A REVIEW ON THE RECENT DEVELOPMENT IN ENHANCING THE THERMAL CONDUCTIVITY IN NANOFIUIDS

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ABSTRACT
Nanofluid, the synergy of base fluid and nanoparticles, has exhibited many compulsive properties, and the unique attributes offer an unmatched potential for future applications. This review aims to compile the recent developments in enhancing the thermal conductivity (k) of nanofluids. Most of the papers reviewed here reported an enhancement by focusing on volume concentration. The nanofluid exhibits wide-ranging applications in numerous domains including electronics, biomedical and mechanical fields. And lastly, this review guides to directions for future research and developments of contention issues.

Key words: effective thermal conductivity, Nanofluid, particle volume concentration, Brownian motion.

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1. INTRODUCTION
Nanotechnology has been a very effective field in terms of research and development in the past two decades. S.U.S. Choi [1] in 1995 suggested amalgamating nanoparticles with conventional fluids. The nanoparticles dispersed in base fluids are usually metals, metal oxides, carbon-nanotubes. Conventional base fluids such as water, ethylene-glycol, and transformer oil are used as base fluids. The researchers are focusing on using nanofluids due to its enhanced heat transfer capabilities.

Nanofluids show very anomalous enhancement in \( k \) when compared to the conventional fluids. Hrishikesh E. Patel et al. [2], E.V. Timofeeva et al. [3], Ravi Prasher et al. [4,5], Calvin H. Li et al. [6], Q.Z. Xue [7], Junemo Koo et al. [8], P. Bhattacharya et al. [9], worked on the effects of particle size, shape of the nanoparticles, material of the nanoparticles, volume fraction or volume concentration, agglomeration, Brownian motion (BM) and aggregation of nanoparticles to observe enhancement in \( k \) of nanofluids.

This review paper also aims to list out various applications and the potential for future research on nanofluids.

2. LITERATURE REVIEW

2.1. Conventional models
Maxwell-Garnett model (MG model) [10] was based on the method of Effective medium theory (EMT). The Effective medium theory is a theory or method having a macroscopic medium in which quantities such as conductivity varies in space. The particles are randomly disseminated and are similarly sized having a spherical shape.

Hamilton-Crosser model (HC model) [11] is a further modification of MG model [10] which included \( k \) of nanoparticles is dependent upon the particles shape suspended in base fluid. This model concluded that only spherical and cylindrical shaped particles come under this model.

Hui, X. Zhang model [12] [4] reveals that the MG model [2] is applicable only for low particle concentration. They studied particles interaction and its effects on the enhancement of \( k \). This model concludes that there are no limitations for particle volume fraction.

Wasp model was advanced by Xuan and Li [13] [5], they discussed macroscopic system model. This model evolved by the modernization of HC model [3] with empirical shape factor equal to unity. This model fits the requirements for MG model [2] but does not focus on the shape of the particles. It mainly worked on the convection heat transfer issues.

Therefore, the conventional models cannot exactly predict the \( k \) of nanofluids. These conventional models do not focus on the effects of temperature, particle size, the interfacial layer of fluid-particle, aggregation, nanoparticles clustering and BM into consideration.

2.2. Models derived from conventional models
Hrishikesh E. Patel et al. [2] performed experimentally and measure temperature with Transient Hot Wire (THO) and Temperature Oscillation (TO) equipment. Nanoparticles of Aluminium oxide and Copper(II) oxide were dispersed in water, ethylene glycol and transformer oil. The averaged surface area sizes were categorized into 11nm, 45nm, and 150nm. The results obtained shows that the metallic nanofluid gives higher enhancements
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than oxide nanofluids. It was also observed by the researcher that the $k$ is higher at lower volume fraction.

E.V Timofeeva et al. [3] measured the intensity by Dynamic Light Scattering (DLS) technology. The researchers in this paper investigated on nanoparticles of Alumina suspended in base fluids water and ethylene glycol. The results showed that the nanoparticles are highly agglomerated and it varies with time and age. The results also show an enhancement in the rate of $k$ due to agglomeration of nanoparticles.

Ravi Prasher et al. [4] were assumed the particles shape to be spherical. The results showed that there was a change in thermal conductivity due to aggregation in nanofluid; it was also observed that the micro-convective effect occurs due to BM in the nanofluids. This investigation shows that there is an enhancement in the $k$ due to increase in aggregation.

Calvin H. Li et al. [6] investigated on volume fraction at 2%, 4%, 6% and 10% of CuO and Al$_2$O$_3$ nanoparticles of diameters ranging from 29nm to 36nm in size with temperature ranging from 27.5°C to 34°C. The result of experimental values showed enhancement in the effectiveness of CuO at 6% volume concentration and Al$_2$O$_3$ at 10% volume concentration by 1.52 times and 1.3 times respectively at 34°C temperature of the nanofluid. It was also reported from the results that as the temperature increases the $k$ increases and also shows that there is an optimum volume fraction or volume concentration to give stirring effect in the fluid which increases the rate of heat transfer.

Q.Z. Xue [7] compared their results with Choi et al. [1] and HC model [3] and also with four other models. The investigation reported, Choi et al. [1] conducted on volume concentration 1% having nanoparticles of carbon nanotube suspended in oil. An enhancement by 160% has been found whereas this was greater than 10% predicted by HC model [3] and four other models. The volume concentration used by them is 1% carbon nanotube particles suspended in oil as well and this reports 19.6% enhancement which is again greater than HC model [3] prediction. It was observed in this paper that the $k$ of nanofluid is very much dependent on the selection of base fluid. The experimental data showed higher enhancement percentage than all the models and even when compared with the theoretical data higher enhancement have been found but it lies within a reasonable range covered by models.

Junemo Koo et al. [8] studied the movement of nanoparticles in the base fluid. The researcher also discussed the effects of BM, thermophoresis, and osmophoresis on $k$. The paper defines BM as random movement of microscopic particles in base fluid. Thermophoresis is defined as phenomena in which the nanoparticles experiences movement in base fluid due to difference in temperature gradient whereas, osmophoresis can be explained as a phenomenon in which the nanoparticles experiences movement due to difference in temperature gradient as well as pressure difference. It was reported from the paper that the particles arriving from higher temperature have greater momentum than one at lower temperature this is due to the change in density, this difference in momentum showed that particles have different energy level at different temperatures. As observed from results, BM showed the greatest enhancement in $k$ than thermophoresis and osmophoresis. This paper concludes with a statement reporting that the BM effect on $k$ decreases if the particle size decreases whereas, thermophoresis and osmophoresis is independent of the size of the nanoparticles.

Ravi Prasher et al. [5] neglected the impact of layering whereas, effects of three other mechanisms for energy transfer are taken into consideration and they are ‘translational BM, interparticle potential, and convection due to BM. Nanoparticles of Aluminium oxide and Copper(II) oxide were dispersed in water and ethylene glycol. It was reported that the simple single-sphere BM results in greater enhancement in $k$ than MG model [2]. In this paper, it is observed that even at very small volume fraction the particles experience the interaction
between them. The results showed that the induced convection due to BM as well as by MG model [2].

P. Bhattacharya et al. [9] have observed the use of alumina-ethylene glycol and CuO-ethylene glycol as nanofluids. In their study they have worked on a very different technique of computation known as Brownian dynamics simulation, it has been reported that the technique was economical than the molecular dynamics. Brownian dynamics can be explained in such a way that the Newton’s equation of motion is replaced by the Langevin’s equation (Brownian dynamics). It is also observed that the Brownian dynamics simulation resulted in high accuracy comparatively. The researchers varied the number of particles such as 32, 108 and 256 in the fluid. They also performed three different simulations of duration's 100, 1000 and 10,000-time steps and this resulted that the duration of 100-time steps at 300K was more economical than the other two durations. This paper concluded as a result of the simulation resulting within 3% of experimental data for alumina-ethylene glycol and for CuO-ethylene glycol resembles very much with the experimental data.

Junemoo Koo and Clement Kleinstreuer [14] focused on effects of particle size, volume fraction, and temperature. They also considered properties of the base fluid and compared it with the results of different studies. It was reported that there are strong relation and dependency of effective $k$ on temperature and material of the particle. The study validates that for given heat flux, the temperature gradient changes due to varying $k$ which majorly depends on volume fraction, particle size, particle material and temperature. It is observed that the BM is more effective at a higher temperature. The study concluded that with an opinion for improving the accuracy of effective $k$ model by collecting more experimental data.

R. H. Davis [15] proposed a model on the interaction of spherically shaped nanoparticles. It has been observed that the temperature is assumed to uniform at the surface of the large body. This model used Green’s theorem to calculate the rate of heat transfer between the heated body and the composite material.

Table I shows the different correlations that have been obtained by the researchers while performing experimental and computational studies of nanofluids.

Table 1 Different Theoretical and Experimental Correlations of Thermal Conductivity

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
<th>Correlation</th>
<th>Relevant information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxwell 1881 [16]</td>
<td>$k_{eff} = k_p + 2k_f + 2\phi(k_p - k_f)$</td>
<td>Liquid and Solid Suspension</td>
<td>Spherical Particles</td>
</tr>
<tr>
<td>Hamilton and Crosser 1962 [16]</td>
<td>$k_{eff} = k_p + (n-1)k_f + (n-1)\phi(k_p - k_f)$</td>
<td>$k_p &gt; 100$, $n = 3$</td>
<td>Spherical and Non-Spherical Particles Micro-dimension</td>
</tr>
<tr>
<td>Wasp 1977 [16]</td>
<td>$k_{eff} = k_p + 2k_f + 2\phi(k_p - k_f)$</td>
<td>Various Particle shape</td>
<td></td>
</tr>
</tbody>
</table>
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### 3. CONCLUSIONS

This review paper covers research done by various researchers on the development and enhancement of thermal conductivity of nanofluids; it also covers models, affecting parameters and mechanisms essential for enhancing the $k$ of the nanofluid. The conventional models only worked on parameters such as the particle size, particle shape, particle volume fraction, base fluid and lastly particle $k$. The derived models dealt with some additional parameters than conventional models in order to enhance the $k$ of the nanofluid up to its maximum effectiveness. It is also observed that there is an optimum point which exists when considering a parameter. There are few important parameters which are widely discussed such as BM, temperature, volume concentration, size of the particle and particle material. Hence, the review comes to a conclusion that there is a need to further work and optimize in finding the critical size and critical temperature for the optimum points to attain maximum enhancement.

### REFERENCES


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<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Equation</th>
<th>Nanofluid Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davis 1986</td>
<td>[16]</td>
<td>$k_{\text{eff}} = 1 + \frac{3(k-1)}{k-2} \left[ \phi + f(k) \phi^3 + O\phi^4 \right]$</td>
<td>Spherical and Non-spherical particles</td>
</tr>
<tr>
<td>Lu and Lin 1996</td>
<td>[16]</td>
<td>$\frac{k_{\text{eff}}}{k_f} = 1 + a\phi + b\phi^2$</td>
<td>Nanospheres with interfacial shell</td>
</tr>
<tr>
<td>Xue 2005</td>
<td>[16]</td>
<td>$k_{\text{eff}} = \left( 1-\phi + 2\phi \frac{k_{s_{\text{eff}}}}{k_f} \right) \left( \ln \frac{k_{\text{eff}}}{k_f} \right)$</td>
<td>Al$_2$O$_3$/Water Nanofluids</td>
</tr>
<tr>
<td>Li and Peterson 2006</td>
<td>[16]</td>
<td>$\frac{k_{\text{eff}}-k_f}{k_f} = 0.764\phi + 0.0187(T - 273.15) - 0.462$</td>
<td>CuO/Water Nanofluids</td>
</tr>
<tr>
<td>Timofeeva et al 2007</td>
<td>[16]</td>
<td>$k_{\text{eff}} = (1 + 3\phi)k_f$</td>
<td>Al$_2$O$_3$/Water Nanofluids</td>
</tr>
<tr>
<td>Duangthongsu and Wongwises 2009</td>
<td>[16]</td>
<td>$k_{\text{eff}} = a + b\phi$</td>
<td>EG/Water Nanofluids</td>
</tr>
<tr>
<td>Godson et al 2010</td>
<td>[16]</td>
<td>$k_{\text{eff}} = 0.9692\phi + 0.9508$</td>
<td>Ag/Water Nanofluids</td>
</tr>
</tbody>
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