in POE oil by incorporating 50g of R600a in refrigeration system gives optimum result as shown shown in Fig. 15.

3.2 Refrigerating Effect

The refrigeration impact of the VCR device under various operation situations is shown in Figure 16. The findings show that, for all evaluated refrigerant volume charges of R600a, using graphene oxide (GO) nano-lubricating agent greatly enhances system performance as compared to traditional POE oil. The addition of scattered GO nanoparticles in the nano-lubricant has improved its thermophysical capabilities and heat transmission characteristics.

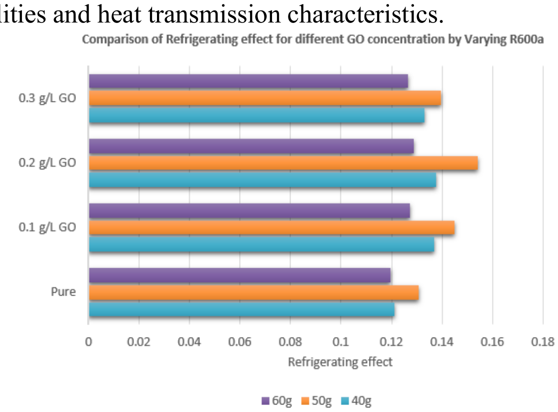

Fig. 16: Comparison of Refrigerating Effect for different GO concentration

At the ideal ratio of 50 gram gas charge and 0.2 gram/L GO content, the maximum refrigeration effect, measured at 0.1539 kW, is achieved. The evaporator's ability to absorb heat is enhanced by this condition, which effectively balances the amount of refrigerant and the concentration of nano-lubricant. Conversely, the system using only POE oil performs relatively poorly. The refrigeration effects observed for refrigerant charges of 40 gram, 50 gram and 60 gram are 0.8545 kW, 1.0378 kW and 0.7960 kW, respectively. This reduced efficiency is mainly due to the lower thermal conductivity and weaker heat transfer capability of the base lubricant.

3.3 Power Consumption

To evaluate the system performance, experiments were carried out using varying concentrations of graphene oxide (GO) dispersed in polyol ester (POE) oil, along with different refrigerant mass charges of R600a. Figure 17 presents the corresponding variation in compressor power consumption under these operating conditions.

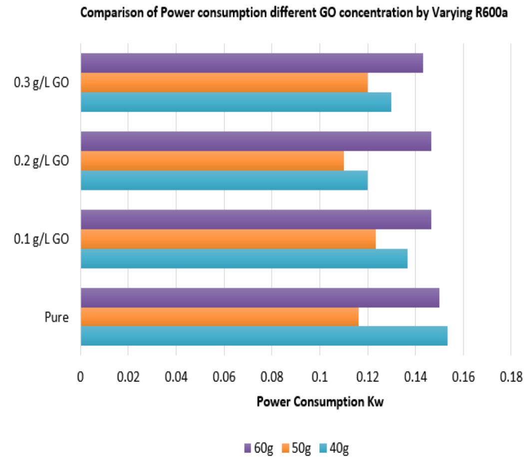

Fig. 17: Comparison of Power Consumption for different GO concentration

The compressor power requirement was analyzed for GO nano-lubricant concentrations of 0.1 gram/L, 0.2 gram/L and 0.3 gram/L, combined with refrigerant charges of 40 gram, 50 gram and 60 gram. The results clearly indicate that the addition of GO nano-lubricant has a pronounced effect on compressor energy consumption.
The lowest compressor power consumption of 0.11 kW is observed at an optimal condition of 50 gram refrigerant charge and 0.2 gram/L GO concentration. The nano-lubricant's superior lubricating properties and increased thermal conductivity are responsible for this decrease in power consumption. GO nanoparticles improve heat dissipation and lower frictional losses inside the compressor, which lowers the total workload and energy consumption.

3.4 Coefficient of Performance

The coefficient of performance is a critical parameter used to determine the acceptability and effectiveness of replacement cooling gas in VCR devices. Figure 18 illustrates how COP fluctuates based on the operational environment. Figure 18 illustrates how COP fluctuates according to the operational environment.

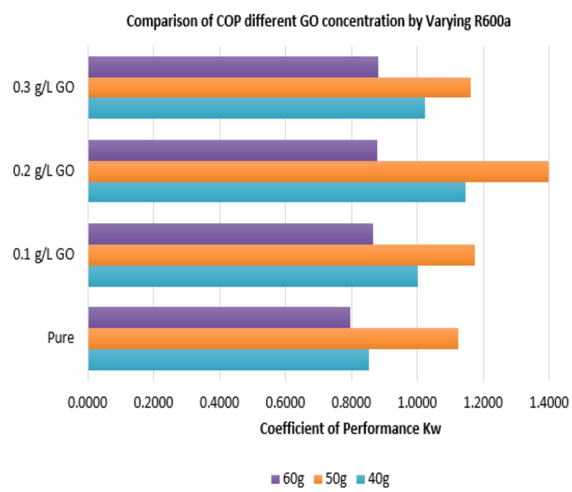

Fig. 18: Comparison of coefficient of performance for different GO concentration

In comparison to the traditional pure lubricant, the experimental results show that the addition of graphene oxide (GO)-based nano-lubricating substances considerably improves system performance. Whenever GO nano-lubricant is used, the COP values are found in values ranging of 1.00–1.02, 1.17–1.19, and 0.86–0.88 for refrigerant volume concentrations of 30 g, 40 gram, and 50 gram, respectively.

The variation of GO nanoparticles improves the system's general performance by encouraging effective heating energy exchange and lowering mechanical and frictional losses. At an optimal GO level of 0.2 gram/L, a maximum value of COP of 1.39 is achieved, indicating a substantial rise in system efficiency. This improvement is primarily attributed to the nano-lubricant's higher lubricating qualities and enhanced heat transfer capabilities. This increase is mostly attributed to the nano-lubricant's superior lubricating properties and improved heat transmission capabilities. The variety of GO nanoparticles improves the system's overall efficiency by promoting efficient thermal energy exchange and minimizing mechanical and friction losses.

3. Conclusion

This study employed a graphene oxide based nano-lubricant to investigate the transient and Energy-Efficient Cooling Performance of a vapour compression refrigeration system that used Eco-Friendly R600a refrigerant. In compared to the usual lubricant, the results indisputably reveal that dispersing nanomaterials carrying GO in polyolester oil significantly improves system performance. The addition of GO nano-lubricant produced a considerable reduction in pull-down time, implying improved transient cooling qualities. At optimum operating parameters of 50 gram gas charge and 0.2 gram/L GO, the refrigeration effect reached its peak of 0.1539 kW, suggesting enhanced absorption of heat in the evaporator. Furthermore, under the same conditions, the compressor component power consumption was reduced to a low of 0.11 kW, suggesting improved energy efficiency. With a maximum value of 1.39 at a GO concentration of 0.2 gram/L, the value of the coefficient performance (COP) improved significantly. The COP values were discovered to be in the variable ranges of 1.00-1.02, 1.17-1.19, and 0.86-0.88 for refrigerant charge levels of 30 gram, 40 gram and 50 gram, respectively, suggesting the beneficial effect of nano-lubricant on system effectiveness.

Results illustrate that employing a low-GWP R600a refrigerant and combination of 50 gram refrigerant charge with 0.2 gram/L GO nano-lubricant percentage produced the best results among all the examined operating circumstances, leading to a quicker cooling reaction, improved refrigeration effect, greater COP, and lower compressor power consumption.

Conflicts of Interest

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

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