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ORIGINAL ARTICLE

A novel approach of using TiO_2 and SiO_2 nanoparticles and hydrocarbon refrigerant R600a in retrofitted vapour compression refrigeration system for environment protection and system performance enhancement

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Abstract

The environment effect of conventional refrigerants can be improved by adopting eco-friendly hydrocarbon (HC) refrigerants in a vapour compression refrigeration (VCR) system. In this work, various factors such as neutral ozone depletion potential (ODP) and low global warming potential (GWP), use of a lesser quantity of refrigerant, power saving, and retrofitting to the existing VCR system, are encouraged by opting for the HC refrigerant R600a. The mono and the hybrid nano-lubricants prepared by dispersing different concentrations of metallic oxide (TiO_2) and non-metallic oxide (SiO_2) nanoparticles in POE oil were used as the compressor lubricant. The morphology and crystal structure of each nanoparticle were analysed with the FE-SEM and XRD analysis. The performance parameters of the VCR system were analysed to study the effect of different nano-lubricants. In contrast to the better performance of TiO_2 in mono form, a combination of 25% TiO_2 and 75% SiO_2 in hybrid form performed better amongst all the tested lubricant samples. As compared to the base lubricant (POE oil). This hybrid nano-lubricant combination reduced the compressor power consumption by about 8% and enhanced the refrigeration effect by more than 13%. It resulted in the enhancement in COP by more than 23%. The compressor suction and delivery characteristics (such as pressure) and the pull-down temperature were also studied to evaluate the effect of different nano-lubricants. Furthermore, the viscosity and thermal conductivity analysis at various temperatures were also conducted to observe the tribological and thermo-physical property influence of the mono and hybrid forms of nano-lubricants on VCR system performance.

Keywords Vapour compression refrigeration system · Refrigerant R600a · POE oil · TiO_2/SiO_2 nanoparticles · Hybrid nano-lubricant

Abbreviations

Abbreviations

COP	Coefficient of performance
FE-SEM	Field emission scanning electron microscope
HC	Hydrocarbon
HFC	Hydrofluorocarbon
POE	Polyolester
VCR	Vapour compression refrigeration
LPG	Liquefied petroleum gas
TiO_2	Titanium dioxide
SiO_2	Silicon dioxide
kPa	Kilopascal
m^2s^{-1}	Square metre per second
$Wm^{-1}\ K^{-1}$	Watt per metre-kelvin
P	Pressure
T	Temperature
XRD	X-ray diffraction

Symbols

ΔT	Temperature difference [K]
m	Mass of water [kg]
C_p	Specific heat capacity of water [$kJkg^{-1}\ K^{-1}$]

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K	Energy meter constant [impulse kW^{-1} h^{-1}]
n	Number of pulses taken in energy meter
t	Time [s]
°C	Degree celsius
gL^{-1}	Grams per litre
W	Watt

Subscripts

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

Introduction

Despite large power consumption by the vapour compression refrigeration (VCR) system, the world is mostly dependent on it in refrigeration and air conditioning devices (Marcucci Pico et al. 2019). The VCR systems consume about 15% of word's total energy demand (Nair et al. 2020; Yıldız et al. 2021). In addition to the energy, the environment aspect of the refrigerant used in VCR system is also of great concern. Therefore, eco-friendly refrigerants and more energy-efficient methods need to be developed. The VCR systems are switching to the use of eco-friendly hydrocarbon (HC) refrigerants from conventional ones. The HC refrigerants offer lower global warming potential (GWP), lower ozone depletion potential (ODP) and are compatible with system sub-components (Corberán et al. 2008; Adelekan et al. 2019a, 2021). Also, as per Montreal and Kyoto protocols (Padmanabhan and Palanisamy 2012; Madyira et al. 2022) and United Nations Environment Programme (UNEP), a treaty was signed to limit the use of hydrofluorocarbons (HFCs), with a phase-out of HFCs by 2020 in developed countries and worldwide by 2030 (Babarinde et al. 2020; Joybari et al. 2013; Rasti et al. 2013). The HC refrigerants not only help to protect the environment, but also offer retrofitting flexibility and reduced power consumption, resulting in enhanced COP (El-Morsi 2015; Shengshan. Bi et al. 2011; Corberán et al. 2008). The only concern related to the usage of HCs is the risk of flammability (Adelekan et al. 2019a; Ohunakin et al. 2018; Harby 2017). It becomes negligible when used in lesser quantities (less than or equal to150 g) (Corberán et al. 2008).

Nanoparticles of size less than 100 nm (Azmi et al. 2016; Narayanasarma and Kuzhiveli 2019; Shah et al. 2017; Khan et al. 2019) have a wide range of applications in various fields (Khan et al. 2019).

Nanoparticles are used to develop novel green chemical mechanical polishing (CMP) for copper (Zhang et al. 2019), sapphire (Zhang et al. 2021), alloys (Zhang et al. 2020) and diamond (Liao et al. 2021). Traditional chemical mechanical polishing employs toxic and corrosive slurries for the integrated circuit (IC), semiconductors and microelectronics industries (Zhang et al. 2018). These studies contributed extensively in reducing or eliminating the pollution caused to the environment in the conventional manufacturing. (Xie et al. 2020).

To overcome this challenge, nanoparticles are used to develop novel green CMP for copper (Zhang et al. 2019), sapphire (Zhang et al. 2021), alloys (Zhang et al. 2020) and diamond (Liao et al. 2021). Using the green CMP, high-performance surfaces are manufactured for use in industries. In addition, nanoparticles are applied to develop a novel approach at nanoscale depth of cut, in which the speeds used are four to seven orders of magnitude higher than those in nanoscratching and conventional scratching (Zhang et al. 2015). This approach opens a new pathway to investigate the fundamental mechanisms of abrasive machining (B. Wang et al. 2018). Under the breakthrough of theories, nanoparticles are used to develop novel diamond wheels and approaches (Zhang et al. 2017).

The use of nanoparticles in the refrigeration systems can also be observed in literature to address the energy consumption issue. A small amount of nanoparticles also reduce the agglomeration and make the experiments more effective and viable (Sabareesh et al. 2012). The nano size of the dispersed particles offers large surface area, which makes them a promising candidate for performance enhancement in any thermal system (Adelekan et al. 2021; Narayanasarma and Kuzhiveli 2019).

The nanoparticles are dispersed in any heat transfer base fluid to prepare the nanofluid (Minea and Moldoveanu 2018). The dispersion of a small quantity of nanoparticles transforms any heat transfer fluid into a more energy-efficient nanofluid (Devendiran and Amirtham 2016; Chakraborty and Panigrahi 2020; Nabil et al. 2017b; Saidur et al. 2011). The concept of nanofluids was coined by Stephen U.S. Choi in 1995 (Devendiran and Amirtham 2016; Huminic and Huminic 2012; Yogesh et al. 2021; Sanukrishna et al. 2019; Mallick et al. 2013; Sanukrishna and Prakash 2018; Azmi et al. 2016; Ahmad et al. 2020; Mansourian et al. 2020; Gaganpreet and Srivastava 2012), which later opened a new dimension to work for performance enhancement of the VCR systems. For VCR systems, the nanofluid prepared by dispersing nanoparticles, either in the compressor lubricant or in the refrigerant, is called nano-lubricant or nano-refrigerant respectively (Sharif et al. 2018; Nair et al. 2020). About 26% fall in energy consumption of a domestic refrigerator was reported by Sheng-shan. Bi et al. (2008), after addition of a mere 0.1% mass fraction of metallic oxide nanoparticles of TiO_2 in the refrigerant R134a.

Many researchers opted for the HC refrigerants such as R600a and LPG, with TiO_2 nanoparticles in different concentrations and observed a great energy savings and COP enhancement in domestic refrigerators (Bi et al. 2011; Adelekan et al. 2019a, 2018, 2017, 2021; Babarinde et al. 2019; Gill et al. 2018; Jatinder et al. 2019). Not only metallic, but also non-metallic oxide nanoparticles such as SiO_2contribute in reducing power consumption, when LPG (a HC refrigerant) is retrofitted to a domestic refrigeration system designed for R134a (Ohunakin et al. 2018). In addition, the thermal conductivity, an important thermo-physical property of any heat transfer fluid, affects its heat transfer performance (Hamid et al. 2018; Zawawi et al. 2017; Karimi et al. 2015). Generally, the heat conduction of fluids is lesser than that of the solid particles (Narayanasarma and Kuzhiveli 2019; Khan et al. 2019; Yıldız et al. 2021; Hamzah et al. 2017). Therefore, the congenitally poor thermal conductivity of conventional heat transfer fluids is enhanced by appending conductive solid particles with them (Zawawi et al. 2017; Ranga Babu et al. 2017; Leong et al. 2017). The better thermo-physical and heat transfer characteristics make the nanofluids potential and more energy-efficient fluids (Sidik et al. 2016; Yıldız et al. 2021; Zawawi et al. 2017). Extensive works have reported that nanofluids have higher thermal conductivity than conventional heat transfer fluids and contribute to enhance the refrigerant system performance (Narayanasarma and Kuzhiveli 2019; Sharif et al. 2018; Zawawi et al. 2017; Ahmed and Elsaid 2019; Nair et al. 2020; Cheng and Liu 2013; Mahbubul et al. 2013; Ding et al. 2009; Sanukrishna and Prakash 2018; Karimi et al. 2015; Ghorbani et al. 2017; Akhavan-Behabadi et al. 2015; Leong et al. 2017; Mohammad Hemmat Esfe et al. 2018; Bakhtiari et al. 2021). Viscosity, an important tribological parameter (Azmi et al. 2017; Sharif et al. 2018), has an equal weightage as that of thermal conductivity and also governs the VCR system performance characteristics (Zawawi et al. 2017; Kumar and Singh 2016; Sabareesh et al. 2012).

Recently, researchers have turned their attention towards the advanced and novel form of nanofluid known as ‘hybrid nanofluid’ to make the conventional heat transfer fluid more effective than mono nanofluid for any thermal system (Sidik et al. 2016; Huminic and Huminic 2018; Zawawi et al. 2017). For VCR systems, hybrid nanofluid, known as hybrid nano-lubricants, is prepared using more than one type of nanoparticles in base compressor lubricant (Nabil et al. 2017a; Akilu et al. 2018; Sidik et al. 2016; Ranga Babu et al. 2017; Huminic and Huminic 2018). This further enhanced the system performance and the research in this field has gained momentum in about the last two decades (Nabil et al. 2017b; Muneeshwaran et al. 2021; Sidik et al. 2016; Ahmed and Elsaid 2019). Recently, the performances of hybrid nano-lubricants using combinations of different nanoparticles such as SiO_2–Al_2O_3, SiO_2–ZnO, CuO–Al_2O_3 and SiO_2–CuO were experimentally investigated by researchers using the HC refrigerant R600a in the VCR system. An improvement in COP and a drop in power consumption, within the range of 27–42% and 24–57%, respectively, were reported as compared to those with the use of the base lubricants (Senthilkumar et al. 2021a, 2020a, 2021b; b). It can be shown that the non-metallic oxide nanoparticles (like SiO_2) when mixed with metal oxide nanoparticles (like Al_2O_3, ZnO, or CuO) performed better than the individuals when used in mono form with HC refrigerants (Kumar and Singh 2016; Ohunakin et al. 2017; Krishnan et al. 2019; Singh and Ansari 2017). Due to excellent heat transfer characteristics, the metallic oxide nanoparticles received wide attention. Especially, the TiO_2 nanoparticles offered excellent results in improving the VCR system performance with HC refrigerants (Shengshan. Bi et al. 2011; Sabareesh et al. 2012; Adelekan et al. 2019a; Adelekan et al. (2019b); Jatinder et al. 2019; Babarinde et al. 2019; Adelekan et al. 2021). Looking at the excellent performance of TiO_2 nanoparticles-based nano-lubricants with eco-friendly HC refrigerants, the performance of its hybrid form with SiO_2 nanoparticles needs to be explored. Moreover, the low toxicity and chemical stability of TiO_2 and SiO_2 nanoparticles (Narayanasarma and Kuzhiveli 2019) and the low dielectric constant of SiO_2 nanoparticle (Robertson 2004; Nair et al. 2020) make them a promising candidates to use in hybrid form.

A limited work available on the hybrid nano-lubricants based on both metallic and non-metallic oxide nanoparticles portrays their better performance as compared to that of the mono form (Saravanan and Vijayan 2018; Sidik et al. 2016; Senthilkumar et al. 2020b; Senthilkumar et al. 2021b). Also, the hybrid nanoparticles have higher thermal conductivity than the same distinct nanoparticles (in mono forms) when used individually (Vaka et al. 2020; Akilu et al. 2018; Akhavan-Behabadi et al. 2015; Kakavandi and Akbari 2018; Liu et al. 2021; Jin et al. 2021; Ma et al. 2020). Therefore, the hybrid nano-lubricant is expected to show better thermal conductivity than mono nano-lubricant due to synergistic effect and Brownian motion of each nanoparticle in the base lubricant (Huminic and Huminic 2018; Zawawi et al. 2017; Sidik et al. 2016; Devendiran and Amirtham 2016; Vallejo et al. 2022; Jin et al. 2021; Ahmad et al. 2020). The viscosity of hybrid nano-lubricant also plays a vital role in improving the compressor working efficiency and hence overall VCR system performance (Nabil et al. 2017a, b; Huminic and Huminic 2018; Hamzah et al. 2017). Previous studies have showed that the hybrid nanofluid prepared using hybrid TiO_2:SiO_2 nanoparticles in different concentrations and base fluids have better thermal conductivity and viscosity than the mono nanofluid and the base fluid (Hamid et al. 2018; Le Ba et al. 2020; Nabil et al. 2017a). This has resulted in its use as heat transfer fluid in various thermal applications.

The eco-friendly HC refrigerant R600a, having low GWP and ODP index (Ahmadpour and Akhavan-Behabadi 2019; Ghorbani et al. 2017; Cao et al. 2021; Akhavan-Behabadi et al. 2015; Fatouh and Abou-Ziyan 2018), was opted in this study, as even a 50–60% less mass charge compared to synthetic refrigerants, gives better performance (Rasti et al. 2013; Jwo et al. 2009; Ghorbani et al. 2017; Akhavan-Behabadi et al. 2015; Jatinder et al. 2019). Also, it has excellent performance compared to other HC refrigerants such as LPG as observed by Jatinder et al. (2019). The opted POE oil also has good compatibility with the HC refrigerant R600a, which is commonly preferred with R134a refrigerant (Narayanasarma and Kuzhiveli 2019; Akhavan-Behabadi et al. 2015).

It is hard to find any comprehensive work on the performance of HC refrigerant R600a-based retrofitted VCR system using POE oil compressor lubricant with distinct concentrations (in mono and hybrid form: total of 0.1 gL^{-1}) of SiO_2 and TiO_2 nanoparticles, which indicates the gap in this research area and also reflects the novelty of the present work.

The thermal conductivity and viscosity of POE oil and each prepared lubricant sample were measured in the temperature range of 35–95 ℃. These are the important parameters that affect the system performance. In this work, HC refrigerant R600a with POE oil and each prepared sample in the retrofitted VCR system test rig were analysed in the context of power consumption, refrigeration effect, COP, pressure ratio and pull-down temperatures. The present research results reveal that appending granular shape nanoparticles with vapour compressor refrigeration system is a promising method of enhancing the overall system performance. The hybrid nano-lubricant with a higher concentration of SiO_2 nanoparticles performed better as compared to other hybrid nano-lubricant, mono nano-lubricants and neat base lubricant (POE oil) sample.

Materials and experimental procedures

Materials

The TiO_2 and SiO_2 nanoparticles, appended to the VCR system via compressor lubricant (POE oil), were procured from M/s. Reinste Nano Ventures Private Limited, New Delhi (India). The FE-SEM and X-ray diffractometer were used to identify the morphologies and crystal structure of SiO_2 and TiO_2 nanoparticles, respectively. The FE-SEM micrographs were obtained from Jeol FE-SEM facility available at Lovely Professional University, Phagwara, Punjab (India). The XRD was obtained from X-ray diffractometer (PANalytical, Empyrean, Netherlands) at Central University of Punjab (CUP), Bathinda, Punjab (India). The compressor lubricant (POE oil) and HC refrigerant R600a were procured from the local market. The basic characteristics of the procured nanoparticles provided by suppliers are as shown in Table 1.

Experimental procedures

In this section, the preparation of mono and hybrid nano-lubricants, stability of nano-lubricant achieved by ultrasonication and magnetic stirring, viscosity and thermal conductivity measurement of POE oil and prepared samples, VCR system test rig setup and uncertainty analysis are described.

Preparation of nano-lubricants (mono and hybrid) and their stability

Each sample of nano-lubricant was prepared by dispersing different compositions of SiO_2 and TiO_2 nanoparticles, as shown in Table 2, in 500 mL (each) POE oil. A digital weighing device (model CX 220 of Citizen make) having a least count of 0.1 mg was used for weighing the nanoparticles. Nanofluids are generally prepared by adopting

Table 1 The characteristic of SiO_2 and TiO_2 nanoparticles

S. No	Property	SiO_2 nanoparticles	TiO_2 nanoparticles
1	Physical state	Powder form	Powder form
2	Color	White to gray white	Transparent to white
3	Odor	Odorless	Odorless
4	Solubility in water	Insoluble	Insoluble
5	Purity (%)	99.99	99.99
6	Boiling point (℃)	2230	2972
7	Melting point (℃)	1710	1843
8	Density (kg/m^3)	2220	4230
9	Molecular weight (g/mol.)	60.08	79.86
10	Specific heat (J/kg.K)	754	692
11	Thermal conductivity (Wm^{-1} K^{-1})	1.4	8.4
12	Average particle diameter (nm)	60	20

Table 2 Composition of distinct mono and hybrid nanoparticles in 500 mL of POE oil

Sample ID	TiO_2 nanoparticles		SiO_2 nanoparticles		Total nanoparticles (gL^{-1})
	Wt. %	Wt. (g)	Wt. %	Wt. (g)	
N1	0.0	0.0	0.0	0.0	Nil
N2	0.0	0.0	100	0.05	0.1
N3	100	0.05	0.0	0.0	0.1
N4	75	0.0375	25	0.0125	0.1
N5	25	0.0125	75	0.0375	0.1

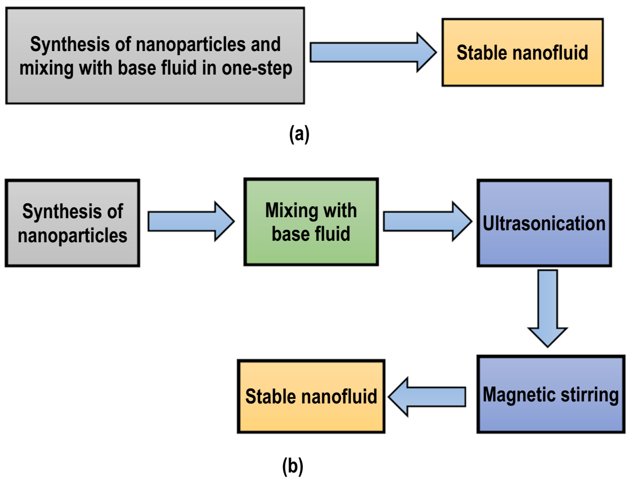


Fig. 1 Nanofluid preparation methods: **a** one-step method and **b** two-step method

two basic methods: the one-step method, and the two-step method as described in Fig. 1. (Chakraborty and Panigrahi 2020; Xiang-Qi Wang and Mujumdar 2007; Sidik et al. 2014; Narayanasarma and Kuzhiveli 2019; Yıldız et al. 2021; Ranga Babu et al. 2017; Afrand and Ranjbarzadeh 2020; Devendiran and Amirtham 2016; Yang et al. 2020; Okonkwo et al. 2020; Sidik et al. 2016; Kaggwa and Carson 2019; Borode et al. 2019; Gupta et al. 2017; Shah et al. 2017; Sangapatanam et al. 2022; Dhanola and Garg 2020). Mainly, a two-step method is preferred, as it is easily implemented and cost-effective (Yıldız et al. 2021; Mohammad Hemmat Esfe et al. 2018; Hamzah et al. 2017; Ma et al. 2020; Chakraborty and Panigrahi 2020; Yang et al. 2020; Okonkwo et al. 2020; Kaggwa and Carson 2019; Borode et al. 2019). The only drawback of this method is the nanoparticle agglomeration (Nabil et al. 2017b; Chakraborty and Panigrahi 2020; Afrand and Ranjbarzadeh 2020). Such unstable nanofluids exhibit weak thermophysical properties (Mansourian et al. 2020). To obtain stable nanofluid (nano-lubricants), the mixtures in the glass vessels were kept separately on bath ultrasonicator and the magnetic stirrer for 3 and 2 h, respectively, as shown in Fig. 2 (Kumar and Singh 2016). No surfactants were added to any of the nano-lubricant samples (Saravanan and Vijayan 2018).

Viscosity measurements

The neat POE oil and each prepared samples were characterized with the measurement of viscosity with the Redwood viscometer. The lubricant sample was maintained at constant temperature with a surrounding water bath that was heated with a thermostatically controlled immersed electric heater. The water bath was incorporated with a stirrer to maintain uniform temperature throughout. To ensure that the viscosity testing was carried out at the set constant temperature, the temperatures of both water bath and that of the lubricant samples were also measured during the testing with the

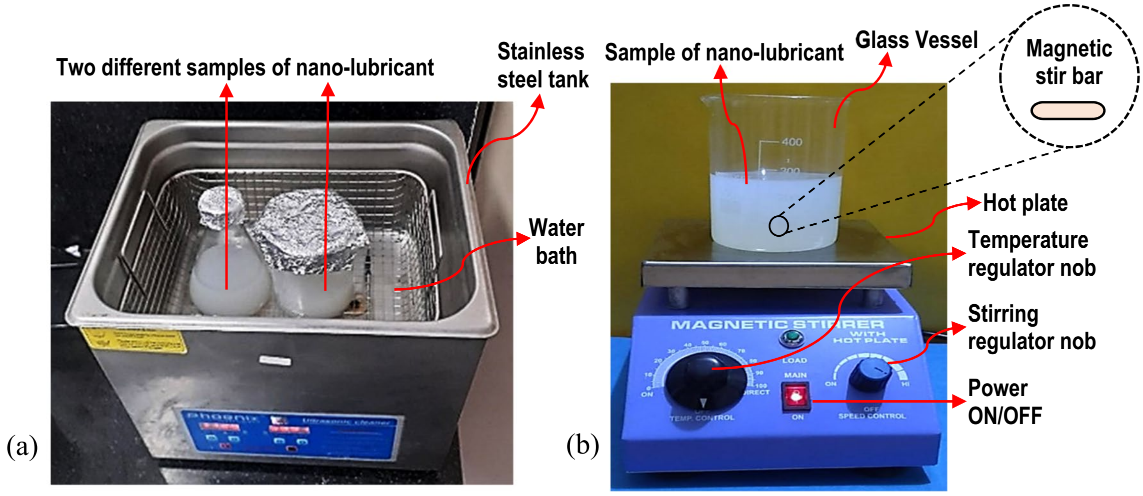


Fig. 2 Stabilization of nano-lubricants using: **a** bath ultrasonicator, **b** magnetic stirrer

help of separate thermometers. The principle of falling head gravitational flow through a standard dimension capillary tube was utilized in the measurement (Sabareesh et al. 2012; Kumar et al. 2020; Kumar and Singh 2016). In the present work, the viscosity of neat POE oil and mono and hybrid nano-lubricants was measured at different temperatures (35, 50, 65, 80 and 95 °C). Each reported value of viscosity is an average of five different measurements, at the respective test temperatures, to strike out the possibility of any experimental error.

Thermal conductivity measurement

The thermal conductivity of each sample was measured by an instrument KD2 Pro thermal property analyser (Decagon Devices, Inc., USA make) at Thapar University, Patiala, Punjab (India). The instrument met the standards of ASTM D5334 and works on the principle of transient hot-wire method (Narayanasarma and Kuzhiveli 2019; Sanukrishna and Prakash 2018; Hamid et al. 2018; Asadi et al. 2019). As shown in the schematic diagram (Fig. 3), the thermal conductivity measurement was made with a small single needle probe (KS-1) that was inserted into each lubricant sample kept in a glass tube. To maintain a constant temperature during each thermal conductivity measurement test, the glass tube containing lubricant samples was kept in a water bath maintained at a constant test temperature. Each successive thermal conductivity test was carried out after an interval of 15 min. In the present research work, thermal conductivity of each sample was measured at five different temperatures (35, 50, 65, 80 and 95℃) and the average values are reported in the results.

VCR system experiments

All the experiments were performed on a VCR system test rig available at Yadavindra Department of Engineering, Punjabi University Guru Kashi Campus, Talwandi Sabo, Bathinda, Punjab (India). Figure 4 shows the schematic diagram and the actual experimental VCR test rig. The test rig contains four main parts: a reciprocating compressor (designed for R134a refrigerant), an evaporator (13 L capacity, water tank coil type) with cooling coils attached to its inner cylindrical wall, a forced air-cooled condenser and an expansion device (capillary tube). The specifications of the test rig are given in Table 3. A T-type thermocouple was used for the temperature measurement of the water in the evaporator, as shown in Fig. 4a. The pressure measurements at the suction and the delivery lines of the compressor were made with the help of Bourdon-type pressure gauges. The measurement of the compressor power consumption during the refrigeration experimentation was carried out with the help of an analogue static energy meter (counting accuracy: 3200 impulse kW^{-1} h^{-1}) (Sabareesh et al. 2012; Kumar and Singh 2016; Yilmaz 2020). After one set of experiments with a specific lubricant sample, the compressor was detached from the test rig. After replacing the next kind of lubricant sample, the compressor was attached back to the system line. Before charging it with the chosen refrigerant, the VCR system was evacuated each time. For evacuation, a vacuum pump was run for 2 h to remove all the moisture from it (Sabareesh et al. 2012; Madyira et al. 2022; Gill et al. 2018). The filled mass charge of the HC refrigerant R600a was about 50–60% of the replaced mass charge of R134a (Babarinde et al. 2020; Poggi et al. 2008).

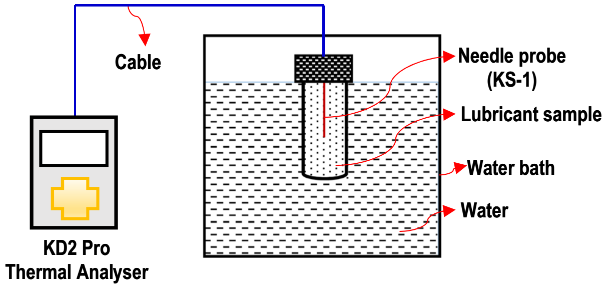


Fig. 3 Schematic diagram of KD2 Pro thermal conductivity measurement instrument

During experimentation, all the parameters required for calculating the refrigeration effect, power consumption and COP were recorded. For each experiment, the VCR test rig was run for 180 min, and each set of readings was taken after a regular interval of 5 min. The initial and the final water temperatures in the evaporator cabin were measured with the thermocouple with a time lapse ‘t’. The compressor energy consumption was determined by recording the time taken data of the analogue energy meter for each of the 10 pulses using a stopwatch. Using the aforementioned data, the refrigeration effect, compressor power consumption and COP of the refrigeration system were calculated using the standard expressions as given in Eqs. 1, 2 and 3, respectively (Sabareesh et al. 2012; Kumar and Singh 2016; Yilmaz 2020). Every experiment was conducted at the atmospheric temperature of 29–30 °C. The schematic diagram summarizing the whole experimental procedure is shown in Fig. 5.

The uncertainty of each measuring instrument was calculated as per Schultz and Cole’s (1979) methodology, and furthermore the uncertainty of the desired parameter such as P was calculated using Eq. 4 (Ohunakin et al. 2017; Adelekan et al. 2021; Jatinder et al. 2019; Babarinde et al. 2019; Sheikholeslami and Ganji 2016; Akhavan-Behabadi et al. 2015; Sanukrishna et al. 2019).

$$\text{Refrigeration effect} = \frac{m \times C_p \times \Delta T}{t}\ \text{W}, \tag{1}$$

Fig. 4 VCR system: **a** schematic diagram and **b** actual experimental test rig

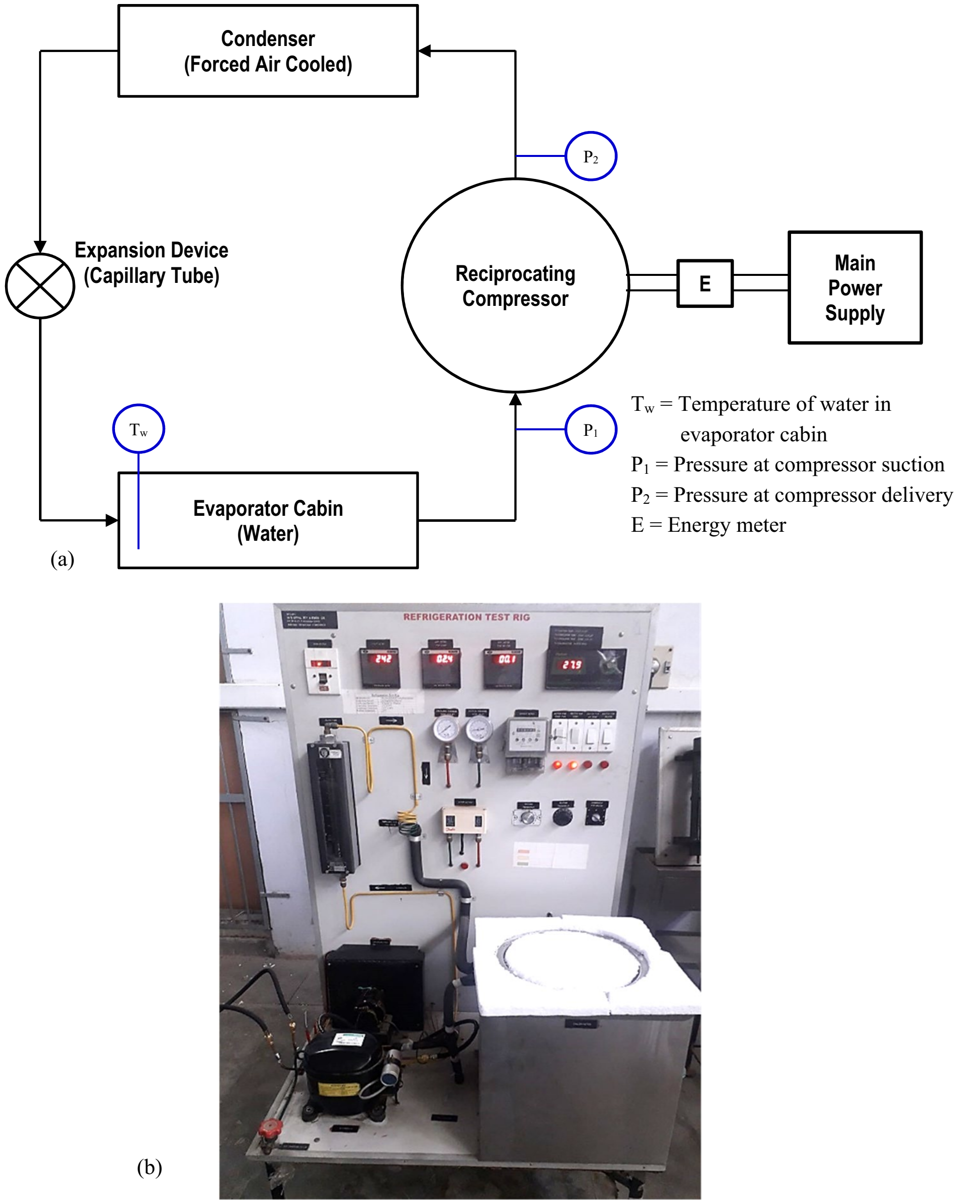


Table 3 Specifications of VCR test rig

S. No	Parameter	Value/specification
1	Refrigerant mass charge	85 g
2	Refrigerant type	HC R600a
3	Compressor	1/5 hp (HFC type)
4	Compressor lubricant	POE oil (N1)/Prepared nano-lubricants (N2/N3/N4/N5)
5	Capillary length	2.74 m
6	Capillary diameter	9.14×10^{-4} m
7	Condenser	Air-cooled
8	Evaporator load	Water

$$\text{Compressor power consumption} = \frac{\text{n} \times 3600}{\text{t} \times \text{K}} \text{W}, \tag{2}$$

$$\text{COP} = \frac{\text{RE}}{\text{P}_\text{c}}, \tag{3}$$

$$U_P = \left[\sum_{i=1}^{n} \left(\frac{\partial P}{\partial v_i} U_{v_i} \right)^2 \right]^{0.5}. \tag{4}$$

Here, P is the desired parameter, U_P represents the total uncertainty, U_{v_i} is the uncertainty of each independent variable, and n is the total number of variables. The obtained experimental uncertainties are shown in Table 4.

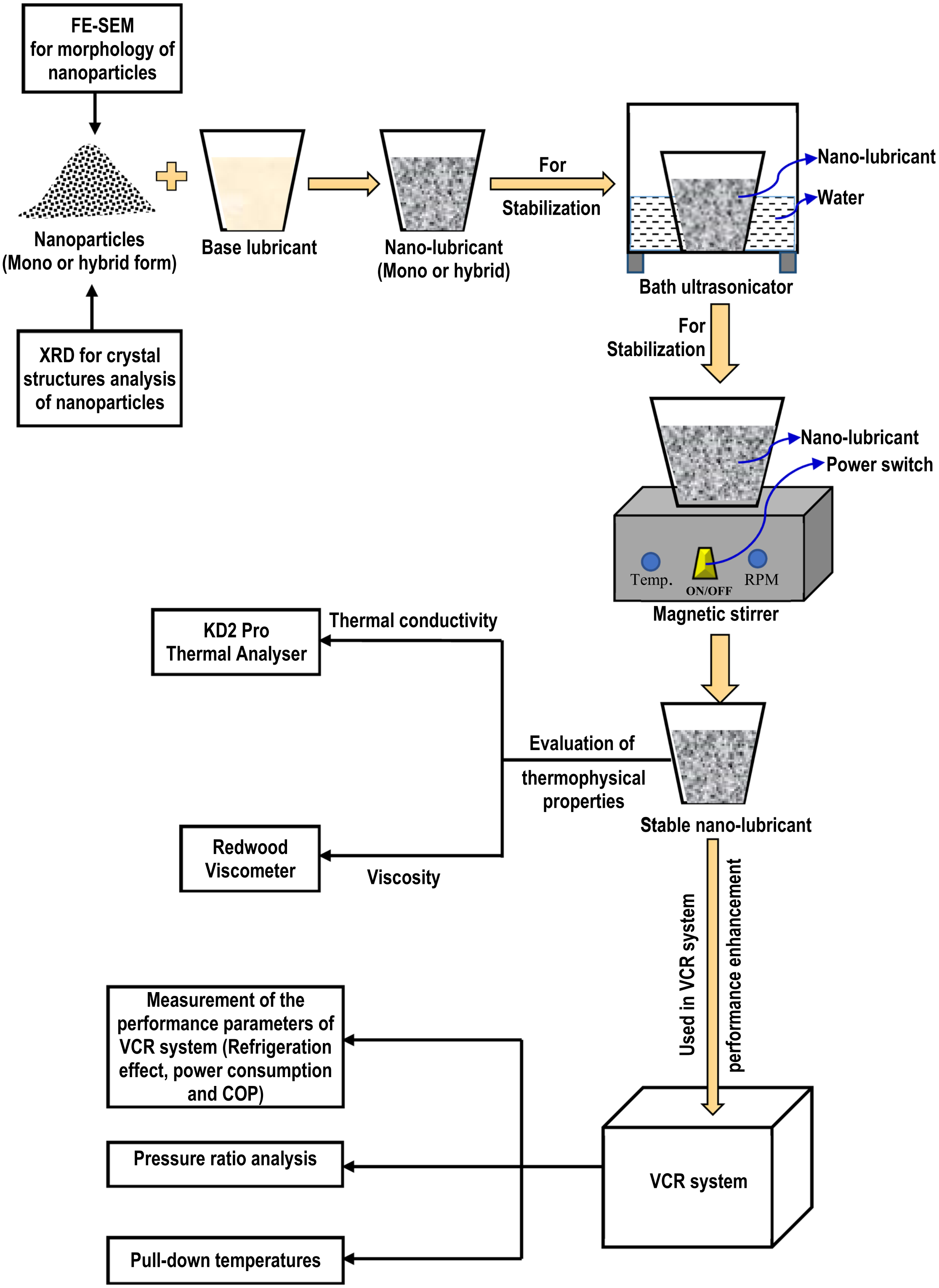


Fig. 5 Schematic diagram of the experimental procedure

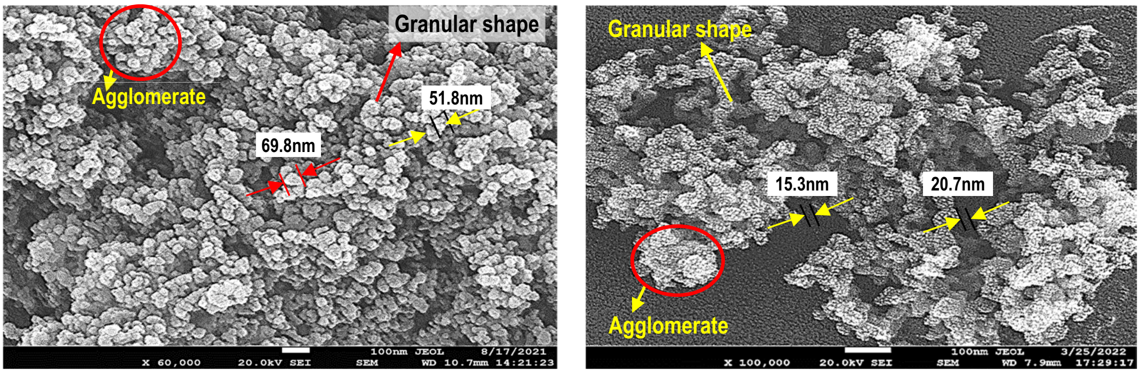
Table 4 Uncertainty of the measured parameters

S.No	Parameters	Uncertainty
1	Temperature of water in the evaporator cabin, T_w (℃)	±0.1
2	Compressor suction pressure, P_1 (kPa)	±1.1
3	Compressor discharge pressure, P_2 (kPa)	±5.0
4	Refrigeration effect (W)	±0.5
5	Power consumption (W)	±0.14
6	COP (%)	±0.5

Results and discussion

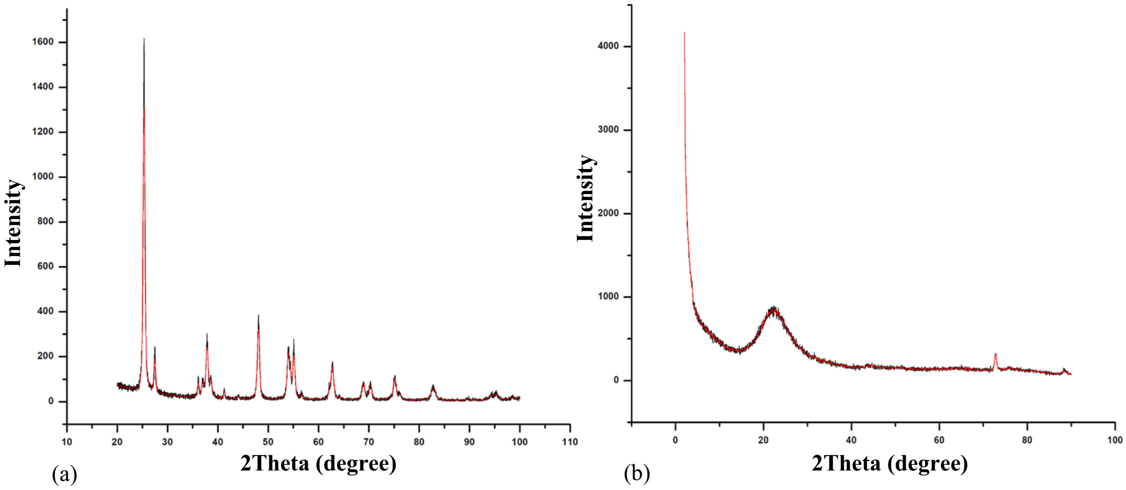
Characterization of nanoparticles

The characterization of the procured nanoparticles was elucidated by FE-SEM and XRD analysis. The nano-sized particles of granular shape and agglomeration can be clearly seen in the FE-SEM micrographs of SiO_2 and TiO_2 nanoparticles in Fig. 6. The aggregation size of SiO_2 nanoparticles is observed to be larger than that of TiO_2 nanoparticles, which is also in accordance with the supplier's specifications. The similar observation was also reported by Le Ba et al. (2020), in the thermophysical analysis of TiO_2 and SiO_2 nanoparticles. The XRD patterns of the SiO_2 and TiO_2 nanoparticles sample are shown in Fig. 7. The XRD of SiO_2 confirmed that the particles are amorphous in nature (Tkachenko et al. 2020; Le Ba et al. 2020). The XRD of TiO_2 nanoparticles showed that the peaks and all diffraction lines confirmed the presence of the crystallite anatase and rutile phase in the sample (Le Ba et al. 2020). For TiO_2 nanoparticles, the intense diffraction peak at 25.356° is attributed to the anatase phase (main component) and the minor peaks at 27.504°, 36.097°, 41.253°, 54.266°, 56.691° and 94.548° are attributed to the rutile phase (Jeba Beula et al. 2019;



(a) (b)

Fig. 6 Morphology of nanoparticles through FE-SEM micrographs: **a** SiO_2 and **b** TiO_2



(a) (b)

Fig. 7 XRD of nanoparticles through X-ray diffractometer: **a** TiO_2 and **b** SiO_2

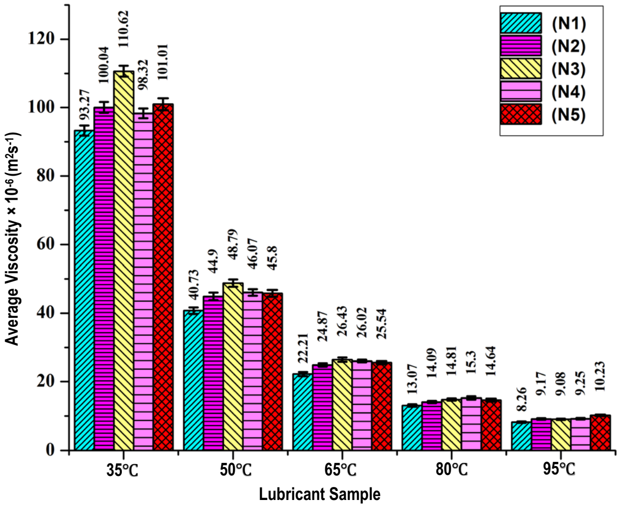


Fig. 8 Average viscosity of different oil samples at different temperatures

Iqbal et al. 2021; Kucio et al. 2020; El-Sherbiny et al. 2013; Thamaphat and Limsuwan 2008; Irshad et al. 2020; Le Ba et al. 2020; Dhanola and Garg 2020).

Viscosity analysis

As revealed from the bar graph (Fig. 8), the average viscosity of POE oil, at the respective test temperatures, is observed to have increased after addition of any kind of nanoparticles (mono or hybrid). This might be due to the enhancement in intermolecular forces of attraction among the lubricant particles (Kumar et al. 2020). However, it is also observed that the average viscosity of each sample decreased with every 15 °C increase in temperature. Figure 8 depicts that in the temperature range of 35–95 °C, the decrease in the average viscosity for each sample with an increase in temperature does not follow a consistent trend. From 35 to 65 °C, TiO_2-based mono nano-lubricant sample, N3, exhibited higher average viscosity as compared to that of the SiO_2-based mono nano-lubricant sample (N2) and each hybrid nano-lubricant sample (N4 and N5). But at the temperature 80 °C, the hybrid sample N4 exhibited viscosity more than any of the other lubricant sample. Further, at temperature even higher (95 °C), the hybrid lubricant sample N5 exhibited average viscosity higher than any of the tested lubricant samples and is about 23% higher than the neat POE lubricant sample N1. At higher temperatures, the tested mono nano-lubricant samples (N2 and N3) lost their viscosity more as compared to the tested hybrid nano-lubricant samples (N4 and N5). It might be due to a decrease in fluid layer resistance, which is expected to be maintained by the hybrid nano-lubricant (Sabareesh et al. 2012). The sustainability of viscosity at higher temperature of hybrid lubricant sample N5 promotes more viscous layer between the running parts of the compressor. This further enhances the life span of the compressor and hence the overall performance of the system (Kumar and Singh 2016). Similar results of enhancement of viscosity of hybrid nanofluid prepared using hybrid TiO_2:SiO_2 nanoparticles were observed in the previous studies of Hamid et al. (2018), Le Ba et al. (2020) and Nabil et al. (2017a).

Thermal conductivity analysis

The average thermal conductivity of each compressor lubricant sample at different temperatures is shown in Fig. 9. The bar graph reveals that for each lubricant sample, the thermal conductivity decreased with the increase in temperature. This is normally due to less number of collisions as the mean path between the molecules increase at higher temperatures (Sharif et al. 2016; Kumar et al. 2020). It can be observed that at each test temperature, the average thermal conductivity of the lubricant samples containing nanoparticles (mono or hybrid, N2 to N5) is higher than that of the neat POE oil (N1). It might be due to the development of micro-convection effect by the dispersed nanoparticles in the base lubricant (Mallick et al. 2013; Huminic and Huminic 2018). Among the nano-lubricant samples (N2–N5), the hybrid nano-lubricants (N4 and N5) exhibited a higher thermal conductivity than the mono nano-lubricant oil samples (N2 and N3), at each test temperature. Furthermore, the bar graph also reveals that at higher temperature, the hybrid nano-lubricant samples possessed much higher thermal conductivity than the mono nano-lubricant samples and the neat POE oil (N1). At temperatures of 35 °C and 95 °C, the sample N5 possessed about 40% and 165% higher thermal

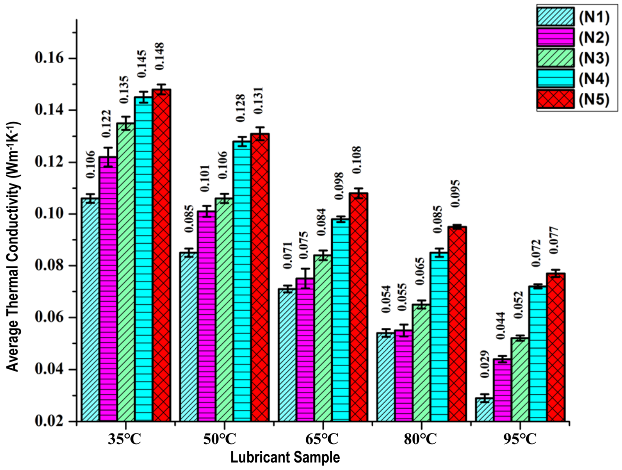


Fig. 9 Average thermal conductivity of compressor lubricant samples at different temperatures

conductivity, respectively, than the lubricant sample N1. The higher thermal conductivity at higher temperature than lower temperature might be due to the increased Brownian motion (one of the key mechanism) of the dispersed nanoparticles (Kotia et al. 2018; Hamid et al. 2018). This could have further enhanced the heat transfer capacity of the molecules as observed by Zawawi et al. (2017) and Nabil et al. (2017a). The incorporation of nanoparticles in base lubricant increases the number of collisions. It further increases the surface to volume ratio which becomes responsible for enhancement in thermal conductivity and the heat transfer characteristics (Jatinder et al. 2019; Bakhtiari et al. 2021). In comparison to the SiO_2 nanoparticles in mono nano-lubricant sample N2, the dispersion of TiO_2 nanoparticles enhanced the thermal conductivity more in the mono nano-lubricant sample N3. However, the thermal conductivity of hybrid nano-lubricant sample N5 was more than that of N4. N5 contained more quantity of SiO_2 nanoparticles (than TiO_2), which could improve the thermal conductivity less in the mono form (in N2) as compared to TiO_2 in the mono form (in N3). Some synergistic effect is expected to have played some role in uplifting the thermal conductivity in hybrid nano-lubricant sample N5 (Sidik et al. 2016; Devendiran and Amirtham 2016; Jin et al. 2021; Ma et al. 2020). The present research work shows better results of thermal conductivity of hybrid nanofluid as compared to previous studies (used the same hybrid nanoparticles) by Hamid et al. (2018), Le Ba et al. (2020) and Nabil et al. (2017a).

Refrigeration effect

The average refrigeration effect of the VCR system using HC refrigerant R600a, as obtained with neat and modified POE oils in compressor, can be well compared from the bar graph shown in Fig. 10. In every test, a minimum of about 7% improvement in average refrigeration effect could be observed after addition of nanoparticles in neat POE oil. The average refrigeration effect of the hybrid nano-lubricant samples (N4, N5) is seen to be much better than that of mono nano-lubricant samples (N2, N3). Further, among the hybrid nano-lubricants, the one which contained higher concentration of non-metallic oxide nanoparticles of SiO_2 (sample N5) resulted in better average refrigeration effect. An improvement of about more than 13% was observed with N5 hybrid nano-lubricant sample as compared to that obtained with lubricant sample N1. This might be due to a significant reduction in compressor suction and delivery pressures due to the incorporation of hybrid nanoparticles in the POE oil. During the running cycle, the refrigerant might carry some of the nanoparticles along with it due to its mixing with the nano-lubricant while traveling throughout the system (Narayanasarma and Kuzhiveli 2019). It is expected to further improve the refrigerant heat transfer capacity in the VCR test rig evaporator cabin (Yilmaz 2020). The higher value of thermal conductivity of the N5 nano-lubricant sample also indicated the same, as more improvement in the refrigeration effect was observed with the N5 sample. Although, through observed characteristics, the improvement in viscosity could not be directly linked to the refrigeration effect, it might have played a role in improving the refrigeration effect. The improvement in viscosity leads to less frictional losses in the compressor and hence less amount of heat produced in the compressor. The reduced suction and delivery pressures also indicate the same.

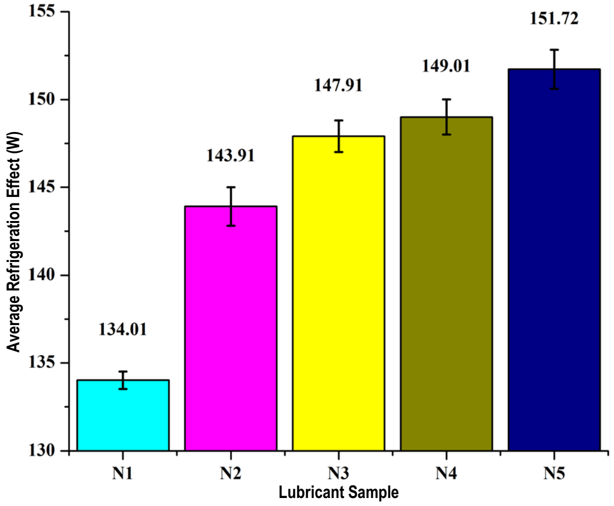


Fig. 10 Average refrigeration effect of VCR system with different lubricant samples in the compressor

Compressor power consumption

The compressor is the main source of energy consumption in the VCR system (Kumar and Singh 2016). The average power consumption (in W) in each experiment with different samples of compressor lubricants can be well compared through the bar graph shown in Fig. 11. It is clearly visible that the addition of any mono or hybrid nanoparticles resulted in reduced average power consumption. Further, the results also reveal that among the mono nano-lubricants, the average power consumption was less with the metallic nanoparticles (N3) as compared to that with the non-metallic nanoparticles (N2) sample. But the average power consumption is seen to be even less with either of the hybrid nano-lubricants (N4 or N5) as compared to that with the any of the mono nano-lubricants (N2 or N3). Looking at the better power saving characteristic of mono metallic nanoparticle (TiO_2)-based nano-lubricant (N3), it seems that the higher proportion of TiO_2 in hybrid nano-lubricant would result in reduced average power consumption. But surprisingly, the hybrid nano-lubricant (N5) having higher proportion of

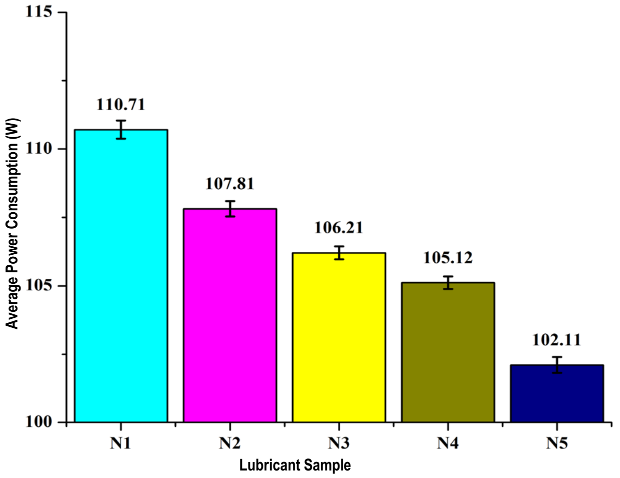


Fig. 11 Average power consumption by the VCR system with different lubricant samples in the compressor

non-metallic nanoparticles (SiO_2) resulted in much better power saving among all the tested samples. It may be due to some potential synergistic effect produced with this combination of metallic and non-metallic nanoparticle-based nano-lubricant (Vallejo et al. 2022). The average power consumption with N5 sample is about 8% lower than that with the neat POE oil. Almost spherical nano-sized particles (Fig. 6) dispersed in POE oil are expected to have reduced the contact surface between the rubbing parts, due to behaving like nano-bearing (rolling effect, Fig. 12a) as observed by Rawat et al. (2018). The nano-sized particles also fill the micro-grooves (mending effect, Fig. 12b) on the contacting surfaces, resulting in smoother mating surfaces and hence reducing the power loss due to friction as reported by Yilmaz (2020), Sanukrishna et al. (2019) and Rawat et al. (2018). The polishing effect produced by the nanoparticles by removing the surface asperities also contributes to make the mating surfaces smooth, as shown in Fig. 12d. Further, the higher value of high temperature viscosity of the hybrid nano-lubricant is reported to generate a thin protective film at the inner lining of the cylinder and the moving parts of the compressor, thereby reducing the friction substantially (Kumar and Singh 2016), as shown in Fig. 12c.

The difference in sizes of TiO_2 and SiO_2 nanoparticles in hybrid form might have played specific roles in the aforementioned multiple mechanisms. Relatively big-sized SiO_2 and small-sized TiO_2 nanoparticles might have filled the large and the small surface pits, respectively, which is also known as the mending effect, as shown in Fig. 12b. According to Hall–Petch strengthening effect, with a reduction in particle size, the mechanical properties such as yield strength and hardness of nanoparticles increase (Sanukrishna et al. 2019; Xu and Dávila 2018). The small-sized TiO_2 nanoparticles might have played a role in reducing the surface asperities (polishing effect), leading to smoother surfaces and hence lesser friction between the mating surfaces, as shown in Fig. 12d. Furthermore, as reported by Qunji et al. (1997) and Sanukrishna et al. (2019), the better anti-wear and friction reducing capacity of mono TiO_2 and SiO_2 nanoparticles increase the tribological capabilities of the compressor lubricant, when dispersed individually. This further leads to improving the tribological properties of compressor lubricant in hybrid form. The different lubrication mechanisms as shown in the schematic diagram Fig. 12 are motivated from Ali et al. (2019), Birleanu et al. (2022) and Hemmat Esfe et al. (2020).

Also in hybrid nanolubricant, the space filled by small TiO_2 nanoparticles between the large SiO_2 nanoparticles might have contributed to enhance the thermo-physical properties of the base lubricant as similarly observed by Hamid et al. (2018). This further leads to the enhancement in the thermal conductivity of hybrid nano-lubricant, as heat transfer becomes faster due to increase in the surface area, and it might have played vital role in power saving.

The decrease in values of the compressor suction and delivery characteristics such as pressures might also be responsible for lesser power consumption by the compressor as reported by Kumar et al. (2020). In addition to this, the enhanced thermal conductivity of nano-lubricants at higher temperature also played a dominating role in reducing the power consumption by the compressor (Kotia et al. 2018). This leads to transfer of heat in the evaporator and condenser in a more efficient way, resulting in reduced power consumption by the compressor. As revealed from Fig. 9, the sample N5 shows the higher average thermal conductivity at higher temperature than the other lubricant samples. This might also be responsible for reduction in power consumption in case of hybrid nano-lubricant sample N5.

Coefficient of performance

The average COP values of the VCR system for different lubricant samples in the compressor are shown in Fig. 13. The average value of COP is observed to be higher with each nano-lubricant sample (mono or hybrid), as compared to that with the neat POE oil. The COP follows a similar trend for each tested lubricant sample as the refrigeration effect. Further, the trend of power consumption also supports this trend of COP. Therefore, both factors acted favourably to improve the COP. The sample N5 showed the highest average COP among all the tested samples and was about 23% higher than that with neat POE oil (N1). This is obviously due to the combined effect of enhanced refrigeration effect and a reduced power consumption (Sabareesh et al. 2012; Senthilkumar et al. 2021b; Yilmaz 2020). The previous research work also experienced an improvement in the COP of the VCR system using different hybrid

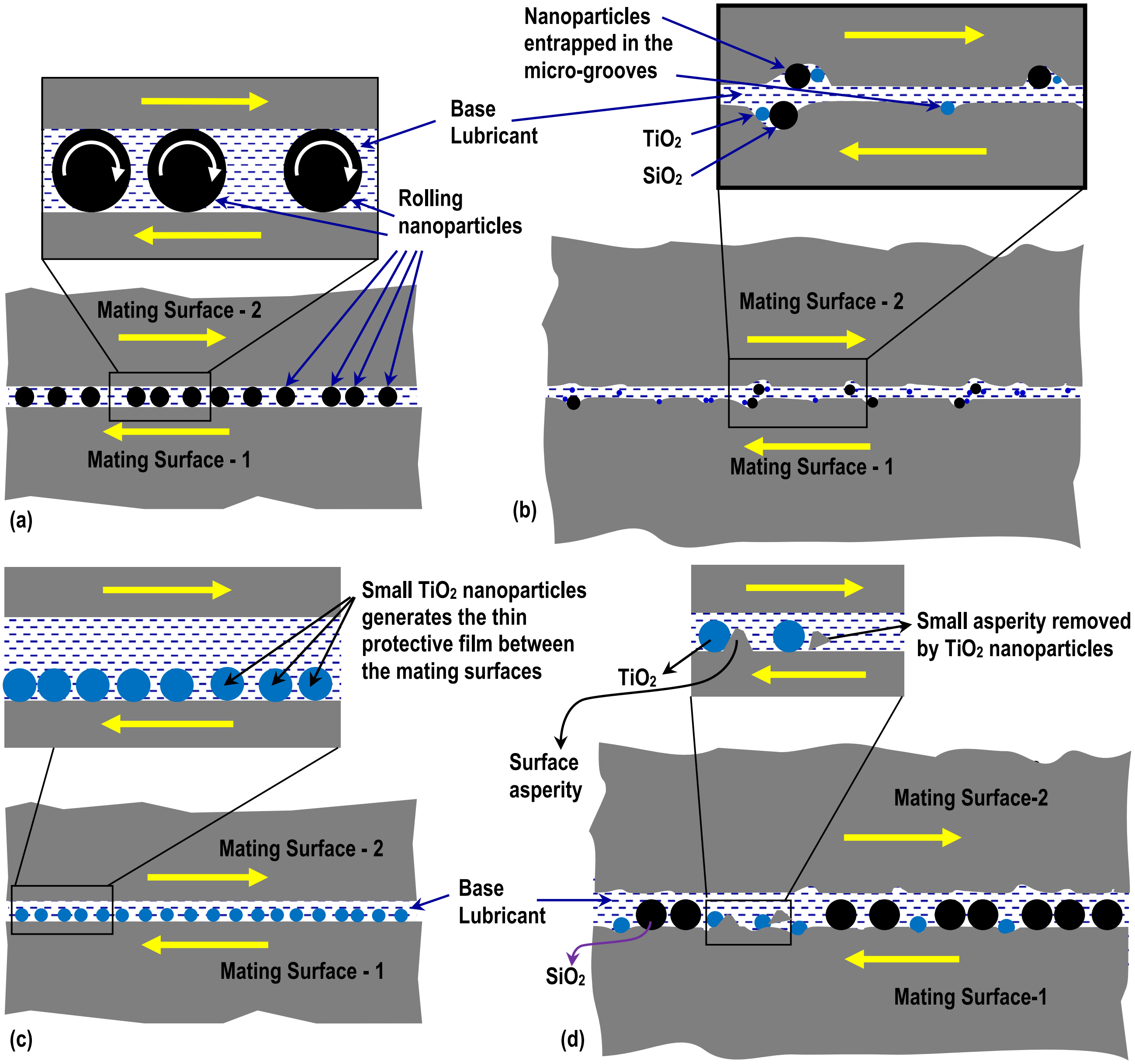


Fig. 12 Different lubricant mechanisms of: **a** rolling effect, **b** mending effect, **c** protective thin film and **d** polishing effect

nano-lubricants with various combinations of nanoparticles (Karthick et al. 2020; Senthilkumar et al. 2020a, b, 2021a, b). The present work shows much better result of COP as compared to a previous work of Saravanan and Vijayan (2018). The authors used the same compressor lubricant (POE oil) and ratios of mono and hybrid nanoparticles (TiO_2 and Al_2O_3) with a total of 0.1 gL^{-1} base oil. The maximum COP enhancement was observed to be 11.89% as compared to that of base oil, which was about 48% lower than that in the present work.

Pressure ratio analysis

Figure 14 shows the average pressure ratio of the compressor for different lubricant samples. The results reveal that addition of nanoparticles in the compressor lubricant (either mono or hybrid form) offered reduced pressure ratio. Among all the tested samples, the highest reduction in average pressure ratio of about 6% was obtained when the compressor was charged with hybrid nano-lubricant sample N5 compared to that with neat POE oil (N1). It may be due to the carrying of nanoparticles by the refrigerant, which enhances the heat carrying capacity of the refrigerant. It reduces the

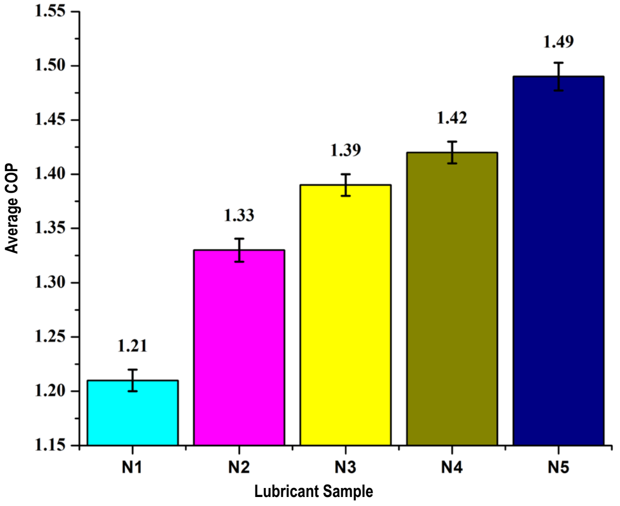


Fig. 13 Average COP of the VCR system for different lubricant samples in the compressor

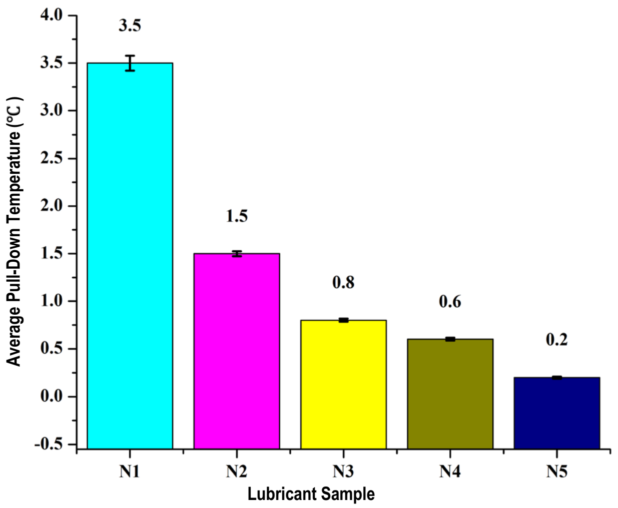


Fig. 15 Average pull-down temperature of the VCR system with different lubricant samples in the compressor

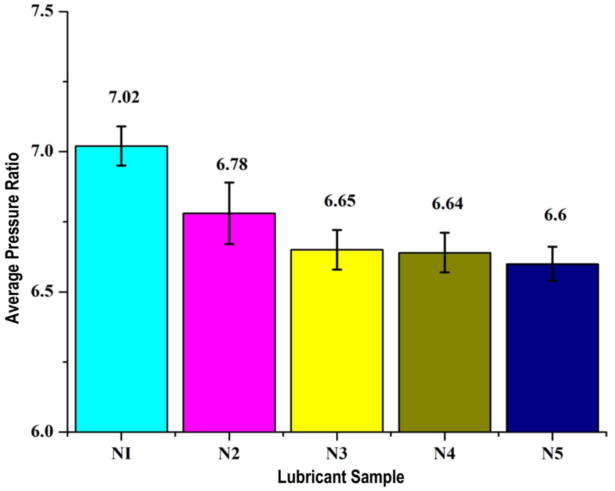


Fig. 14 Average pressure ratio of the VCR system with different lubricant samples in the compressor

pressures at the compressor suction and delivery, leading to a decrease in pressure ratio as reported by Yilmaz (2020). Further, the higher thermal conductivity of the N5 sample also supports this observation, as it results in a greater drop in pressure ratio compared to the other samples.

Pull-down temperature

The pull-down temperature reduced after a specific time. Figure 15 shows the average pull-down temperature of the VCR system for all the prepared samples of compressor lubricants. The pull-down temperature achieved with each sample was noted after a run time of 180 min. The results reveal that the average pull-down temperature values obtained with mono or hybrid nano-lubricant samples N2–N5 are much lower than that with neat POE oil (sample N1). The hybrid nano-lubricant sample N5 offered the lowest pull-down temperature amongst all the tested lubricant samples. This could be due to enhanced refrigeration effect of the VCR system by incorporating hybrid nanoparticles into the compressor lubricant as discussed in the previous section. The pull-down temperature values with each of the tested lubricant samples are in accordance with the results of the refrigeration effect. A previous research work (from literature) also shows similar results of lower pull-down temperature of hybrid nano-lubricant as compared to the mono form and neat base oil (Senthilkumar et al. 2020a; Senthilkumar et al. 2021b).

Conclusions

In this work, the effect of low concentration metallic oxide (TiO_2) and non-metallic oxide (SiO_2) nanoparticles incorporated in compressor lubricant (POE oil) of the VCR system is investigated. The VCR system used an HC refrigerant, R600a and its overall performance was investigated. The conclusions drawn are as follows:

The FE-SEM and XRD were utilized to confirm the granular shape and crystal structure of each nanoparticle. Eco-friendly HC refrigerant R600a and prepared nano-lubricants with different concentrations of SiO_2 and TiO_2 nanoparticles (mono and hybrid form) in POE oil were retrofitted successfully to existing HFC-based VCR system. Among all the tested nano-lubricant samples, maximum improvement in refrigeration effect, power saving and hence COP were observed with the hybrid nano-lubricant sample N5. The combined effect of nano-sized particles filling the micro-grooves on the contacting surfaces and the improved high temperature viscosity and thermal conductivity and least pressure ratio of sample N5 are expected to have played a significant role. The average pull-down temperature in the VCR system was observed to be reduced with the contribution of mono and hybrid nanoparticles in compressor lubricant. It was found to be the lowest with hybrid sample N5 as compared to all other tested samples. In each aspect, the performance of metallic oxide nanoparticles (TiO_2, i.e. sample N3) was observed to be better than that of the non-metallic oxide nanoparticles (SiO_2, i.e. sample N2) when used in mono form. Whereas in hybrid form (sample N5), the higher proportion of non-metallic oxide nanoparticles (SiO_2) resulted in better performance in VCR system. The combined effect of improved tribological and thermal properties (viscosity and thermal conductivity) due to dispersion of hybrid nanoparticles of TiO_2/SiO_2 and the excellent heat transfer performance was expected to have played a synergistic role through the N5 hybrid nano-lubricant sample.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Adelekan DS, Ohunakin OS, Babarinde TO, Odunfa MK, Leramo RO, Oyedepo SO et al (2017) Experimental performance of LPG refrigerant charges with varied concentration of TiO_2 nano-lubricants in a domestic refrigerator. Case Stud Therm Eng 9:55–61. https://doi.org/10.1016/j.csite.2016.12.002

Adelekan DS, Ohunakin OS, Gill J, Atayero AA, Diarra CD, Asuzu EA (2018) Experimental performance of a safe charge of LPG refrigerant enhanced with varying concentrations of TiO_2 nano-lubricant in a domestic refrigerator. J Therm Anal Calorim 136(6):2439–2448. https://doi.org/10.1007/s10973-018-7879-2

Adelekan DS, Ohunakin OS, Gill J, Atiba OE, Okokpujie IP, Atayero AA (2019a) Experimental investigation of vapour compression system with 15nm TiO_2-R600a nano-refrigerant as the working fluid. Procedia Manufacturing 35:1222–1227

Adelekan DS, Ohunakin OS, Gill J, Atiba OE, Okokpujie IP, Atayero AA (2019b) Performance of a domestic refrigerator infused with safe charge of R600a refrigerant and various concentrations of TiO_2 nanolubricant. Procedia Manuf 35:1158–1164

Adelekan DS, Ohunakin OS, Oladeinde MH, Jatinder G, Atiba OE, Nkiko MO et al (2021) Performance of a domestic refrigerator in varying ambient temperatures, concentrations of TiO_2 nano-lubricants and R600a refrigerant charges. Heliyon 7(2):e06156. https://doi.org/10.1016/j.heliyon.2021.e06156

Afrand M, Ranjbarzadeh R (2020) Hybrid nanofluids preparation method. Hybrid Nanofluids Convect Heat Transf. https://doi.org/10.1016/b978-0-12-819280-1.00002-1

Ahmad S, Nadeem S, Ullah N (2020) Entropy generation and temperature-dependent viscosity in the study of SWCNT–MWCNT hybrid nanofluid. Appl Nanosci 10(12):5107–5119. https://doi.org/10.1007/s13204-020-01306-0

Ahmadpour MM, Akhavan-Behabadi MA (2019) Experimental investigation of heat transfer during flow condensation of HC-R600a based nano-refrigerant inside a horizontal U-shaped tube. Int J Therm Sci. https://doi.org/10.1016/j.ijthermalsci.2019.106110

Ahmed MS, Elsaid AM (2019) Effect of hybrid and single nanofluids on the performance characteristics of chilled water air conditioning system. Appl Therm Eng. https://doi.org/10.1016/j.applthermaleng.2019.114398

Akhavan-Behabadi MA, Sadoughi MK, Darzi M, Fakoor-Pakdaman M (2015) Experimental study on heat transfer characteristics of R600a/POE/CuO nano-refrigerant flow condensation. Exp Thermal Fluid Sci 66:46–52. https://doi.org/10.1016/j.expthermflusci.2015.02.027

Akilu S, Baheta AT, Said MA, Minea AA, Sharma KV (2018) Properties of glycerol and ethylene glycol mixture based SiO_2-CuO/C hybrid nanofluid for enhanced solar energy transport. Solar Energy Mater Solar Cells 179:118–128. https://doi.org/10.1016/j.solmat.2017.10.027

Ali I, Basheer AA, Kucherova A, Memetov N, Pasko T, Ovchinnikov K et al (2019) Advances in carbon nanomaterials as lubricants modifiers. J Mol Liq 279:251–266. https://doi.org/10.1016/j.molliq.2019.01.113

Asadi A, Alarifi IM, Ali V, Nguyen HM (2019) An experimental investigation on the effects of ultrasonication time on stability and thermal conductivity of MWCNT-water nanofluid: finding the optimum ultrasonication time. Ultrason Sonochem 58:104639. https://doi.org/10.1016/j.ultsonch.2019.104639

Azmi WH, Sharma KV, Mamat R, Najafi G, Mohamad MS (2016) The enhancement of effective thermal conductivity and effective dynamic viscosity of nanofluids – a review. Renew Sustain Energy Rev 53:1046–1058. https://doi.org/10.1016/j.rser.2015.09.081

Azmi WH, Sharif MZ, Yusof TM, Mamat R, Redhwan AAM (2017) Potential of nanorefrigerant and nanolubricant on energy saving in refrigeration system–a review. Renew Sustain Energy Rev 69:415–428. https://doi.org/10.1016/j.rser.2016.11.207

Babarinde TO, Akinlabi SA, Madyira DM (2019) Experimental investigation of R600a/TiO_2/mineral oil as a drop-in replacement for R134a/POE oil in a household refrigeration system. Int J Ambient Energy. https://doi.org/10.1080/01430750.2019.1653983

Babarinde TO, Akinlabib SA, Madyiraa DM, Ekundayod FM (2020) Enhancing the energy efficiency of vapour compression refrigerator system using R600a with graphene nanolubricant. Energy Rep 6:1–10. https://doi.org/10.1016/j.egyr.2019.11.031

Bakhtiari R, Kamkari B, Afrand M, Abdollahi A (2021) Preparation of stable TiO_2-graphene/water hybrid nanofluids and development of a new correlation for thermal conductivity. Powder Technol 385:466–477. https://doi.org/10.1016/j.powtec.2021.03.010

Bi S-S, Shi L, Zhang L-L (2008) Application of nanoparticles in domestic refrigerators. Appl Therm Eng 28(14–15):1834–1843. https://doi.org/10.1016/j.applthermaleng.2007.11.018

Bi S, Guo K, Liu Z, Wu J (2011) Performance of a domestic refrigerator using TiO_2-R600a nano-refrigerant as working fluid. Energy Convers Manage 52(1):733–737. https://doi.org/10.1016/j.enconman.2010.07.052

Birleanu C, Pustan M, Cioaza M, Molea A, Popa F, Contiu G (2022) Effect of TiO_2 nanoparticles on the tribological properties of lubricating oil: an experimental investigation. Sci Rep 12(1):5201. https://doi.org/10.1038/s41598-022-09245-2

Borode AO, Ahmed NA, Olubambi PA (2019) A review of heat transfer application of carbon-based nanofluid in heat exchangers. Nano-Str Nano-Objects. https://doi.org/10.1016/j.nanoso.2019.100394

Cao X, Wang X, Song Q, Wang D, Li Y (2021) Experimental investigation on the heat transfer and pressure drop characteristics of

R600a in a minichannel condenser with different inclined angles. Appl Therm Eng. https://doi.org/10.1016/j.applthermaleng.2021.117227

Chakraborty S, Panigrahi PK (2020) Stability of nanofluid: a review. Appl Therm Eng. https://doi.org/10.1016/j.applthermaleng.2020.115259

Cheng L, Liu L (2013) Boiling and two-phase flow phenomena of refrigerant-based nanofluids: fundamentals, applications and challenges. Int J Refrig 36(2):421–446. https://doi.org/10.1016/j.ijrefrig.2012.11.010

Corberán JM, Segurado J, Colbourne D, Gonzálvez J (2008) Review of standards for the use of hydrocarbon refrigerants in A/C, heat pump and refrigeration equipment. Int J Refrig 31(4):748–756. https://doi.org/10.1016/j.ijrefrig.2007.12.007

Devendiran DK, Amirtham VA (2016) A review on preparation, characterization, properties and applications of nanofluids. Renew Sustain Energy Rev 60:21–40. https://doi.org/10.1016/j.rser.2016.01.055

Dhanola A, Garg HC (2020) Influence of different surfactants on the stability and varying concentrations of TiO2 nanoparticles on the rheological properties of canola oil-based nanolubricants. Appl Nanosci 10(9):3617–3637. https://doi.org/10.1007/s13204-020-01467-y

Ding G, Peng H, Jiang W, Gao Y (2009) The migration characteristics of nanoparticles in the pool boiling process of nanorefrigerant and nanorefrigerant–oil mixture. Int J Refrig 32(1):114–123. https://doi.org/10.1016/j.ijrefrig.2008.08.007

El-Morsi M (2015) Energy and exergy analysis of LPG (liquefied petroleum gas) as a drop in replacement for R134a in domestic refrigerators. Energy 86:344–353. https://doi.org/10.1016/j.energy.2015.04.035

El-Sherbiny S, Morsy F, Samir M, Fouad OA (2013) Synthesis, characterization and application of TiO_2 nanopowders as special paper coating pigment. Appl Nanosci 4(3):305–313. https://doi.org/10.1007/s13204-013-0196-y

Fatouh M, Abou-Ziyan H (2018) Energy and exergy analysis of a household refrigerator using a ternary hydrocarbon mixture in tropical environment – effects of refrigerant charge and capillary length. Appl Therm Eng 145:14–26. https://doi.org/10.1016/j.applthermaleng.2018.09.008

Gaganpreet, Srivastava S (2012) Effect of aggregation on thermal conductivity and viscosity of nanofluids. Appl Nanosci 2(3):325–331. https://doi.org/10.1007/s13204-012-0082-z

Ghorbani B, Akhavan-Behabadi MA, Ebrahimi S, Vijayaraghavan K (2017) Experimental investigation of condensation heat transfer of R600a/POE/CuO nano-refrigerant in flattened tubes. Int Commun Heat Mass Transfer 88:236–244. https://doi.org/10.1016/j.icheatmasstransfer.2017.09.011

Gill J, Singh J, Ohunakin OS, Adelekan DS (2018) Artificial neural network approach for irreversibility performance analysis of domestic refrigerator by utilizing LPG with TiO_2–lubricant as replacement of R134a. Int J Refrig 89:159–176. https://doi.org/10.1016/j.ijrefrig.2018.02.025

Gupta M, Singh V, Kumar R, Said Z (2017) A review on thermophysical properties of nanofluids and heat transfer applications. Renew Sustain Energy Rev 74:638–670. https://doi.org/10.1016/j.rser.2017.02.073

Hamid KA, Azmi WH, Nabil MF, Mamat R, Sharma KV (2018) Experimental investigation of thermal conductivity and dynamic viscosity on nanoparticle mixture ratios of TiO_2-SiO_2 nanofluids. Int J Heat Mass Transf 116:1143–1152. https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.087

Hamzah MH, Sidik NAC, Ken TL, Mamat R, Najafi G (2017) Factors affecting the performance of hybrid nanofluids: a comprehensive review. Int J Heat Mass Transf 115:630–646. https://doi.org/10.1016/j.ijheatmasstransfer.2017.07.021

Harby K (2017) Hydrocarbons and their mixtures as alternatives to environmental unfriendly halogenated refrigerants: an updated overview. Renew Sustain Energy Rev 73:1247–1264. https://doi.org/10.1016/j.rser.2017.02.039

Hemmat Esfe M, Kiannejad Amiri M, Alirezaie A (2018) Thermal conductivity of a hybrid nanofluid. J Therm Anal Calorim 134(2):1113–1122. https://doi.org/10.1007/s10973-017-6836-9

Hemmat Esfe M, Bahiraei M, Mir A (2020) Application of conventional and hybrid nanofluids in different machining processes: a critical review. Adv Colloid Interface Sci 282:102199. https://doi.org/10.1016/j.cis.2020.102199

Huminic G, Huminic A (2012) Application of nanofluids in heat exchangers: a review. Renew Sustain Energy Rev 16(8):5625–5638. https://doi.org/10.1016/j.rser.2012.05.023

Huminic G, Huminic A (2018) Hybrid nanofluids for heat transfer applications – a state-of-the-art review. Int J Heat Mass Transf 125:82–103. https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.059

Iqbal T, Irfan F, Afsheen S, Zafar M, Naeem S, Raza A (2021) Synthesis and characterization of Ag–TiO_2 nano-composites to study their effect on seed germination. Appl Nanosci 11(7):2043–2057. https://doi.org/10.1007/s13204-021-01912-6

Irshad MA, Nawaz R, Zia Ur Rehman M, Imran M, Ahmad J, Ahmad S et al (2020) Synthesis and characterization of titanium dioxide nanoparticles by chemical and green methods and their antifungal activities against wheat rust. Chemosphere 258:127352. https://doi.org/10.1016/j.chemosphere.2020.127352

Jatinder G, Ohunakin OS, Adelekan DS, Atiba OE, Daniel AB, Singh J et al (2019) Performance of a domestic refrigerator using selected hydrocarbon working fluids and TiO_2–MO nanolubricant. Appl Therm Eng. https://doi.org/10.1016/j.applthermaleng.2019.114004

Jeba Beula R, Suganthi D, Abiram A, Vidhya B (2019) Transforming polymorphs of Co-doped TiO_2 nanoparticles: an efficient photo-electrode for dye-sensitized solar cells. Appl Nanosci 10(4):1173–1181. https://doi.org/10.1007/s13204-019-01182-3

Jin C, Wu Q, Yang G, Zhang H, Zhong Y (2021) Investigation on hybrid nanofluids based on carbon nanotubes filled with metal nanoparticles: stability, thermal conductivity, and viscosity. Powder Technol 389:1–10. https://doi.org/10.1016/j.powtec.2021.05.007

Joybari MM, Hatamipour MS, Rahimi A, Modarres FG (2013) Exergy analysis and optimization of R600a as a replacement of R134a in a domestic refrigerator system. Int J Refrig 36(4):1233–1242. https://doi.org/10.1016/j.ijrefrig.2013.02.012

Jwo C-S, Ting C-C, Wang W-R (2009) Efficiency analysis of home refrigerators by replacing hydrocarbon refrigerants. Measurement 42(5):697–701. https://doi.org/10.1016/j.measurement.2008.11.006

Kaggwa A, Carson JK (2019) Developments and future insights of using nanofluids for heat transfer enhancements in thermal systems: a review of recent literature. Int Nano Lett 9(4):277–288. https://doi.org/10.1007/s40089-019-00281-x

Kakavandi A, Akbari M (2018) Experimental investigation of thermal conductivity of nanofluids containing of hybrid nanoparticles suspended in binary base fluids and propose a new correlation. Int J Heat Mass Transf 124:742–751. https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.103

Karimi A, Sadatlu MAA, Saberi B, Shariatmadar H, Ashjaee M (2015) Experimental investigation on thermal conductivity of water based nickel ferrite nanofluids. Adv Powder Technol 26(6):1529–1536. https://doi.org/10.1016/j.apt.2015.08.015

Karthick M, Karuppiah S, Kanthan V (2020) Performance investigation and exergy analysis of vapor compression refrigeration system operated using R600a refrigerant and nanoadditive compressor oil. Therm Sci 24(5 Part A):2977–2989. https://doi.org/10.2298/tsci180527024m

Khan I, Saeed K, Khan I (2019) Nanoparticles: properties, applications and toxicities. Arab J Chem 12(7):908–931. https://doi.org/10.1016/j.arabjc.2017.05.011

Kotia A, Rajkhowa P, Rao GS, Ghosh SK (2018) Thermophysical and tribological properties of nanolubricants: a review. Heat Mass Transf 54(11):3493–3508. https://doi.org/10.1007/s00231-018-2351-1

Krishnan BP, Vijayan R, Gokulnath K, Vivek S, Sathyamoorthy G (2019) Experimental analysis of a vapour compression refrigeration system by using nano refrigerant (R290/R600a/Al_2O_3). (Paper presented at the International Conference on Materials, Manufacturing and Machining 2019)

Kucio K, Charmas B, Pasieczna-Patkowska S, Zięzio M (2020) Mechanochemical synthesis of nanophotocatalysts SiO_2/TiO_2/Fe_2O_3: their structural, thermal and photocatalytic properties. Appl Nanosci 10(12):4733–4746. https://doi.org/10.1007/s13204-020-01462-3

Kumar R, Singh J (2016) Effect of ZnO nanoparticles in R290/R600a (50/50) based vapour compression refrigeration system added via lubricant oil on compressor suction and discharge characteristics. Heat Mass Transf 53(5):1579–1587. https://doi.org/10.1007/s00231-016-1921-3

Kumar R, Singh DK, Chander S (2020) An experimental approach to study thermal and tribology behavior of LPG refrigerant and MO lubricant appended with ZnO nanoparticles in domestic refrigeration cycle. Heat Mass Transf 56(7):2303–2311. https://doi.org/10.1007/s00231-020-02860-7

Le Ba T, Várady ZI, Lukács IE, Molnár J, Balczár IA, Wongwises S et al (2020) Experimental investigation of rheological properties and thermal conductivity of SiO_2–P25 TiO_2 hybrid nanofluids. J Therm Anal Calorim 146(1):493–507. https://doi.org/10.1007/s10973-020-10022-4

Leong KY, Ku Ahmad KZ, Ong HC, Ghazali MJ, Baharum A (2017) Synthesis and thermal conductivity characteristic of hybrid nanofluids – a review. Renew Sustain Energy Rev 75:868–878. https://doi.org/10.1016/j.rser.2016.11.068

Liao L, Zhang Z, Meng F, Liu D, Wu B, Li Y et al (2021) A novel slurry for chemical mechanical polishing of single crystal diamond. Appl Surf Sci. https://doi.org/10.1016/j.apsusc.2021.150431

Liu K, Zhang Y, Dai F, Sun W (2021) Improved heat transfer of the engine oil by changing it to hybrid nanofluid: adding hybrid nano-powders. Powder Technol 383:56–64. https://doi.org/10.1016/j.powtec.2021.01.005

Ma M, Zhai Y, Yao P, Li Y, Wang H (2020) Synergistic mechanism of thermal conductivity enhancement and economic analysis of hybrid nanofluids. Powder Technol 373:702–715. https://doi.org/10.1016/j.powtec.2020.07.020

Madyira DM, Babarinde TO, Mashinini PM (2022) Performance improvement of R600a with graphene nanolubricant in a domestic refrigerator as a potential substitute for R134a. Fuel Commun. https://doi.org/10.1016/j.jfueco.2021.100034

Mahbubul IM, Saidur R, Amalina MA (2013) Thermal conductivity, viscosity and density of R141b refrigerant based nanofluid. Procedia Eng 56:310–315. https://doi.org/10.1016/j.proeng.2013.03.124

Mallick SS, Mishra A, Kundan L (2013) An investigation into modelling thermal conductivity for alumina–water nanofluids. Powder Technol 233:234–244. https://doi.org/10.1016/j.powtec.2012.08.003

Mansourian R, Mousavi SM, Michaelides EE (2020) Improving the thermo-physical and rheological properties of crude oil (CO) by the synthesized CuO/SiO_2/CaP nanocomposite for drag reduction through horizontal pipelines. Appl Nanosci 11(2):347–362. https://doi.org/10.1007/s13204-020-01597-3

Marcucci Pico DF, da Silva LRR, Schneider PS, Bandarra Filho EP (2019) Performance evaluation of diamond nanolubricants applied to a refrigeration system. Int J Refrig 100(100):104–112. https://doi.org/10.1016/j.ijrefrig.2018.12.009

Minea AA, Moldoveanu MG (2018) Overview of hybrid nanofluids development and enefits. J Eng Thermophys 27(4):507–514. https://doi.org/10.1134/s1810232818040124

Muneeshwaran M, Srinivasan G, Muthukumar P, Wang C-C (2021) Role of hybrid-nanofluid in heat transfer enhancement – a review. Int Commun Heat Mass Transf. https://doi.org/10.1016/j.icheatmasstransfer.2021.105341

Nabil MF, Azmi WH, Abdul Hamid K, Mamat R, Hagos FY (2017a) An experimental study on the thermal conductivity and dynamic viscosity of TiO_2-SiO_2 nanofluids in water: ethylene glycol mixture. Int Commun Heat Mass Transfer 86:181–189. https://doi.org/10.1016/j.icheatmasstransfer.2017.05.024

Nabil MF, Azmi WH, Hamid KA, Zawawi NNM, Priyandoko G, Mamat R (2017b) Thermo-physical properties of hybrid nanofluids and hybrid nanolubricants: a comprehensive review on performance. Int Commun Heat Mass Transfer 83:30–39. https://doi.org/10.1016/j.icheatmasstransfer.2017.03.008

Nair V, Parekh AD, Tailor PR (2020) Experimental investigation of a vapour compression refrigeration system using R134a/nano-oil mixture. Int J Refrig 112:21–36. https://doi.org/10.1016/j.ijrefrig.2019.12.009

Narayanasarma S, Kuzhiveli BT (2019) Evaluation of the properties of POE/SiO_2 nanolubricant for an energy-efficient refrigeration system – an experimental assessment. Powder Technol 356:1029–1044. https://doi.org/10.1016/j.powtec.2019.09.024

Ohunakin OS, Adelekan DS, Babarinde TO, Leramo RO, Abam FI, Diarra CD (2017) Experimental investigation of TiO_2-, SiO_2- and Al_2O_3-lubricants for a domestic refrigerator system using LPG as working fluid. Appl Therm Eng 127:1469–1477. https://doi.org/10.1016/j.applthermaleng.2017.08.153

Ohunakin OS, Adelekan DS, Gill J, Atayero AA, Atiba OE, Okokpujie IP et al (2018) Performance of a hydrocarbon driven domestic refrigerator based on varying concentration of SiO_2 nanolubricant. Int J Refrig 94:59–70. https://doi.org/10.1016/j.ijrefrig.2018.07.022

Okonkwo EC, Wole-Osho I, Almanassra IW, Abdullatif YM, Al-Ansari T (2020) An updated review of nanofluids in various heat transfer devices. J Therm Anal Calorim 145(6):2817–2872. https://doi.org/10.1007/s10973-020-09760-2

Padmanabhan VMV, Palanisamy S (2012) The use of TiO_2 nanoparticles to reduce refrigerator ir-reversibility. Energy Convers Manage 59:122–132. https://doi.org/10.1016/j.enconman.2012.03.002

Poggi F, Macchi-Tejeda H, Leducq D, Bontemps A (2008) Refrigerant charge in refrigerating systems and strategies of charge reduction. Int J Refrig 31(3):353–370. https://doi.org/10.1016/j.ijrefrig.2007.05.014

Qunji X, Liu W, Zhang Z (1997) Friction and wear properties of a surface-modified TiO_2 nanoparticle as an additive in liquid paraffin. Wear 213:29–32

Ranga Babu JA, Kumar KK, Srinivasa Rao S (2017) State-of-art review on hybrid nanofluids. Renew Sustain Energy Rev 77:551–565. https://doi.org/10.1016/j.rser.2017.04.040

Rasti M, Aghamiri S, Hatamipour M-S (2013) Energy efficiency enhancement of a domestic refrigerator using R436A and R600a as alternative refrigerants to R134a. Int J Therm Sci 74:86–94. https://doi.org/10.1016/j.ijthermalsci.2013.07.009

Rawat SS, Harsha AP, Deepak AP (2018) Tribological performance of paraffin grease with silica nanoparticles as an additive. Appl Nanosci 9(3):305–315. https://doi.org/10.1007/s13204-018-0911-9

Robertson J (2004) High dielectric constant oxides. Eur Phys J Appl Phys 28(3):265–291. https://doi.org/10.1051/epjap:2004206

Sabareesh RK, Gobinath N, Sajith V, Das S, Sobhan CB (2012) Application of TiO_2 nanoparticles as a lubricant-additive for vapor compression refrigeration systems -an experimental investigation. Int J Refrig 35:1989–1996. https://doi.org/10.1016/j.ijrefrig.2012.07.002

Saidur R, Kazi SN, Hossain MS, Rahman MM, Mohammed HA (2011) A review on the performance of nanoparticles suspended with refrigerants and lubricating oils in refrigeration systems. Renew Sustain Energy Rev 15(1):310–323. https://doi.org/10.1016/j.rser.2010.08.018

Sangapatanam S, Subbarayudu K, Polu BR (2022) Hybrid nanofluids development and benefits: a comprehensive review. J Therm Eng 8:1–11. https://doi.org/10.14744/jten.2022.0000

Sanukrishna SS, Prakash MJ (2018) Experimental studies on thermal and rheological behaviour of TiO_2-PAG nanolubricant for refrigeration system. Int J Refrig 86:356–372. https://doi.org/10.1016/j.ijrefrig.2017.11.014

Sanukrishna SS, Shafi M, Murukan M, Jose Prakash M (2019) Effect of SiO_2 nanoparticles on the heat transfer characteristics of refrigerant and tribological behaviour of lubricant. Powder Technol 356:39–49. https://doi.org/10.1016/j.powtec.2019.07.083

Saravanan K, Vijayan R (2018) Performance of Al_2O_3/TiO_2 nano composite particles in domestic refrigerator. J Exp Nanosci 13(1):245–257. https://doi.org/10.1080/17458080.2018.1491066

Schultz R, Cole R (1979) Uncertainty analysis in boiling nucleation, AICHE symposium series. 75(189): 32–39

Senthilkumar A, Abhijith EP, Jawhar CAA, Jamshid (2020a) Experimental investigation of Al_2O_3/SiO_2 hybrid nanolubriant in R600a vapour compression refrigeration system. Mater Today Proc. https://doi.org/10.1016/j.matpr.2020.08.779

Senthilkumar A, Mohammed Sahaluddeen PA, Nufais Noushad M, Mohammed Musthafa EK (2020b) Experimental investigation of ZnO/SiO_2 hybrid nano-lubricant in R600a vapour compression refrigeration system. Mater Today Proc. https://doi.org/10.1016/j.matpr.2020.10.180

Senthilkumar A, Abhishek PV, Adithyan M, Arjun A (2021a) Experimental investigation of CuO/SiO_2 hybrid nano-lubricant in R600a vapour compression refrigeration system. Mater Today Proc 45:6083–6086. https://doi.org/10.1016/j.matpr.2020.10.178

Senthilkumar A, Anderson A, Sekar M (2021b) Performance analysis of R600a vapour compression refrigeration system using CuO/Al_2O_3 hybrid nanolubricants. Appl Nanosci. https://doi.org/10.1007/s13204-021-01936-y

Shah J, Ranjan M, Davariya V, Gupta SK, Sonvane Y (2017) Temperature-dependent thermal conductivity and viscosity of synthesized α-alumina nanofluids. Appl Nanosci 7(8):803–813. https://doi.org/10.1007/s13204-017-0594-7

Sharif MZ, Azmi WH, Redhwan AAM, Mamat R (2016) Investigation of thermal conductivity and viscosity of Al_2O_3/PAG nanolubricant for application in automotive air conditioning system. Int J Refrig 70:93–102. https://doi.org/10.1016/j.ijrefrig.2016.06.025

Sharif MZ, Azmia WH, Mamata R, Shaifuld AIM (2018) Mechanism for improvement in refrigeration system performance by using nanorefrigerants and nanolubricants – a review. Int Commun Heat Mass Transf. https://doi.org/10.1016/j.icheatmasstransfer.2018.02.012

Sheikholeslami M, Ganji DD (2016) Heat transfer enhancement in an air to water heat exchanger with discontinuous helical turbulators; experimental and numerical studies. Energy 116:341–352. https://doi.org/10.1016/j.energy.2016.09.120

Sidik NAC, Mohammed HA, Alawi OA, Samion S (2014) A review on preparation methods and challenges of nanofluids. Int Commun Heat Mass Transfer 54:115–125. https://doi.org/10.1016/j.icheatmasstransfer.2014.03.002

Sidik NAC, Adamu IM, Jamil MM, Kefayati GHR, Mamat R, Najafi G (2016) Recent progress on hybrid nanofluids in heat transfer applications: a comprehensive review. Int Commun Heat Mass Transfer 78:68–79. https://doi.org/10.1016/j.icheatmasstransfer.2016.08.019

Singh BK, Ansari MS (2017) An experimental study of nanorefrigerant (HC+CuO) based refrigeration system. IJSRSET 3(8):1073–1076

Thamaphat K, Limsuwan P (2008) Phase characterization of TiO_2 powder by XRD and TEM. Agric Nat Resour 42:357–361

Tkachenko T, Yevdokymenko V, Kamenskyh D, Sheludko Y, Povazhnyi V, Kashkovskyi V (2020) Physico-chemical properties of biogenic SiO_2 nanoparticles obtained from agriculture residue. Appl Nanosci 10(12):4617–4623. https://doi.org/10.1007/s13204-020-01383-1

Vaka M, Walvekar R, Khalid M, Jagadish P, Mubarak NM, Panchal H (2020) Synthesis of hybrid graphene/TiO_2 nanoparticles based high-temperature quinary salt mixture for energy storage application. J Energy Storage. https://doi.org/10.1016/j.est.2020.101540

Vallejo JP, Prado JI, Lugo L (2022) Hybrid or mono nanofluids for convective heat transfer applications. a critical review of experimental research. Appl Therm Eng. https://doi.org/10.1016/j.applthermaleng.2021.117926

Wang X-Q, Mujumdar AS (2007) Heat transfer characteristics of nanofluids: a review. Int J Therm Sci 46(1):1–19. https://doi.org/10.1016/j.ijthermalsci.2006.06.010

Wang B, Zhang Z, Chang K, Cui J, Rosenkranz A, Yu J et al (2018) New deformation-induced nanostructure in silicon. Nano Lett 18(7):4611–4617. https://doi.org/10.1021/acs.nanolett.8b01910

Xie W, Zhang Z, Liao L, Liu J, Su H, Wang S et al (2020) Green chemical mechanical polishing of sapphire wafers using a novel slurry. Nanoscale 12(44):22518–22526. https://doi.org/10.1039/d0nr04705h

Xu W, Dávila LP (2018) Tensile nanomechanics and the Hall-Petch effect in nanocrystalline aluminium. Mater Sci Eng, A 710:413–418. https://doi.org/10.1016/j.msea.2017.10.021

Yang L, Ji W, Mao M, Huang J-N (2020) An updated review on the properties, fabrication and application of hybrid-nanofluids along with their environmental effects. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.120408

Yıldız G, Ağbulut Ü, Gürel AE (2021) A review of stability, thermophysical properties and impact of using nanofluids on the performance of refrigeration systems. Int J Refrig 129:342–364. https://doi.org/10.1016/j.ijrefrig.2021.05.016

Yilmaz AC (2020) Performance evaluation of a refrigeration system using nanolubricant. Appl Nanosci 10(5):1667–1678. https://doi.org/10.1007/s13204-020-01258-5

Yogesh J, Dinesh Z, Sandeep J (2021) Performance investigation of vapor compression refrigeration system using R134a and R600a refrigerants and Al_2O_3 nanoparticle based suspension. Mater Today Proc 44:1511–1519. https://doi.org/10.1016/j.matpr.2020.11.732

Zawawi NNM, Azmi WH, Redhwan AAM, Sharif MZ, Sharma KV (2017) Thermo-physical properties of Al_2O_3-SiO_2/PAG composite nanolubricant for refrigeration system. Int J Refrig 80:1–10. https://doi.org/10.1016/j.ijrefrig.2017.04.024

Zhang Z, Wang B, Kang R, Zhang B, Guo D (2015) Changes in surface layer of silicon wafers from diamond scratching. CIRP Ann 64(1):349–352. https://doi.org/10.1016/j.cirp.2015.04.005

Zhang Z, Cui J, Wang B, Wang Z, Kang R, Guo D (2017) A novel approach of mechanical chemical grinding. J Alloy Compd 726:514–524. https://doi.org/10.1016/j.jallcom.2017.08.024

Zhang Z, Shi Z, Du Y, Yu Z, Guo L, Guo D (2018) A novel approach of chemical mechanical polishing for a titanium alloy using an environment-friendly slurry. Appl Surf Sci 427:409–415. https://doi.org/10.1016/j.apsusc.2017.08.064

Zhang Z, Cui J, Zhang J, Liu D, Yu Z, Guo D (2019) Environment friendly chemical mechanical polishing of copper. Appl Surf Sci 467–468:5–11. https://doi.org/10.1016/j.apsusc.2018.10.133

Zhang Z, Liao L, Wang X, Xie W, Guo D (2020) Development of a novel chemical mechanical polishing slurry and its polishing mechanisms on a nickel alloy. Appl Surf Sci. https://doi.org/10.1016/j.apsusc.2019.144670

Zhang Z, Liu J, Hu W, Zhang L, Xie W, Liao L (2021) Chemical mechanical polishing for sapphire wafers using a developed slurry. J Manuf Process 62:762–771. https://doi.org/10.1016/j.jmapro.2021.01.004