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Metallic Oxides for Innovative Refrigerant Thermo-Physical Properties: Mathematical Models

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A B S T R A C T

Nano-refrigerant is announced to become an excellent refrigerant, which often improves heat transfer efficiency in the cooling systems. Different materials can be applied to be suspended in traditional coolants in the same way as nanoparticles. In this comprehensive research, mathematical modeling was used to investigate the effect of suspended nanoparticles (Al_2O_3, CuO, SiO_2 and ZnO) on 1,1,1,2-Tetrafluoroethane, R-134a. The thermal conductivity, dynamic viscosity, density and specific heat capacity of the nano-refrigerant in an evaporator pipe were investigated. Compared to conventional refrigerants, the maximum increase in thermal conductivity was achieved by Al_2O_3/R-134a (96.23%) at a volume concentration of 0.04. At the same time, all nano-refrigerant types presented the same viscosity enhancement of (45.89%) at the same conditions. These types of complex thermophysical properties have enhanced the heat transfer tendencies in the pipe. Finally, the nano-refrigerant could be a likely working fluid generally used in the cooling unit to improve high-temperature transfer characteristics and save energy use.

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النمذجة الرياضية للخصائص الحرارية-الفيزيائية لأكاسيد معدنية مبتكرة لأغراض التثليج

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الخلاصة

تم التوصل الى أن المبردات النانوية هي سائلاً جيد ومبردًا ممتازً ، وغالباً تؤدي إلى تحسين واداء كفاءة نقل الحرارة في أنظمة التبريد. هناك مواد مختلفة كالجسيمات النانوية يمكن استخدامها او خلطها و نقلها ليتم تعليقها في المبردات التقليدية بنفس طريقة الجسيمات النانوية. في هذا البحث الشامل ، فقد تم استخدام النمذجة الرياضية لدراسة تأثير الجسيمات النانوية المعلقة

(Al_2O_3 ، CuO ، SiO_2 و ZnO) خلال R-134a، 1،1،1،2-Tetrafluoroethane

تم فحص وقياس الخواص الحرارية التالية: الموصلية الحرارية واللزوجة الديناميكية والكثافة والسعة الحرارية النوعية لمادة التبريد النانوية في أنبوب المبخر, بالمقارنة مع المبردات التقليدية ، تم تحقيق أقصى زيادة في التوصيل الحراري بواسطة (96.23%) Al_2O_3 / R-134a و بتركيز حجمي 0.04. حيث قدمت جميع أنواع المبردات النانوية نفس زيادة اللزوجة بنسبة (45.89%) في نفس الظروف. ان هذه الأنواع من الخصائص الفيزيائية الحرارية المعقدة عززت ميول نقل الحرارة في الأنبوب. خلاصة البحث ، يمكن أن يكون المبرد النانوي عبارة عن سائل عامل محتمل يتم استخدامه بشكل عام في وحدة التبريد لتحسين خصائص نقل درجات الحرارة العالية وتوفير استخدام الطاقة الى حد عالي نسبياً.

الكلمات الدالة: مبردات نانو، مبخر الأنبوب لنظام التبريد، الخصائص الحرارية الفيزيائية.

NOMENCLATURE

Al_2O_3	Aluminum oxide	Re_m	Nanorefrigerant Reynolds number
C_p	Specific Heat, J/(kg K)	R_{in}	Inner radius, mm
CuO	Copper oxide	R_o	Outer radius, mm
d_p	Diameter of nanoparticles, nm	SiO_2	Silicon oxide
g	Gravitational acceleration, m/s²	T_i	Temperature of the inner cylinder, K
h_{air}	Air heat transfer coefficient, W/(m² K)	T_o	Temperature of the outer cylinder, K
k	Thermal conductivity, W/(m K)	V	Refrigerant velocity, m/s
k_{Copper}	Thermal conductivity of copper, W/(m K)	ZnO	Zinc oxide
L	Tube length, mm		

Greek symbols

α	Thermal diffusivity, m² s⁻¹	ν	Kinematic viscosity, m² s⁻¹
β	Coefficient of thermal expansion, 1/K	ρ	Density, kg/m³
μ	Dynamic viscosity, Pa s	φ	Volume fraction of nanoparticles

Subscripts

f	Fluid	n_p	Nanoparticles
m	Refrigerant	s	Solid
n_f	Nanorefrigerant		

1. INTRODUCTION

Replacement of conventional refrigerants such as R134a and R12, in system refrigerants is essential and currently ongoing. This effort is to reduce: (i) the impact of conventional refrigerants on climate change (especially Ozone depletion and/or high global warming) [1], (ii) high energy consumption and exergy destruction [2], thereby enabling compact design of refrigerator systems [3], and (iii) rate of refrigerant leakage to the environment [4]. Design simplicity and economic advantage of domestic refrigerators are increasing their applications in households, and commercial buildings. According to International Institute of Refrigeration (IIR), more than 17 % of energy consumption globally are from refrigeration and air conditioning systems [5].

Nanotechnology can be described as a science and technology area for modifying and using of particles within the atomic and molecular structure. A particle is recognized as a small element that usually provides a unique transportation factor and its specific characteristics [6]. Despite the need for established physical properties from mass materials, the material characteristics vary with their unique nano-size specifications [7]. Depending on their diameter, these types of particles could be classified into three categories, including coarse-particles (10,000-2500) nm, fine-particles (2500-100) nm, and ultrafine-particles or perhaps nano-particles (1-100) nm. In heat transfer approaches, the application of ultrafine particles becomes necessary, as the use of the particles with a larger size contributes to many complications, such as fouling, sedimentation and then a reduction in pressure [8].

The use of conventional heat transfer fluids, including water, engine oil, and ethylene glycol, often leads to limitations in the efficiency and performance of thermal devices of a given size. The increase in heat transfer could be allowed by maintaining suspended solid particles as a chemical component in these conventional fluids [6]. Thermal conductivity is undoubtedly an essential thermophysical feature to improve the performance of such suspension systems [4,5]. To improve the thermal conductivity of standard fluids, nanoparticles in a base fluid, in which the thermal conductivity of the particles is incredibly higher than the base fluid, are suspended. Nanoparticles and the base fluid are called nano-fluids, which are a sophisticated form of heat transfer fluids [11].

A new promising heat transfer fluid known as nanofluid has contributed to many applications today, such as electronics, nuclear reactors, biomedical, motor vehicle, and industrial cooling. Recently, nano-refrigerants have been introduced as significant effects of nanoparticles on heat transfer efficiency and energy consumption elimination [12]. Past nanofluid experiments have presented that small nano particular concentrations have a promising potential to enhance base-fluid thermo-physical properties [13]. Subsequently, there was a tremendous investigation into the suspension of nanoparticles in the conventional refrigerant. Research has shown that nanoparticles suspended in Malaysian residential refrigerators can reduce energy consumption by approximately 10,863 MWh by 2030 [14].

Many studies to analyze the thermal conductivity of the nanofluids have already been carried out. On the other hand, there are specific pieces of literature on the thermal conductivity of nano-refrigerants [15]. Once again, researchers agreed that the concentration of nanoparticles and various nanoparticles improved the thermal conductivity of the nano-refrigerant [16]. Long-term stability of the dispersion of nanoparticles affects the thermal conductivity of the nano-refrigerant, as a better dispersion tendency reveals the superior thermal conductivity of the nano-refrigerant [17]. Also, it demonstrated significant impacts of Al_2O_3 nano-particle volume percentage on the thermal and pressure drop of R141b refrigerants using constant temperature, mass flow, and pressure by using mathematical modeling suggestions [12]. It is recommended that the suspension system of Al_2O_3 nanoparticles in R-134a refrigerant reduces power consumption by about 10.32% by just 0.2% of the suspension of nanoparticles [18]. Under the standard reports, TiO_2-R600a concentrations of 0.1 and 0.5 g L^{-1} decreased by 5.94% and energy performance by 9.60% in the residential refrigerator respectively [19]. The cooling unit with mineral oil and Al_2O_3 nanoparticles electricity consumption by about 25% compared to conventional oil [20]. Subsequently, the nano-lubricant Al_2O_3/R600a reduced the electric power consumption of the compressor by approximately 11.5% increased by 19.6% due to the nano lubricant compared to the standard POE (polyol-ester) oil and the coefficient of performance of the refrigeration unit [21]. There are many reasons for the thermal conductivity of the nano-refrigerant, for example, the fraction of particle volume, the classes of nanoparticles, refrigerants, particle sizes and particle patterns [22]. The thermal conductivity of the Al_2O_3 nanoparticles could be improved by only increasing the volume of nanoparticles suspended in the R-134a refrigerant [23]. The thermal conductivity of Al_2O_3/R141b nano-refrigerant improved with 0.5-2 nanoparticle volume concentrations and temperature range of 5-20^{o}C, while the viscosity of the nano-refrigerant increased with increase the concentration of nanoparticles but reduced with temperature [15].

The viscosity of nanoparticles based on R-134a refrigerant could also be theoretically improved due to the nanoparticles concentration of 0.01 to 0.05 [18]. The study usually showed that the concentration of the TiO_2 nanoparticles in a horizontally smooth tube led to the drop in pumping power, pressure and heat transfer coefficient of nano-refrigerant [24]. The coefficient of heat transfer in the cooling unit affected the heat transfer rate. The increase in the heat transfer coefficient due to the concentration of Al_2O_3 nanoparticles was acquired for single-phase laminar flow in the micro channel, while external deposition, clustering of nanoparticles and cluster occur in the two-phase system [25]. The objective of this research is to improve the thermal conductivity, dynamic viscosity, density and specific heat capacity of the nano-refrigerants in an evaporator tube using mathematical models.

Table 1
Thermo-physical properties of pure refrigerant and various types of nano-fluids at 300 K [18].

Thermophysical Properties	R134a	Al_2O_3	CuO	ZnO	SiO_2
Density, ρ (kg/m³)	1199.7	3970	6500	5600	2200
Dynamic viscosity, μ (*mPa s*)	0.191	-	-	-	-
Thermal Conductivity, k (W/m K)	8.03×10^{-2}	36	17.65	13	1.4
Specific heat, Cp (J/ kg K)	1432	765	535	495.2	745

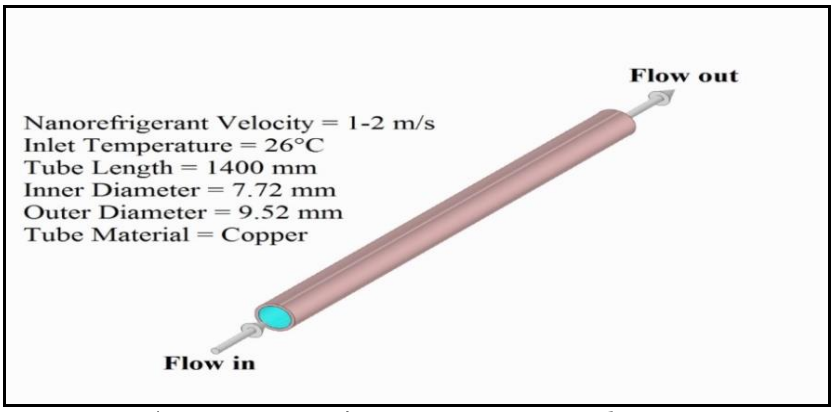


Fig. 1. A nano-refrigerant evaporator tube [27].

Table 2
Values of specification for nano-refrigerant properties [27].

Constant parameter	Value
Refrigerant velocity, V	1-2 m/s
Diameter of nanoparticles, d_p	20-80 nm
Thermal Conductivity of copper, k_{copper}	401W/(m K)
Heat transfer coefficient for air, h_{air}	50W/(m² K)
T_{inlet}, T_i	26 °C
Temperature outlet, T_o	10 °C

2. THERMO-PHYSICAL PROPERTIES AND MATHEMATICAL MODELS

2.1. *Nano-refrigerant and Tube Design*

The thermo-physical properties of nano-refrigerants were studied in this research by investigating nano-particles (Al_2O_3, CuO, SiO_2, and ZnO) and the regular refrigerant R-134a. Table 1 shows physical characteristics of nanoadditives and pure cooling [26]. A copper smooth flat evaporator pipe was created with a CAD software program with internal diameter (Di), and length (L), (7.72 mm) and (1400 mm), respectively. Fig. 1 shows the evaporator copper tube. In determining the properties of the nano-refrigerant, various factors of the initial state in the evaporation approach were fully developed flow. Table 2 displays the constant parameters used for this research study.

2.2. *Mathematical Models of Nano-refrigerant*

Nano-refrigerant thermal conductivity is estimated using data from Table 3 and the mathematical modeling of [28] as follows:

$$\frac{k_{nf}}{k_m} = cRe_m^{0.175}\varphi_p^{0.05}\left[\frac{k_p}{k_m}\right]^{0.2324} \quad (1)$$

where k_{nf} is the thermal conductivity of nano-fluid, k_m is the thermal conductivity of refrigerant, k_p is the thermal conductivity of nanoparticles, c is constant in the equation (1.298), φ_p is the particle volume fraction, V_m is the velocity of the refrigerant in the rang(1-2 m s^{-1}), ρ_p is the density of nanoparticles, d_p is the diameter of nanoparticles refrigerant in the rang (20-80nm), and T_{in} is the temperature inlet. Table 3 displays the constant parameters used for this research study.
The Reynolds number of nano-refrigerant is estimated by applying equation (2) as follows:

$$Re_m = \left(\frac{1}{v_m}\right)\left[\frac{18k_pT_{in}}{\pi\rho_pd_p}\right]^{0.5} \quad (2)$$

By using Brownian nano-particular motion, the effective viscosity can be obtained through subsequent empirical correlation [29]:

$$\frac{\mu_{eff}}{\mu_f} = \frac{1}{1-34.87\left(\frac{d_p}{d_f}\right)^{-0.3}\varphi^{1.03}} \quad (3)$$

Equivalent diameter of base-fluid molecule [29]:

$$d_f = \frac{6M}{N\pi\rho b_f} \quad (4)$$

where M is the molecular weight of the base fluid, N is the Avogadro number, f refers to nanofluid, b_f refers to base fluid and p refers to nanoparticle.
The density of the nano-fluid ρ_{nf} can be evaluated [30]:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_{np} \quad (5)$$

The mass densities of the base-fluid and the solid nano-particles were ρ_f and ρ_{np}, respectively. The effect of the specific heat capacity $(\rho Cp)_{nf}$ could be determined at a constant pressure of the nano-fluid [30]:

$$(\rho Cp)_{nf} = (1-\varphi)(\rho Cp)_f + \varphi(\rho Cp)_{np} \quad (6)$$

Table 3
Values of specification for nano-refrigerant properties.

Constant parameter	Value
Refrigerant velocity, V	1-2 m/s
Diameter of-nanoparticles, d_p	20-80 nm
T_{inlet}, T_i	26 °C
Temperature outlet, T_o	10 °C

3. RESULTS AND DISCUSSION

3.1. *Thermal Conductivity of Nano-refrigerants*

Fig. 2 and Table 4 showed the association with nano-refrigerant thermal conductivity, R-134a refrigerant and nano-particle volume fraction. Nanorefrigerant thermal conductivity k_{nf} was directly proportional to the nanoparticle volume fraction. The thermal conductivity of pure coolant, 0.0803 W(m K) improved by adding 0.01 volume fraction of nanoparticles and an increase in 95.96%, 94.7%, 89.16% and 94.23%, respectively.

The substantial improvement was due to the consideration of the surface layer in mathematical modeling. It designed the corresponding particles without overlying between particles [31]. Applying a nano-particle volume fraction of about 0.04 improved the thermal conductivity of the nano-refrigerant by far extra than 100%, as the standard refrigerant R-134a offered superior thermal conductivity to various base-fluids, such as water, oil and ethylene glycol.

In particular, the thermal conductivity of the nano-refrigerant will probably be improved as a result of the addition of nanoparticles to the nano-refrigerant [32]. The viscosity of the nano-refrigerant should as well be measured, as it could affect the overall enactment of the cooling unit.

Results show the thermal conductivity of the metal oxides nanofluids increases linearly with nanoparticle concentration. By applying the current proposed model of, Al_2O_3, CuO, and ZnO have greater thermal conductivity ratio compared to Maxwell model [33]. On the other hand, SiO_2 shows less thermal conductivity ratio due to its lower thermal conductivity among the four metal oxides nanofluid used in this investigation. Overall, it can be concluded that the thermal conductivity of nanofluid increases with nanoparticle volume fractions.

Based on the results in Table 4, it is outstandingly evident that nano-refrigerant provide a significant thermal conductivity enhancement compared to those of other works

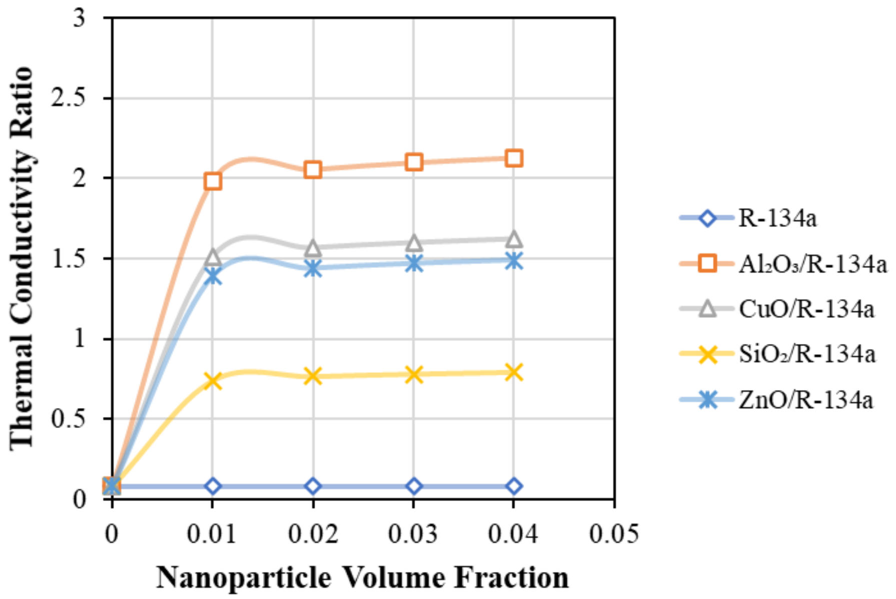


Fig. 2. Variation of thermal conductivity as a function of φ with different types of nanoparticles at *V*= 1 m/s and d_p = 20 nm

Table 4
Summary of thermal conductivity investigations of nano-refrigerants.

Reference	NPs	Refrigerant	Operational conditions	Findings
[31]	Cu, Al, Ni, CuO, Al_2O_3	R-113	T= 303 K	Increases sharply up to 20% with increase in φ (0.01).
[34]	Al_2O_3	R-141b	(T= 5–30°C), (φ = 0.1–0.4)	It increases by 1.626 times on (0.2) concentration and 20°C.
[35]	Al_2O_3	R–134a	T= 283–308 K, u= 5 m/s, (φ= 0.01–0.05), mass flux= 100 kg m^{-2}	Maximum improvement of 28.58%.
[22]	CuO	R–134a	(φ= 0.01–0.05), d_p= 20 nm, (T= 300–325 K)	Maximum improvement of 43%.
[18]	Al_2O_3	R–134a	(φ= 0.01–0.05), d_p= 20 nm, (T=300–325 K)	Rises with an increase in particle concentration and temperature and with decrease in additives size.
[36]	SWCNT	R–134a	φ= (0.01–0.05), d_p= 20 nm, T= 300–325 K	Increases with increase in particle concentration and temperature.
Current study	Al_2O_3, CuO, SiO_2, ZnO	R–134a	φ= (0.01–0.04), d_p= 20-80 nm, T= 225–325 K, u=1-2 m s^{-1}	Increases with increase in particle volume and temperature.

when they have higher concentrations of nanoparticles. These results show that using a low concentration of nano-refrigerant can achieve good thermal conductivity enhancement for medium-temperature applications including cooling and heat exchanger systems.

Figs. 3-5 showed thermal conductivity of (Al_2O_3/R-134a) with different nanoparticle diameters, nano-refrigerant temperatures, and velocity as a function of the nanoparticle volume fraction. Nano-refrigerant thermal conductivity decreases by increasing the diameter of nanoparticles. This was due to smaller particles that convey more collision space. The arbitrary movement of microscopic particles mixed in the base-fluid allows other collisions with bordering structure molecules and minimizes the wall temperature [28]. By increasing the nano-refrigerant temperature, the thermal conductivity was shown in Fig. 4 improved because of equation (2), the number of Reynolds was immediately proportional to the nano-refrigerant temperature. As a result of equation (2), the thermal conductivity of nano-refrigerants was reduced by increasing the fluid velocity, as shown in Fig. 5.

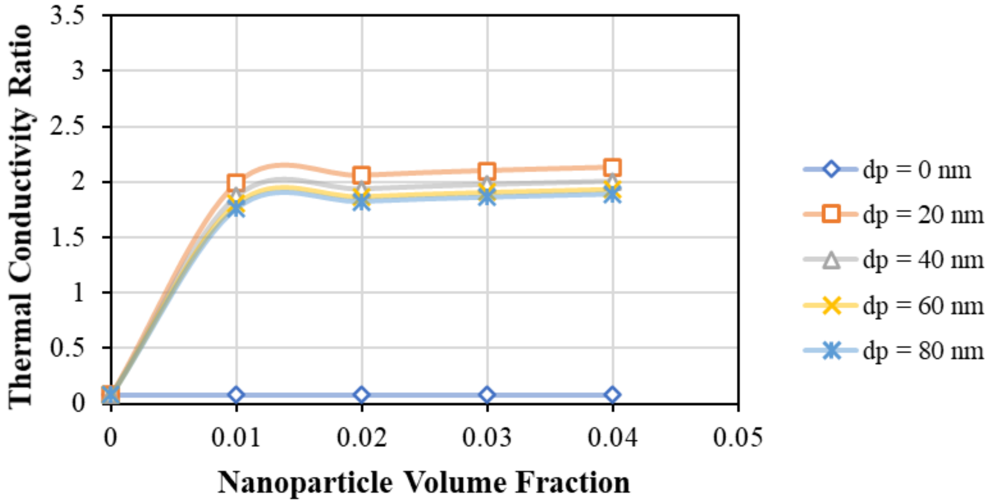


Fig. 3. Variation of thermal conductivity as a function of nano-particle volume fraction with different diameters of nanoparticles at V= 1m/s.

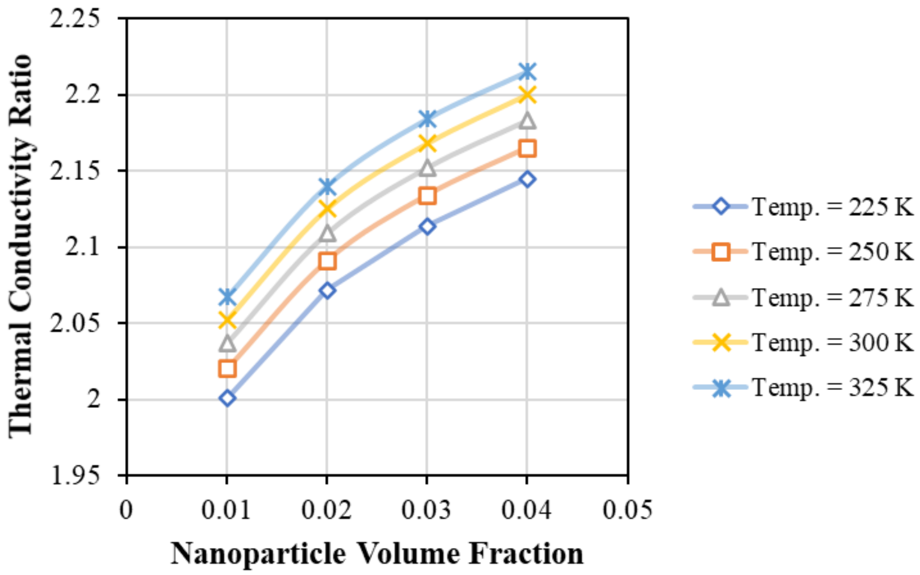


Fig. 4. Variation of thermal conductivity as a function of nano-particle volume fraction with different nano-refrigerant temperatures at V= 1m/s and d_p = 20 nm.

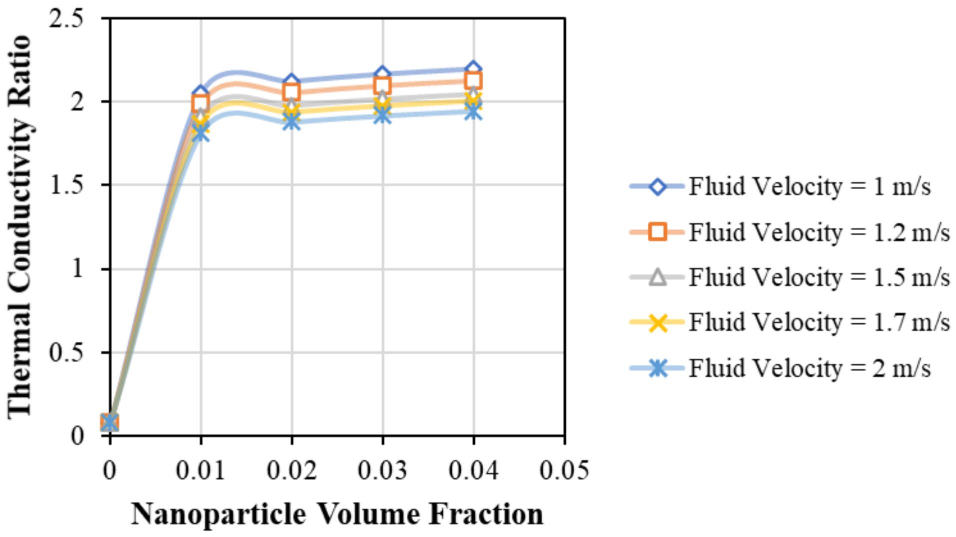


Fig. 5. Variation of thermal conductivity as a function of nano-particle volume fraction with different nano-refrigerant velocities at Temp.= 325 K and d_p = 20 nm.

3.2. Dynamic Viscosity of Nano-refrigerants

Increases in nano-refrigerant viscosity in line for the nanoparticle remark presented in Fig. 6. The viscosity was instantly proportionate to the volume of nanoparticles. R-134a viscosity at 300 K was 0.191 mPa s. After the nanoparticles were suspended in the refrigerant at 0.01 nano-particle volume, the viscosity improved to 0.214 mPa s, about 10.75% improvement, as shown in Fig. 9. A more significant increase in the nano-refrigerant's viscosity was achieved by suspending an additional 0.01 of the nanoparticle volumes. The pendent nano-particles have improved the surface area through the R-134a refrigerant and the additives. The Brownian motion arbitrarily drifted the nano-particles into the nano-refrigerant, which improved the tube convection process. As metal oxides in size of nanoparticles, it allows even additional motions caused by the gap between particles and collisions [27]. Table 5 summarizes the results of dynamic viscosity measurement from different researchers on nano-refrigerants.

More recent works that compared the Current study are listed in Table 5. Based on Table 5, improve viscosity offers significant evidence that nano-refrigerant, had higher concentrations of additives or nanoparticle in comparison to other samples. It is highlighted here that medium-temperature applications can achieve suitable viscosity by using low-volume fraction.

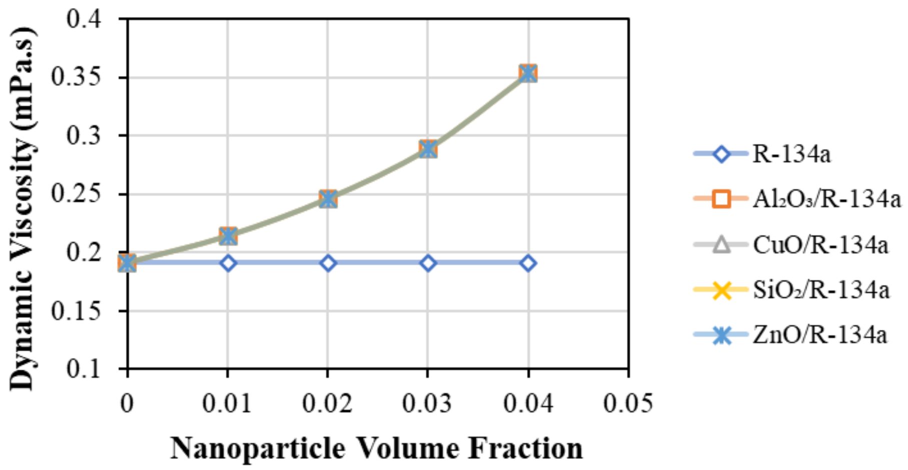


Fig. 6. Variation of viscosity as a function of nano-particle volume fraction at V= 1m/s and d_p = 20 nm.

Table 5
Summary of investigations on dynamic viscosity of nano-refrigerants.

Reference	NPs	Refrigerant	Operational conditions	Findings
[37]	TiO_2	R-123	(Temp.= 5–20°C), φ = 0.5–2.0	Viscosity increased with the rise in φ and reduction with an increase in T.
[15]	Al_2O_3	R-141b	(Temp.= 5–30°C), φ= 0.1–0.4	Viscosity growing by 179 times at 5°Cand 0.2
[35]	Al_2O_3	R−134a	(Temp.= 283–308 K), u= 5 m s^{-1}, (φ= 0.01–0.05), mass flux= 100 kg m^{-2}	Increased by 13.68% for same temperature.
[22]	CuO	R−134a	φ_{np}= (0.01–0.05), d_p= 20 nm, T= 300–325 K	Viscosity raise with the increase in φ and reduce in T.
[18]	Al_2O_3	R−134a	φ_{np} = (0.01–0.05), d_p= 20 nm, T= 300–325 K	Viscosity increases with the increase in φ.
[36]	SWCNT	R−134a	φ_{np} = (0.01–0.05), d_p= 20 nm, T= 300–325 K	Viscosity increases with the increase in φ and decrease in T.
Current study	Al_2O_3, CuO, SiO_2, ZnO	(R−134a)	φ_{np} = (0.01–0.04), d_p= 20-80 nm, T= 225–325 K, u=1-2 m s^{-1}	Viscosity increased with the rise in φ and reduction with increase in T.

3.3. Density of Nano-refrigerants

Fig. 7 presents the variation of the prepared nano-refrigerant density with respect to the change in volume concentration. From the graph, it is clear that the density of the proposed fluids decreased dramatically except R-134a which doesn't show any significant change. The density was directly proportionate to the volume fraction of nanoparticles. R-134a density in 300K is 1199.7 kg m^{-3}. After the nano additives in the refrigerant were suspended at 0.01 nanoparticle volume fraction, the density of Al_2O_3, CuO, SiO_2 and ZnO obtained by approximately 2.26, 4.23, 0.83 and 3.54% respectively, as shown in Fig. 9. Table 6 summarizes the results of density measurement from different researchers on nano-refrigerants.

The results show the different behaviour of the density of the nanofluids, while the data confirm that the temperature affects the density of the nanofluids. The density of the nanofluids exceeds that of its basefluid due to the increase in the temperature. If the nanoparticles volume concentration increases from 0.01 to 0.04, its density decreases as shown in Fig. 7.

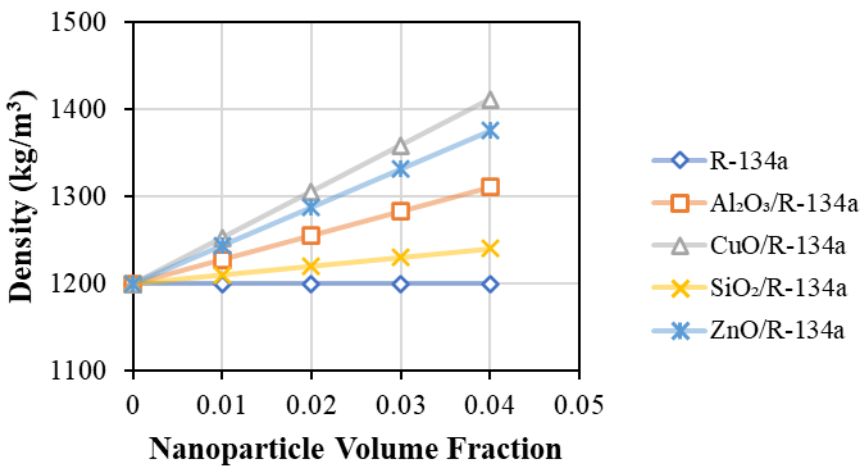


Fig. 7. Variation of density as a function of nanoparticle volume fraction at V= 1m/s and d_p = 20 nm.

Table 6
Summary of investigations on density of nano-refrigerants.

Reference	NPs	Refrigerant	Operational conditions	Findings
[34]	Al_2O_3	R-141b	Temp.= 5–30°C, φ = 0.0–0.4	increases with the increase in φ and decrease in T.
[22]	CuO	R-134a	φ_{np}= 0.01–0.05, d_p= 20 nm, T= 300–325 K	Density increased with the raise in φ and reduce in T.
[35]	Al_2O_3	R-134a	Temp.= 283–308 K, φ= 0.05	Density increases by using nano refrigerant.
[36]	SWCNT	R-134a	φ_{np} = 0.01–0.05, d_p= 20 nm, Temp.= 300–325 K	Density increases with the increase in φ and reduce in T.
Current study	Al_2O_3, CuO, SiO_2, ZnO	R−134a	φ_{np} = 0.01–0.04, d_p= 20-80 nm, T= 225–325 K, u=1-2 m s^{-1}	Decreases with the increase in nanoparticles.

More recent works that compared the Current study are listed in Table 6. Based on Table 6, improve density offers significant evidence that nano-refrigerant, had higher nanoparticle concentrations in comparison to other samples. It is highlighted here that medium-temperature applications can achieve suitable density by using low-volume fractions.

3.4. *Specific Heat Capacity of Nano-refrigerants*

The decreased in specific heat capacity due to nano-particle suspension was shown in Fig. 8. The obtained specific heat capacity was directly proportionate to the volume fraction of nanoparticles. R-134a 's specific heat capacity at 300K was 1432 J (kg K)$^{-1}$. Once the nano-particles in the refrigerant were suspended at 0.01, nanoparticle volume fraction, specific heat capacity of Al_2O_3, CuO, SiO_2, and ZnO decreased by -1.53, - 3.37, - 0.88 and -3.03%, respectively as shown in Fig. 9. On the other hand, the specific heat capacity of R-134a illustrated a small upward trend contrary to other fluids. Table 7 summarizes the results of specific heat capacity measurement from different researchers on nano-refrigerants.

More recent works that compared the Current study are listed in Table 7. Based on Table 7, specific heat capacity offers significant evidence that nano-refrigerant had higher concentrations of additives or nanoparticle in comparison to other samples. It is highlighted here that medium-temperature applications can achieve suitable specific heat capacity by using low-volume fractions.

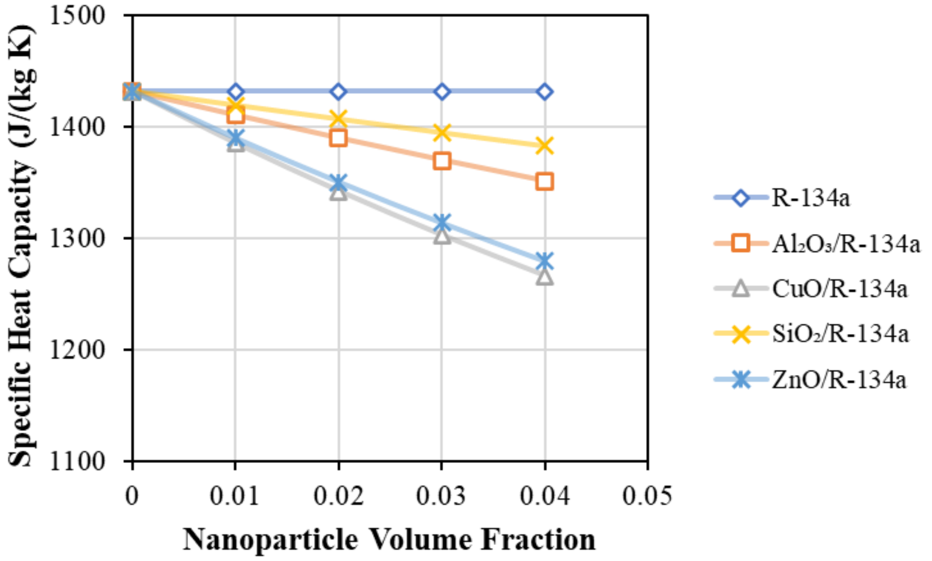
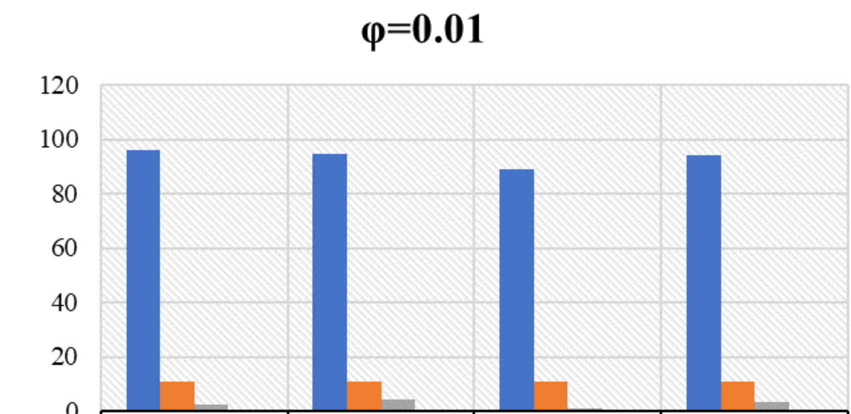
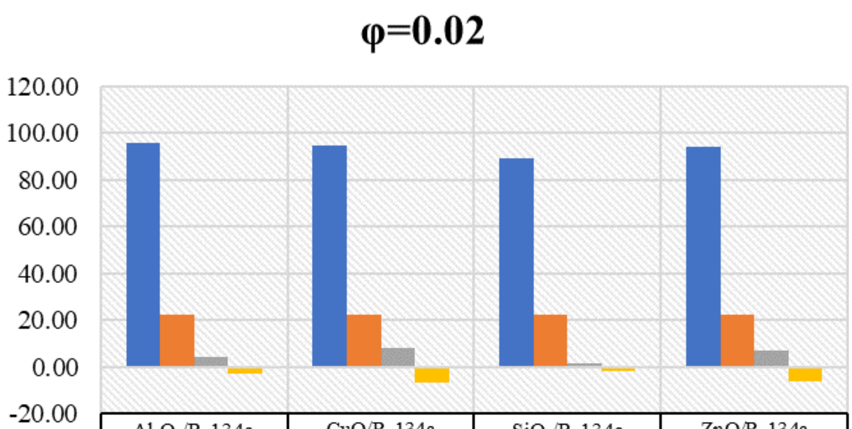


Fig. 8. Variation of specific Heat as a function of φ at V= 1m/s and d_p = 20 nm.



	Al_2O_3/R-134a	CuO/R-134a	SiO_2/R-134a	ZnO/R-134a
K(%)	95.96	94.7	89.16	94.23
μ(%)	10.75	10.75	10.75	10.75
ρ(%)	2.26	4.23	0.83	3.54
Cp(%)	-1.53	-3.37	-0.88	-3.03



	Al_2O_3/R-134a	CuO/R-134a	SiO_2/R-134a	ZnO/R-134a
K(%)	96.10	94.88	89.53	94.43
μ(%)	22.36	22.36	22.36	22.36
ρ(%)	4.41	8.12	1.64	6.83
Cp(%)	-3.04	-6.67	-1.76	-6.03

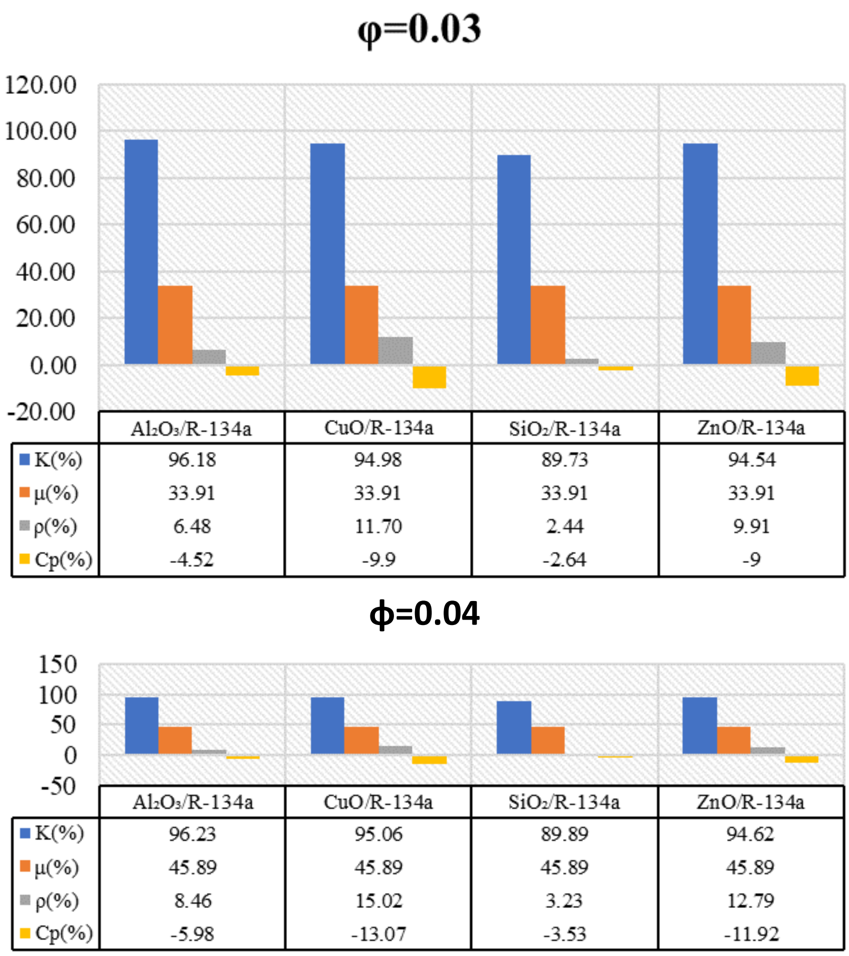


Fig. 9. Nano-refrigerant thermo-physical properties enhancement at different nano-particles volume fractions.

Table 7
Summary of investigations on the specific heat capacity of nano-refrigerants.

Reference	NPs	Refrigerant	Operational conditions	Findings
[35]	Al_2O_3	R-134a	Temp.= 283–308 K, φ_{np} = 0.05	Heat capacity increases with temperature.
[36]	SWCNT	R-134a	φ_{np}= 0.01–0.05, d_p= 20 nm, T= 300–325 K	Specific heat rises with increase in T and φ.
Current study	Al_2O_3, CuO, SiO_2, ZnO	R–134a	φ_{np} = 0.01–0.04, d_p= 20-80 nm, Temp.= 225–325 K, u=1-2 m/s^{-1}	Decreases with increase in φ.

4. CONCLUSION

The thermal conductivity and the rheological behaviour of nano refrigerants based on metallic oxides were discussed. Mathematical models using different types of nanoparticles (Al_2O_3, CuO, SiO_2, and ZnO) were used to estimate the thermo-physical properties of nano-refrigerants using a cooling unit evaporator tube. The thermal conductivity of the Al_2O_3/R-134a coolant was 0.0803 W/m. K at 300K temperature and 0.01 of the nanoparticles volume fractions Suspending. The fraction of refrigerant nano-particles improved thermal conductivity by around 95.96% (Al_2O_3/R-134a). More than 0.01 of the nanoparticles volume fractions had thermal conductivity ranging from 95.96 to 96.23 within 0.01 to 0.04 of the nanoparticles volume fractions. The viscosity of the nano-refrigerant also showed a remarkable increase of 10.75% compared to the standard refrigerant, with only 0.01 of the nanoparticles volume fractions. Volume fractions of nanoparticles and the temperature of the mixture have significant effects on the thermal conductivity and viscosity of the nanofluids. Results indicate that viscosity increases with the increment of the particle volume fractions. However, it decreases when the temperature increases.

Nano-refrigerant density and specific heat capacity showed significant improvements in nano-particles suspended based on a volume fraction. It is essential to have the nano-refrigerant's excellent thermal properties that can withstand the variation of temperature and pressure, and the nanoparticles would probably not cause the cooling, corrosion or pressure drop in the cooling unit's efficiency.

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