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Experimental Investigation of Various Parameters on Thermal Conductivity of Al_2O_3 Based Nanorefrigerant

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Abstract: *In this experimentation, the Al_2O_3 /R-11 nanorefrigerants produced from the two step method are used as the experimental samples and ultrasonic vibration is used for dispersing the nanoparticles into five types of different weight fractions (0.02, 0.04, 0.06, 0.08 & 0.10 wt.%). The objective of this study is to investigate the dependence of thermal conductivity of Al_2O_3/R-11 nanorefrigerant on temperature (4-16°C) at different weight concentrations, shape (spherical & elongated) and size (20 nm & 40 nm). Based on the experimental analysis it is observed that thermal conductivity augmented significantly with the increase of weight concentrations. Thermal conductivity increase around 42% at 0.10 wt. % (4°C) of 40 nm elongated Al_2O_3 nanoparticles. The thermal conductivity enhancement of nanorefrigerant with elongated shaped Al_2O_3 nanoparticles (40 nm) is more than spherical shaped (40 nm) Al_2O_3 nanoparticles within measured temperature range (4-16°C). The mean deviation of thermal conductivity for 20 & 40 nm (spherical) Al_2O_3 nanoparticles is 11% and 6% respectively for Hamilton & Crosser model. From the results, low weight concentration (up to 0.08 wt.%) of 20 nm (spherical) size nanoparticles is suggested to improve the performance of a refrigeration system in the temperature range from 4-16°C.*

1. Introduction

In the last decade, a significant amount of experimental and theoretical research has been done to investigate the thermo physical behavior of nanofluids. In these studies, it was observed that a high thermal conductivity enhancement can be obtained with nanofluids, when small amount of nanoparticles are added in the base fluids. Most of the experimental work showed that the thermal conductivity enhancement obtained by using nanoparticle suspensions is relatively higher than that obtained by using conventional suspensions with particles which are millimeter or micrometer-sized. The nano-refrigerant is one kind of nanofluid and its host fluid is refrigerant. Refrigerant have poor heat transfer properties like other conventional thermo fluids. Various researchers have proposed theoretical models to explain and predict those anomalous thermal conductivity ratios, defined as thermal conductivity of the nanofluid (k_{nf}) divided by the thermal conductivity of the base fluid (k_f) (Turgut et al., 2009). But still the debates are going on to confirm this anomalous behavior of thermal conductivity.

Jwo et al. [1] conducted studies on thermal conductivity of lubricant of R-134a refrigeration system. The objectives of the study were to discuss the dependence of thermal conductivity of Al_2O_3 nanorefrigerants on the temperature (20-40°C) under different weight fractions (1.0, 1.5, 2.0 wt.%). The results showed that the thermal conductivity was enhanced by 2.0%, 4.6%, and 2.5% when the nanoparticles of Al_2O_3 of 1.0, 1.5, and 2.0 wt.% were added at 40°C. It was found that optimal enhancement of the thermal conductivity was at 1.5 wt.%. The enhancement of thermal conductivity did not grow with the increase of weight ratios and it was different from the general nanofluids with lubricant as the basic solvent. Besides, thermal conductivity was increased from 1.5 to 4.6% when the sample temperature was varied from 20°C to 40°C at 1.5 wt.%, and the trend of growth rates of the thermal conductivity was proportional to the temperature. From the results, it can be found that temperature has greater effects than weight fraction on the increase of thermal conductivities. Thus, it is better for nanorefrigerants of Al_2O_3 to be applied in the high temperature field than in the low temperature field.

NOMENCLATURE

K	Thermal conductivity, W/mK
T	Temperature, K
ODP	Ozone depletion potential
GWP	Glowal warming potential
Greek letters	
ϕ	Particle volume fraction
Ψ	Sphericity
φ	Weight concentration
Subscripts	
f	Base fluid
nf	Nanofluid
p	Nanoparticle

Jiang et al. [2] measured thermal conductivity of carbon nanotube nanorefrigerants and build a model for predicting the thermal conductivities of CNT nanorefrigerants. The effects of CNT diameters and CNT aspect ratios on nanorefrigerant's thermal conductivity were reflected in the experiments, and R-113 was used as the host refrigerant for the convenience of the experiments. The experimental results predicted that the thermal conductivity of CNT nanorefrigerants is much higher than those of CNT–water nanofluids or spherical nanoparticle R113 nanorefrigerants. Experiments also showed that the smaller the diameter of CNT or larger the aspect ratio of CNT, larger the thermal conductivity enhancement of CNT nanorefrigerant is. The existing models for predicting thermal conductivity of CNT nanofluids, including Hamilton- Crosser model, Xue model and Yu-Choi model were verified by the experimental data of CNT nanorefrigerants. The study predicted that Yu & Choi model has the mean deviation of 15.1% and it is more accurate than the other two models. And a modified Yu-Choi model was presented by improving the empirical constant of Yu & Choi model, and the mean deviation of the modified Yu-Choi model from the experimental results was 5.5%.

Mahbubul et al. [3] investigated the thermal conductivity of Al_2O_3 nanoparticles suspended in R-134a. Suitable models from existing studies have been used to determine the thermal conductivity of the nanorefrigerants for the nanoparticle concentrations of 1 to 5 vol.%. It was found that the thermal conductivity of Al_2O_3/R-134a nanorefrigerant increased with the augmentation of particle concentration and temperature, but decreased with particle size intensification. Therefore, optimal particle volume fraction is important to be considered in producing nanorefrigerants that can enhance the performance of refrigeration systems.

The effect of particle size on the thermal conductivity of nanorefrigerant was investigated by using the modified model. Instead of using nanoparticles with constant particle size of 30 nm, the particle radius was assumed to be about 5 to 25 nm. The thermal conductivity of Al_2O_3/R-134a nanorefrigerant decreased with increasing particle size of Al_2O_3 due to nanolayer or interfacial layer consideration. The interfacial layers around the nanoparticles are enhancement mechanisms that increase the thermal conductivity of nanorefrigerant as the augmentation effects of interfacial layer's increases by increasing the specific surface area of nanoparticles.

Effects of temperature on the thermal conductivity of nanorefrigerant have been investigated by changing the temperatures from 300 to 325 K. The thermal conductivity enhancement was about 43% at a temperature of 325 K with 5 vol. % of nanoparticle concentration. For temperature of 300 K and particle concentration of 1 vol. %, the obtained result shows lowest thermal conductivity increase of only about 4%. The results showed that the thermal conductivity of nanorefrigerant is proportional to temperature and the thermal conductivity enhancement can be considered low with temperature increment of 5 K for low concentration of nanoparticles. The high nanorefrigerant temperature intensifies the Brownian motion of nanoparticles and reduces the viscosity of nanorefrigerant. With the intensified Brownian motion, the contribution of micro convection in heat transport also could be increased. It was shown that the thermal conductivity of nanorefrigerant can be enhanced by increasing the temperature.

It has been observed that most of work is done on high pressure refrigerants such as R134a, R141b, R12 etc. At atmospheric conditions it is difficult to maintain high pressure refrigerant into liquid form to prepare nanorefrigerant. Mostly researchers have investigated the performance by dispersing nanoparticles in lubricants of the refrigerant system and found that performance of refrigerant's thermo physical properties is improved. From the list of various available refrigerants, R-11 is a low pressure refrigerant which is commonly used in chiller refrigerant systems. But it is found unsuitable for future use due to its high ozone depletion potential (ODP). So, it is replaced by R-123 which has better properties than R-11 and is environmental friendly. For experimental investigation R-11 has been chosen in place of R123 because it was available in Thapar University RAC lab and R-11 has similar themophysical properties as R123 refrigerant.

The objective of this investigation is to discuss the dependence of thermal conductivity of Al_2O_3/R11 nanorefrigerant at different weight concentrations and temperature with varying size and shape of nanoparticles. Al_2O_3 (20 nm-spherical, 40 nm-spherical and 40 nm-elongated) nanoparticles are mixed with the refrigerant R-11 at varying concentration (0.02-0.10 wt. %) In the subsequent sections related theories, preparation and characterization of nanorefrigerant, experimental procedures, result and discussions have been described consecutively.

2. Related Theories

More than a century ago, Maxwell derived an equation for calculating the effective thermal conductivity of solid-liquid mixtures consisting of spherical particles (Maxwell, 1873):

$$k_{n_f} = \frac{k_p + 2k_f + 2(k_p - k_f)\phi}{k_p + 2k_f - (k_p - k_f)\phi} k_f, \qquad (2.1)$$

where, k_{n_f}, k_p, and k_f are the thermal conductivity of the nanofluid, nanoparticles and base fluid, respectively. ϕ is the volume fraction of particles in the mixture. As seen from the expression, the effect of the size and shape of the particles was not included in the analysis. It should be noted that the interaction between the particles was also neglected in the derivation.

Hamilton and Crosser [5] extended the Maxwell model in order to take the effect of the shape of the solid particles into account, in addition to the thermal conductivities of solid and liquid phases and particle volume fraction. The model is as follows:

$$k_{n_f} = \frac{k_p + (n-1)k_f + (n-1)(k_p - k_f)\phi}{k_p + (n-1)k_f - (k_p - k_f)\phi} k_f \qquad (2.2)$$

where n is the empirical shape factor and it is defined as:

$$n = \frac{3}{\Psi} \qquad (2.3)$$

where Ψ is the sphericity. Sphericity is the ratio of the surface area of a sphere with a volume equal to that of the particle to the surface area of the particle. Therefore, n = 3 for a sphere and in that case the Hamilton and Crosser model becomes identical to the Maxwell model.

Both Maxwell and Hamilton and Crosser models were originally derived for relatively larger solid particles that have diameters on the order of millimeters or micrometers. Therefore, it is questionable whether these models are able to predict the effective thermal conductivity of nanofluids. Nevertheless, these models are utilized frequently due to their simplicity in the study of nanofluids to have a comparison between theoretical and experimental findings [4].

3. Preparation and Characterization

Nanorefrigerant is a refrigerant in which particles of nanometer dimensions are mixed. The preparation of nanorefrigerant is important aspect to achieve uniform and stable suspension.

In the present study, Al_2O_3 is used as a nanoparticle and R11 as a base fluid. The reason for choosing R-11 refrigerant for research work is that it is low pressure refrigerant which can be kept at liquid state under normal atmospheric conditions. The material of nanoparticles is chosen as Al_2O_3 because it is chemically more stable and its cost is less than their metallic counterparts.

The properties of R-11 and Al_2O_3 are given in Tables 2 & 3 respectively. The pictures of Al_2O_3 nanoparticles obtained from the transmission electron microscopy (TEM) are shown in Fig. 1. The X-Ray diffraction is also shown in Fig. 2. Nanofluid with different concentrations is prepared for the experiments. Nanoparticles of the required amount and base fluid are then mixed together. Ultrasonication is done for 4 hours in order to stabilize the dispersion of the nanoparticles. In this study, the Al_2O_3 nanoparticles are used at the concentration from 0.02–0.10 wt.. %.

Table 2 Properties of Al_2O_3 nanoparticles

Property	Unit	Value	Value	Value
Purity	%	99.9	99.99	99.8
Diameter	nm	40	20	40
Density	g/cm^3	3.8	3.8	3.8
Shape		Spherical	Spherical	Elongated

Table 3 Properties of R-11 refrigerant at 4.44 ^0C

Property	Unit	Value
Chemical formula		CCl_3F
Normal boiling point	^oC	23.7
Liquid Viscosity	cP	0.539
Thermal conductivity	W/mC	0.094
Critical temperature	^oC	198
Critical pressure	bar	44

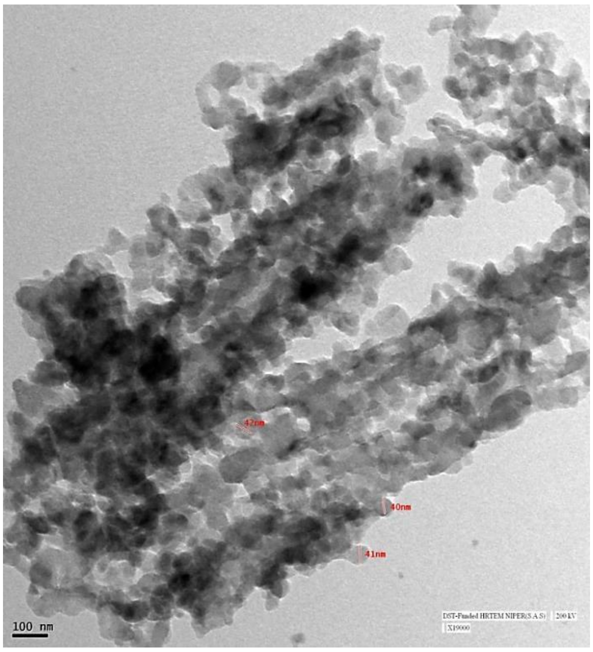

Fig.1 TEM photograph of 40 nm (spherical) Al_2O_3 nanoparticles

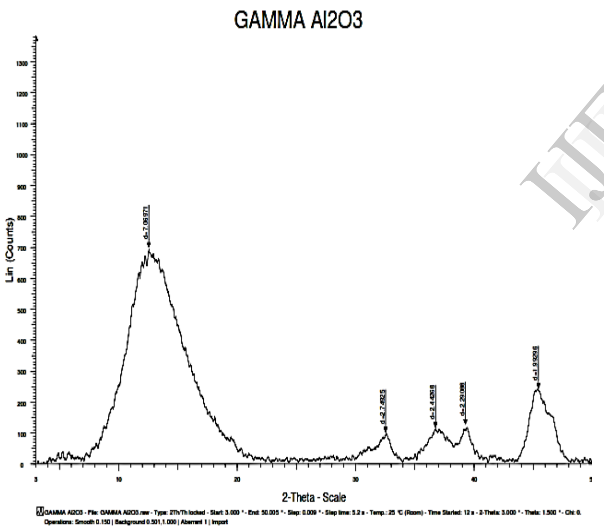

Fig. 2 X-Ray Diffraction (XRD) of 40 nm (spherical) Al_2O_3 nanoparticles

Fig. 3 Oscar Ultrasonicator Pr-250 M

Fig. 4 KD2 Pro

4. Experimental Apparatus and Procedure

This study used nanorefrigerant, which is prepared by mixing Al_2O_3 nanoparticles in R11 refrigerant. Under the control of environmental temperature 16 ˚C, five types of concentration of different volume fractions (0.02, 0.04, 0.06, 0.08, 0.10 wt. %) are produced. Ultrasonic vibrator is used to mix the nanoparticles with refrigerant as base fluid.

The experimental methods and approach are as follows:

1. Measure the weight of Al_2O_3 nanoparticles and the preparation is done with two step technique. Al_2O_3 particles are dispersed in liquid R-11 after weighing in required proportion. The weight of Al_2O_3 particles is measured by electronic weighing pan. The weight concentrations of nanoparticles are

(0.02%, 0.04%, 0.06%, 0.08% and 0.10%) prepared at 20 °C for all sizes nanoparticles.

2. Sonication is done for Al_2O_3-R11 solution in an Ultrasonicator shown in Fig. 3 (Oscar Ultra-sonicator Pr-250 MP) for 4 hours. The temperature around beaker is maintained below 20°C to avoid evaporation of refrigerant. It is done by keeping beaker inside a larger size plastic cup and ice cubes are kept between plastic box and beaker as shown in Figure 3.
3. Thermal conductivity of nanorefrigerant is measured by using KD2 Pro instrument. The sample of Al_2O_3/R-11 nanorefrigerant is taken into test tube which is covered with rubber cork. The temperature of nanorefrigerant is maintained by keeping chilled water inside a beaker as shown in Figure 4.

5. Results and Discussion

5.1. Effect of weight concentration on thermal conductivity

Concentration of particles would be regarded as one of the most significant features affecting thermal conductivity of nanorefrigerants.

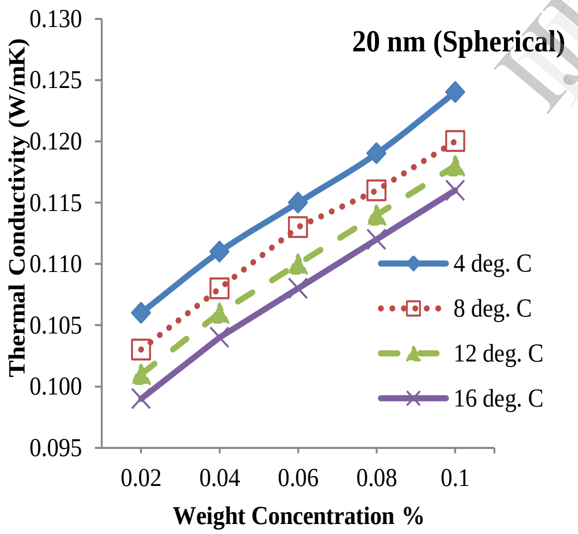

Fig. 5 Thermal conductivity v/s wt % of Al_2O_3 nanoparticles at different temperatures

Basically, it is expected that adding nanoparticles would improve heat transfer performance of nanorefrigerants and also would increase thermal conductivity of them. The results of thermal conductivity v/s weight concentration % at different temperatures are shown in the Figure 5, 6 & 7.

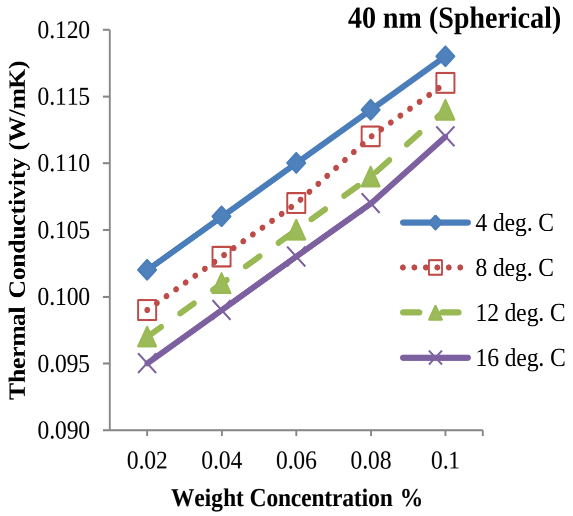

Fig. 6 Thermal conductivity v/s wt. % at different temperatures

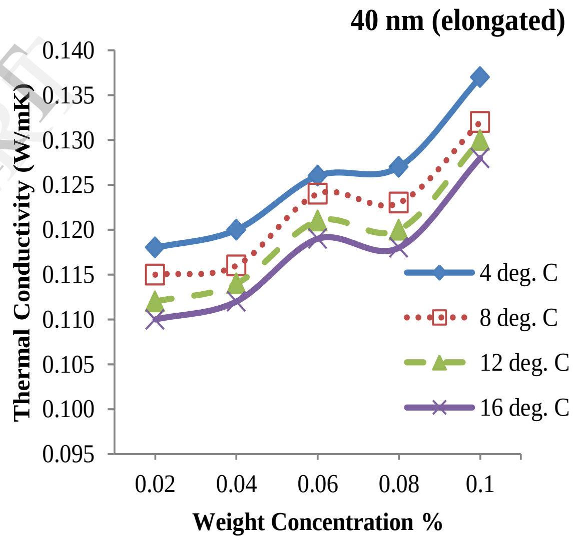

Fig. 7 Thermal conductivity v/s wt.% of Al_2O_3 nanoparticles at different temperatures

It has been observed that the thermal conductivity of Al_2O_3/R-11 nanorefrigerant is increasing with the weight concentration (0.02- 10%) of nanoparticles. The enhancement in thermal conductivity is mainly due to micro convection caused by the Brownian motion of the nanoparticles and aggregation of nanoparticles causing a local percolation and clustering to the nanoparticle occurs more actively in fluid with higher concentration.

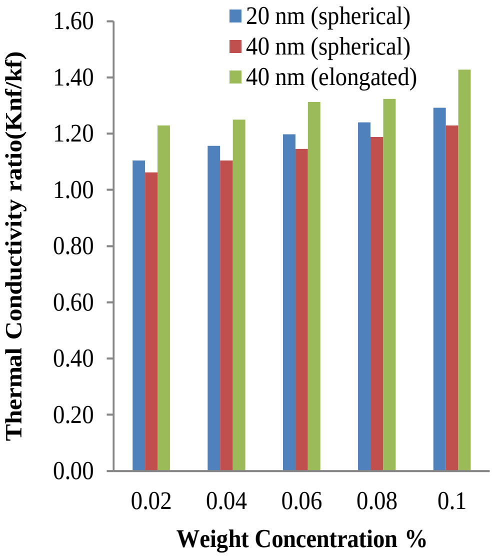

Fig. 8 Thermal conductivity ratio v/s wt.% for Al_2O_3 nanoparticles

The use of Al_2O_3 20nm in diameter at 0.1 wt. % concentration and at 4°C temperature increased the thermal conductivity of refrigerant R-11 under stationary conditions by 29 %. The highest enhancement of thermal conductivity observed is 42% at 0.1% wt. concentration of 40 nm (elongated) Al_2O_3 nanoparticles. The behavior of increase in thermal conductivity is almost linear for 20 nm (spherical) & 40 nm (spherical) nanoparticles. A nonlinear relationship is observed between thermal conductivity and particle weight concentrations for 40 nm (elongated) nanoparticles. The nonlinearity is attributed to the rapid clustering of elongated nanoparticles which is an indication of interactions between particles due to high nanoparticle concentrations.

In Figure 8 thermal conductivity enhancement of nanorefrigerant can be observed. Among them nanorefrigerant with 0.1 % weight percentage of Al_2O_3 nanoparticles shows maximum increase in thermal conductivity. There are three types of Al_2O_3 (20 nm-spherical, 40 nm-spherical, 40 nm- elongated) nano-particles with same concentration of nanoparticles showing different values of enhancement.

5.2. Effect of temperature on thermal conductivity

In conventional suspensions of solid particles (with sizes on the order of millimeters or micrometers) in liquids, thermal conductivity of the mixture depends on temperature only due to the dependence of thermal conductivity of base liquid and solid particles on temperature. However, in case of nanorefrigerants the change of temperature affects the Brownian motion of nanoparticles. The results of thermal conductivity v/s temperatures at different weight concentrations are shown in Figure 9, 10 &11.

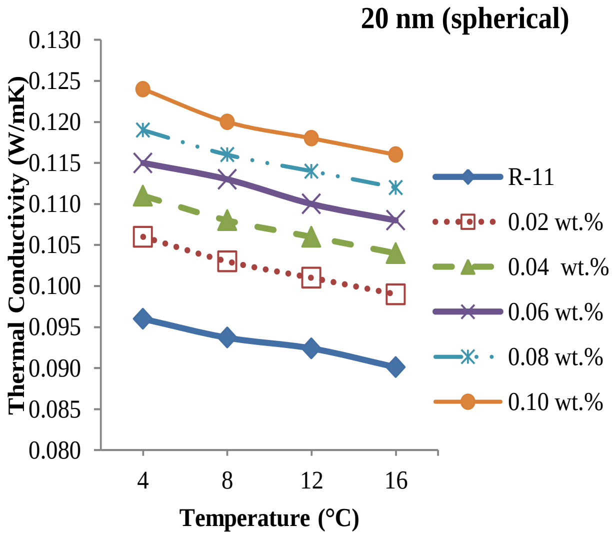

Fig. 9 Thermal conductivity v/s temperature at different weight concentrations % of 20 nm (spherical) Al_2O_3 nanoparticles

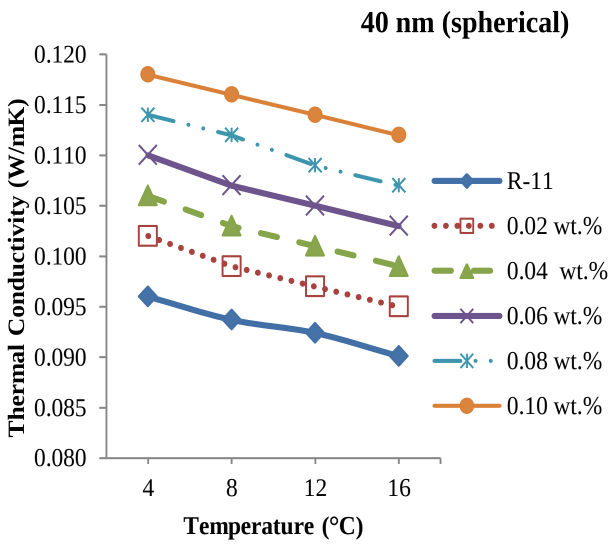

Fig. 10 Thermal conductivity v/s temperature at different weight concentrations % of 40 nm (spherical) Al_2O_3 nanoparticles

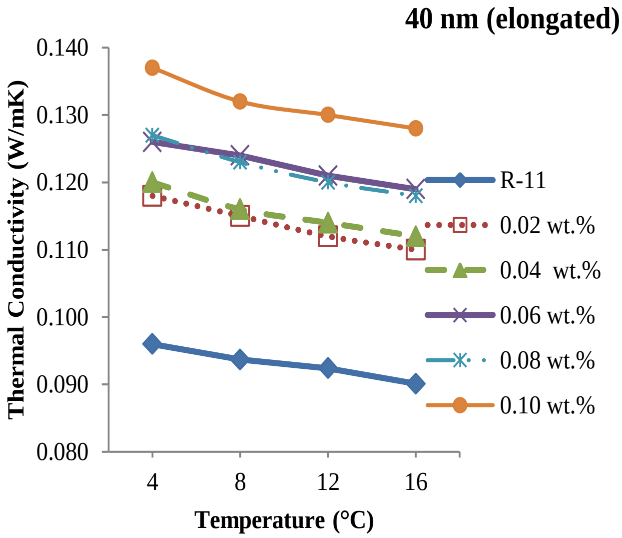

Fig. 11 Thermal conductivity v/s temperature at different wt. % of Al_2O_3 nanoparticles

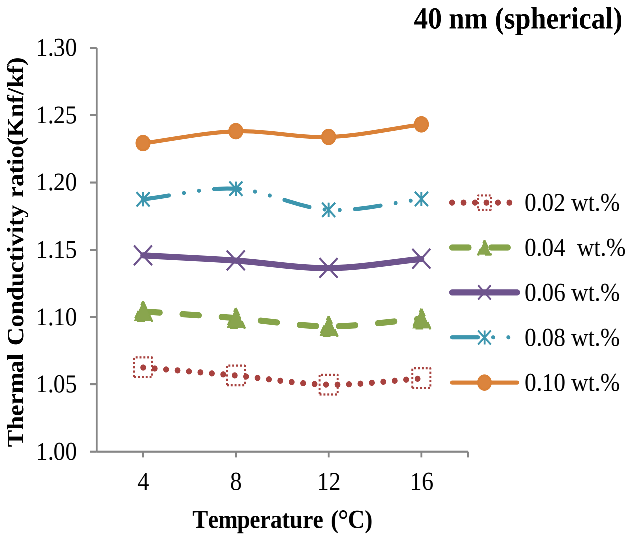

Fig. 13 Thermal conductivity ratio v/s temperature at different wt. % of Al_2O_3 nanoparticles

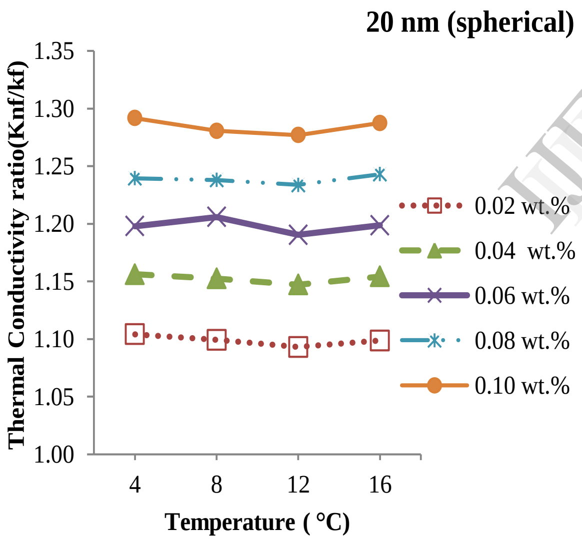

Fig. 12 Thermal conductivity ratio v/s temperature at different wt. % of Al_2O_3 nanoparticles

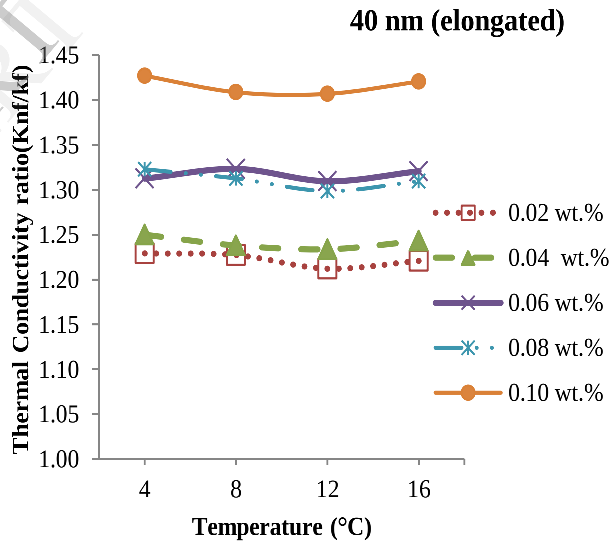

Fig. 14 Thermal conductivity ratio v/s temperature at different wt. % of Al_2O_3 nanoparticles

Measurements has been done at four different temperatures; 4, 8, 12 and 16°C. Particle weight concentration was varied between 0.02 and 0.1wt. %. It is found that thermal conductivity decreases with the temperature. For the nanorefrigerant, the mean distance of separation of the centers of the molecules decrease with rising temperature, so that thermal conductivity is expected to decrease with rising temperature. A maximum drop of thermal conductivity is achieved from 4 to 8°C for 0.1 wt% concentration of 40 nm (elongated) Al_2O_3 nanoparticle i.e. from 0.137 to 0.132 W/mK.. It is observed from Figure 12, 13 & 14 shows that thermal conductivity ratio remains almost invariant (1% variation).

5.3. Effect of size of Al_2O_3 nanoparticles on thermal conductivity

The results of thermal conductivity ratio v/s weight concentration % are shown in Figure 15. The thermal conductivity ratio is the ratio of thermal conductivity of nanorefrigerant to thermal conductivity of fluid i.e. R-11 refrigerant (K_{nf}/K_f).

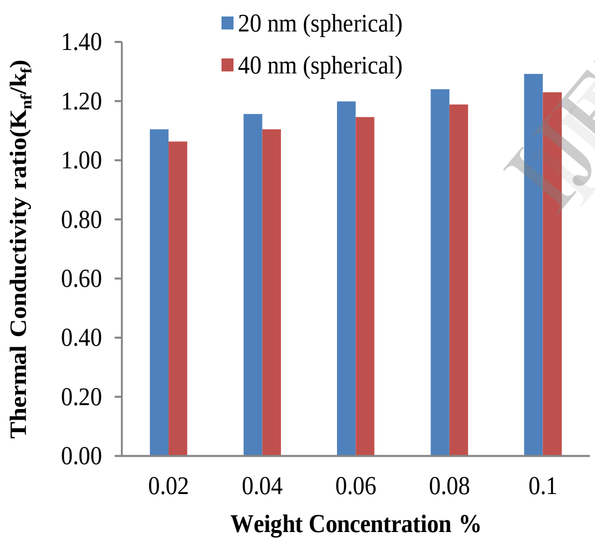

Fig. 15 Thermal conductivity ratio v/s wt. % for different size of Al_2O_3 nanoparticles

It is observed that for the same particle weight concentration, thermal conductivity decreases with increasing particle size. The results are with the effect of Brownian motion, since the effect of Brownian motion decreases with increasing particle size, which decreases the associated thermal conductivity enhancement. Al_2O_3 nanoparticles of size 20 nm have higher value of thermal conductivity than 40 nm particles within measured temperature range (4-16°C). Figure 15 shows thermal conductivity ratio v/s wt. concentration % for 20 & 40 nm size of Al_2O_3 nanoparticles. It has been observed that for 0.1 wt. % nanorefrigerant, thermal conductivity enhancement decreased from 29 to 23% by increasing the particle size from 20 to 40 nm.

The general trend in the experimental data is that the thermal conductivity of nanorefrigerants increases with decreasing particle size. The trend is theoretically supported by two mechanisms of thermal conductivity enhancement; Brownian motion of nanoparticles and liquid layering around nanoparticles.

5.4. Effect of shape of Al_2O_3 nanoparticles on thermal conductivity

The results of thermal conductivity ratio v/s weight concentration % for different shapes Al_2O_3 nanoparticles are shown in Figure 16.

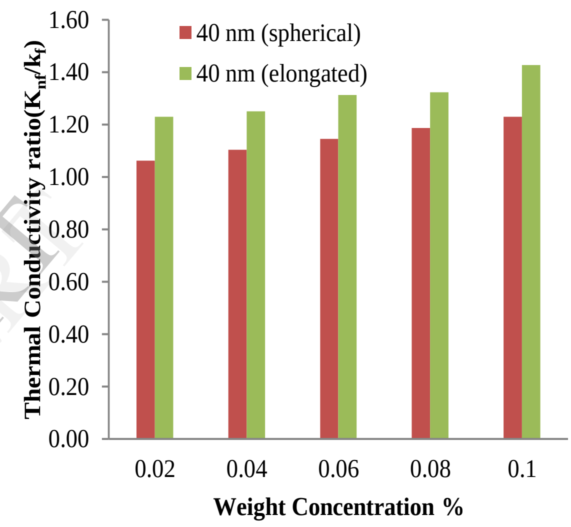

Fig. 16 Thermal conductivity ratio v/s wt. concentration % for different shape of Al_2O_3 nanoparticles

Two types of nanoparticles shapes are used for the preparation of nanorefrigerant; spherical particles with 40 nm average diameter and elongated particles with 40 nm average diameter. It is found that 0.1 wt.% Al_2O_3/R-11 nanorefrigerant with spherical particles had a thermal conductivity enhancement of 24%, whereas 0.1 wt. % nanofluid with elongated particles had a thermal conductivity enhancement of 43%.

In addition to these experimental results, the fact that thermal conductivity enhancement of nanorefrigerants with elongated shaped Al_2O_3 nano-particles (40 nm) is more than spherical shaped (40 nm) Al_2O_3 nanoparticles within measured temperature range (4-16°C). As a result, one can conclude that elongated nanoparticles provide higher thermal conductivity enhancement than spherical particles. Among the possible reasons of this is the rapid heat transport along relatively larger distances in elongated particles since elongated particles usually have larger lengths as compare to its diameter.

5.5. Comparison of experimental data of thermal conductivity with theoretical models

The values for the effective thermal conductivities were calculated for Hamilton Crosser [5], Jeffrey [6], Lu & Lin [7] models. The experimental data along with theoretical models is plotted as a function of the weight concentration (0.02, 0.04, 0.06, 0.08 & 0.10 %) for 20 nm (spherical), 40 nm (spherical) Al_2O_3 nanoparticles in Figure 17.

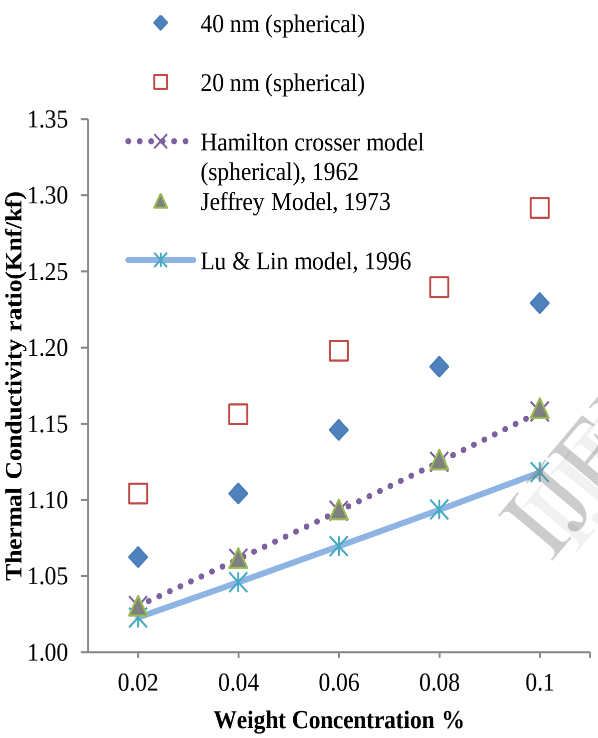

Fig. 17 Measured thermal conductivities of Al_2O_3/R-11 nanorefrigerant v/s effective thermal conductivities calculated from theories for spherical nanoparticles

When the predictions of the models are compared , it is seen that Hamilton Crosser & Jeffrey models provide very close results. The data shown in Figure 17 shows some degree of under prediction by theoretical models than the experimental values of thermal conductivity. The Hamilton and Crosser model may be under predicting since it does not incorporate the Brownian motion and the resulting heat transfer by convection. At such low particle sizes (20 nm & 40 nm), Brownian motion should not be neglected. Also, the Hamilton and Crosser model does not take the effect of particle size on thermal conductivity into account. At this point, it should be noted that thermal conductivity increases with decreasing particle size when Brownian motion is considered as the main mechanism of thermal conductivity enhancement, because the effect of Brownian motion increases with decreasing particle size, which improves micro-convection around nanoparticles.

When the experimental results are observed, it is seen that the discrepancy in the data is somewhat larger for the 0.01 wt. % case. This might be due to the fact that at higher particle weight concentrations, clustering of particles is more pronounced, which affects the thermal conductivity of nanorefrigerants. It should be noted that clustering may increase or decrease the thermal conductivity enhancement. If a network of nanoparticles is formed as a result of clustering, this may enable fast heat transport along nanoparticles. On the other hand, excessive clustering may result in sedimentation, which decreases the effective particle weight concentration of nanorefrigerant.

The maximum thermal conductivity deviation from Hamilton & Crosser model for 20 & 40 nm (spherical) Al_2O_3 nanoparticles is 13% and 10% respectively at 0.10 % weight concentration. But the minimum deviation of thermal conductivity for 20 & 40 nm (spherical) Al_2O_3 nanoparticles is 7% and 3% respectively at 0.02 % weight concentration. Also, the mean deviation of thermal conductivity for 20 & 40 nm (spherical) Al_2O_3 nanoparticles is 11% and 6% respectively for Hamilton & Crosser model.

6. Conclusion

The present investigations show a prominent role of weight concentration on enhancements of the thermal conductivity of nanorefrigerant. It increases with rise in weight concentration. The enhancement in thermal conductivity is mainly due to micro convection caused by the Brownian motion of the nanoparticles and aggregation of nanoparticles causing a local percolation and clustering to the nanoparticle occurs more actively in fluid with higher concentration. The highest enhancement of thermal conductivity observed is 42% at 0.1% wt. concentration of 40 nm (elongated) Al_2O_3 nanoparticles.

The behavior of increase in thermal conductivity is almost linear for 20 nm (spherical) & 40 nm (spherical) nanoparticles. A nonlinear relationship is observed between thermal conductivity and particle weight concentrations for 40 nm (elongated) nanoparticles. The thermal conductivity of nanorefrigerant decrease with temperature (4-16°C) because the mean distance of separation of the centers of the molecules decrease with rising temperature while it shows increase in aqueous nanofluids.

Al_2O_3 nanoparticles of size 20 nm have more thermal conductivity than 40 nm particles within measured temperature range (4-16°C). The thermal conductivity enhancement of nanorefrigerant with elongated shaped Al_2O_3 nanoparticles (40 nm) is more than spherical shaped (40 nm) Al_2O_3 nanoparticles within measured temperature range (4-16°C). It is because of rapid heat transport along relatively larger distances in elongated particles since elongated particles usually have larger lengths as compare to its diameter.

It is found that 0.1 wt.% Al_2O_3/R-11 nanorefrigerant with spherical particles had a thermal conductivity enhancement of 24%, whereas 0.1 wt.% nanorefrigerant with elongated particles had a thermal conductivity enhancement of 43%. It is observed that Hamilton and Crosser model is successful in predicting the enhancement of thermal conductivity of elongated particles.

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