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Numerical Analysis of the Thermophysical Properties of R600a Refrigerant Enhanced with Diamond Nanoparticles in Vapour Compression Refrigerating System

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ABSTRACT

Addition of nanoparticles to lubricants and refrigerants in vapour compression refrigerating systems has been a subject of consideration for engineers and researchers worldwide due to its heat transfer enhancement properties coupled with power consumption reduction capacity. Nanolubricants and nanorefrigerants are forms of nanofluids which possess better heat transfer performance than pure lubricants and refrigerants. For performance analysis to be carried out, basic thermophysical properties of nanolubricant and nanorefrigerant such as density, heat capacity and thermal conductivity must be calculated and analysed. In this paper, a computer application was developed based on several derived numerical equations to calculate the density, heat capacity and thermal conductivity of diamond/mineral oil nanolubricant and diamond/mineral oil/R600a nanorefrigerant. This study showed that the thermal conductivities at various diamond nanoparticle volume fractions are higher than pure lubricant and refrigerant. The densities of the nanolubricant and nanorefrigerant were lower than that of the pure lubricant and refrigerant. However, the heat capacities decreased with increase in nanoparticle volume fractions and these were found to be less than that of pure lubricant and refrigerant. The study therefore established that heat transfer performances increase with thermal conductivity and heat capacity while pumping power increases with enhanced density. Hence, the addition of diamond nanoparticles to mineral oil and R600a refrigerant improves performance of system.

***Keywords*—** Vapour, Nanolubricants, Thermophysical

I. INTRODUCTION

Vapour-compression refrigeration system is used worldwide in building and automobile air-conditioners, as well as in home and commercial refrigerators to preserve food materials and for other purposes. Large vapour-compression refrigeration systems are used in industrial plants found in oil refineries, petrochemical, natural gas and chemical processing industries. Refrigeration systems utilized large amount of energy.Lubrication is essential in compressors to lubricate and seal the moving parts. Therefore, a small amount of oil is needed. Hence, in the process of finding energy-efficient and environmental-friendly refrigerants, researchers have come up with nanolubricants and nanorefrigerants. The rapid advances in nanotechnology have lead to emerging of new generation heat transfer fluids called nanofluids. Nanofluids are prepared by suspending nano sized particles (1-100nm) in conventional fluids and have higher thermal conductivity than the base fluids. Nanofluids have the following characteristics compared to the normal solithe particles and fluids due to the high surface area of the particles (i) better dispersion stability with predominant Brownian motion (ii) reduces particle clogging (iii) reduced pumping power as compared to base fluid to obtain equivalent heat transfer. Based on the application nanoparticles are currently made out of a very wide variety of materials, the most common of the new generation of nanoparticles being ceramics, which are best split into metal oxide ceramics, such as titanium, zinc, aluminium and iron oxides, to name a prominent few and silicate nanoparticles, generally in the form of nanoscale flakes of clay. Addition of nanoparticles changes the boiling characteristics of the base fluids. Nanoparticles can be used in refrigeration systems because of its remarkable improvement in thermophysical and heat transfer capabilities to enhance the performance of refrigeration systems. When the refrigerant is circulated through the compressor it will carry traces nanolubricants so that the other parts of the system will have nanolubricant -refrigerant mixture. The advantages of adding nanoparticles to the refrigeration system are manifold: First addition of nanoparticles to the refrigerants improves the thermo physical and heat transfer characteristics of the refrigerant which in turn results in the enhancement in the refrigerating effect Addition of nanoparticles to the lubricant improves tribological characteristics of the lubricant, so that there are improvements in the performance of the compressor. Secondly presence of nanoparticles in the refrigeration system enhances the solubility between the lubricant and

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refrigerant and returns more lubricant oil back to the compressor. In the past few decades, rapid advances in nanotechnology have lead to emerging of new generation of heat transfer fluids called ‘‘nanofluids’’. Nanofluids are defined as suspension of nanoparticles in a basefluid. Compared to conventional solid–liquid suspensions for heat transfer intensifications, nanofluids possess the following advantages. High specific surface area and therefore more heat transfer surface between particles and fluids. High dispersion stability with predominant Brownian motion of particles. Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification. Reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization. Recently scientists used nanoparticles in refrigeration systems because of its remarkable improvement in thermo-physical, and thus, the use of nanoparticles in refrigeration systems is a new, innovative way to enhance the efficiency and reliability in the refrigeration system. As stated by Kumar *et al.* (2013), nanofluids have the following characteristics compared to the normal solid liquid suspensions: higher heat transfer between the particles and fluids due to the high surface area of the particles; better dispersion stability with predominant Brownian motion; reduces particle clogging; reduced pumping power as compared to base fluid to obtain equivalent heat transfer. Nanorefrigerants have the ability to improve heat transfer rate thereby making the refrigeration equipment compact. Consequently, there will be a reduction in the energy consumption of industries utilizing refrigeration systems, emission reduction; ability to contribute to global warming and greenhouse gas effects (Mahbubul*et al.*, 2013). Researchers have worked on the pool boiling; nucleate boiling, as well as convective heat transfer, energy performance and lubrication of nanorefrigerants. For a substance with heat transfer potential, its performance is directly related to its thermal conductivity. The density of a fluid has impact on the pressure drop and pumping power characteristics (Mahbubul*et al.*, 2013). The aim of this study is to use numerically analysis to explain the thermal conductivity, density and specific heat of diamond nanoparticles suspended in mineral oil lubricant mixed with R600a refrigerant at different concentrations of nanoparticles. Hussein *et al.* (2013) suspended alumina, titanium and silica nanoparticles in water in order to determine their thermal conductivity and viscosity. Volume concentrations ranging between 1 and 2.5% were used for the experiment. Thermal conductivity was measured by hot wire method and viscosity with viscometer equipment. It was observed that the thermal conductivity of the nanofluids was enhanced by 0.5 – 20% when compared with the base fluid. Also, the viscosity was enhanced by 0.5 – 60%. Their experimental data was compared with that of other researchers and was in agreement with deviation of less than 5%. The experimental data showed that the thermal conductivity increased from titania to alumina while the viscosity increased from silica to alumina. In an experimental study carried out by Sen Gupta *et al.*(2011) to measure the thermal conductivity in grapheme oxide and carbon nanotube nanofluids using transient hot wire method, a magnitude of enhancement between the two nanofluids was observed. Namburu *et al.* (2007) investigated the viscosity and specific heat of silicon dioxide (SiO2) nanoparticles with various diameters (20, 50 and 100 nm) suspended in ethylene glycol and water mixture (60:40 weight proportion) experimentally. They obtained a new correlation from the experimental data which shows a relationship between viscosity and particle volume percentage and nanofluid temperature. Xie *et al.* (2011) gave some factors that could influence the thermal enhancements of nanofluids. The factors include the pre-treatment process, thermal conductivity of the base fluid, volume fraction of the nanoparticles, the tested temperature, size of the nanoparticles, and the additives of the fluids. They used various nanoparticles involving magnesium oxide (MgO), aluminum oxide (Al2O3) of different sizes, titanium oxide (TiO2), silicon carbide (SiC) with different shapes, zinc oxide (ZnO), silicon oxide (SiO2), iron oxide (Fe3O4), diamond and carbon nanotubes to determine the factors. In the studies conducted by Jwo *et al.* (2009) using R134a refrigerant and mineral lubricant mixed aluminum oxide nanoparticles to improve the lubrication and heat transfer performance with various percentage of the refrigerant, it was observed that the 60% R-134a and 0.1 wt % Al2O3 nanoparticles were optimal. There was power consumption reduction of about 2.4% and 4.4% increment in the coefficient of performance.

Nomenclature

ρ –	[Kg/m^3]	Density
μ -	[Ns/m^2]	Viscosity -
c -	**[**J/Kg.K]	Specific heat capacity
k -	[W/m.K]	Thermal conductivity
T -	[K]	Temperature

II. METHODOLOGY

In order to analyse the thermophysical properties of refrigerant/lubricant mixture with diamond nanoparticles numerically, mineral oil was considered as lubricant while R600a refrigerant was selected. Common usage and superior quality are the factors of selection. The physical and thermophysical properties of mineral oil, R600a refrigerant and diamond nanoparticles are shown in table1, 2 and 3respectively.

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Table 1: Physical and thermophysical properties of mineral oil (Science and Engineering Encyclopedia, 2016)

Property	Value
Density	800 Kg/m^3
Specific heat capacity	2130 J/Kg.K
Thermal conductivity	0.15 W/m.K
Surface tension	0.026 N/m
Viscosity	1 Ns/m^2
Kinematic viscosity	0.00125 m^2/s

Table 2: Properties of R600a refrigerant (The Engineering ToolBox, 2016)

Property	Value
Density	551 Kg/m^3
Specific heat capacity	2380 KJ/Kg.K
Thermal conductivity	0.107 W/m.K
Molecular mass	58.12
Boiling point (at atmospheric pressure)	-11.8 ºC
Freezing point (at atmospheric pressure)	-145 ºC
Critical point temperature	135 ºC
Critical point pressure	27357 mmHg

Table 3: Properties of Diamond nanoparticles (Peng *et al.*, 2009)

Property	Value
Density	160 Kg/m^3
Molecular mass	12.01 g/mol
Average particle diameter	10 nm
Thermal conductivity	2300 W/m.K
Specific heat capacity	2300 W/m.K
Specific heat capacity	509.1 J/kg.K

Calculation of thermophysical properties of nanoparticles/lubricant suspension

The diamond nanoparticles/lubricant suspension is the mixture of mineral oil and diamond nanoparticles with primary diameter 10nm. Three diamond nanoparticles concentrations of 5 wt%, 10 wt% and 15 wt% in the nanoparticles/lubricant suspension were considered. The concentration of the nanoparticles in the nanoparticles/lubricant suspension is needed to analyse the effect of its addition on the thermophysical properties of the suspension. The nanoparticles concentration (mass fraction) in the nanoparticles/lubricant suspension for each suspension, ω_n, is calculated using equation (1) below:(Peng *et al.*, 2009)

$$\omega_n = \frac{Mn}{Mn + Mo} \qquad 1$$

where Mn is the mass of nanoparticles in the nanoparticles/lubricant suspension and Mo is the mass of lubricating oil in the nanoparticles/lubricant suspension. The volume fraction of nanoparticle in the nanoparticle/lubricant suspension is calculated using equation (2) below:(Subramani and Prakash, 2011)

$$\Psi_n = \omega_n \rho_o / [\omega_n \rho_o + (1 - \omega_n)\rho_n] \qquad 2$$

where ρ_o = density of lubricant; ρ_n = density of nanoparticle

The density of the nanoparticle/lubricant suspension is calculated using equation (3) below:

$$\rho_{no} = (1- \Psi_n)\, \rho_o + \Psi_n\, \rho_n \qquad 3$$

where ρ_o = density of lubricant; ρ_n = density of nanoparticle

The thermal conductivity of the nanoparticle/lubricant suspension is calculated using equation (4) below:(Hamilton and Crosser, 1962)

$$K_{no} = K_o[(K_n + 2K_o - 2\Psi_n(K_o - K_n)) / (K_n + 2K_o + \Psi_n(K_o - K_n))] \qquad 4$$

Where K_o = thermal conductivity of lubricant; K_n = thermal conductivity of nanoparticle

The specific heat of the nanoparticle/lubricant suspension is calculated using equation (5) below:

$$C_{no} = (1 - \Psi_n)\, C_o + \Psi_n C_n \qquad 5$$

Where C_o = specific heat of lubricant, C_n = specific heat of nanoparticle

Calculation of the thermophysical properties of nanoparticle/lubricant/refrigerant mixture

The nanoparticles/lubricant suspension is mixed with the R600a refrigerant to have the refrigerant/lubricant mixture with diamond nanoparticles. Three nanoparticles/lubricant suspension concentrations of 1 wt%, 3 wt%, and 5 wt% were considered for this analysis. The thermophysical properties of the mixture were calculated using equations put forward by researchers. The concentration of the nanoparticles/lubricant suspension in the nanoparticles/lubricant/refrigerant mixture is calculated with the following equation:(Subramani and Prakash, 2011).

$$X_{no} = m_{no} / (m_{no} + m_r) \qquad 6$$

Where m_{no} is the mass of nanoparticles/lubricant suspension in the nanoparticles/lubricant/refrigerant

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mixture and m_r is the mass of refrigerant in the nanoparticles/lubricant/refrigerant mixture.

The nanoparticles concentration in the nanoparticles/lubricant/refrigerant mixture, y_n, is calculated with the following equation:(Subramani and Prakash, 2011).

$$y_n = \omega_n . x_{no} \qquad 7$$

Density of nanoparticles/lubricant/refrigerant mixture, $\rho_{rno,}$ is calculated using the following equation:(Subramani and Prakash, 2011),

$$\rho_{rno} = [(X_{no} / \rho_{no}) + ((1 - X_{no}) / \rho_r)]^{-1} \qquad 8$$

where ρ_r is the density of refrigerant

Thermal conductivity of nanoparticles/lubricant/refrigerant mixture, K_{rno}, is calculated using the following equation:(Baustian *et al.*, 1988),

$$K_{rno} = K_r(1 – X_{no}) + (K_{no} X_{no}) – (0.72X_{no} (1 – X_{no})(K_{no} – K_r)) \qquad 9$$

where K_r is the thermal conductivity of the refrigerant. The specific heat of the nanoparticles/lubricant/refrigerant mixture, $C_{rno,}$ is calculated using the following equation:(Jensen and Jackman, 1984),

$$C_{rno} = (1 - X_{no}) C_r + X_{no}C_{no} \qquad 10$$

where C_r is the specific heat of the refrigerant

The parameters ρ_n, ρ_o, ρ_r, K_o, K_n, $C_{o,}$ and C_n used in the equations for the calculations are in tables 1, 2 and 3. The conditions applied in the calculations are summarised in table 4 below:

Table 4: Conditions for calculations

Test fluid and its composition (mass fraction in the mixture)	ω_n (wt%)	X_{no} (wt%)	y_n
R600a/mineral oil/diamond (99/0.95/0.05)	5	1	0.05
R600a/mineral oil/diamond (99/0.9/0.1)	10	1	0.10
R600a/mineral oil/diamond (99/0.85/0.15)	15	1	0.15
R600a/mineral oil/diamond (97/2.85/0.15)	5	3	0.15
R600a/mineral oil/diamond (97/2.7/0.3)	10	3	0.30
R600a/mineral oil/diamond (97/2.55/0.45)	15	3	0.45
R600a/mineral oil/diamond (95/4.75/0.25)	5	5	0.25
R600a/mineral oil/diamond (95/4.5/0.5)	10	5	0.50
R600a/mineral oil/diamond (95/4.25/0.75)	15	5	0.75

III. RESULTS AND DISCUSSION

Analyses of mineral oil/diamond nanoparticles mixture. Table 5 and figure 5 show the densities of the lubricant/nanoparticles suspensions at varying nanoparticles volume fractions and concentrations. It can be seen that the densities of the mixtures are smaller than that of pure mineral oil, and decreases with the increase of the nanoparticles volume fraction and concentration, meaning that the presence of the nanoparticles improves the density of the lubricant. The densities of the mineral oil/diamond mixture with 5wt%, 10wt% and 15wt% diamond concentrations are 16.25%, 28.75% and 37.5% smaller than that of pure mineral oil, respectively.

Table 5: Densities of mineral oil/diamond mixture at varying nanoparticle concentrations and volume fractions

Test fluid	ω_n (wt%)	Ψ_n	ρ_{no} (g/cm^3)
mineral oil/diamond	5	0.21	0.67
mineral oil/diamond	10	0.36	0.57
mineral oil/diamond	15	0.47	0.50

Table 6: Thermal Conductivities of mineral oil/diamond mixture at varying nanoparticle concentrations and volume fractions

Test fluid	ω_n (wt%)	Ψ_n	K_{no} (W/cm.K)
mineral oil/diamond	5	0.21	0.00018
mineral oil/diamond	10	0.36	0.00019
mineral oil/diamond	15	0.47	0.00020

Table 7: Specific heats of mineral oil/diamond mixture at varying nanoparticle concentrations and volume fractions

Test fluid	ω_n (wt%)	Ψ_n	C_{no} (J/g.K)
mineral oil/diamond	5	0.21	1.79
mineral oil/diamond	10	0.36	1.55
mineral oil/diamond	15	0.47	1.37

The thermal conductivities of the mineral oil/diamond suspension are greater than that of pure mineral oil, and increases with the increase of the nanoparticles volume fraction and concentration as shown in table 4.2 and figure 4.2, meaning that the presence of

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the nanoparticles improves the thermal conductivity of the lubricant. The thermal conductivities of the mineral oil/diamond mixture with 5wt%, 10wt% and 15wt% diamond concentrations were increased by 20%, 26.7% and 33.33%, respectively as compared with pure mineral oil. However, the heat capacities of the mineral oil/diamond suspensions with 5wt%, 10wt% and 15wt% diamond concentrations decreased as the volume fraction of diamond nanoparticles increased. The percentage decrements were 15.96%, 27.23% and 35.68%, respectively.

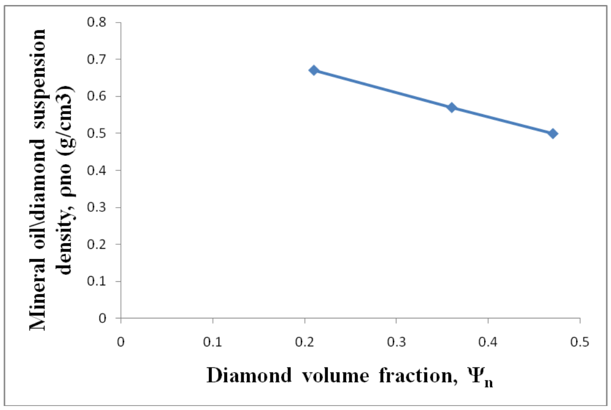

Figure 1: Densities of mineral oil/diamond suspension with varying diamond volume fractions

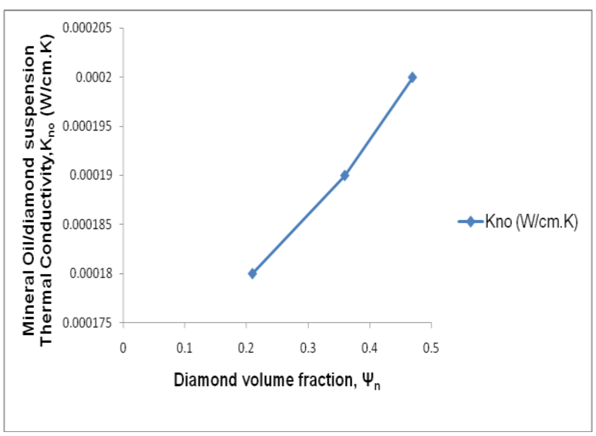

Figure 2: Thermal conductivities of mineral oil/diamond suspension with varying diamond volume fractions

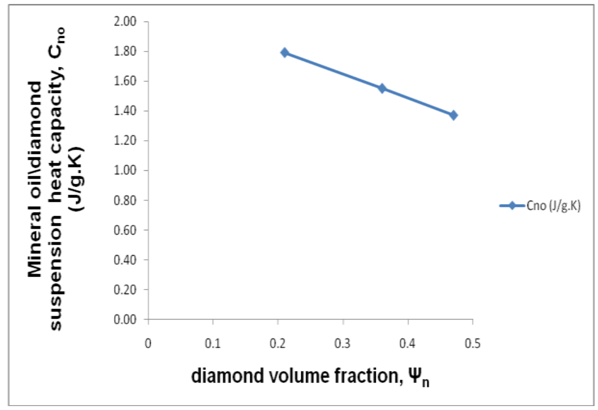

Figure 3: Heat capacities of mineral oil/diamond suspension with varying diamond volume fractions

Analyses of mineral oil/diamond/R600a mixture

Table 4 shows the relationship between the density, thermal conductivity and heat capacity of the nanorefrigerant, refrigerant R600a, and nanoparticle volume fraction. The density of nanorefrigerant, $\rho_{r,n,o}$, is inversely proportional to the nanoparticle volume fraction, as it decreases with increase in volume fraction of the nanoparticles. The decrements are shown in figure 1. When compared with the density of the pure refrigerant, there was a maximum increment of 1.63%, which is quite low. The thermal conductivity of the conventional refrigerant, 0.107 W/cm·K, is increased with nanoparticle volume fraction with the increment being about 0.0002 W/cm·K to 0.0015 W/cm.K for each 5% diamond nanoparticle concentration addition. A maximum increment of 1.40% was obtained when the concentration of nanoparticle in the nanorefrigerant, y_n,was 0.75. This correlates with the submission in several literatures that nanofluids have higher thermal conductivity. The variations are shown in figure 4.5. However, the specific heat of the nanorefrigerant decreases with increase in volume concentrations of the nanoparticle. This establishes the results of several experiments carried out by researchers on the effect of nanoparticle volume concentration on the heat capacity of refrigerants enhanced with nanoparticles. As compared with the conventional refrigerant, there was a drop in the heat capacity. A largest decrement of 21.01% was obtained when the concentration of nanoparticle in the nanorefrigerant, y_n,was 0.75. The variations are shown in figure 4.6.

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Table 8: Densities, thermal conductivities and heat capacities of R600a/mineral oil/diamond mixture at varying nanoparticle concentrations and volume fractions

Test fluid and its composition (mass fraction in the mixture)	ω_n (wt%)	X_{no} (wt%)	y_n (wt%)	Ψ_n	$\rho_{r,n,o}$ (g/cm^3)	$K_{r,n,o}$ (W/cm.K)	$C_{r,n,o}$ (J/g.K)
R600a/mineral oil/diamond (99/0.95/0.05)	5	1	0.05	0.21	0.552	0.0001072	2.374
R600a/mineral oil/diamond (99/0.9/0.1)	10	1	0.10	0.36	0.551	0.0001072	2.372
R600a/mineral oil/diamond (99/0.85/0.15)	15	1	0.15	0.47	0.550	0.0001073	2.369
R600a/mineral oil/diamond (97/2.85/0.15)	5	3	0.15	0.21	0.554	0.0001077	2.362
R600a/mineral oil/diamond (97/2.7/0.3)	10	3	0.30	0.36	0.552	0.0001078	2.355
R600a/mineral oil/diamond (97/2.55/0.45)	15	3	0.45	0.47	0.549	0.0001078	2.350
R600a/mineral oil/diamond (95/4.75/0.25)	5	5	0.25	0.21	0.556	0.0001082	2.351
R600a/mineral oil/diamond (95/4.5/0.5)	10	5	0.50	0.36	0.552	0.0001083	2.339
R600a/mineral oil/diamond (95/4.25/0.75)	15	5	0.75	0.75	0.548	0.0001085	2.330

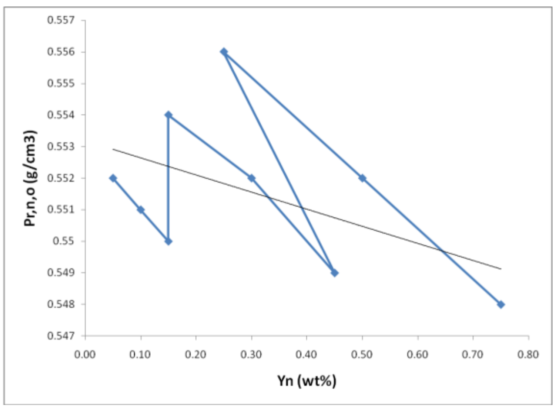

Figure 4: Densities of R600a/mineral oil/diamond suspension with varying diamond volume fractions.

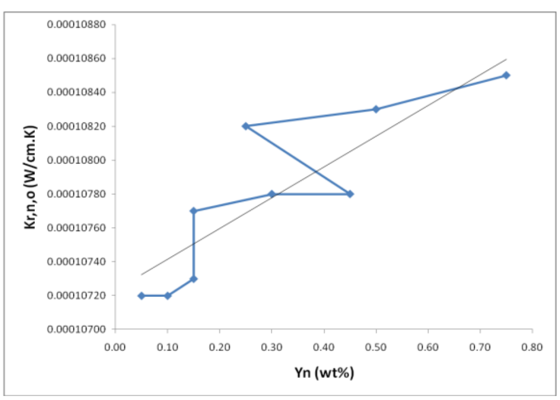

Figure 5: Thermal conductivities of R600a/mineral oil/diamond suspension with varying diamond volume fractions.

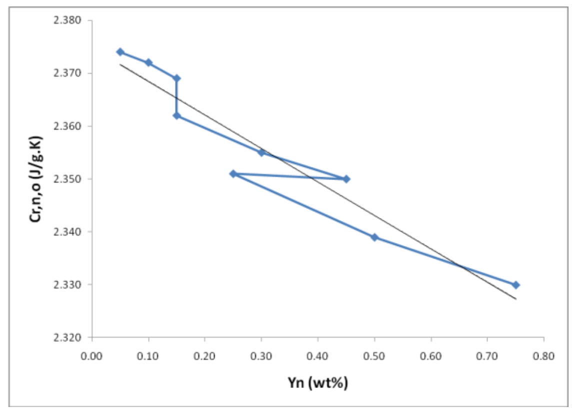

Figure 6: Specific heat capacities of R600a/mineral oil/diamond suspension with varying diamond volume fractions

IV. CONCLUSION

The thermophysical properties (density, thermal conductivity and heat capacity) of mineral oil mixed with diamond nanoparticles (nanolubricant) and mineral oil/diamond mixed with R600a refrigerant (nanorefrigerant) have been calculated and analysed numerically using a computer program. The results correlate with that of researchers in literatures. In literatures, it has been found that the thermal conductivities of nanolubricants and nanorefrigerants are higher than pure lubricants and refrigerants. It was also observed that increased thermal conductivity of nanolubricants and nanorefrigerants are comparable with the increased thermal conductivities of other nanofluids. The thermal conductivities of the nanolubricant and nanorefrigerant in this study increased with increased nanoparticle volume fractions. The thermal conductivities of the nanolubricant and nanorfrigerant are greater than that of the pure lubricant and refrigerant. The densities of the nanolubricant and nanorefrigerant also decreased with increase in nanoparticle volume fractions. It was also

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observed that the densities of both nanolubricant and nanorefrigerant are less than that of the pure lubricant and nanorefrigerant. The heat capacities of the nanolubricant and nanorefrigerant also decreased with increase in nanoparticle volume fractions. It was also observed that the heat capacities of both nanolubricant and nanorefrigerant are less than that of the pure lubricant and nanorefrigerant. This study has established the possibility of using diamond nanoparticles to enhance the thermophysical properties of lubricants and refrigerants in vapour compression refrigeration systems. Experimental investigation of these properties is worthwhile in this area for the purpose of validation. It is important to have superior thermophysical properties of the nanolubricant and nanorefrigerant that could withstand the variation of temperature and pressures and the nanoparticles would not cause the clogging, corrosion, or pressure drop in the overall performance of vapour pressure refrigeration system.

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