



Performance evaluation of a refrigeration system using nanolubricant

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Abstract

This research presents the effects of copper(II) oxide (CuO) and copper/silver (Cu/Ag) alloy nanoparticle incorporation on compressor oil (POE) of a vapor compression refrigeration system using HFC-R134a as refrigerant. Coefficient of performance (COP) was considered as performance parameter and evaluated based on the heat release rate and the compressor work. Friction and wear analyses of the reciprocating mechanism were also conducted to observe tribological effects of the nanoadditives on COP of the system. Furthermore, suction–discharge parameters of the compressor were evaluated to conduct precise determination of nanolubricant effect. The morphology of both nanoadditives and worn surfaces was analyzed via scanning electron microscopy. Energy-dispersive X-ray analyses were conducted to observe the chemical composition of the worn surfaces and thermogravimetric analyses were carried to determine the thermal stability of the nano-additives. The surface roughness's of the specimens were also examined to analyze wear characteristics. According to analyses, the most suitable amount of 0.5 vol% of Cu/Ag alloy and CuO nanolubricants provided the COP increments of 20.88% and 14.55%, respectively, with comparison to that of the compressor oil without nanoadditives due to tribological enhancement of the nanoparticles in the lubricant. Furthermore, the average coefficient of friction for Cu/Ag alloy nanolubricant was 5.5% lower than that of CuO nanolubricant and 9.9% lower than that of the pure lubricant.

Keywords Nanoparticle · Tribology · Coefficient of performance · Refrigeration system · Lubricant

Introduction

The shortage of energy sources across the world has directed researchers to energy-efficient systems, especially in the last few decades. The thermal systems such as refrigerators and air conditioners consuming huge amount of energy have been in the radar of the scientists to substitute more energy-efficient systems (Coumaressin and Palaniradja 2014). Thus, nanofluids are quite important thanks to their colossal heat transfer performance which plays a key role in cooling performance of a refrigeration system (Xing et al. 2014; Godson et al. 2010; Saidur et al. 2011).

The refrigerant fluid in a system undergoes perpetual phase changes while flowing throughout the system; heat is rejected in the condenser and heat is absorbed in the evaporator. Coefficient of performance (COP) is the parameter used to define cooling performance of a system and

expressed as the ratio of the heat release rate (HRR) at the evaporator to the compressor work (CW) (Sabareesh et al. 2012):

$$\text{COP} = \frac{\text{HRR}}{\text{CW}} \quad (1)$$

The COP of a system can be increased by improving HRR, and the metallic nanoparticles are well known for their good heat transfer performance. Jiang et al. (2009) conducted an experimental study on thermal conductivity characteristics of carbon nanotube (CNT) additives in R113 host refrigerant. They revealed that diameter and aspect ratio of the CNTs have substantial effects on thermal conductivity of the nanorefrigerant. Thermal conductivity was improved by up to 104% when the CNT volume fraction is 1.0 vol%. Bi et al. (2011) depicted the improved freezing capacity of a refrigeration system when 0.5 g/L of TiO₂ was added to the R600a refrigerant. Mahbulul et al. (2013) carried out a study on the influence of Al₂O₃ nanoparticle concentration in terms of thermal conductivity of R141b refrigerant and they found that the thermal conductivity was improved by 162% with the R141b + 2 vol% Al₂O₃ nanoparticle blend. Akhavan-Behabadi et al. (2015) observed the heat transfer

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characteristics of nanorefrigerant during condensation in a horizontal tube along with changing CuO nanoparticle concentrations in R600a-compressor oil blend. The results presented that heat transfer rate of nanorefrigerant was 1.83 times higher than that of the pure R600a. Another study on condensation heat transfer of R600a/compressor oil/CuO nano-refrigerant in flattened tubes has been implemented by Ghorbani et al. (2017). It was shown that 0.5%, 1% and 1.5% nanoparticle concentration in the mixture resulted in 4.1%, 8.11%, and 13.7% average increments in condensing heat transfer coefficient, respectively. However, there are also studies (Bobbo et al. 2010; Zhang et al. 2006; Heris et al. 2007) suggesting the independence of the thermodynamic properties of the oil from the presence of nanoparticles due to the fact that nanoparticles have variety of characteristics depending on several parameters (size, shape, material, dispersion, Brownian motion and particle migration of nanoparticles, etc.) and nano-oils are to be properly designed. Various studies on heat transfer rate of refrigerants blended with metallic nanoparticles can also be found in Kedzierski (2012), Bartelt et al. (2008), and Kedzierski and Gong (2009).

Reducing compressor work is another way of improving COP of a system. This enhancement is referred to advantageous tribological features of nanoparticles in mechanical systems. Sabareesh et al. (2012) implemented an experimental study on COP improvement of a vapor compression refrigeration system by dispersing TiO₂ nanoparticles in the compressor lubricant. Their results showed that only 0.01% volume fraction of TiO₂ nanoparticle in the lubricant was sufficient to enhance the system COP by 17% and reduce the compressor work by about 11%. Lee et al. (2009) conducted a research on performance evaluation of fullerene nanoparticles in refrigeration mineral oil with 0.01 vol% and 0.1 vol% concentrations. They reported that just by adding 0.1 vol% fullerene in the lubricant provides a reduction of 90% in the coefficient of friction and reduced compressor work. Kumar and Singh (2017) appended ZnO nanoparticles with refrigeration system using R290/R600a refrigerant via compressor lubricating oil. Their results revealed that incorporation of ZnO nanoparticles in the mass fraction of 0.1% provided an energy saving of 7.5% as well as reducing suction and discharge temperature and pressure of the compressor. Zhang et al. (2013) demonstrated the positive effects of Sn and Fe nanoparticles as additives of multialkylated cyclopentanes under vacuum condition in terms of tribological performance enhancement. Selimefendigil and Bingolbali (2019) conducted an experimental investigation on doping TiO₂ nanoparticles in the compressor oil of a refrigeration system using R134 to observe COP performance under various nanoparticle concentrations. They concluded that 1% of nanoparticle addition to the compressor oil results in COP increment of 21.42%. Another study on COP enhancement

by doping Al₂O₃ nanoparticles in refrigerant of the system has been made by Mahdi et al. (2017) and they reported that the COP of the system was increased by 3.33% and 12% when 0.01 vol% and 0.02 vol% of nanoparticle was blended with the refrigerant, respectively. Comprehensive studies on heat transfer performance and rheological behavior of nanofluids can also be found in (Asadi and Pourfattah 2019; Alarifi et al. 2019).

Implementation of nanoparticles in refrigeration system is a promising method of reducing energy consumption and increasing COP due to their good tribological and thermo-physical features. This study focuses on enhancing performance of a vapor compression refrigeration system (VCRS) using Cu/Ag alloy and CuO nanoparticles in the compressor lubricant (polyester, POE) and making a comparison with POE without nanoparticles in the context of suction–discharge pressure and temperature, tribological performance and COP. Though there are several studies on effects of metallic nanoparticle (in compound and/or elemental form) on refrigeration performance, there exists no comprehensive study on performance of a refrigeration system using nanolubricant containing nanoparticles in alloy form. On the other hand, according to the literature review, there exists no such comprehensive study on both tribological performance of nanoparticles in compressor lubricant and its effects on refrigeration performance. Related studies (i.e., references indicated above) generally focus on only COP increment by incorporating nanoparticles in the compressor lubricant. Furthermore, copper (Cu) is known for its good thermal conductivity and friction reduction characteristics studied by several researchers (Padgurskas et al. 2013; Mangam et al. 2010). Silver (Ag) has high abrasion resistance (Fasahat et al. 2015) as well as good thermal conductivity. Thus, alloy of these two metals are expected to give better results compared to that of their elemental forms. The influence of nanoparticles with various volume fractions in the POE on COP and other aforementioned measures was observed and discussed.

Experimental procedure

The experimentation sequence is as follows:

- Morphology and thermal stability analyses of the CuO and Cu/Ag alloy nanoparticles,
- Preparation of the nanolubricants (suspensions) with the specified volume fractions followed by suspension stability (dispersion) and viscosity analyses at various temperatures,
- Performing friction tests and wear analyses on the samples made up of similar material to that of the reciprocating compressor piston–cylinder liner,

- Investigating thermal stability of the nanoparticles (TG–DSC),
- Surface roughness and elemental analyses of the worn surfaces to prove existence of the nanoparticles on the sample surface during friction tests,
- Evaluation of suction–discharge characteristics of the compressor,
- Determination of COP and making a comparison between pure POE oil and nanolubricant ambients.

Morphology and thermal stability of the nanoparticles

CuO (~ 55 nm) and Cu/Ag alloy (~ 30 nm) nanoparticles were procured from Sigma-Aldrich. The geometry and dispersion of the nanoadditive in the structure itself have strong effects on tribological characteristics in the mechanical systems such as being in sphere-like shape which is effective on reducing contact regions and wear, known as rolling effect (Zhang et al. 2013; Padgurskas et al. 2013). Thus, morphology analysis is important to observe the geometry and/or clustering of the particles in the self-structure of the nanoparticle. SEM images (Fig. 1) depict that Cu/Ag alloy nanoparticles have more sphere-like geometry and homogeneous dispersion in the structure itself compared to that of CuO. The influence of this morphology is discussed in “Results of friction-wear tests”.

Preparation of the nanolubricants

The CuO and Cu/Ag alloy nanoparticles with mass purity rate of 99.7% were dispersed in the POE of the compressor operating in a VCRS using HFC-R134a as refrigerant. The nanoparticles with 0.5 vol%, 1 vol% and 1.5 vol% were added in the 150 mL of POE lubricant and underwent a

magnetic stirring process for 1 h followed by sonication (0.25 kW and 44 kHz) for 3 h. The nanolubricants were prepared without any modification to prevent any possible negative effect on thermophysical feature of the refrigerant. The good dispersion of the nanoparticles in lubricant plays an important role in tribological performance characteristics of the system and cooling performance of the system can be negatively affected due to high sedimentation. Furthermore, clustering of the nanoparticles may cause agglomeration on the contacting surfaces of the compressor mechanism and increase friction-wear rate. Thus, in this study, dynamic light scattering (DLS) method was utilized to observe the dispersion characteristics of the nanoparticles in the lubricant via a device with 3.8–100 μm particle diameter measurement capacity, zeta potential mobility range of $\pm 20 \mu\text{cm/V s}$ and average measurement sensitivity of $\pm 2 \text{ mV}$ (10%). DLS is one of the most commonly used techniques consisting of He–Ne laser operating at a specified wavelength (633 nm for this study) and a detection angle (173° for this study) for measuring size distributions, dispersion (electrokinetic phenomena of sedimentation potential) and (in some cases) the shapes of dry and powdered nanoparticles in liquids (Pecora 2000; Murdock et al. 2008). This instrument simply consists of a laser source, lens, and a photodetector. The laser is sent onto the nanolubricant and the beams scattered from the nanoparticles are sensed by a detector and processed through a data acquisition system. Zeta potential ($\zeta-p$) is the parameter defined as the electrical potential of a plane on which a particle moves and provides information related to the suspension stability (Xu 2008; Delgado et al. 2007). In other words, it is an important parameter to define particle agglomeration, sedimentation, interaction, and complexation of nanoparticles with other media constituents in suspension (Hunter

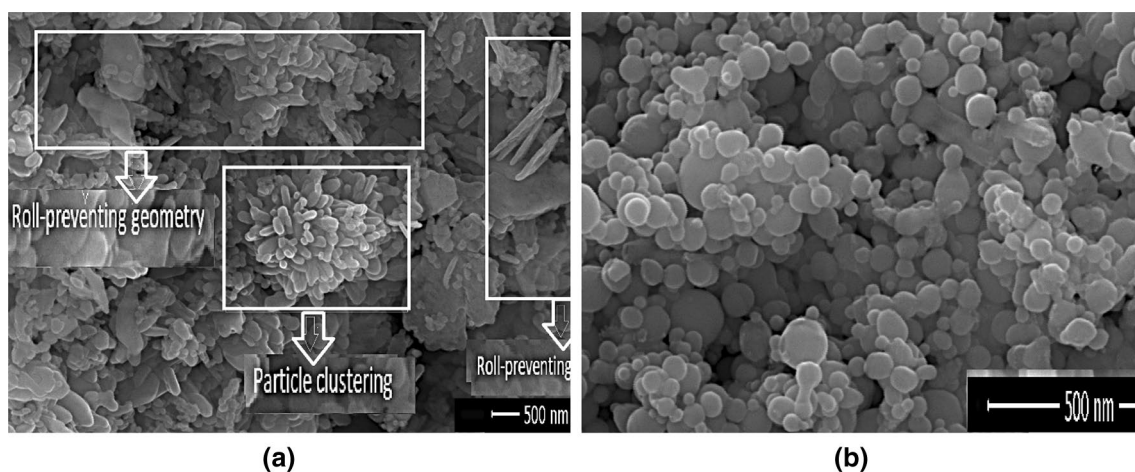


Fig. 1 SEM images of nanoparticles **a** CuO, **b** Cu/Ag alloy

1993). For particle size below 100 nm, Hückel equation may be used to compute $\zeta-p$ as shown in the following equation (Fairhurst 2013):

$$\zeta = 3\eta \times v / 2\epsilon \times \epsilon_0, \tag{2}$$

where v is the electrophoretic mobility in mm^2/Vs , η is the liquid viscosity in $\text{kg}/\text{mm s}$, ϵ is the dielectric constant, and ϵ_0 is the permittivity of free space, respectively in $\text{C}/\text{V}\cdot\text{mm}$.

Considering $\zeta-p$ value greater than 30 mV is a stable suspension for dispersion in liquids of low ionic strength (Sabareesh et al. 2012; Lee et al. 2008), average $\zeta-p$ values of the CuO and Cu/Ag alloy nanolubricants were in the range of acceptable levels even 20 days after their preparation (Table 1). However, the $\zeta-p$ of the both suspensions was prone to decrease as the nanoparticle concentration increases due to probable sedimentation in the nanolubricant. Thus, 0.5 vol% fraction was eligible to be used in the POE in terms of suspension homogeneity. On the other hand, conventional methods for suspension stability such as using surfactants were not used to prevent froth and deterioration of thermal stability of the refrigerant. Therefore, it was rational to use the smallest volume fraction among the specified amounts.

Viscosity is an influential parameter especially for tribological characteristics of a lubricant and needs to be well analyzed to obtain comprehensive data related to the nanoliquid (Lijesh et al. 2015). Thus, the viscosity measurements were conducted using a programmable rheometer with measurement capacity range of 0.001–6000 Pa s. The measurements were carried out between 20 and 80 °C, considering average working condition of a compressor (Table 2). The coefficient of friction (CF) results (discussed later) were also

very similar to each other for both nanolubricants prepared in the specified volume fractions. Therefore, all tribological and COP analyses were performed using 0.5 vol% nanolubricants (POE + 0.5vol% CuO and POE + 0.5vol% Cu/Ag alloy). The observations on viscosity variation under various temperatures depicted that as the nanoparticle concentration increases, viscosity of the nanolubricant also increases for the same temperature. However, high viscosity above a certain limit tends to make possible clustering of the nanoparticles on the surfaces; thus, it is plausible to consider $\zeta-p$ values along with the viscosity. It is known that a suitable amount of viscosity increment in lubricating oil has positive effects on enhancing tribological performance and COP.

Friction and wear tests

The friction and wear tests were implemented on X20Cr16 high-alloy steel specimens in sizes of 10 mm × 10 mm × 2 mm ($L \times W \times H$) using reciprocating tribometer (linear piston module) (Table 3) to mimic the compressor mechanism. Each specimen underwent a linear friction test using an abrasive ball (5 mm diameter) traveling at a linear speed of 2400 mm/min and total distance of 500 m. CF values during the tests were computed via a load cell and the data were collected by a data acquisition system in the intervals of 10 ms. Each experiment was performed under the normal load of 20 N exerted perpendicular to the sample surface (cleaned and dried for each test) immersed in 150 mL of POE oil and fixed onto the oil vessel. All experiments were conducted at the oil temperature of 60 °C

Table 1 $\zeta-p$ values of nanolubricants with different concentrations (20 days after the preparation)

	Average zeta-potential (mV)	
	POE + CuO	POE + Cu/Ag alloy
0.5 vol%	84	81
1 vol%	78	74
1.5 vol%	75	70

Table 3 Friction test rig specifications

Type	Reciprocating
Linear speed range, mm/s	0–140
Stroke, mm	0–35
Frequency (full stroke), Hz	2
Maximum frequency, Hz	40
Oil vessel size ($L \times W \times H$), mm	54 × 90 × 30
Oil bath temperature range, °C	20–100
CF measurement sensitivity	±0.5%

Table 2 Approximate viscosity (μ) values of the lubricants with different concentrations under various temperatures

	μ (Pa s)											
	POE				CuO–POE				Cu/Ag alloy–POE			
	20 °C	40 °C	60 °C	80 °C	20 °C	40 °C	60 °C	80 °C	20 °C	40 °C	60 °C	80 °C
0 vol%	36	21	14	3	–	–	–	–	–	–	–	–
0.5 vol%	–	–	–	–	37	30	25	18	38	30	29	21
1 vol%	–	–	–	–	35	33	29	24	40	37	34	26
1.5 vol%	–	–	–	–	40	39	30	29	42	41	37	30

(average mechanism working condition) and roughly 70% relative humidity. All tests were carried out in triplicate and averaged to ensure repeatability.

In the subsequent stage of the tribological tests, the worn surfaces of the samples were analyzed. First, each test specimen was weighed via a precision digital balance before and after the test to obtain weight losses. Then the morphology of the surfaces was observed via SEM and surface roughness determination was performed using 3D optical profile modulus with 1.3 MP (1280×1024) display resolution and 10×–230× magnification capacity. Energy-dispersive X-ray (EDX) spectrometer was utilized to prove the presence of the nanoparticles on the wear scar formed on the sample surfaces after friction tests.

Refrigeration system test rig

The refrigeration test rig used in this study was a specially designed vapor compression refrigeration type system (VCRS) consisting of a hermetically sealed reciprocating type compressor, an air-cooled condenser, an expansion valve and an evaporator (Table 4). Four thermocouples (*T*) were placed in the evaporator water cabin, compressor inlet–outlet, and condenser outlet (Fig. 2) to acquire necessary data to calculate HRR and CW as expressed in Eqs. (3) and (4), respectively (Sabareesh 2012; Kumar and Singh 2017). Two pressure gauges (*P*) were located in the inlet and outlet of the compressor to read suction and discharge pressure values. Before every test, the system was vacuumed to low pressure and recharged with HFC-R134a refrigerant to eliminate moisture. To improve the reliability of the measurement, thermocouples and pressure gauges were mounted onto the thermally insulated pipe walls. An energy meter was used to measure the energy consumption of the compressor. The temperature and pressure readings were taken every 3 min and HRR was evaluated considering initial (*T*₁) and final temperatures (*T*₂) of the water in the evaporator cabin and the time lapse (*t*) to reduce the *T*₁ to *T*₂ (*m* mass of water, kg; *c* specific heat capacity, J/kg °C; *K* energy meter constant, impulse/kWh; *n* number of

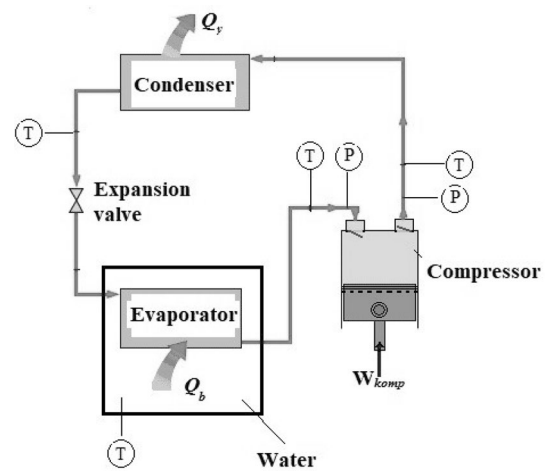


Fig. 2 Illustration of the refrigeration test rig

pulses taken in energy meter; ΔT temperature difference for the cooled water in the evaporator, °C).

$$HRR = \frac{m \cdot c \cdot \Delta T}{t}, \text{ kW}, \tag{3}$$

$$CW = \frac{3600 \cdot n}{t \cdot K}, \text{ kW}. \tag{4}$$

The absolute errors for the directly measured parameters (coefficient of friction, viscosity, temperature, pressure) were to be found using the following equations (Sanukrishna et al. 2017):

$$\Delta\psi_{\max} = \pm (0.3 + 0.5\psi_{\max}), \tag{5}$$

$$\epsilon_{\psi} (\%) = (\Delta\psi_{\max} / \ell) \times 100, \tag{6}$$

where ψ_{\max} is the maximum of the measured parameter, ϵ_{ψ} is the percentage error and ℓ is the measurement range.

The uncertainty of the COP could be found utilizing the propagation of error approach indicated in Eqs. (7) and (8) (Taylor and Kuyatt 1994; Messerly 2016):

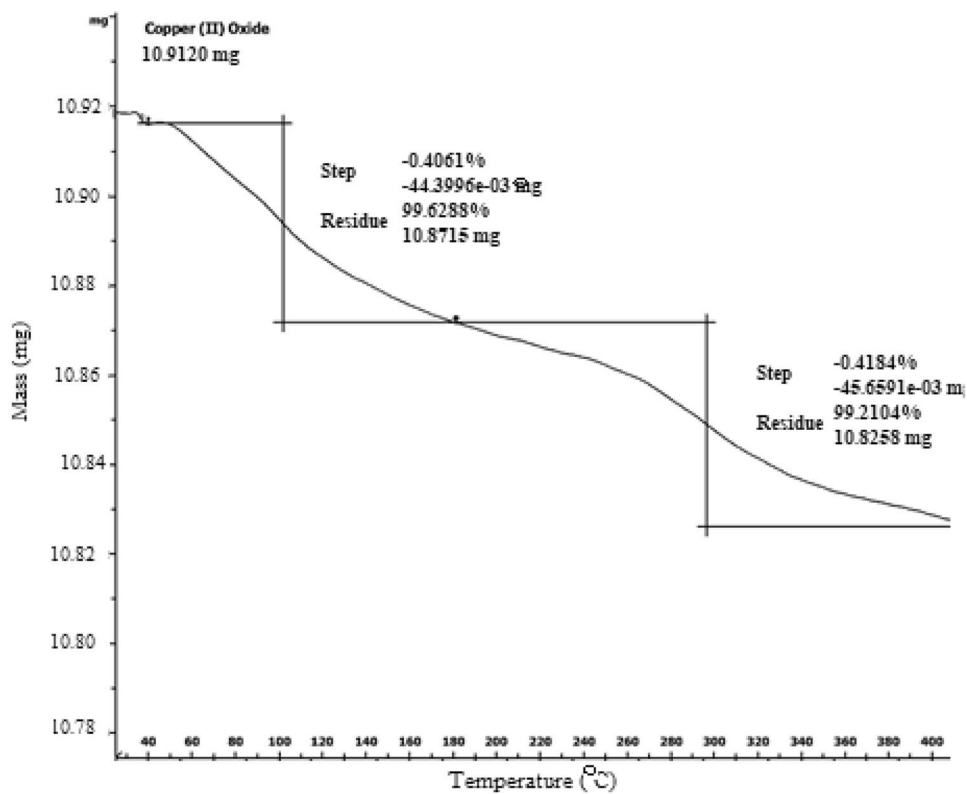
Table 4 VCRS test rig specifications

Refrigeration system type	Vapor compression
Reciprocating compressor power	0.18 kW (hermetically sealed)
Evaporator water capacity	25 L
System pipe diameter	10 mm
Evap. and cond. tube diameter	7 mm each
Pressure gauge	±0.5 kPa with ~0 to 700 bar range
Thermocouples	K-type ±0.2 °C with – 20 to – 250 °C range
Energy meter	3200 Imp./kWh, 10 pulse-measurement with 0.01 s accuracy

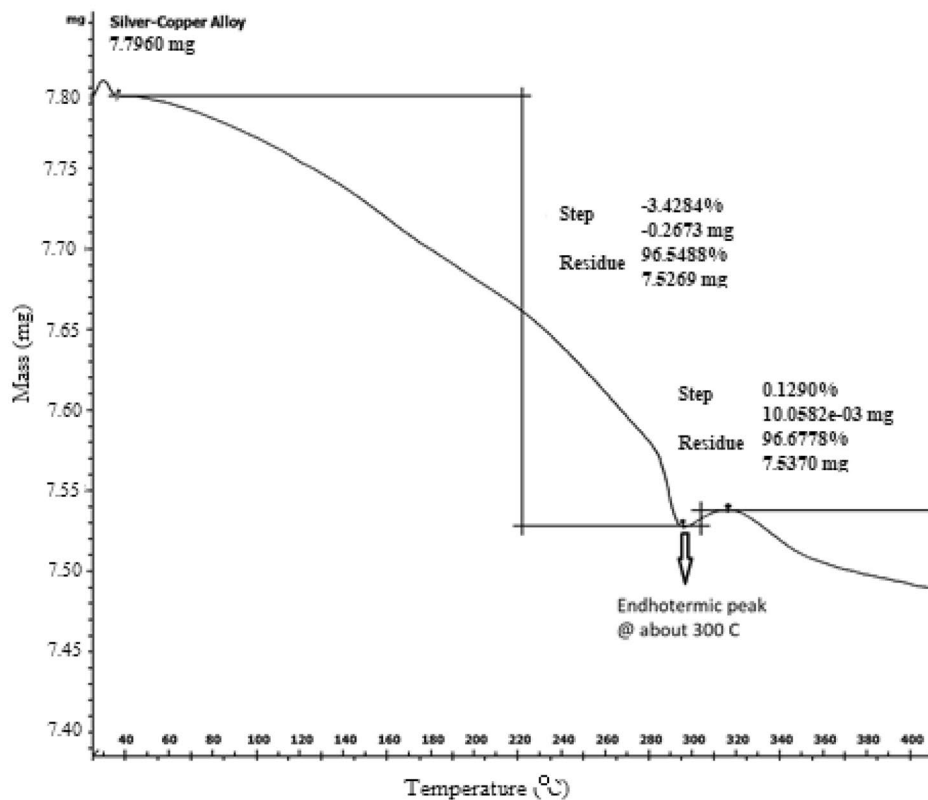
Table 5 Error data

Parameter	Error (%)
Viscosity	~0.3
Temperature	~0.35
Pressure	~6.5
Coefficient of friction	~0.5
Heat release rate	~2.0
Compressor work	~3.0
Coefficient of performance	~0.7

Fig. 3 Thermal stability characteristics of the nanoparticles: **a** CuO; **b** Cu/Ag alloy



(a)



(b)

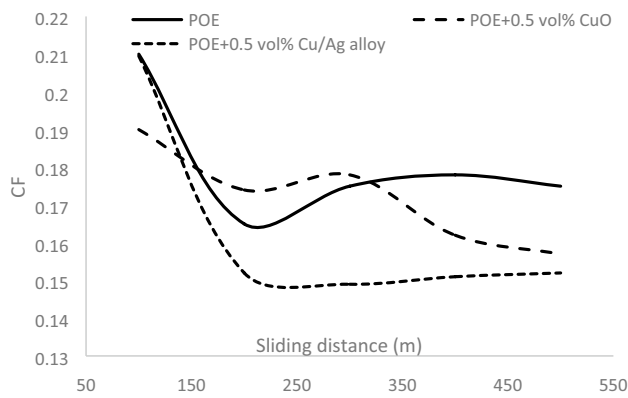


Fig. 4 CF values vs. sliding distance

$$s(COP) = [(\partial COP/\partial HRR)^2 s(HRR)^2 + (\partial COP/\partial CW)^2 s(CW)^2]^{1/2} \tag{7}$$

and the estimated relative uncertainty of the COP is

$$s(COP)/COP = [s(HRR)^2/HRR^2 + s(CW)^2/CW^2]^{1/2}, \tag{8}$$

where $s(HRR)$ and $s(CW)$ represent the standard deviations of the related data, and considering the number of data taken, the standard error could be found. The approximate error data observed considering measurement range and error of the devices as well as calculated values according to the test trials are indicated in Table 5.

Results and discussion

Thermal stability of the nanoparticles

Thermo-gravimetric (TG) method was utilized to observe any possible changes in the structure of powder nanoparticle even under high-temperature conditions. The existence of exothermic peaks usually points at polymerization or crystallization whereas endothermic peaks indicate phase

changes, reduction reactions, etc. Thus, it can be said that the absence of peaks indicates high thermal stability of the structure operating under all working temperature of the system (Ali et al. 2016; Zin et al. 2014). CuO nanoparticle depicted a high thermal stability (endothermic/exothermic) in the wide range of temperature and Cu/Ag alloy has a similar trend except for a small peak at about 280–300 °C which is a negligible phase change (Fig. 3). TG results revealed that both of the nanoparticles demonstrated high thermal stability and are appropriate candidates even for the systems working under severe temperature conditions.

Results of friction-wear tests

The friction between two solid surfaces can be decreased either by reducing contact surfaces (rolling effect) or by diminishing surface roughness (polishing effect). Figure 4 demonstrates the average CF values obtained from the nanolubricant ambients. The average CF for Cu/Ag alloy nanolubricant was 5.5% lower than that of CuO nanolubricant and 9.9% lower than that of the pure POE. This can be attributed to four reasons: (1) referring to SEM images of the nanoparticles (Fig. 1), the Cu/Ag alloy depicted more sphere-like geometry and uniform dispersion in the structure itself. The sphere-like geometry provided rolling effect and reduced contact zones between the friction pairs; (2) higher zeta potential (Table 1) of the Cu/Ag alloy nanolubricant than that of CuO nanolubricant indicates more homogenous dispersion of the nanoparticles in the lubricant and reduced possibility of sedimentation and clustering in the suspension; (3) the smaller grain size of Cu/Ag alloy nanoparticles than CuO nanoparticles yielded more nanoparticles to fill in the crevices or grooves on the contacting surfaces, thus smoother surface; (4) higher viscosity value of the Cu/Ag alloy nanolubricant ensured more stable tribofilm formation between contact surfaces and increased load bearing capacity.

Wear analyses were interpreted based on the SEM images (Fig. 5) of the worn surfaces. As can be seen from the SEM images, the depth of wear tracks obviously

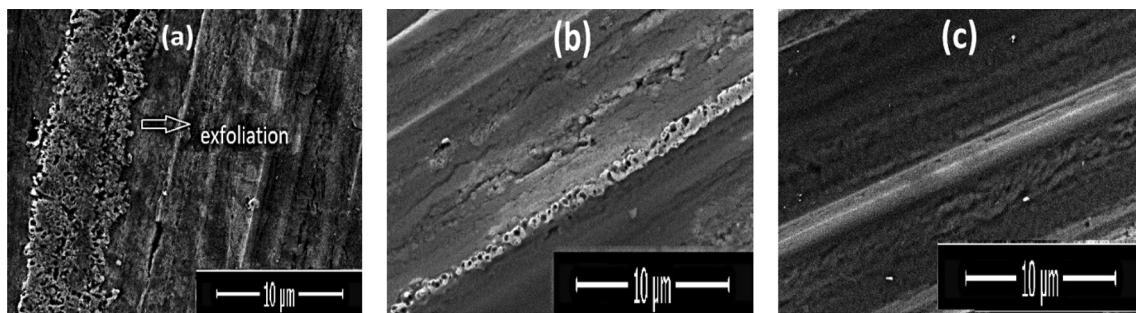


Fig. 5 SEM images of the worn surfaces in a POE, b POE + 0.5 vol% CuO, c POE + 0.5 vol% Cu/Ag alloy

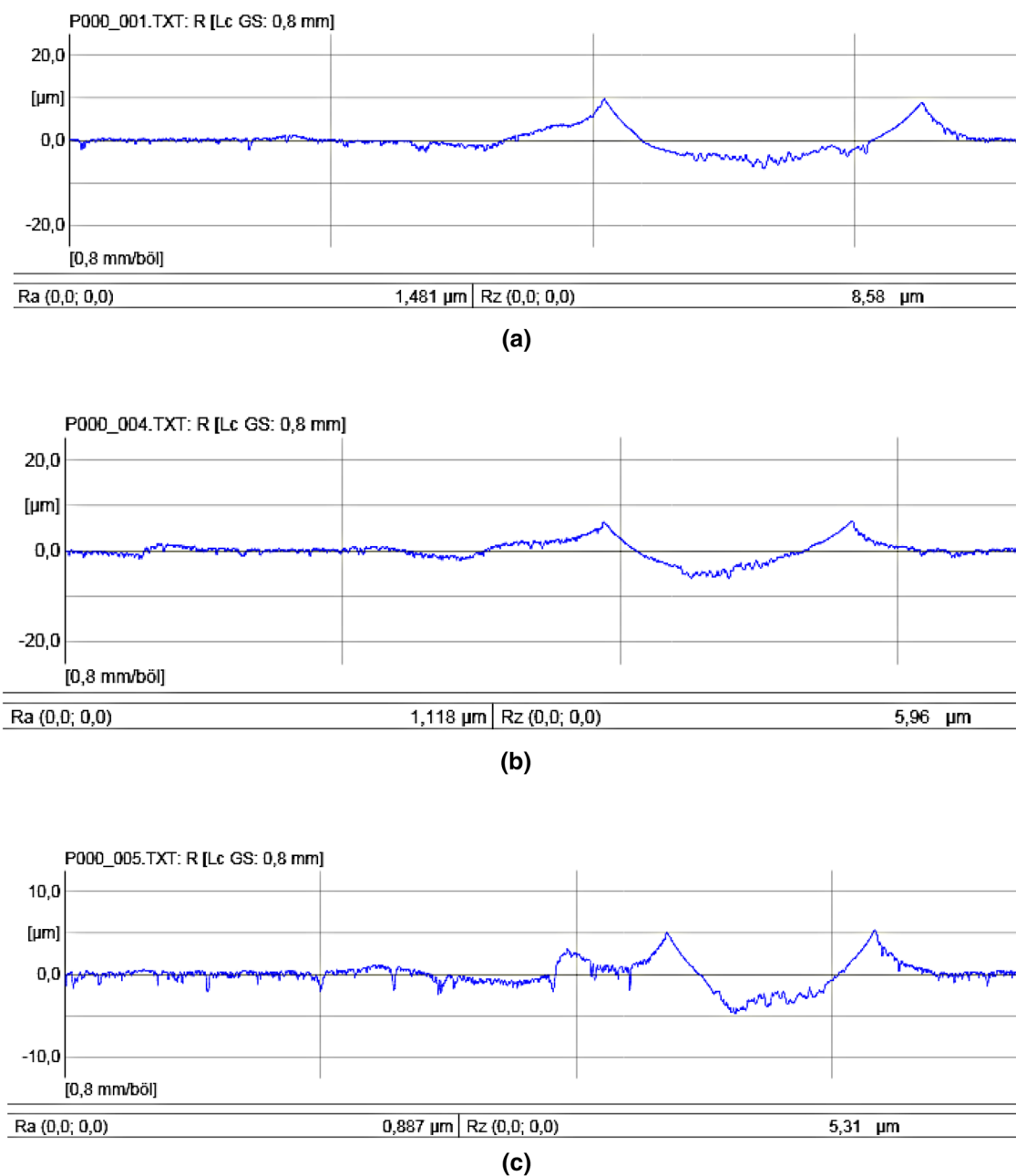


Fig. 6 Surface profile of sample worn in **a** POE, **b** POE + 0.5 vol% CuO, **c** POE + 0.5 vol% Cu/Ag alloy

decreased with the incorporation of nanoparticles. In general, the scars on the surface of the specimen submerged in Cu/Ag alloy nanolubricant were smoother than those of CuO nanolubricant. Similarly, smoother surface can be explained with lower CF values of Cu/Ag alloy as well as high viscosity. High viscosity helped slight fluid pressure increment which also facilitated entrainment of the fluid into the crevices and separation of the substrate. Besides, good thermal stability of Cu/Ag alloy provided maintenance of sphere-like geometry, that is, better rolling effect between interaction surfaces and lower wear. Smaller grain

size of Cu/Ag alloy nanoparticle may be another explanation for the reduced wear tracks. The average surface roughness (R_a) of the samples is shown in Fig. 6. It was clearly shown that the R_a value of the surface operated in Cu/Ag alloy nanolubricant was 40.1% lower than that of POE and 20.6% lower than that of CuO nanolubricant. The maximum roughness was obtained at mid-strokes (peaks in Fig. 6) where sliding speed reaches its maximum causing increased shear stress in the lubricant film.

EDX spectral analysis (Tables 6, 7, 8) depicts the precipitated nanoparticles on the surfaces during the friction

Table 6 Elemental composition of the sample surface immersed in POE

Element	Weight %	Atomic %	Net intensity
C	6.78	24.18	92.38
Na	2.58	4.81	60.49
Al	0.17	0.27	11.26
Ca	0.17	0.18	16.29
Cr	16.31	13.44	1121.64
Mn	1.33	1.04	68.96
Fe	65.28	50.08	2770.41
Ni	6.48	4.73	195.54

Table 7 Elemental composition of the sample surface immersed in POE+0.5 vol% CuO

Element	Weight %	Atomic %	Net intensity
C	19.36	51.48	326.95
Na	1.8	2.51	51.85
S	0.43	0.43	55.25
Ca	0.14	0.12	15.43
Cr	14.32	8.79	1095.17
Mn	1.14	0.67	65.96
Fe	56.48	32.3	2675.16
Ni	5.65	3.07	192.04
Cu	0.16	0.08	4.56

Table 8 Elemental composition of the sample surface immersed in POE+0.5 vol% Cu/Ag alloy

Element	Weight %	Atomic %	Net intensity
C	40.75	75.24	1032.69
Na	1.28	1.24	54.23
Si	0.09	0.07	12.81
P	0.2	0.14	28.34
S	0.36	0.25	58.69
Ag	0.14	0.07	4.42
Ca	0.3	0.23	53.66
Cr	10.74	4.58	973.99
Mn	1.05	0.42	71.89
Fe	40.89	16.24	2317.7
Ni	4.01	1.51	165.91
Cu	0.21	0.07	7.07

tests. The analysis confirms the presence of corresponding chemicals when the friction pairs were operated in lubricant ambients. Chromium (Cr) is originated from both sample itself and the abrasive ball whereas sulphur (S) generally presents in the oil. The EDX analyses prove that a tribolayer from the elements of the nanoparticles forms on the contact surfaces.

Suction–discharge characteristics of the compressor

The suction and discharge pressure characteristics of the compressor charged with pure POE and POE with nanoparticles are shown in Figs. 7 and 8. The results revealed that, in general, nanoparticle incorporation in lubricant of the compressor leads to a reduction in both suction and discharge pressures. The highest reduction of 15.4% in suction pressure was obtained when the compressor was charged with

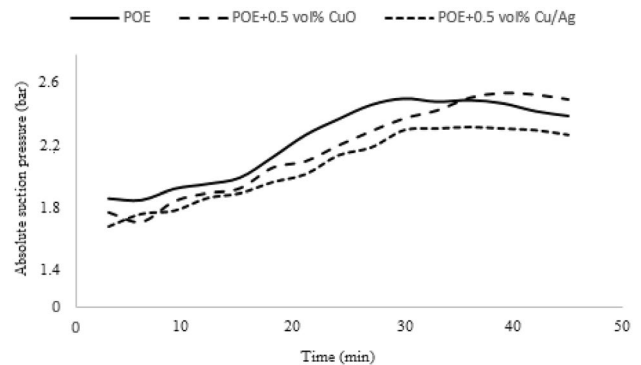


Fig. 7 Compressor suction pressure vs. test duration

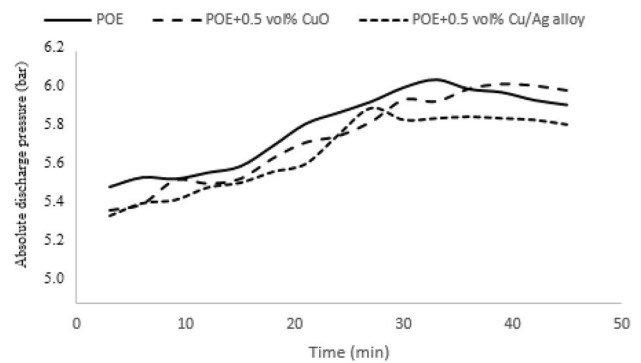


Fig. 8 Compressor discharge pressure vs. test duration

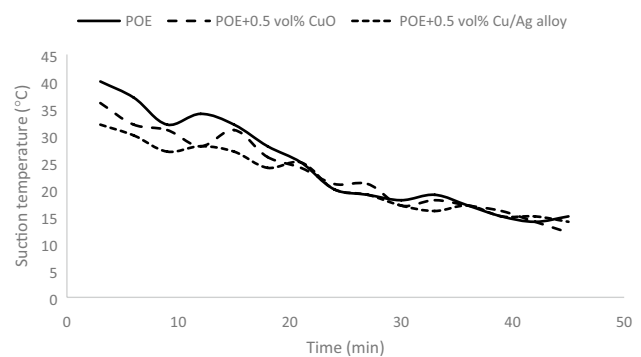


Fig. 9 Compressor suction temperature vs. test duration

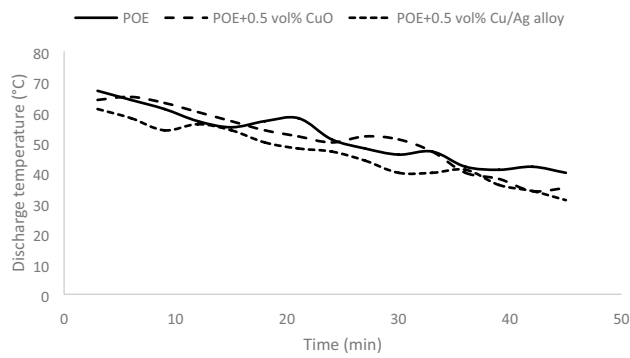


Fig. 10 Compressor discharge temperature vs. test duration

POE + Cu/Ag alloy nanolubricant with comparison to the POE without nanoparticle. The similar trend for POE + Cu/Ag alloy nanolubricant was also determined for discharge pressure with the highest average reduction of 13.9% compared to that of the POE. It can be attributed to the mixing of some lubricant with refrigerant (stable as of about 35th minute) while travelling throughout the system. This mixing phenomenon increases the viscosity of the refrigerant and reduces the suction–discharge pressure values. Furthermore, reduction in condenser and evaporator temperature also provides reduction in pressure ratio.

The suction and discharge temperatures recorded in 3-min intervals are depicted in Figs. 9 and 10. Both suction and discharge temperatures were lower when the compressor runs with CuO and Cu/Ag alloy nanolubricants compared to that of the POE without nanoparticles. The average reductions in suction temperatures were 5.75% and 10.7%; the average decreases in discharge temperatures were found to be 2.01% and 10.5% for CuO and Cu/Ag alloy nanolubricants, respectively compared to that of the POE oil. The probable mixing of nanoparticles (as of about 35th minute) with the refrigerant increases heat transfer capacity of the refrigerant both in the evaporator and the condenser.

Coefficient of performance analysis

The COP of the system was calculated utilizing related equations depicted in the previous sections and computed results for the compressor using three lubricants are shown in Table 9. The energy consumption data of the compressor were collected considering the time taken by the energy meter for ten pulses. The highest COP was obtained for Cu/Ag alloy nanolubricant which was 20.88% higher than that of POE without nanoparticle and 5.52% higher than that of POE + 0.5 vol% CuO nanolubricant. Better thermal conductivity of Cu/Ag alloy increased the heat release rate in the evaporator due to probable mixing of Cu/Ag alloy nanolubricant with refrigerant within the stabilization period. Furthermore, high viscosity of the nanolubricant compared to POE, facilitated tribofilm formation between the friction pairs (piston–cylinder of the compressor) and separated the solid surfaces. On the other hand, due to the best anti-friction and anti-wear characteristics of the Cu/Ag alloy nanolubricant among others (rolling effect due to sphere-like geometry, polishing effect due to smaller grain size, as explained in the previous sections), friction and wear rate in the compressor mechanism were prone to decrease and the compressor operated under smoother working conditions which provided reduced compressor work.

Conclusions

The present study aims to observe the effects of CuO and Cu/Ag alloy nanoparticle incorporation in POE oil of the compressor of a VCRS using HFC-R134a refrigerant on cooling performance of the system and tribological characteristics of the compressor mechanism. The results indicated that 0.5 vol% of both CuO and Cu/Ag alloy nanoparticle addition in POE oil has considerable effects in the context of tribological performance and COP enhancement

Table 9 Obtained data related to cooling performance parameters

	Test	T_1 (°C)	T_2 (°C)	HRR (kW)	CW (kW)	COP
POE without nanoparticles	1	18.1	18	0.242	0.162	1.49
	2	17.8	17.6	0.263	0.154	1.71
	3	18.2	18.1	0.232	0.149	1.55
						Average COP = 1.58
POE + 0.5 vol% CuO	1	18.4	18.2	0.284	0.159	1.78
	2	18.9	18.8	0.277	0.151	1.84
	3	18.2	18.1	0.256	0.145	1.76
						Average COP = 1.81
POE + 0.5 vol% Cu/Ag alloy	1	18.3	18.1	0.302	0.154	1.96
	2	18.1	18	0.311	0.155	2.01
	3	18.7	18.4	0.243	0.139	1.74
						Average COP = 1.91

as well as positive influences on compressor suction–discharge characteristics. In terms of aforementioned performance characteristics, Cu/Ag alloy nanoparticle gave the best results among other lubricant ambients. Small grain size, sphere-like geometry with uniform dispersion in the structure itself, higher thermal conductivity (Cu/Ag alloy, two metals), and better dispersion in the POE lubricant made Cu/Ag alloy nanoparticle a good candidate to improve tribological and cooling performance characteristics of a VCRS. The highest reduction in CF was 9.9% (5.5% lower than that of POE + 0.5 vol% CuO) when the friction tests were conducted on the samples immersed in POE + 0.5 vol% Cu/Ag alloy nanolubricant with comparison to POE lubricant. Similarly, the minimum R_a was achieved on the samples submerged in the POE + 0.5 vol% Cu/Ag alloy nanolubricant which was 40.1% lower than that of POE (20.6% lower than that of POE + 0.5 vol% CuO). The highest reduction of 15.4% in suction pressure was obtained when the compressor was charged with POE + Cu/Ag alloy nanolubricant with comparison to POE without nanoparticle. The similar trend for POE + Cu/Ag alloy nanolubricant was also determined for discharge pressure with the highest average reduction of 13.9% compared to that of the POE. Both suction and discharge temperatures were lower when the compressor was lubricated with POE + CuO and POE + Cu/Ag alloy nanolubricants. The average reductions in suction temperatures were 5.75% and 10.7%; the average decreases in discharge temperatures were found to be 2.01% and 10.5% CuO and Cu/Ag alloy nanolubricants, respectively, compared to that of the POE oil. The maximum COP of 1.91 was obtained for the system operating with POE + Cu/Ag alloy nanolubricant which was 20.88% higher than that of the system operating with POE without nanoparticle (5.52% higher than that of POE + 0.5 vol% CuO). Consequently, Cu/Ag alloy nanoparticle is a promising material to be used in the mechanical systems due to its good tribological and thermophysical performance. The author expects that this study will be useful to fill the gap in the literature in terms of nanoparticle usage in alloy form rather than elemental and/or compound form in the mechanical systems.

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Compliance with ethical standards

Conflict of interest The author has no competing interests to declare.

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