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# PREDICTIVE ANALYSIS ON THE INFLUENCE OF Al2O3 AND CuO NANOPARTICLES ON THE THERMAL CONDUCTIVITY OF R1234yf-BASED REFRIGERANTS

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**Abstract:** Nano-enhanced refrigerants are substances in which the nanoparticles are suspended in the refrigerantatthe desired concentration. They have the potential to improve the performance of refrigeration and air-conditioning systems that use vapour compression. This study focuses on the thermal conductivity of alumina (Al2O3) and cupric oxide (CuO) nanoparticles immersed in 2,3,3,3-tetrafluoropropene (R1234yf). The thermal conductivity of nano-refrigerants was investigated using appropriate models from earlier studies where the volume concentration of particles and temperatures were varied from 1% to 5% and from 273 K to 323K, respectively. The acquired results are supported by prior experimental investigations on R134a-based nano-refrigerants undertaken by the researchers. The main investigation results indicate that the thermal conductivity of Al2O3/R1234yf and CuO/R1234yf is enhanced with the particle concentrations, interfacial layer thickness, and temperature. Also, the thermal conductivity of Al2O3/R1234yf and CuO/R1234yf decreases with particle size. The thermal conductivity of Al2O3/R1234yf and CuO/R1234yf nano-refrigerants become enhanced with a volume concentration of nano-sized particles by 41.2% and 148.1% respectively at 5% volume concentration and 323K temperature. The thermal conductivity of Al2O3/R1234yf reduces with temperature, by upto 3% of nanoparticle addition and after that, it enhances. Meanwhile, it declines with temperature, by upto 1% of CuO nanoparticle inclusion for CuO/R1234yf. CuO/R1234yf has a thermal conductivity of 16.69% greater than Al2O3/R1234yf at a 5% volume concentration. This paper also concludes that, among the models for thermal conductivity study, Stiprasert's model is the most accurate and advanced.

**Keywords:** heat transfer fluid, nanoparticles, nano-refrigerants, thermal conductivity models, thermo-physical properties, nanofluids, temperature, volume concentration

## 1. INTRODUCTION

Nanofluids have piqued the interest of researchers all over the world as a viable option for improving the efficiency of heat transfer. Nanofluids were first exhibited by Choi and Eastman [1] at Argonne National Laboratory as immersed nano-sized materials in base fluids with a standard particle size of 1–100 nm. Nanofluid is a heat transport medium, which is inflexible and established by suspending nano-sized particles unvarying isolated into heat transfer fluid (HTF). The merit of these particles progresses bythe fluid heat transportation created by their advanced thermal conductivity. Nanofluids are of boundless worth due to their higher enactment on the advancement of the Thermal Act. Nanofluids are used in a variety of heat transfer applications, including electronic cooling, aerospace industries, refrigeration, and air-conditioning [2]. Two approaches are used to improve the heat transfer coefficient of nanofluids. The first approach is to boost the Nusselt number, which is impacted by the Reynolds, Prandtl, and geometry. The second strategy is to shorten the characteristic length, which is inversely related to the heat transfer coefficient. The heat transfer coefficient is determined using the Nusselt number, nanofluid thermal conductivity, and characteristic length in this approach. These approaches are used to create microchannel heat sinks [3]. Recent studies analyse the thermal performance of Joule heating, Brownian motion and thermo-phoretic diffusion on Carreau, Casson-Willianson and Maxwell nanofluids [4–14]. These investigations are leading to more practical applications of nanofluids. The thermophysical properties of nano-fluids influence the performance of the systems. One of their most critical thermo-physical properties is thermal conductivity, which is related to the convective heat transfer and boiling coefficients. As a result, thermal conductivity has gained a lot of attention in current research, and the non-linear dependency of temperature on thermal conductivity has been verified [15–23]. Alhajaj et al. [24] identified the thermal conductivity of 0.5% of $Al_2O_3$ and $TiO_2$ nanoparticles with water and ethylene glycol. Plant and Saghir [25] studied the heat transfer performance of the three-channel heat exchanger using 1% $Al_2O_3$/water and 2% $Al_2O_3$/water nanofluids. In their study, they concluded that heat transfer is enhanced by the increase in the volume concentration of the nanoparticle in the base fluid. From their analysis, it is clear that the thermal conductivity of the nanofluid greatly impacts the performance of systems.

Nano-refrigerants are a novel kind of nanofluids, in which the nanoparticles are suspended on the base refrigerants. Many researchers have identified the '*k*' value of different refrigerants [26–28]. This novel kind of refrigerant is used for enhancing the performance of refrigeration systems. The '*k*' value of the working fluid influences the heat transfer of the system [29]. Three key benefits could be achieved by using nanoparticles in refrigeration systems [30]: (a) nanoparticles as an additive could improve the mixing of the lubricant and the refrigerant. (b) the refrigerant's '*k*' value and other thermo-physical properties could be enhanced and (c) dispersion of nanoparticles in the refrigerant could increase the coefficient of performance and cooling effect and enhance the energy efficiency of the system. The experiments showed that the nano-refrigerant has a greater thermal conductivity compared with that of the base refrigerant [15]. In addition, the vapour compression refrigeration system works with the nano-enhanced refrigerant and outperforms the traditional pure refrigerant refrigeration system [31–33]. On the contrary, the clustering or settlement of nanoparticles in refrigerants could reduce the steadiness of the nano-refrigerant and restrict its use in refrigeration systems. Many studies have been carried out on the thermo-physical properties and the ability of heat transport of nano-refrigerants. According to the literature, suspending nanoparticles in refrigerants could improve the thermal conductivity (*k*) and heat transfer efficiency [16, 17].

Recently researchers have tried to identify the '*k*' values of various nano-enhanced refrigerants. Jiang et al. [17] calculated the value of '*k*' for four distinct forms of carbon nanotubes at particle concentrations of 0.2%–1% added in R113 refrigerant. With regulated volume concentrations of 0.1%–1.2%, Jiang et al. [15] studied the '*k*' value of R113-based nano-refrigerant, in which they used various nanoparticles such as Cu, Al, Ni, CuO, and $Al_2O_3$. Alawi et al.[18] analysed the value of '*k*' for R134a with CuO nanoparticles for different volume concentrations varying from 1% to 5% and temperatures in the range of 300–320K. Mahbubulet al. [19] also explored the influence of '*k*' on the R134a-based nano-refrigerant. They used $Al_2O_3$ as the suspended particle with concentrations of 1–5 vol%. Another work by Alawi et al. [34] analysed the value of '*k*' for nano-refrigerants containing alumina nanoparticles and R141b as the base refrigerant with the variation in concentration from 1 vol% to 4 vol%. The impacts of the volume concentration of nanoparticles present in the base fluid, types of nanoparticles, refrigerants, sizes of particles, and shapes of particles could all affect the value of '*k*'. Thermal conductivity could be improved as interfacial layers are created in nanofluids [35–37]. Likewise, Patil et al. [38] identified that the '*k*' value of the nano-refrigerant declined with the particle size. According to Zawawi et al. [39], the '*k*' value of nanofluids is influenced by their volume concentration and temperature. The value of '*k*' was improved with the concentration of nanomaterial and it declined with temperature. Yang et al. [40] found that increasing the volume fraction of $TiO_2$ increased the value of '*k*' of R134a/$TiO_2$, 30% of the '*k*' value was enhanced by adding 5% of the volume concentration of $TiO_2$ to the standard fluid. They also realised a decrease in thermal conductivity with an increase in temperature. Ammar Hassan et al. [41] explored the thermal conductivity of the R134a-based nano-refrigerant. They used $Al_2O_3$, $SiO_2$, $ZrO_2$, and CNT (Carbon nano-tubes) as nano inhibitors with different mass concentrations. From these, they identified that the thermal conductivity was improved with the nanomaterial concentration in the refrigerant. The main advantagesof the nanoparticles in the refrigeration systems are given in Fig. 1.

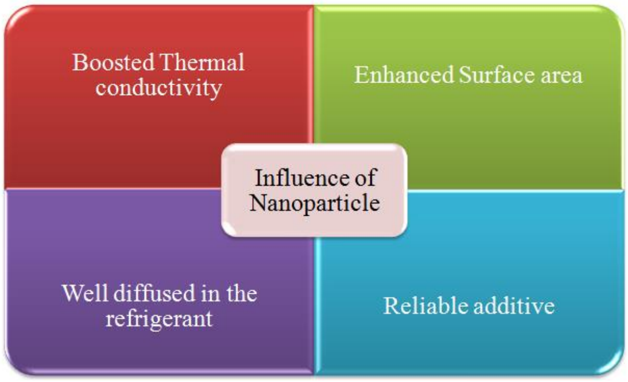


**Fig.1.** Significant benefits of nanoparticles in refrigeration system

Hydro-fluoro-olefin (HFO) refrigerants are the fourth generation, which have low global warming potential (GWP) and zero ozone depletion potential (ODP). Hence, it is a green refrigerant. These mixtures can replace HFCs like R125, R134a, R32 and others legally or with a small system modification [42]. There are two important types of HFO refrigerants: R1234ze(E) and R1234yf. The major limitation of R1234yf is its lesser performance than R134a. So, this article focuses on the system's efficiency improvement with R1234yf using nanoparticles.

However, investigations on the thermo-physical properties of HFO-based (R1234yf) nano-refrigerants are limited. The major goal of this analysis is to evaluate the thermal conductivity of $Al_2O_3$/R1234yf and CuO/R1234yf nano-refrigerants using mathematical models. The study examines the impact of nanoparticle concentrations ranging from 1% to 5% by volume. The investigation of nano-refrigerant thermal conductivity, on the contrary, is broadened by identifying and including the effects of nano-refrigerant temperature and particle size, as well as the interfacial layer on the thermal conductivity of the novel refrigerant.

## 2. METHODOLOGY

The '*k*' values of $Al_2O_3$/R1234yf and CuO/R1234yf nano-refrigerants are predicted by advanced Stipresert's model and compared with classical models such as those of Maxwell, Crosser & Hamilton and Yu and Choi. In Tabs. 1 and 2 are tabulated the properties of $Al_2O_3$ and CuO nanomaterials and the R1234yf refrigerant. The nano-refrigerant efficacy is investigated by studying the effects of $Al_2O_3$ and CuO nanoparticle concentration of 1–5 vol% in R1234yf refrigerant. The average particle size of nanoparticles was 40nm. However, when studying the influence of the temperature and size of nanoparticles on the '*k*' value of nano-added refrigerant, the nano-sized particles radius is considered to be 10–50nm and the temperature varied from 273 K to 323K. For the stability of the nano-refrigerant, no surfactant was used. As a result, the effect of surfactants was overlooked during the research. The mathematical models of nanofluids and nano-refrigerants from different authorities and the thermal conductivity of CuO/R1234yf and $Al_2O_3$/R1234yf nano-enhanced refrigerants were analysed.

**Tab. 1.** The properties of Al2O3 and CuO nanoparticles

| Nano particle | Molecular weight (kg/kmol) | Density (kg/m³) | Thermal conductivity (W/mK) | Specific heat (J/kgK) | Source |
|---|---|---|---|---|---|
| $Al_2O_3$ | 101.96 | 3,880 | 40 | 729 | [43] |
| CuO | - | 6,320 | 32.9 | 550.5 | [44] |

**Tab. 2.** Properties of R1234yf refrigerant [45]

| `Tem-pera-ture (K) | Pressure (kPa) | Density (kg/m³) | Viscosity (μPa/s) | Thermal conduc-tivity (W/mK) | Specific heat (kJ/kgK) |
|---|---|---|---|---|---|
| 273 | 315 | 1,175 | 220 | 0.0746 | 1.259 |
| 283 | 436 | 1,144 | 194 | 0.0713 | 1.293 |
| 293 | 590 | 1,111 | 171 | 0.0672 | 1.332 |
| 303 | 782 | 1,075 | 152 | 0.0631 | 1.379 |
| 313 | 1017 | 1,037 | 134 | 0.0586 | 1.498 |
| 323 | 1301 | 993.3 | 118 | 0.054 | 1.566 |

## 3. MATHEMATICAL MODELS

### 3.1. Maxwell's Model

Thermal conductivity models were built based on Maxwell's classic research into conduction through amalgamated media. This model was created by Maxwell under the premise that the solid phase is spherical. According to Maxwell's model, the thermal conductivity of the base fluid, sphere-shaped particles and particle volume percentage impact the '*k*' value of the nano-refrigerant. In addition, this model was found to be valid only in the case when φ << 2.5%. However, the model considers the mixture of fluid and nanoparticle as a homogeneous fluid. Maxwell [46] looked at the efficient thermal conductivity of a multi-phase mixture of solid and liquid states, and the efficient '*k*' value of nano-refrigerant, $k_{nr}$ is given as

$$\frac{k_{\mathrm{nr}}}{k_{\mathrm{r}}}=\frac{k_{\mathrm{np}}+2k_{\mathrm{r}}-2\varphi(k_{\mathrm{r}}-k_{\mathrm{np}})}{k_{\mathrm{np}}+2k_{\mathrm{r}}+\varphi(k_{\mathrm{r}}-k_{\mathrm{np}})} \quad (1)$$

According to Maxwell's model, the '*k*' value of the nano-refrigerant is influenced by the particle volume concentration and thermal conductivity of the nano-sized particles and fluids. Meanwhile, the other classical models include the impact of particle shape, particle distribution and particle interactions. These models predict almost identical improvements at low concentrations. However, the classical models donot account for the particle size and the interfacial layer.

### 3.2. Hamilton & crosser model

The shape factor (*f*) was introduced by Hamilton and Crosser [47], who extended Maxwell's work to non-sphere-shaped particles and termed it a new parameter that is related to the structure of the particles. The shape factor has been measured experimentally for various materials. They tried to establish a model that took particle structure, composition, and conductivity into account in both the solid and fluid phases. The Hamilton & Crosser model estimates the value of '*k*' for a nano-refrigerant as follows:

$$\frac{k_{\mathrm{nr}}}{k_{\mathrm{r}}}=\frac{k_{\mathrm{np}}+(f-1)k_{\mathrm{r}}-(f-1)(k_{\mathrm{r}}-k_{\mathrm{np}})\varphi}{k_{\mathrm{np}}+(f-1)k_{\mathrm{r}}+(k_{\mathrm{r}}-k_{\mathrm{np}})\varphi} \quad (2)$$

The shape factor (*f*) is calculated by the formula $f = 3/\chi$ and χ is known as sphericity, which is the ratio of a particle's surface area to its volume. The sphericity of spherical and cylindrical shapes is 1 and 0.5 respectively.

### 3.3. Yu and Choi Model

By assuming that, the pure refrigerant molecules near the solid surface of nanoparticles form layered structures that approximate solids, Yu and Choi [35] altered Maxwell's model. Consequently, the interfacial nano-layer works as a thermal link between the pure refrigerant and the solid nano-sized particles, enhancing the value of '*k*'. To account for the role of the nanolayer in measuring efficient '*k*' value, Yu and Choi considered a spherical nano-sized particle of radius enclosed by an interfacial nano-layer of thickness. They also believed that the thermal conductivity of the interfacial nano-layer is greater than thatof the refrigerant. The value of '*k*' of the nano-enhanced refrigerant is determined as:

$$\frac{k_{\mathrm{nr}}}{k_{\mathrm{r}}}=\frac{k_{\mathrm{np}}+2k_{\mathrm{r}}-2\varphi(k_{\mathrm{r}}-k_{\mathrm{np}})(1+\beta)^3}{k_{\mathrm{np}}+2k_{\mathrm{r}}+\varphi(k_{\mathrm{r}}-k_{\mathrm{np}})(1+\beta)^3} \quad (3)$$

The '*k*' of solid nano-sized particles and the base refrigerant, as well as the volume fraction of suspended particle, particle structure, interfacial nanolayer thickness and '*k*', all affect the '*k*' value of nano-refrigerants. The β is the ratio of the equivalent particle (with interfacial nano-layer) radius to the nanoparticle radius. This is influenced by the nano-particle size and the interfacial thickness.

### 3.4. Stiprasert's Model

The thermal conductivity of nano-refrigerant was measured using the Sitprasert et al. [36] correlation. This model could be used to quantify the influences of nanoparticle size, nanoparticle volume, and a temperature-dependent interfacial layer. Fig.2 shows a diagrammatic representation of the interfacial layer.

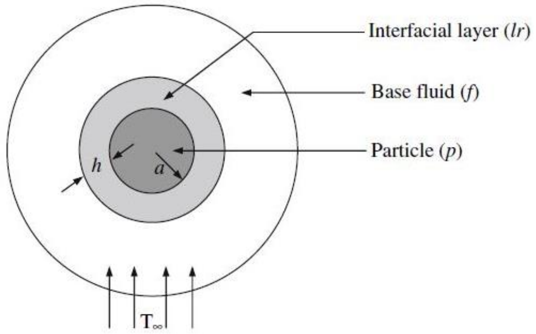


**Fig.2.** Solid nanoparticle interfacewithfluid medium [29]

The effective thermal conductivity is determined as:

$$k_{\mathrm{nr}} = \frac{(k_{\mathrm{np}}-k_{\mathrm{lr}})\varphi k_{\mathrm{lr}}(2\beta_1^3-\beta^3+1)+(k_{\mathrm{np}}+2k_{\mathrm{lr}})\beta_1^3[\varphi\beta^3(k_{\mathrm{lr}}-k_{\mathrm{r}})+k_{\mathrm{r}}]}{\beta_1^3(k_{\mathrm{np}}+2k_{\mathrm{lr}})-(k_{\mathrm{np}}-k_{\mathrm{lr}})\varphi[\beta_1^3+\beta^3-1]} \quad (4)$$

Where,

$$\beta = 1 + \frac{h}{a} \quad (5)$$

$$\beta_1 = 1 + \frac{h}{2a} \quad (6)$$

$$h = 0.01(T - 273)a^{0.35} \quad (7)$$

$$k_{lr} = C\frac{h}{a}k_r \quad (8)$$

The value of $C$ = 30 for $Al_2O_3$ and $C$ = 110 for CuO nanoparticles [36].

## 4. RESULTS AND DISCUSSION

### 4.1. Influence of nano-enhanced refrigerant volume fraction and temperature on thermal conductivity

The volume concentration of nanoparticles in the base refrigerant and temperature are major parameters influencing thermal conductivity. When intensifying the amount of nanoparticles in the refrigerant the properties will change. In addition, the properties vary with the temperature. Due to this fact, all the mathematical models have considered volume concentration and temperature as prime parameters influencing the propertiesof the refrigerant.

Figs. 3 and 4 depict the '*k*' value of $Al_2O_3$/R1234yf and CuO/R1234yf nano-refrigerant respectively. Here the volume concentrations change from 1% to 5% and the temperature ranges from 273K to 323K. The '*k*' value of nano-refrigerant is predicted using Stiprasert's model. The nano-enhanced refrigerants show the highest '*k*' value at 5% of nanoparticle concentration and a temperature of 323K. The rise in the value of '*k*' is proportional to the increase in the volume fraction of $Al_2O_3$ and CuO, as seen in the figures. Fig.3 indicates that the thermal conductivity of the $Al_2O_3$/R1234yf refrigerant is enhanced by 41.2% at 323K temperature and 5% volume concentration. From Fig.4, the improvement in the '*k*' value of CuO/R1234yf refrigerant is obtained as 148.1% at 5% volume concentration and 323K temperature. The enhancement of '*k*' values with the addition of nanoparticles to the base refrigerant is due to the enlargement of specific surface areas for heat transfer. The nanoparticles have more surface area than the bulk materials, hence when these are added to the base refrigerant, heat transfer increases due to more specific surface area. Therefore the '*k*' value of the nano-added refrigerant increases together with the concentration (vol.%) of nanoparticles.

From Figs.3 and 4 it is seen that the variation of the '*k*' value of both nano-enhanced refrigerants with temperature is different. The '*k*' value of $Al_2O_3$/R1234yf is continuously reduced with the rise in temperature of upto 3% of $Al_2O_3$ nanoparticle addition. At higher concentrations, it enhanced with temperature. At 323K, the '*k*' value is reduced by 27.61% with 1% addition and it is enhances by 2.2% with 5% inclusion of nanoparticles as compared with 273K. However, for CuO/R1234yf nano-enhanced refrigerant the '*k*' value is reduced with temperature by upto 1% inclusion of CuO nanoparticle. After that, the thermal conductivity of the nano-refrigerant improved with temperature. The '*k*' value is reduced by upto 7.2% at 323K and 1% volume concentration. Meanwhile, it is enhanced by 79.59% with 5% CuO nano-sized particle addition and 323K temperature as compared with 273K. At low volume concentrations of the nanoparticle in the base-refrigerant, the molecules of the refrigerant move apart from each other when heated, this leads to increasing their mean path. Thus this reduces the probability of molecular collision. Hence at lower concentrations, the '*k*' value of the nano-refrigerants reduces with a rise in temperature [48]. However, at high-volume concentrations, the density of the nanoparticles is high,so that when heat is added to the fluid, the molecules move rapidly. Consequently, the nanoparticles in the refrigerant tend to move faster due to the Brownian motion and high energy content, which leads to improving the '*k*' value with the temperature rise [39, 49].

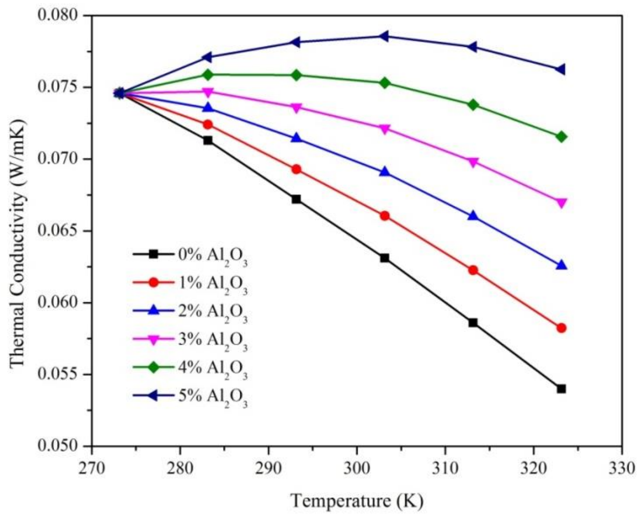


**Fig.3.** Dependency of Al2O3 on thermal conductivity at different temperatures obtained by Stiprasert's model

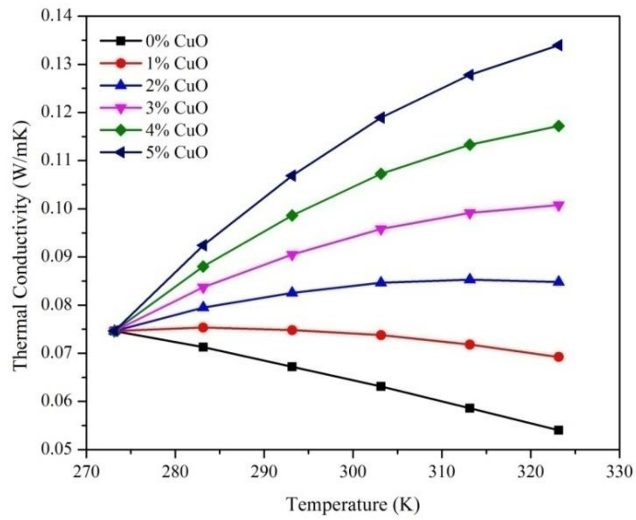


**Fig.4.** Impact of CuO on thermal conductivity at different temperatures obtained by Stiprasert's model

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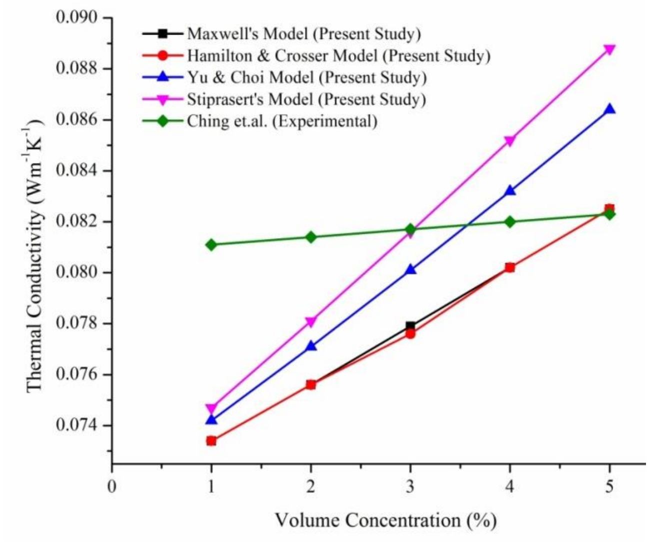


**Fig.5.** Dependency of volume concentration of thermal conductivity

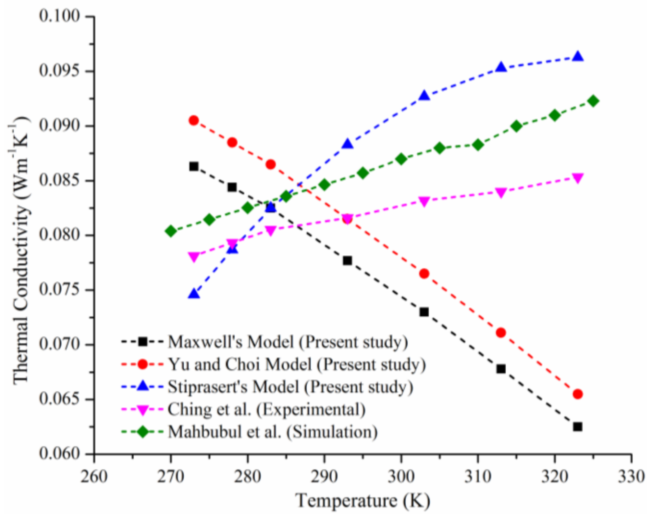


**Fig.6.** Validation of results with experimental and simulation studies of Al2O3/R134a

The R134a-based nano refrigerant is chosen for validation of the mathematical models. Fig.5 compares the '*k*' value of R134a-based nano refrigerant with different nanoparticle volume concentrations of $Al_2O_3$ in the refrigerant obtained by various thermal conductivity models at constant temperature (283K) and the particle having constant size (40nm). The '*k*' value of the nano-enhanced refrigerant is improved with increase in volume fractions. The value of '*k*' varies with models due to the assumptions made by each model being different. From the figure, it is established that the highest value of '*k*' is obtained by Stiprasert's model. This is because Stiprasert's model considers the influence of the interfacial nano-layer between nanoparticles as well as refrigerant. As the spherical shape of nanoparticles is considered, the '*k*' value of Maxwell and Hamilton & Crosser models is the same. Fig.5 also indicates that the present study result shows a similar variation to the experimental data by Jwo et al. [50], that is, the '*k*' value enhances with the volume concentration of nanoparticles. The experimental values are different from the predicted values. This is because of the assumptions taken for the predictions. However, the variation of the '*k*' value with volume concentration is in the same trend. They studied experimentally to identify the '*k*' value of nano-refrigerant containing R134a as refrigerant and $Al_2O_3$ as the nanoparticle. In this case, the '*k*' value of the nano-refrigerant is also slightly enhanced with the volume fraction of nanoparticles in the mixture.

Fig.6 shows the influence of temperature on the thermal conductivity of nano-added refrigerants by various mathematical models at a particular volume concentration (equals 5%) and constant particle size (40nm). The Maxwell and Yu and Choi models, demonstrate that as the temperature rises, the value of '*k*' for nano-enhanced refrigerant is lessened. The value of '*k*' for the nano-refrigerant improved with temperature according to Stiprasert's model. The same kind of variation is obtained in the studies conducted by Jwo et al. [50] and Mahbubul et al. [19] with a 5% particle concentration. The thermal conductivity of the nano-refrigerant is analysed using mathematical correlation by Mahbubul et al. [19]. The researchers worked with an R134a-based nano-refrigerant and they obtained that the '*k*' value of the $Al_2O_3$/R134a refrigerant is enhanced with temperature. Therefore Stiprasert's model is closer to the real case in comparison with other investigated models.

Since the value of '*k*' for nano-sized particles is usually more compared to the base refrigerant, the '*k*' value of the nano-refrigerant must also be higher [17]. The Brownian motion of the nanoparticle is intensified with the temperature rise and the heat transfer is boosted with the contribution of micro convection, which leads to the thermal conductivity enhancement [19]. The result shows as the temperature rises, the '*k*' value of nano-refrigerant also rises.

### 4.2. Impact of the nano-enhanced refrigerant particle size on thermal conductivity

Particle size is a critical parameter that acts on the property of nano-refrigerant. This parameter is considered in the Yu and Choi model as well as in the Stiprasert model.

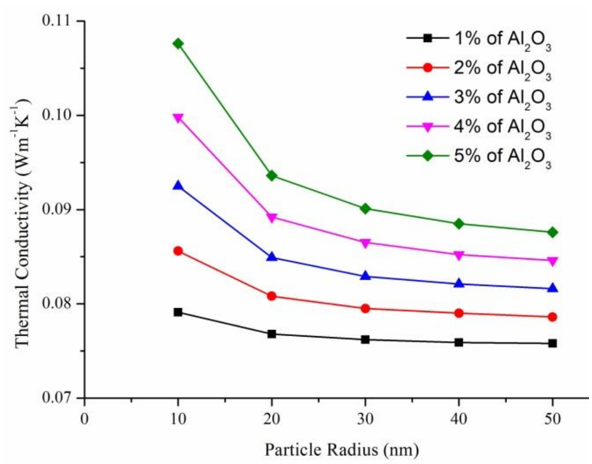


**Fig.7.** Influence of Al2O3 particle radius on thermal conductivity of R1234yf

Fig.7 depicts the influences of the size of $Al_2O_3$ nanoparticles on thermal conductivity at a constant temperature (283K) obtained by the Yu and Choi model. From the figure, it is seen that the '*k*' value is reduced with nanoparticle size increment. A similar trend is observed with Stipersert's modelas shown in Fig.8. The '*k*' value of the CuO-based nano-refrigerant is decreased with a particle size that is revealed in Fig.8. Both Figs.7 and 8 also indicate that the '*k*' values of both nano-enhanced refrigerants increased with the increase in volume fraction of $Al_2O_3$ and CuO nanoparticles.

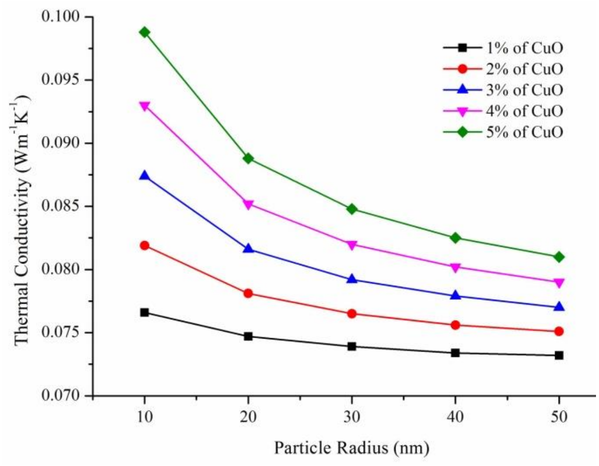


**Fig.8.** Influence of particle radius on thermal conductivity of CuO/R1234yf refrigerant

The '*k*' value of nano-enhanced refrigerants is decreased with particle size. This is because when the particle size increases the bulkiness of the material increases. The material's specific surface area is reduced as a result of its increased bulkiness. Heat transfer is diminished as the specific surface area is decreased. Hence the thermal conductivity reduces with the enlargement of particles.

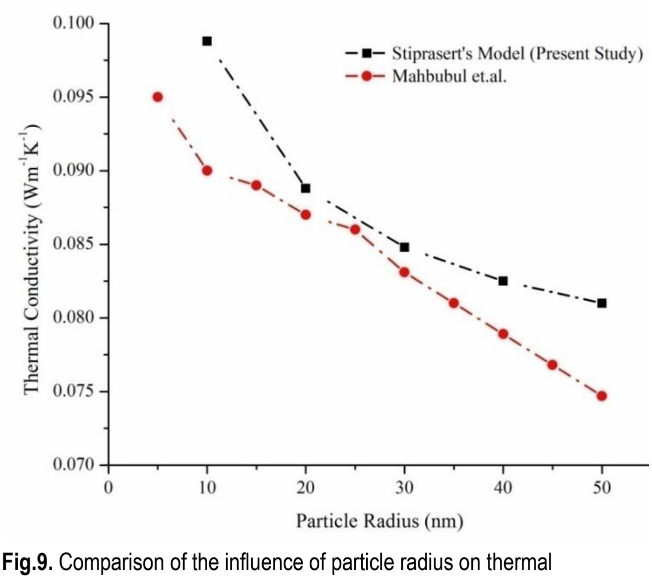


**Fig.9.** Comparison of the influence of particle radius on thermal conductivity with the previous study

Fig.9 shows a comparison of the trend in variation of the '*k*' value of the nano-refrigerant with particle radius with a previous study by Mahbubul et al. [19]. They studied the thermal conductivity of R134a-based nano-refrigerants whereas the present study is on R1234yf-based nano-refrigerants. Due to the insufficient experimental work carried out with R1234yf-based nano-refrigerant, the comparison is done with R134a-based nano-refrigerant. For comparison, the result obtained using Stiprasert's model in R1234yf-based nano-refrigeranthas been considered. From Fig.9, it is clear that the '*k*' value of both studies decreases with an increase in nanoparticle radius. Hence the mathematical model developed by Stiprasert is suitable for the analysis of the effect of particle radius on the '*k*' value in nano-refrigerant studies.

### 4.3. Impact of the interfacial nanolayer between nanoparticle and refrigerant on thermal conductivity

By adding nanoparticles to the refrigerant, a layer between the substances is formed. This layer is called the interfacial layer. The thickness of this layer also influences the properties of the nano-refrigerant. Yu and Choi and Stiprasert have considered that interfacial nanolayer is an important parameter that affects thermal conductivity.

Figs.10 and 11 show the influence of nanolayer or interfacial layer thickness on thermal conductivity at a constant particle radius (equals 20nm). The '*k*' value of nano-refrigerant is improved by enhancement in nanolayer thickness in both cases of CuO/R1234yf and $Al_2O_3$/R1234yf nano-refrigerants. Due to the imperfect contact between the solid–solid interfaces, a resistance is created in the interface. This interface resistance is known as Kapitza resistance, which acts as a barrier to heat transfer and lowers the effective thermal conductivity. However, this resistance phenomenon is not predominant at the solid–liquid interface of particles in liquid suspension. Due to these, the nanolayer enhances the thermal conductivity of the nano-refrigerant [35]. The interfacial layers surrounding the nanoparticles are enhancement mechanisms that raise the '*k*' value of nano-refrigerant by raising the specific surface area of the nanoparticles [19]. The total surface area per unit mass of a nanoparticle is referred to as the specific surface area.

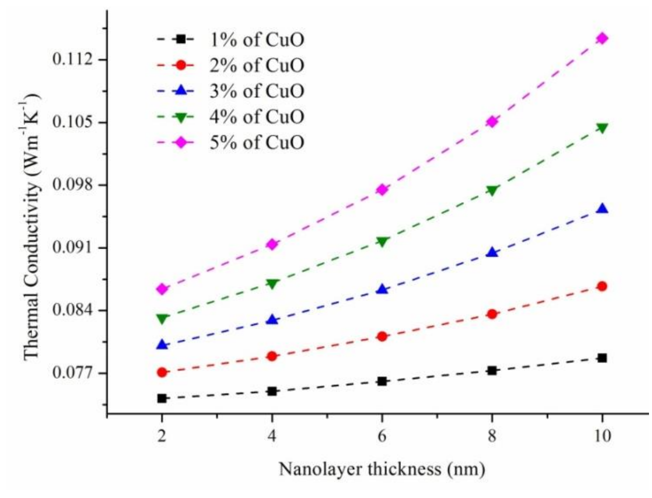


**Fig.10.** Variation of thermal conductivity with nano interfacial layer for CuO/R1234yf

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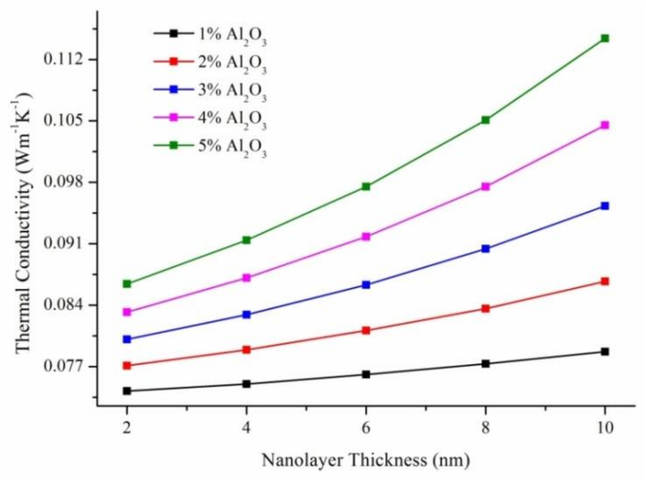


**Fig.11.** Rise in thermal conductivity with nano interfacial layer for Al2O3/R1234yf

### 4.4. Effect of type of nanoparticle on the thermal conductivity

In common, each nanoparticlehas different values of thermal conductivity. However, based on the models developed by Maxwell, Hamilton & Crosser and Yu and Choi, the value of '*k*' of $Al_2O_3$ and CuO nanoparticles added to the refrigerant gives similar values and does not influence the type of nanoparticles. However, this is not practically correct as the type of nanoparticle and refrigerant affects the '*k*' value of the nanofluid. The nanoparticle type dependency is seen in the Stipresert model.

Fig. 12 compares the thermal conductivity of CuO/R1234yf and $Al_2O_3$/R1234yf nano-refrigerant at 283K and the particles having a size of 40nm, which is obtained by Stiprasert's mathematical model. From the figure, it is clear that the '*k*' value of the nano-refrigerant depends on the kind of nanoparticles which are added to the base refrigerants. The highest values of '*k*' are obtained when the R1234yf refrigerant is mixed with CuO. At 5% volume concentration, the thermal conductivity observed by adding CuO in R1234yf is 16.69% greater than that of $Al_2O_3$ nanoparticles added to the same refrigerant.

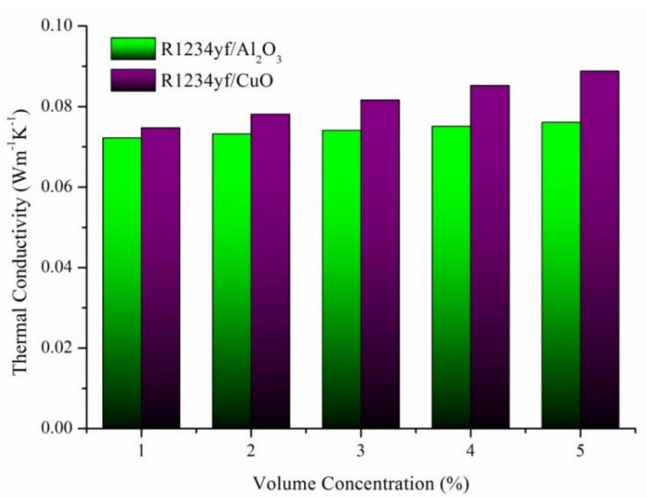


**Fig.12.** Comparison of thermal conductivity of R1234yf-based nano-refrigerant

## 5. CONCLUSION

The thermal conductivity of the R1234yf refrigerant-based nano-refrigerant has been investigated using mathematical models such as Maxwell, Crosser & Hamilton, Yu and Choi and Stiprasert's models, and the results have been validated using previous experimental studies conducted by different researchers. The thermal conductivity of $Al_2O_3$/R1234yf and CuO/R1234yf nano-refrigerants improves with increasing nanoparticle volume concentrations, similar to nanofluids, according to the findings. The thermal conductivity of $Al_2O_3$/R1234yf and CuO/R1234yf nano-refrigerants was enhanced with a volume concentration of nano-sized particles by 41.2% and 148.1% respectively at 5% volume concentration and 323K temperature. The thermal conductivity of $Al_2O_3$/R1234yf is reduced with temperature, by upto 3% of nanoparticle addition and after that, it is enhanced. Meanwhile, it declined with temperature, by upto 1% of CuO nanoparticle inclusion for CuO/R1234yf. However, the value of thermal conductivity is improved with temperature at higher concentrations as observed in theStiprasert model which is a positive feature for all real-world applications. By increasing the particle size, the thermal conductivity of CuO/R1234yf and $Al_2O_3$/R1234yf nano-refrigerants is decreased. The interfacial nanolayer also impacted the thermal conductivity value of the nano-refrigerant such that as the thickness ofthe interfacial nanolayer increased the value of thermal conductivity also increased. The thermal conductivity value of CuO/R1234yf is more than that of $Al_2O_3$/R1234yf about 16.69% at a 5% volume concentration. Compared with the results from the mathematical models in previous experimental studies, Stiprasert's model gives more realistic results. Therefore, the Stiprasert model is the best and most advanced model for study of thermal conductivity. The only drawback of this model is that it applies only to $Al_2O_3$ and CuO nanoparticles.

Nomenclature

*Acronyms*

| | |
|---|---|
| *a* | Particle Radius (nm) |
| *f* | Shape factor |
| GWP | Global Warming Potential |
| *h* | Thickness of Interfacial nanolayer (nm) |
| HFO | Hydro fluoro olefin |
| HTF | Heat transfer fluid |
| *k* | Thermal Conductivity (W/mK) |
| ODP | Ozone Depletion Potential |
| *T* | Temperature (K) |
| Vol | Volume |

*Subscripts:*

| | |
|---|---|
| *lr* | Interfacial layer |
| nr | Nano-refrigerant |
| np | Nanoparticle |
| *r* | Refrigerant |

*Greek Symbols:*

| | |
|---|---|
| $\phi$ | Particle Volume fraction |
| $\chi$ | Sphericity |

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