Analysis of nanofluids as a means of thermal conductivity enhancement in heavy machineries

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Abstract

Purpose – Nanofluids exhibit enhanced heat transfer characteristics and are expected to be the future heat transfer fluids particularly the lubricants and transmission fluids used in heavy machinery. For studying the heat transfer behaviour of the nanofluids, precise values of their thermal conductivity are required. For predicting the correct value of thermal conductivity of a nanofluid, mathematical models are necessary. In this paper, the effective thermal conductivity of various nanofluids has been reported by using both experimental and mathematical modelling. The paper aims to discuss these issues.

Design/methodology/approach – Hamilton and Crosser equation was used for predicting the thermal conductivities of nanofluids, and the obtained values were compared with the experimental findings. Nanofluid studied in this paper are Al_2O_3 in base fluid water, Al_2O_3 in base fluid ethylene glycol, CuO in base fluid water, CuO in base fluid ethylene glycol, TiO_2 in base fluid ethylene glycol. In addition, studies have been made on nanofluids with CuO and Al_2O_3 in base fluid SAE 30 particularly for heavy machinery applications.

Findings – The study shows that increase in thermal conductivity of the nanofluid with particle concentration is in good agreement with that predicted by Hamilton and Crosser at typical lower concentrations.

Research limitations/implications – It has been observed that deviation between experimental and theoretical results increases as the volume concentration of nanoparticles increases. Therefore, the mathematical model cannot be used for predicting thermal conductivity at high concentration values.

Originality/value – Studies on nanoparticles with a standard mineral oil as base fluid have not been considered extensively as per the previous literatures available.

Keywords Mining, Lubricants, Machinery

Paper type Research paper

Nomenclature

k_e = thermal conductivity of nanofluid
k_p = particle's thermal conductivity
k_m = thermal conductivity of the base fluid
v_p = volume fraction of nanoparticles suspended in base fluid
ψ = sphericity
γ = ratio of nano-layer's thermal conductivity to particle's thermal conductivity
β = ratio of the nano-layer thickness to the original particle radius
ΔT = temperature rise of the wire
q = heat dissipation per unit length
t = time from the start of heating
α = thermal diffusivity of the fluid
r_w = radius of the wire
C = exponent of Euler's constant

Introduction

For industrial equipment requiring large heat transfer, the thermal conductivity of the fluids has a significant role on energy efficiency. Poor heat transfer properties of traditional heat transfer fluids such as water, ethylene glycol and lubricating oil has always put limitations to use in processes like power generation, chemical processing, heating and cooling, microelectronics, etc. In the past, various techniques were used to enhance the thermal conductivity of the fluids like mixing milli- and micro-sized particles in the base fluid. Experimental studies have been carried out for micro sized particles and dependence on the aspect ratio of the particles was suggested (Cherkasova and Shan, 2008). But their use pose serious problems for system performance such as poor suspension stability, channel clogging, pressure drop, rapid sedimentation, pipeline erosion, etc. (Xuan and Li, 2000).

Since the thermal conductivity of nanofluid is higher than that of base fluid (Lee *et al.*, 1999). It is expected that nanofluids have great promises for future. In the field of heavy machinery heat transfer property of fluid is used directly (as in coolant) or in combination with other uses (as in case of engine oil and transmission fluid). As heavy machineries are costly and produces more heat during their operation, higher rate of heat transfer they require.

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Due to recent advances in material technology its now possible to synthesise nanometre sized particles which has introduced this new term of nanofluids. These new type of fluids named "nanofluids" were introduced in 1995 (Choi, 1995). The effect of particle inclusions on the effective thermal conductivity of liquid has attracted a great interest experimentally and theoretically. Compared to suspended particles of millimeter or micrometer dimensions, nanofluids show not only better stability and rheological properties but also higher thermal conductivities and lower viscosity. Nanofluid is expected to become the next generation of heat transfer fluid for thermal engineering (Xuan and Li, 2003).

Experimental measurement of thermal conductivity of nanofluids

The experimental data used in this paper, taken from works of researchers, were obtained primarily using transient hot wire apparatus method for measuring thermal conductivity. The transient hot wire apparatus and procedure have been described by Bleazard and Teja (Sun and Teja, 2003, 2004; Bleazard *et al.*, 1996; Bleazard and Teja, 1995) who have also reported measurements of the thermal conductivity of a variety of electrically conducting fluids using this apparatus at temperatures as high as 465 K.

A liquid metal transient hot wire device was used to measure the thermal conductivity of each nanofluid. The experimental arrangements of the transient hot-wire system used in the study is shown schematically in Figure 1. Briefly, a mercury filled glass capillary is suspended in the fluid or dispersion, with the glass capillary serving to insulate the mercury "hot-wire" from the electrically conducting fluid or dispersion. The mercury wire forms one resistor in a Wheatstone bridge circuit and is heated when a constant voltage is applied to the bridge. The temperature rise of the wire is calculated from the change in the resistance of the mercury with time, obtained by measuring the voltage offset of the initially balanced Wheatstone bridge. The temperature rise *versus* time data are then used to calculate the thermal conductivity by solving Fourier's equation for an infinite line heat source in an infinite medium:

$$\Delta T = \frac{q}{4\pi k_e} \ln\left(\frac{4\alpha t}{r_w^2 C}\right)$$

A linear relationship between the temperature rise of the wire and the natural log of time is used to confirm that conduction is the primary mode of heat transfer during the measurement. Corrections to the temperature rise are made for the finite characteristics of the wire, the insulating layer around the wire, the finite extent of the fluid, and heat loss due to radiation. Finally, an effective wire length is obtained by calibrating the instrument with a reference fluid in order to account for end effects and the non-uniform thickness of the capillary.

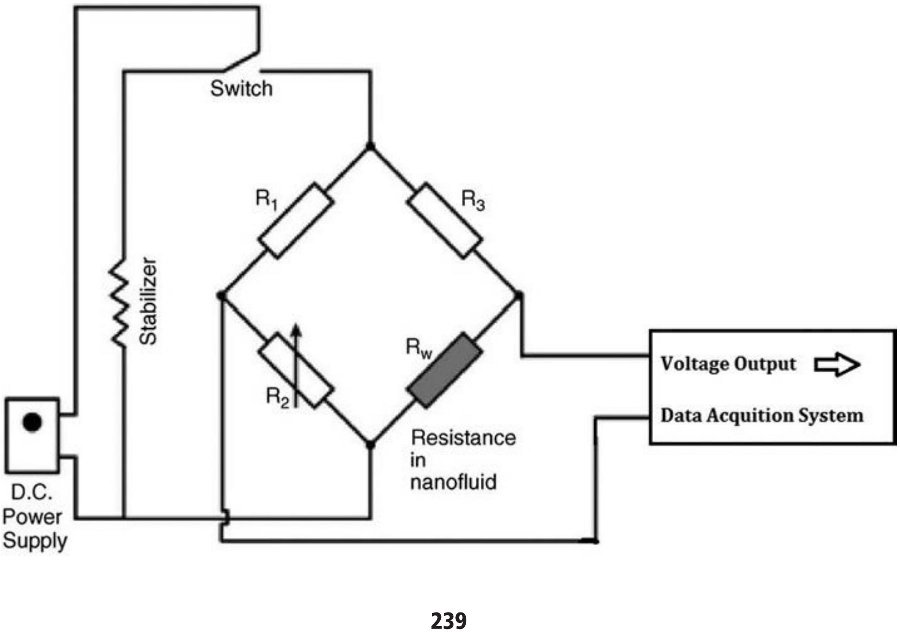
Thermal conductivity modelling of nanofluid

The modelling of nanofluids for the purpose of theoretical study basically treats nanometer sized particles suspended in fluid medium. The equation for estimation and calculation of the amount of solid particles to be added in fluid to increase the thermal conductivity of fluid was earliest induced by Maxwell (1904). Maxwell model used to predict the effective thermal conductivity for solid particles dispersed in fluids. However, model used only thermal properties of the particles and fluids and the volume fraction percentage. The equation is presented as:

$$k_e = k_m + 3v_p \frac{k_p - k_m}{2k_m + k_p - v_p(k_p - k_m)} k_m \tag{1}$$

Another model for solid-liquid mixtures which takes into account the interactions among the randomly distributed particles, was proposed by Bruggemen (1935). Bruggemen model was an implicit model and can be applied to spherical particles with no limitations on the particle volumetric concentrations. However, with increasing concentrations, the deviation between theoretical and experimental data was observed to be too high. The equation representing Bruggemen model is:

Figure 1 Schematic diagram of the transient hot-wire apparatus



$$v_p\left(\frac{k_p-k_e}{k_p+2k_e}\right)+(1-v_p)\left(\frac{k_m-k_e}{k_m+2k_e}\right)=0 \tag{2}$$

Maxwell model clearly predicts the increase in the thermal conductivity of the nanofluid compared to base fluid showing increasing trend with increase in volume fraction. However, the model used in this paper is a modified form of Maxwell model. Hamilton and Crosser (1962) extended the Maxwell's model by introducing a shape factor to account for the effect of the shape of particles. It was used for predicting the thermal conductivity of various nanofluids with nanoparticles of spherical shape. The model considers the effect of particle type, particle concentration, fluid thermal conductivity and particle shape. The equation is presented as:

$$k_e=k_m+3\psi^{-1}v_p\frac{k_p-k_m}{(3\psi^{-1}-1)k_m+k_p-v_p(k_p-k_m)}k_m \tag{3}$$

where: ψ is the sphericity defined as:

$$\psi=\frac{\text{surface area of a sphere with a volume equal to that of the particle}}{\text{surface area of the particle.}}$$

This model shows that non-spherical shape will increase the conductivity above that of spheres. However, for the purpose of analysis, $\psi=1$ was used.

Yu and Choi (2003) proposed a modified Maxwell model considering the effect of the nano-layer by replacing the thermal conductivity of solid particles k_p in equation (1) with the modified thermal conductivity of particles k_{pe}, which is based on the so-called effective medium theory (Schwartz *et al.*, 1995). The equation is presented as:

$$k_e=\frac{[2(1-\gamma)+(1+\beta)^3(1+2\gamma)\gamma]}{-(1-\gamma)+(1+\beta)^3(1+2\gamma)}k_p \tag{4}$$

where $\gamma = k_{layer}/k_p$ is the ratio of nano-layer's thermal conductivity to particle's thermal conductivity and $\beta = h/r$ is the ratio of the nano-layer thickness to the original particle radius. Hence, the Maxwell equation can be modified into:

$$k_{eff}=\frac{k_{pe}}{k_{pe}}k_b \tag{5}$$

$$k_{eff}=\frac{k_{pe}+2k_b+2(k_{pe}-k_b)(1+\beta)^3\phi}{k_{pe}+2k_b-(k_{pe}-k_b)(1+\beta)^3\phi}k_b$$

This modified Maxwell model can predict the presence of very thin nano-layers, particularly when the particle diameter is below 10 nm. It can be concluded that the smaller the particle, the higher the thermal conductivity. In addition, the very small size of nanoparticles should markedly improve the stability of the suspension.

Yu and Choi (2004) proposed a modified Hamilton-Crosser model to include the particle-liquid interfacial layer for non-spherical particles. The effective thermal conductivity is expressed as:

$$k_{eff}=\left(1+\frac{n\phi_{eff}A}{1-\phi_{eff}A}\right)k_b \tag{6}$$

where A is defined as:

$$A=\frac{1}{3}\sum_{i=a,b,c}\frac{(k_{pj}-k_b)}{k_{pj}+(n-1)k_b} \quad \text{and}$$

$$\phi_{eff}=\frac{\sqrt{(a^2+t)(b^2+t)(c^2+t)}}{\sqrt{abc}}$$

Results and discussion

Using the above mathematical model the variation of the thermal conductivities of the mentioned nanofluids at various concentrations was plotted and compared with the experimental findings of various research works and the percentage deviation between them was calculated.

Al_2O_3 in base fluid water

Figure 2 shows a linear and increment trend of Al_2O_3-water nanofluid's relative thermal conductivity (it is the ratio of thermal conductivity of nanofluid to the thermal conductivity of base fluid) with particle volume fraction (per cent). Figure 1 also shows the experimental variation of thermal conductivity of the nanofluid (Xie *et al.*, 2002). At 2.04 and 4.71 per cent volume concentration the percentage deviation between experimental and the value predicted by model is 1.762523 and 4.433 per cent, respectively.

Al_2O_3 in base fluid ethylene glycol

Figure 3 shows the prediction and comparison of theoretical modelling data with the experimental data (Xie *et al.*, 2002) for Al_2O_3 nanoparticles suspended in ethylene glycol. As illustrated, both theoretical model and experimental data shows almost linear and increasing behaviour. The percentage deviation between experimental and the value predicted by model at 1.95 and 4.775 per cent volume concentration is 4.426378 and 10.61 per cent, respectively.

CuO in base fluid water

Figure 4 shows the experimentally measured value (Lee *et al.*, 1999; Wang *et al.*, 1999) and predicted thermal conductivity of CuO-water is presented. The percentage deviation between experimental and the value predicted by model at 1.204 and 8.765 per cent volume concentration is 0.481696 and 3.88 per cent, respectively.

Figure 2 Effect of variation of concentration on relative thermal conductivity of Al_2O_3-water nanofluid

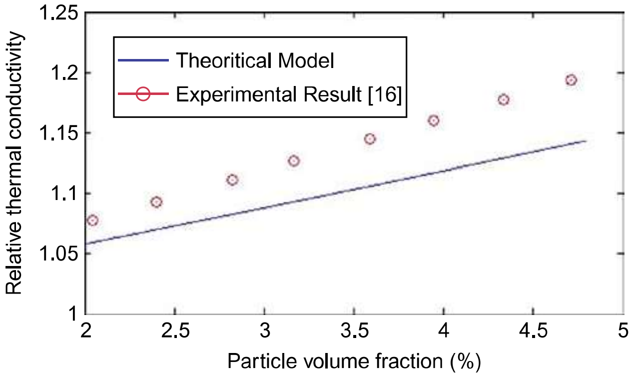


Figure 3 Effect of variation of concentration on relative thermal conductivity of Al$_2$O$_3$-ethylene glycol nanofluid

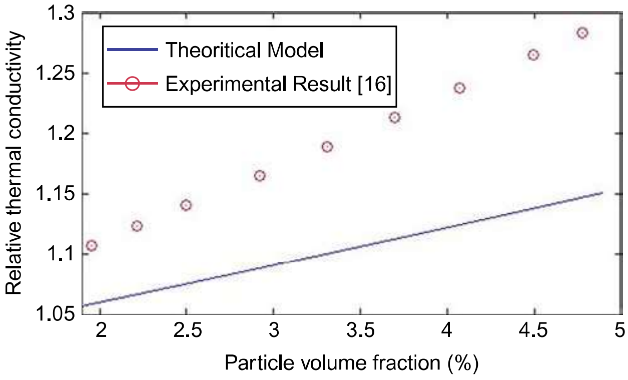
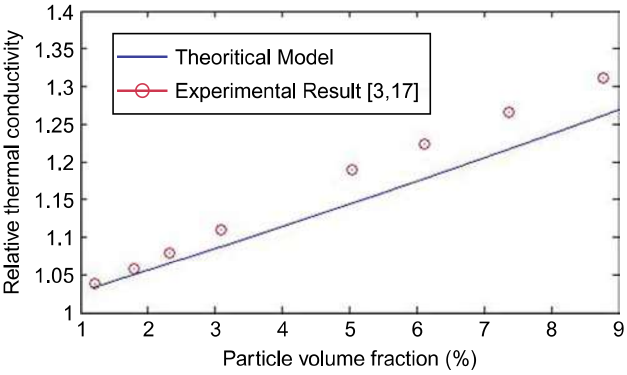


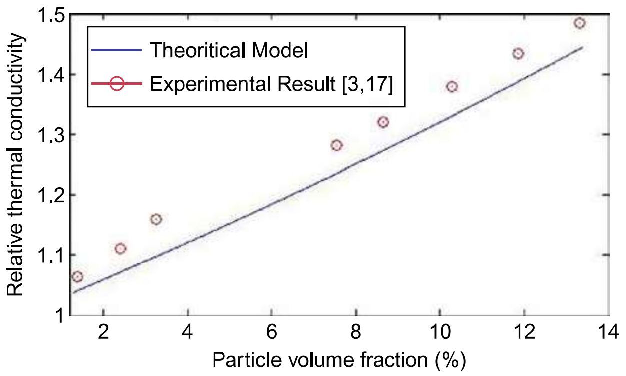
Figure 4 Effect of variation of concentration on relative thermal conductivity of CuO-water nanofluid



CuO in base fluid ethylene glycol

Figure 5 shows the model follow a linear increasing trend of relative thermal conductivity with CuO suspended in ethylene glycol volume fraction (per cent). Figure 5 also shows the experimental variation of thermal conductivity of the nanofluid (Lee *et al.*, 1999; Wang *et al.*, 1999). At 1.396 and 13.3042 per cent volume concentration the percentage deviation between experimental and the value predicted by model is 2.161654 and 3.0476 per cent, respectively.

Figure 5 Effect of variation of concentration on relative thermal conductivity of CuO-ethylene glycol nanofluid



TiO$_2$ in base fluid ethylene glycol

Figure 6 shows the variation of experimental and numerical values of thermal conductivity of TiO$_2$-water nanofluid. The theoretical results has compared with experimental data of Murshed *et al.* (2008). The deviation between the two values at 0.602 and 5.397 per cent concentration is 2.148 and 1.3278 per cent, respectively.

The typical values of volume fraction of solid particles used in preparation of nanofluids are shown in Table I.

Hence, the model can be used to predict the values of thermal conductivity of nanofluid whose concentration is generally low (0.02-5 per cent).

Nanofluid in heavy machinery with lubricating oil as base fluid

Nano-particles of CuO or Al$_2$O$_3$ can be added to conventional coolant (water, ethylene glycol and their mixtures) to have increased thermal conductivity of the resulting suspension. As shown in graph previously at 5 per cent by volume concentration of Al$_2$O$_3$ in ethylene glycol increases its thermal conductivity 1.29 times (Xie *et al.*, 2002), whereas just 0.84 per cent volume concentration of multi walled carbon nano tube (MWCNT) in water increases the thermal conductivity of water 1.24 times (at 20°C) (Wen and Ding, 2004).

Engine oil is used for lubrication of various internal combustion engines. The main function is to lubricate moving parts in contact; it also cleans, inhibits corrosion, improves sealing, and cools the engine by carrying heat away from moving parts. Commonly used engine oils are SAE 30, SAE 40, etc. Multi grade engine oils of various grades (SAE 20 w 40, SAE 10 w 50, etc.) are also available for use in a condition of varying ambient temperature.

Figure 6 Effect of variation of concentration on relative thermal conductivity of TiO$_2$-ethylene glycol nanofluid

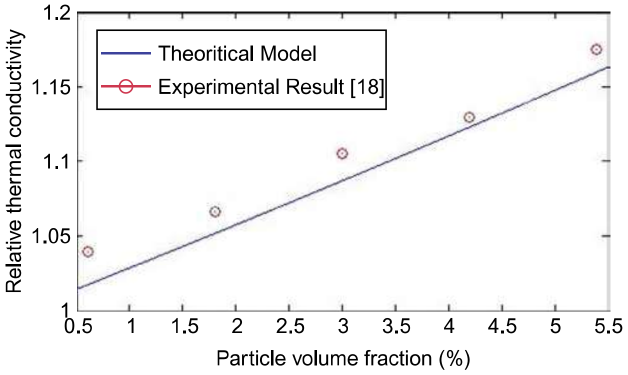


Table I

System	Particle loading (vol%)	System	Particle loading (vol%)
CuO/H$_2$O	5 (Zhang *et al.*, 2006)	Fe$_3$O$_4$/H2O	4 (Zhu *et al.*, 2006)
Cu/EG	0.3 (Eastman and Choi, 2001)	Al$_2$O$_3$/H2O	5 (Xie *et al.*, 2002)
Fe/EG	0.55 (Hong *et al.*, 2005)	Al$_2$O$_3$/EG	0.05 (Xie *et al.*, 2002)

The mathematical model presented in this paper is showing a good agreement with experimental results (Figures 2-6). In the similar manner, the model is applied for a standard engine oil (mineral based oil), normally used as engine oil in heavy mining and construction machinery. Figures 7 and 8 are showing the nature of thermal conductivity of SAE 30 with the variation of percentage volume fraction of Al_2O_3 and CuO nano particles. The variation of thermal conductivity is increasing linearly. The particle volume fraction is up to 5 per cent has been taken care, by keeping in view that the effect of viscosity variation of nanofluids (Jain *et al.*, 2011).

Conclusion

A study of experimental and numerical analysis of thermal conductivity of nanofluids has been presented. Significant linear increase in the effective thermal conductivity was found with increasing particle volume fraction. Results show that thermal conductivity values predicted by the Hamilton Crossers model are slightly lower than the experimental results which are acceptable. Especially, at lower concentrations the numerical and the experimental results are in good agreement. Nanofluids finds potential application in field of heavy machinery and nanoparticles can be added to coolants, engine oil and hydraulic oil to increase its heat transfer properties.

Figure 7 Variation of relative thermal conductivity of SAE 30 with percentage volume fraction of Al_2O_3 nano-particles (theoretical)

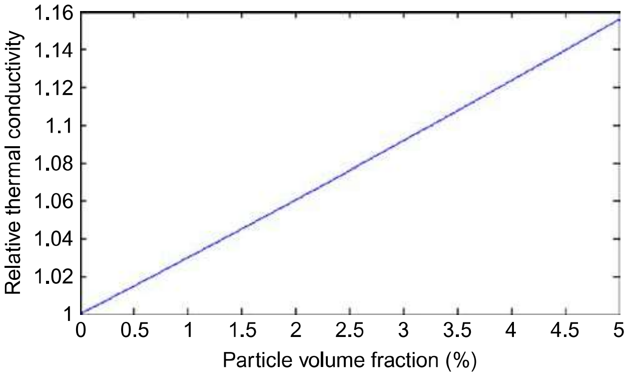
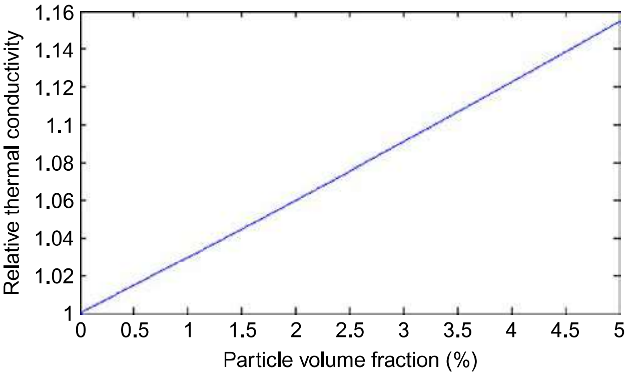


Figure 8 Variation of relative thermal conductivity of SAE 30 with percentage volume fraction of CuO nano-particles (theoretical)



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