Thermo-Physical Properties of Nano Fluids- A Review

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Abstract- Nanofluid is one of the best outcomes of nano-technology advancement. Nanofluid can be considered as a fluid rather than solid-fluid mixture. There is different properties enhancement in the base fluid using nanoparticles i.e. thermal conductivity, heat transfer coefficient, density, viscosity, specific heat etc. Having improved thermo physical properties, nanofluids can be used as a better heat transfer fluid in many engineering applications such as radiator, heat pipe, solar collectors, chillers etc. The most important thermal properties are thermal conductivity and heat transfer coefficient as well as viscosity. It is very complex and difficult to experimentally estimate these thermal properties for nanofluids at different concentration of nano particles. Many researchers have proposed mathematical and analytical works in the literatures for the determining of these thermal properties. A brief review of some common theoretical and analytical models for estimation of thermal properties is presented and also comparisons are made with experimental works in this paper, which can be frequently used.

Keywords – Nanofluid, Thermal Conductivity, Heat Transfer Coefficient, Nanoparticle, Etc.

I. Introduction

Development in nano-technology derives to a new class fluid named as nanofluid. A Nanofluid is a dilute suspension of nano-metered sized particles in base fluid (ethylene glycol, water, engine oil, etc.). Nanometered sized particles may be metallic or nonmetallic. Nanofluids have the potential of improved thermal-physical properties (thermal conductivity, heat transfer coefficient, viscosity, density, heat capacity, etc.).

A large number of theoretical and experimental research works have been conducted since Maxwell [1] publication on suspension of solid particles. Choi et al. [2] first used the term nanofluid proposing heat transfer fluid in Argonne Laboratory. A large number of useful studies have been carried out related to nanofluids properties by Eastman et al. [3], Lee and Choi [4], Jang and Choi [5], Heris et al. [6]. Most of the studies show the enhancement in heat transfer for the nanofluids than the base fluids. From the basic principle of thermal conductivity solid metal has higher thermal conductivity i.e., thermal conductivity of copper at room temperature is about 700 times greater than water and about 3000 times greater than engine oil. This is basically because of small particle size and large surface to volume ratio of nanoparticles. Lee and Choi [4], Chein and Huang [7] found the enhancement in heat transfer in nanofluid than the conventional fluid. Pak and Choi [8], li and Xuan [9] first calculated Nusselt number in laminar and turbulent flow for nanofluids. Viscosity is a flow property that affects the pumping power and pressure drop in laminar flow. Convective heat transfer also depends on the viscosity of fluid. Einstein [10] first developed the nanofluid viscosity formula. Density of nanofluids also increased with concentration of nanoparticles. Heat capacity is also an important property to find out the thermal performance of nanofluids. The purpose of this paper is to provide an understanding about thermo-physical properties of nanofluids such as (thermal conductivity, coefficient of heat transfer, density, viscosity, heat capacity etc.) and properties characteristic with respect to nanoparticle concentration. Many researchers have developed correlations for the determination of thermo-physical properties of nanofluids. In this paper some important and commonly used property relations for nanofluids are presented.
II. THERMAL CONDUCTIVITY

A. Watermark embedding algorithm –

When high conductive nanoparticles are added in the base fluid, having relatively low thermal conductivity, there is remarkably increase in thermal conductivity of nanofluids. Some postulate that the thermal conductivity of nanofluids is because of the nanoparticle’s Brownian motion which produces micro-mixing. Some researchers have suggested that the enhancement is due to the layering of liquid molecules near the solid nanosized particles. The mechanism for thermal conduction between liquid and solid particles is not clear. But there are some empirical relations that can be used to find out thermal conductivity of two phase mixture solution (dispersed solution).

The effective thermal conductivity for a two-phase mixture consisting of a continuous and discontinuous phase has been conducted by Maxwell [1] and the effective thermal conductivity $K_{eff}$ is given by:

$$K_{eff, Maxwell} = K_1 + \frac{2K_2 - K_1}{2K_2 + K_1 - 2\phi(K_2 - K_1)}$$  \hspace{1cm} (1)

Where $K_1$ and $K_2$ are the thermal conductivity of the liquid and the solid particle respectively and $\phi$ is the particle volume fraction. Hamilton and Crosser [11] modified Maxwell work for none spherical particles and introduced the shape factor ($\beta$). Yu and Choi [12] modified the Maxwell model to find out real mechanism of improvement in thermal conductivity. They assumed that base fluid molecules form a layered structure around the solid particles. This layer mechanism can explain the enhancement in effective thermal conductivity. While calculating $K_{eff}$ for nano fluid Yu and Choi assumed higher thermal conductivity of nanolayer ($K_{layer}$) than the base liquid conductivity ($K_1$). When the nano layer is combined with the nanoparticle, an equivalent nano particle with thermal conductivity of $K_{eq}$ is introduced.

It is important to note that the effective thermal conductivity of nanofluids depends on the thermal conductivity of solid nano-sized particles and base fluid, particle volume fraction, shape of particles, size of particles and the thermal conductivity of nano-layer (equivalent nanoparticle).

Bhattacharya et al. [13] developed a correlation to calculate effective thermal conductivity of nanofluids using Brownian motion technique as follow:
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\[ k_{\text{eff}} = \varphi k_{np} + (1-\varphi) k_b \]  

The model shows good agreement with thermal conductivity of experimental result.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Formula ((k_{\text{eff}}/k_b))</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamilton</td>
<td>(K_p+(n-1)K_b - (n-1) \phi (K_b-K_p) /K_p+(n-1)K_b+ \phi (K_b-K_p)) (K_p/K_b&gt;100(n=3/\varphi))</td>
<td>for non-spherical particle</td>
</tr>
<tr>
<td>And cosser [11]</td>
<td>(1+3\left(\frac{K_p}{K_b}\right)^{1/2} \varphi + \left(3\left(\frac{K_p}{K_b}\right)^{1/2} + \varphi \right)^2)</td>
<td>Spherical particle</td>
</tr>
<tr>
<td>Jeffrey [14]</td>
<td>(K_{np}+2K_p+2(K_{np}-K_b)(1-\varphi)^2 \varphi) /K_{np}+2K_p-(K_{np}-K_b)(1+\varphi)^2 \varphi)</td>
<td>A modified Maxwell and Hamilton Cosser Model respectively</td>
</tr>
<tr>
<td>Wang et al. [16]</td>
<td>(1-\varphi + \frac{3 \varphi}{K_p} \int K_n(r)/K_{np}(r)+2K_b \varphi \int K_n(r)/K_{np}(r)+2K_b \varphi)</td>
<td>A fractal model based on effective medium</td>
</tr>
<tr>
<td>Xue and Xu [17]</td>
<td>(1-\varphi + \frac{3 \varphi}{K_p} \int K_n(r)/K_{np}(r)+2K_b \varphi \int K_n(r)/K_{np}(r)+2K_b \varphi)</td>
<td>Includes effect of nanolayer</td>
</tr>
<tr>
<td>Xie et al. [18]</td>
<td>(1 + 3 \varphi T^{2} + \frac{2 \theta^{2} \varphi^{2} T}{1-\varphi T})</td>
<td>Includes effect of random motion of Suspended nanoparticles as well as Interfacial interactions</td>
</tr>
<tr>
<td>Xuan et al. [20]</td>
<td>(1 + c \frac{2 K_b T}{m d_{p} \varphi} = \frac{K_T}{3 \pi r_{c p}})</td>
<td>Includes particle size, concentration, And temperature</td>
</tr>
<tr>
<td>Kumar et al. [21]</td>
<td>(1 + c \frac{2 K_b T}{m d_{p} \varphi} = \frac{K_T}{3 \pi r_{c p}})</td>
<td>Includes particle size, concentration, And temperature</td>
</tr>
<tr>
<td>Jang and Choi [22]</td>
<td>(K_b(1-\varphi) + k_p+3 C_{np} d_{p} K_b Re \varphi^{2} Pr \varphi)</td>
<td>Four modes included</td>
</tr>
<tr>
<td>Prasher [23]</td>
<td>((1+AR^{0.333} \varphi)^{1/2} + (2 kp+2k_{b}- (k_{p}+k_{b}) \varphi)^{1/2})</td>
<td>Effect of convection of the liquid near the Particle included</td>
</tr>
<tr>
<td>Koo and Kleinstreuer [24]</td>
<td>(\frac{K_{\text{eff, Maxwell}}}{K_b} + 5 \times 10^{4} \beta \varphi \rho_{p} C_{p} \sqrt{\frac{kT f(T, \varphi)}{\rho_{p} D}})</td>
<td>Surrounding liquid motion with randomly Moving nanoparticles considere</td>
</tr>
</tbody>
</table>

II. CONVECTIVE HEAT TRANSFER COEFFICIENT

The enhancement in coefficient of heat transfer gives better described phenomenon than enhancement in thermal conductivity because of its relation to size of equipment. Increment in coefficient of convective heat transfer is because of presence of dispersed nanoparticles, which intensify the turbulence of the base fluid. Buongiorno [25] developed a two component four-equation correlation non-homogeneous model for mass, momentum, and heat transfer in nanofluids. Buongiorno finally concluded that only Brownian diffusion and thermophoresis are important characteristics in nanofluids. The random motion of nanoparticles causes slip velocity between solid and liquid layer. Pak and Choi [8] did the experiment on turbulent heat transfer of nanofluids by using Al\textsubscript{2}O\textsubscript{3} and TiO\textsubscript{2} dispersed...
nanoparticles in water. Xuan and Li [9] did theoretical study on single-phase flow for the turbulent and developed the heat transfer correlation from the experimental data as follows:

\[ Nu_{nf} = \frac{h_{nf} d}{K_{nf}} = 0.0059 \left( 1.0 + 7.6286 \phi^{0.6884} P_e_d^{0.001} \right) \left( Re_{nf}^{0.9238} Pr_{nf}^{0.4} \right) \]  

(3)

For laminar flow Xuan and Li [15] also provide a correlation:

\[ Nu_{nf} = \frac{h_{nf} d}{K_{nf}} = 0.4328 \left( 1.0 + 11.25 \phi^{0.7586} P_e_d^{0.218} \right) \left( Re_{nf}^{0.3333} Pr_{nf}^{0.4} \right) \]  

(4)

The Peclet number, Pe describes the effect of thermal dispersion caused by micro-convective and micro diffusion of the suspended nanoparticles. forced convective heat transfer depend on Reynolds and Prandtl’s numbers, temperature , vol. fraction (particles), the dimensions and shape of nano-sized particles. Xuan and Roetzel [26] proposed the following function for calculating Nusselt number:

\[ Nu = f \left( Re, Pr, \frac{\rho_n}{\rho_f}, \phi, \text{partical shape, flow geometry} \right) \]  

(5)

Generally two correlations are used to find out the Nusselt number as a function of Reynolds number and prandtl number:

\[ Nu_{nf} = 0.086 Re^{0.55} Pr^{0.5} \] for constant wall flux.  

(6)

\[ Nu_{nf} = 0.028 Re^{0.35} Pr^{0.36} \] for constant wall temperature.  

(7)

The given correlations are valid for \( Re \leq 1000, 6 \leq Pr \leq 753, \) and \( \phi \leq 10\% \). Wongwises et al. [27] did an experiment using TiO2-water nanofluids under turbulent flow conditions. He used a horizontal double-tube counter flow heat exchanger. They observed increment of (6– 11\%) heat transfer coefficient for the nano-fluid (TiO2-water) compared to pure water. Heris et al. [6] also gave a result of increment of heat transfer coefficient (40\%) for the nanofluid (Al2O3/water). For fully developed laminar flow under constant wall temperature boundary condition:

\[ Nu_{nf} = \frac{h_{nf} d}{K_{nf}} = 3.657 \]  

(8)

And for the turbulent flow, the Petukhof–Krillov [28] correlation

\[ Nu_{nf} = \frac{h_{nf} d}{K_{nf}} = \left( \frac{f}{12} \right) Re^{2} Pr^{0.75} \left( \frac{\mu_b}{\mu_w} \right)^n \]  

(9)

Where \( n = 0.11 \) for \( Tw>Tb \), \( n = 0.25 \) for \( Tw<Tb \), and \( n = 0 \) for constant properties of gases with \( f = (1.82 \log_{10} Re - 1.64)^2 \).

Above correlations show good agreement with experimental results within the boundary conditions. The convective heat transfer coefficient increases with increase in Reynolds number, because of the increase in the flow velocity causes an enhancement in the motion of the dispersed nanoparticles. The increase in particle volume fraction in the base fluid, there is increment in the convective heat transfer coefficient. This may be because of more inter particle collisions and enhanced surface area of heat transfer, with theirincreased volume fractions.

Table 2: Models of effective heat transfer coefficient

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Nano-fluids</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pak and Choi [8]</td>
<td>Al2O3-water, TiO2-water, Turbulent</td>
<td>( Nu_{nf} = 0.021 Re^{0.55} Pr^{0.5} )</td>
</tr>
<tr>
<td>Das et al. [29]</td>
<td>Al2O3-water, pool boiling</td>
<td>( Nu_{nf} = C Re^{0.9238} Pr^{0.4} )</td>
</tr>
<tr>
<td>Xuan and Li [9]</td>
<td>CuO-water, turbulent</td>
<td>( Nu_{nf} = 0.0059 \left[ 1 + 2.5 \phi_{p} \text{num} \right]^{0.001} Re^{0.9238} Pr^{0.4} )</td>
</tr>
</tbody>
</table>

IV. VISCOSITY

Analysis of viscosity is required to determine behavior of heat transfer fluids. Einstein [10] calculated the effective viscosity of solution having spherical solid particles in the base fluid using hydrodynamic equations. He derived the following equations:

\[ \mu_{eff} = (1 + 2.5 \phi_{p} \mu_b) \]  

(10)

This formula has some limitations, It does not include structure and particle-particle interaction and limited to a certain particle concentrations. Mooney [21] suggested a model for higher concentrations of interacting spherical solid particles suspensions is as follows:

\[ \frac{\mu_{eff}}{\mu_b} = \left( \frac{\phi_{p}}{1 - \phi_{p}} \right) \]  

(11)

$$\frac{\mu_{nf}}{\mu_b}=(1+2.5 \phi + 6.5 \phi^2)$$

(12)

If the particle volume concentration ($\phi$) is increased then the nanofluids with bigger size particles shows higher viscosity than the smaller size particles based nanofluids. Almost every research showed that addition of nanoparticle even at a low volume fraction in the base fluid has significant influence the viscosity. Brinkman [31] modified Einstein’s equation for the use of particle concentration up to 4% and developed a formula:

$$\frac{\mu_{nf}}{\mu_b}=(1-\phi)^{2.5}$$

(13)

This formula generally used is to calculate effective viscosity. Pak and Cho [8] developed a viscosity model based on particle volume fraction taking room temperature as reference.

$$\frac{\mu_{nf}}{\mu_b}=(1+3.99 \phi + 533.9 \phi^2)$$

(14)

<table>
<thead>
<tr>
<th>Models</th>
<th>Effective Viscosity</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maiga et al. [32]</td>
<td>$\mu_{nf}/\mu_b = (1 + 7.5 \phi + 123 \phi^2)$</td>
<td>Al2O3 - water, $d_p = 28nm$</td>
</tr>
<tr>
<td>Buongiorno et al. [25]</td>
<td>$\mu_{nf}/\mu_b = (1 + 5.45 \phi + 108.2 \phi^2)$</td>
<td>TiO2 - water, $d_p = 27nm$</td>
</tr>
<tr>
<td>Nguyen et al. [33]</td>
<td>$\mu_{nf}/\mu_b = (1 + 0.025 \phi + 0.015 \phi^2)$</td>
<td>Al2O3 - water, $d_p = 29nm$</td>
</tr>
<tr>
<td>Kampafer et al. [34]</td>
<td>$\mu_{nf}/\mu_b = (1 + 23.09 \phi + 1525.3 \phi^2)$</td>
<td>Al2O3 - water, $d_p = 13nm$</td>
</tr>
<tr>
<td>Nguyen et al. [33]</td>
<td>$\mu_{nf}/\mu_b = (1.475 - 0.319 \phi + 0.051 \phi^2 + 0.009 \phi^3)$</td>
<td>CuO - water, $d_p = 29nm$</td>
</tr>
</tbody>
</table>

Table 3: Models of effective viscosity

V. DENSITY

Density of any nanofluid is directly related to particle volume fraction ($\phi$). It increases approximately in linear manner with fraction volume. Density decreases with increase in temperature of fluid in non-linear manner. The basic reason behind non-linear trend is difference in the coefficient of thermal expansion in base fluid and Nano particles. The density of nano-fluids, $\rho_{nf}$ can be simply estimated as:

$$\rho_{nf} = \rho_b c_{nf} = (1-\phi)\rho_b + \phi \rho_p c_p$$

(15)

$$\rho_{nf} = m_{nf}/vol_{nf} = (m_b + m_p)/(vol_b + vol_p) = (\rho_b vol_b + \rho_p vol_p)/(vol_b + vol_p)$$

(16)

The density may be determined from a simple rule of mixtures given by Pak and Choi (8)

$$\rho_{nf} = (1-\phi)\rho_b + \phi \rho_p$$

(16)

Where $\phi$ is the volume fraction of dispersed phase, $\rho_b$ is the density of the base fluid And $\rho_p$ the density of nanoparticles.

VI. SPECIFIC HEAT

Specific Heat is a measure of heat energy that directly influences the heat transfer rate of Nano-fluids. For a given volume concentration of Nano-particles in the base fluid, the specific heat can be found using a parallel mixture rule:

$$c_{nf} = (1-\phi)c_{nf} + \phi c_p$$

(17)

Hence the specific heat capacity may be determined as

$$C_{nf} = X_{nf}/\rho_{nf} = (1-\phi)c_{nf} + \phi c_p/(1-\phi)\rho_b + \phi \rho_p$$

(18)

Where Xnf = (pc)n

Gherasim et al. [37] discuss an alternative formulation, from the mixture formula:

$$C_{nf} = (1-\phi)C_f + \phi C_p$$

(19)
The specific heat of nanofluids decreases with increase in the fraction volume of nanoparticles and also it increases with increase in the nanofluids temperature.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Density (kg/m³)</th>
<th>Specific heat (J/kg·K)</th>
<th>Conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>4000</td>
<td>880</td>
<td>30</td>
</tr>
<tr>
<td>Copper</td>
<td>8920</td>
<td>390</td>
<td>401</td>
</tr>
<tr>
<td>Water</td>
<td>998</td>
<td>4190</td>
<td>0.58</td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td>1110</td>
<td>2470</td>
<td>0.258</td>
</tr>
</tbody>
</table>

VII. CONCLUSION
Thermophysical characteristics of nanofluids and their role in heat transfer enhancement are reviewed in this work. General correlations for the effective thermal conductivity, viscosity, heat transfer coefficient, density and specific heat capacity of nanofluids are provided. It can be said that nanofluids have greater heat transfer capability than those of conventional heat transfer fluids. There is also effect on thermal conductivity, density, viscosity, heat transfer coefficient and specific heat capacity of base fluid by adding Nanoparticles in base fluids. But there is pressure drop at the time of addition of nanoparticles. It can be observed that thermo physical properties of nanofluids are dependent on the nanoparticles size, shape, and volume fraction. The increment in the values of thermal conductivity, heat transfer coefficient is up to a certain limit. Experimental results and the theoretical understanding of the mechanisms of the nanoparticles are needed to justify for the heat transfer and fluid behavior of nanofluids. Further work is also needed for the treatment of nanofluids as a two-phase flow since slip velocity between the particle and base fluid plays important role on the heat transfer performance of nanofluids.

REFERENCE

