Review of Literature on Nanofluid Flow and Heat Transfer Properties

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***Abstract*–Since the initial discovery of anomalous increases in the thermal conductivity of particle-fluid suspensions (nanofluids), they have become the topic of much research. Other potentially useful properties of nanofluids have also been studied extensively, yet our fundamental understanding of the mechanisms which create these exciting and promising properties is limited. This lack of understanding places limits on the applicability of nanofluids and our ability to accurately model them. As a consequence, further experimental and numerical research is needed that will help to develop better understanding of nanofluid flows and their heat transfer properties. One of the first theoretical investigations regarding the effective thermal conductivity of particle-fluid suspensions was conducted by Maxwell as early as 1873 [1]: Unfortunately, the resulting empirical expression (equation 1) has been found to have limited predictive capability, but since then, several other investigations have expanded on that original work with some success [2, 3, 4, 5]: (refer to equation 2). While the initial experimentation [6, 7, 8, 9, 10] on the effective thermal conductivity of nanoparticle suspension was not performed until the end of last century, other approximate empirical equations have been developed [11]: (refer to equation 3). In 2004, systematic surveys of experimental and modeling reviews [12] revealed that most models were phenomenological in nature, and that they address the problems partially. That work also demonstrated that the effectiveness of nanofluids depended not only on the enhanced thermal conductivity, but also on other properties such as viscosity and specific heat (Figs 1 and 2). The current thinking is that we may have to apply the full Navier Stokes, energy and continuity equations in order to help explain flow property variations in micro-fluid flow, with heat transfer.**

***Index Terms*–Nano-fluid, effective thermal conductivity, viscosity, specific heat, phenomenological, Navier Stokes Equations, enhanced thermal transport phenomenon etc.**

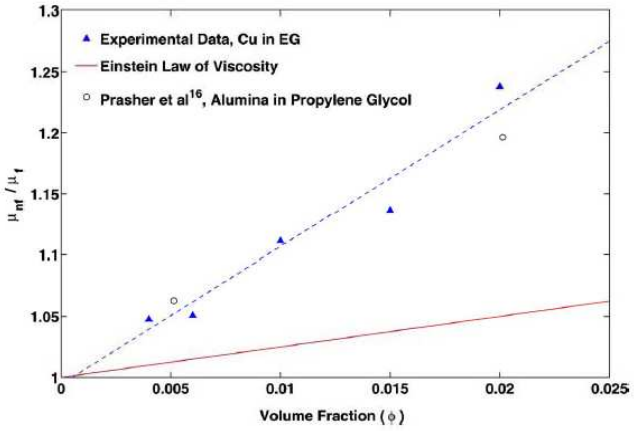

Fig. 1 Viscosity of copper in ethylene glycol nanofluid

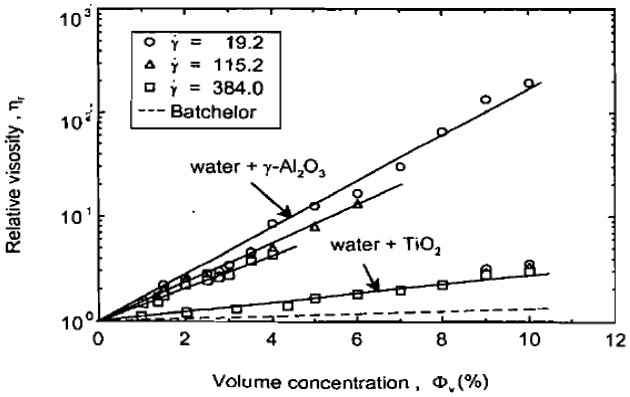

Fig. 2 Relative viscosity versus volume concentration of nanoparticles at different shear rates

I. KEY EQUATIONS AND ANALYSIS

To appreciate the concepts involved, a good understanding of the fundamentals of the basic mechanism that govern the behavior of effective thermal conductivity of nanoparticle suspensions is necessary. The effective thermal conductivity enhancement achievable by nanoparticle suspensions is understood to be as a result of two different mechanisms. The first is the contribution resulting from the thermal conductivity of the nanoparticle, which may be greater or in some situations, less than that of the base fluid, and the second contribution is said to be due to the movement of the Nano-particles themselves, which produces enhanced thermal transport. Maxwell (1873)[1] was said to have been the first to explain that the addition of particles to a base fluid created a suspension-mix that could result in enhanced effective thermal conductivity due to the change in the combined bulk property of the base fluid and the particles. Using this approach Maxwell further developed an analytical expression that has served as the basis for numerous theoretical investigations of the effective thermal conductivity. His model, when combined with works by other numerous authors has been observed to accurately predict the effective thermal conductivity of particle suspensions when the particles are relatively large, but seemed not to be as accurate for suspensions where the particles are very small, as is the case for nanoparticle suspensions.

In 2008, Emily Pfautsch [13] studied forced convection in nano-fluids over a flat plate. Her work analyzed the characteristics, flow development and heat transfer coefficient of nano-fluids under laminar forced convection over a flat plate. In her studies, a system of momentum,

energy and continuity equations were developed and solved using the techniques available in Mathematica. She concluded that varying the nano-particle volume fraction distribution showed that it is important for the nano-particles to stay evenly suspended throughout the flow in order for there to be appreciable enhancements in the heat transfer coefficient. This work additionally revealed that as the nano-particle size decreased below a thresh-hold, appreciable increase (c. 16%) was observed in the heat transfer coefficient for water-based nano-fluid and a significant increase (c. 100%) observed for ethylene glycol-based nano-fluid. It can be concluded that her work showed that decreasing the nano-particle size produce appreciable dispersion of nano-particle volume fraction farther away from the solid boundaries consequently lowering the temperature in the boundary layer region.

The following are examples of the theoretical equations of the effective thermal conductivity of particle-fluid suspensions in the last several years, modeled along the lines of Maxwell and others:

$$\frac{k_{eff}}{k_L} = \frac{2k_L + k_s + 2\varphi_s(k_s - k_L)}{2k_L + k_s - \varphi_s(k_s - k_L)} \quad (1)$$

where K_{eff}, K_S and K_L are the total, the suspension and the liquid thermal conductivities respectively and ϕ_S gives the nanoparticle volume fraction;

$$\frac{k_{eff}}{k_L} = 1 + \frac{3\varphi_s\left(\frac{k_s}{k_L - 1}\right)}{\frac{k_s}{k_L + 2}} + 3\varphi_s{}^2\left(\left(\frac{\frac{k_s}{k_L - 1}}{\frac{k_s}{k_L + 2}}\right)\right)^2$$
$$\rightarrow \left(1 + \frac{1}{4}\left(\left(\frac{\frac{k_s}{k_L - 1}}{\frac{k_s}{k_L + 2}}\right)\right)\right) + \frac{3}{16}\left(\left(\frac{\frac{k_s}{k_L - 1}}{\frac{k_s}{k_L + 2}}\right)\right) + - - - - - (2)$$

where the additional terms stem from paired interactions of particles.

$$\frac{k_{eff}}{k_L} = \frac{k_s + (\eta - 1)k_L - (\eta - 1)\varphi_s(k_L - k_s)}{k_s + (\eta - 1)k_f + \varphi_s(k_L - k_s)} \quad (3)$$

and where η is an empirical shape factor for the nanoparticle. In particular η = 3/2 for cylindrical particles and η = 3 for spherical particles. The effective density of the nanofluid is also given as:

$$\rho = (1 - \varphi_S)\rho_L + \varphi_S\rho_S \quad (4)$$

The thermal diffusivity of the nanofluid is given as:

$$\alpha_{eff} = \frac{k_{eff}}{(\rho c_p)_{eff}} \quad (5)$$

where the heat capacitance of the nanofluid is given by:

$$(\rho c_p)_{eff} = (1 - \varphi_s)(\rho C_p)_L + \varphi_s(\rho C_p)_s \quad (6)$$

where the thermal expansion coefficient of the nanofluid can be determined from:

$$(\rho\beta')_{eff} = (1 - \varphi_s)(\rho\beta')_L + \varphi_s(\rho\beta')_s \quad (7)$$

The effective dynamic viscosity of the nanofluid given by Brinkman [14] is:

$$\mu_{eff} = \frac{\mu_L}{(1 - \varphi_s)^{2.5}} \quad (8)$$

II. INTRODUCTION

As technological ideas evolve, newer and better materials are needed to make such technologies a reality. Nanofluids consist of a base fluid containing colloidal suspension of nanoparticles. Nanoparticles are particles with a range of diameters from 1 – 100 nanometers. Common base fluids are water, oil, and ethylene-glycol mixtures. The literature has revealed that the low thermal conductivity of these common base fluids is a primary limitation in enhancing the performance and the compactness of many devices [15]. When nanoparticles are added to these base fluids, anomalous, but understandable behavior, results. Nanofluids have a substantially larger thermal conductivity compared to that of the common base fluids [16]. The suspended nanoparticles in the fluid can change the transport and thermal properties of the common base fluid [17]. A drastic increase in thermal conductivity is observed with the addition of the nanoparticles to the base fluid and this is observed to increase non-linearly with increased nanoparticle concentration. The thermal conductivity of a nanofluid is found to be highly temperature dependent. Nanofluids also exhibit an increased boiling critical heat flux (CHF) as seen in the graphs in Figs 3 and 4.

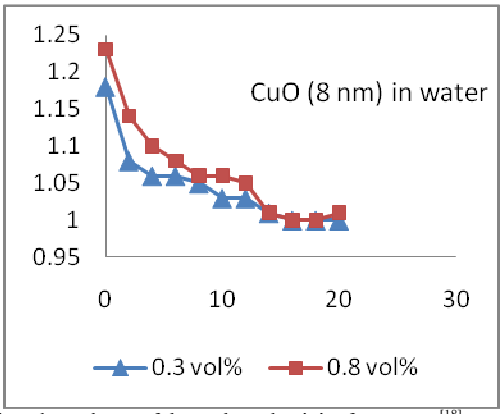

Fig. 3 Time dependence of thermal conductivity for copper [18].

III. PROMISING PROPERTIES

With just a small addition of nanoparticles to a fluid, drastic increases in Thermal Conductivity (TC) have been observed [19]. TC of doped nanofluids is also found to be highly temperature dependent. Das et al [20] studied Al_2O_3 and Cu.O particles in a water base. A "temperature oscillation technique" was used to measure thermal conductivity of the samples at varying temperatures. What was found was a drastic increase in TC over a small temperature range ($20^oC - 50^oC$).

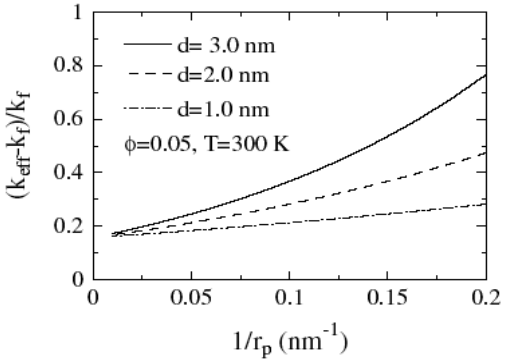

Fig. 4. Dependence of thermal conductivity enhancement on Oxide/water nanofluid [18] on the reciprocal of the nanoparticle radius [19].

Additionally, the increase in thermal conductivity (TC) of doped nanofluids is found to be non-linear with increased nanoparticle concentration [21-24]. This trend is anomalous compared to the expected small linear increases in TC predicted by existing models. Though these may be more drastic in some nanofluid compositions than others, there is still a drastic non-linear increase in TC in doped nanofluids compared to their bases (typically up to a certain saturation volume fraction).

The increases observed in TC of doped nanofluids makes them very appealing because conventional heat transfer fluids have poor TC compared to solids. Nanofluids could be used in new engineering devices that require faster heat transfer in order to produce quicker heating or cooling of a system [25]. Also, nanofluids are more fluid than other particle-liquid systems due to the smaller size of particles in the base. This has numerous advantages because it can prevent clogging of the fluids as technologies miniaturize.

Critical Heat Flux (CHF) was measured by You et al [26] in an Al_2O_3/water nanofluid. With just a small addition of nanoparticles, a very large increase in CHF was observed compared to that of just water. They were not able to explain the almost double increases observed in CHF, but the revelation is quite exciting. This information is of great interest because a higher CHF means greater cooling can be achieved. This is especially of value in the design of nuclear reactors where cooling is critical to the stability of the system [27, 28] and also in the design of MEMS, Graphines and other materials.

IV. OUTLOOK

According to the work of Emily Pfautsch 2008, it was revealed that prior to the development of production methods for creating nano-sized particles of metals and metal oxides; some research was done on the effects of putting millimeter or micrometer-sized particles inside fluids. These revealed that although these particles helped improve the thermal conductivity of the fluid, they also created other problems such as settling, drastic pressure drops, channel clogging, and obvious premature wear on channels and components. Nano-sized particles have obvious advantages over even micro-sized particles because they approach the size of the molecules of the fluid containing them, and this helps prevent the nanoparticles from settling due to gravity and causing clogging and wearing, as mentioned above. Fluid thermal conductivity models as have been proposed by Li & Peterson[29] and Hamilton and Crosser[30], which are effective for calculating thermal conductivities of fluids with micro or larger sized particles [31] exist, but neither can predict the enhanced thermal conductivities of nanofluids because the models do not include any bulk dependence on particle size [32].

To produce a good amount of Nanoparticles, two processes/methods are employed in the literature: (1) physical and (2) chemical processes. The physical methods involve mechanically grinding materials and the inert gas condensation technique. The chemical methods involve chemical precipitation, spray pyrolysis, and thermal spraying.

The two ways in which nanofluids are produced include either a one-step process or a two-step process. The one-step process which is considered to be the most accessible and less disadvantageous involves simultaneously making and dispersing the nanoparticles directly into the base fluid; while with the two-step process, the nanoparticles are made and then dispersed in the fluid later. It has been observed that the two step process has the disadvantage that the nanoparticles tend to agglomerate before the nanoparticles can be dispersed in the fluid, while the one-step process is favored because it prevents the oxidation of the nanoparticle [33] themselves.

While most research work have been done to explain how variables affect the thermal conductivity of nano-fluids, the effects of the same variables on the heat transfer coefficient still remains elusive. According to the work of Emily Pfautsch, Nano-fluid heat transfer enhancement has been attributed to a number of fundamental mechanisms which she listed and described as follows:

- Liquid layering on the nanoparticle-liquid interface
- Volume Fraction
- Particle Agglomeration
- Reduction in thermal boundary layer thickness
- Nanoparticle size
- Particle shape/surface area
- Brownian Motion
- Temperature Effects and
- Thermophoresis

*Liquid layering on the nanoparticle-liquid interface is explained by observing that w*hile the thickness and thermal conductivity of nano-liquid-layer on nanoparticles are yet to be established, the liquid molecules close to a solid surface have been proven by Yu, Richter, Datta, et. al. [34] to form layers which help to enhance the heat transfer properties of the nanofluid of which they are a part. Ren et al established a theoretical model to study the change in thermal conductivity from adding liquid layering on the nanoparticles in which they assumed that the thermal conductivity of the layer would be somewhere between the thermal conductivity of the bulk fluid and that of the nanoparticles themselves. They observed that an increase in the layer thickness lead to large enhancement in thermal conductivity.

Volume Fraction is explained from the work carried out by Jang et al 2007[35], and Karthikeyan at al 2008 [36], who revealed that effective thermal conductivity of nanofluid increases with increasing volume fraction of the nanoparticles, but as the volume fraction of nanoparticles increased themselves, it was observed that it may no longer be valid to assume that the nano-particles remain suspended. This confirms that it is more effective to use small volume fractions than otherwise, in nanofluids.

Nanoparticle size was explained by the observations and confirmation that as nanoparticles are reduced in size, the effective thermal conductivity of the nanofluid also increases [37]. The explanation of this observation was that as the nanoparticle size was reduced, Brownian motion was induced, and lighter and smaller nanoparticles were better at resisting sedimentation [38].

Particle shape/surface area was explained through the observation that rod-shaped nanoparticles as are observed with carbon nano-tubes, have been shown to remove more heat than spherical nanoparticles [39, 40, 41]. This observation may be attributed to the fact that rod-shaped particles have a larger aspect ratio than their spherical counterparts.

Particle Agglomeration was explained with the observations gleaned from research and that due to molecular forces such as Van Der Waals force Karthikeyan, Philip, and Raj [40, 41, 42] found in their experiments with copper oxide/water nanofluid that the nanoparticle size and cluster size have a significant influence on thermal conductivity; just as they also found that agglomeration is time-dependent. As time elapsed in their experiment, agglomeration increased, and this had a tendency to decrease the thermal conductivity.

Brownian Motion, a well established phenomenon, have resulted from the works of Jang et al 2004 and Chon et al 2005 [43] who have revealed that Brownian motion, which is represented by the random movement of particles, is one of the prime movers of heat transfer mechanisms in nanofluids, which is thought to cause a micro-convection heat transfer effect as a result of presence of extremely small particles in the fluid.

Temperature effects have been explained through the research of Chon et al on alumina nanofluid and how their thermal conductivity varies with temperature. They reported observations which show that the effective thermal conductivity and Brownian motion of nanofluids increased with temperature [44, 45 and 46]. In other words, the ratio of the thermal conductivity of the nanofluid to the thermal conductivity of the base-fluid was observed to be highly dependent on temperature as well as volume fraction.

Thermal Conductivity has been explained by Garg, Poudel, Chiesa, et al. [47] who through their investigation on copper/ethylene glycol nanofluid, found that the thermal conductivity was twice the amount as that predicted by the Maxwell effective medium theory.

Thermophoresis - this is a phenomenon that is said to occur as a result of the kinetic theory in nanofluid, where high energy molecules in a warmer region of nanofluid impinges on the molecules with greater momentum, than those molecules from a cold region of the same flow even though the cold molecules appear heavier. This effect leads to a migration of particles in the direction opposite to the temperature gradient, that is to say, from warmer areas to cooler flow regions, contrary to expectations.

V. EXPERIMENTAL TECHNIQUES

The literature has also revealed that the most common method used for measuring thermal conductivity in nanofluids is the transient hot wire method. In this method, a thin platinum wire coated with an electrically insulating layer is immersed in the nanofluid and a constant current is passed through the wire. The temperature rise of the wire is measured as a function of time. The thermal conductivity can then be measured using the equation (9):

$$k = \frac{Q}{4\Pi L \frac{dT}{d(\ln t)}} \quad (9)$$

where k is the thermal conductivity of the nanofluid, Q is the total power dissipated in the wire, L is the length of the wire, T is the wire temperature, and t is the time. In order to measure the temperature rise, the hot wire is made part of a Wheatstone bridge. The change in the wire temperature causes a change in the wire resistance, which causes the bridge to become imbalanced. The change in the wire resistance is then calculated from the voltage imbalance measured in the bridge. The change in wire resistance is compared to data that correlates the change in wire resistance to a change in temperature by calibration, and the temperature difference is obtained. Using the transient hot wire technique correlates a coefficient to the temperature drop, and it should be pointed out that this coefficient encompasses all forms of heat transfer that may be taking place, whether it is conduction, nano-convection, or any other mode.

VI. HEAT CAPACITY

Studies show that the heat capacity of nanofluid is incorporated into the energy equation, so it is important to be able to calculate it accurately. Most researchers use one of two correlations, which are given in Equations 10 below:),

$$C = (1-\varphi)C_{bf} + \varphi_{cp} \quad (10a)$$

$$C = \frac{(1-\varphi)(\rho C)_{bf} + \varphi(\rho c)_p}{\rho} (10b)$$

where C is the heat capacity, φ is the volume fraction of nanoparticles, and ρ is density. The subscript *bf* refers to properties of the base fluid and the subscript *p* refers to properties of the nanoparticles. Equation (10a) is simply the rule of mixtures applied to heat capacity, while Equation (10b) is an altered form. Mansour, Galanis, and Nguyen [48] plotted both functions as a ratio to the specific heat of the base fluid with respect to the nanoparticle concentration in the nanofluid.

Mansour, Galanis, and Nguyen were not sure which correlation was correct, so they assumed both to be valid, but Zhou and Ni [49] investigated both correlations more closely, and found that Eq. (10b) was valid. Their results for alumina nanoparticles in water mimic those of Mansour, Glanis, and Nguyen.

VII. VISCOSITY

Prasher, Song, Wang, et al. [50] found that the viscosity of nanofluids is extremely dependent on nanoparticle volume fraction, but is independent of the shear rate, nanoparticle diameter, and temperature, in a paper published solely on the experimental results of the viscosity of alumina particles in propylene glycol, and its dependency on particle diameter, nanoparticle volume fraction, and temperature. The fact that the nanofluid viscosity is independent of shear rate and nanoparticle diameter indicated that the nanofluid obeys Newtonian flow behavior. From their data, it can be assumed that it is possible for the increase in viscosity to get larger than the increase in thermal conductivity.

Garg, Poudel, Chiesa, et. al. conducted an experiment to test the viscosity of copper nanoparticles in ethylene glycol and found that the increase in viscosity was about four times of that predicted by the Einstein law of viscosity given by (11) below,

$$\frac{\mu}{\mu_{bf}} = 1 + 2.5\varphi (11)$$

where μ is the viscosity of the nanofluid, μ_{bf} is the viscosity of the base fluid, and φ is the nanoparticle volume fraction.
Garg, Poudel, Chiesa et al. found that the 2.5 in Eq. (11) should be about 11 to correlate with their data. They also noted that with such a high viscosity, flow in very small tubes would not be effective in heat transfer, and that larger tubes would be more effective.
In Pak and Cho's [51] experimental study of turbulence of alumina/water and titanium oxide/water nanofluid combination, flowing through a round pipe, it was observed that flow viscosity increased 200 times that of water, for water with 10% volume fraction of alumina and they also found a 3 times increase for 10% volume fraction of titanium oxide nanoparticles in water.

Viscosities of the nanofluids decreased asymptotically with increasing temperature, and the rate of decrease of the viscosity became greater as the volume fraction increased according to the work of Pak and Cho. They suggested that the observed increase in viscosity may be due to the visco-electric effect, which is due to the fact that the effective particle dimension is larger than its radius and equal to the Debye length (the scale over which electrons screen out electric fields). Pak and Cho also found that the sphere size and shape has an effect on viscosity. As the sphere diameter is decreased and the sphere shape becomes more irregular, the viscosity increases. The irregular shape of the nanoparticle is thought to increase viscosity because the surface area to volume ratio has increased.

Nanofluids present many potentially useful properties though the origins of these properties are not well understood. Many theories have been proposed in an attempt to model the behavior of doped nanofluids, but much work remains to be done. A theoretical model based on the 2-D continuity, momentum and energy equations have been proposed and used in the early 2000. That solution procedure was based on the equi-partition theorem which states that when a nanoparticle reaches thermal equilibrium with its environment, the velocity of flow can be described as $U = (kT/m)^{1/2}$, where m is the mass of the nanoparticle, k = 1.38054x10^{-23} J/K is the Boltzmann constant, and T is the temperature of the composite. It is the view here that experimental probing of the nano-scale structure of the fluids as well as advanced computational methods which examine both chemical and physical interactions of the particles and their base fluids, need to be utilized to gain a better understanding of nanofluid systems.

To do the above, we must address the theory from the complete momentum and heat transfer equations set (the complete Navier Stokes Equations). For steady, incompressible and axially symmetric flows ($\partial/\partial\theta = 0$), in cylindrical co-ordinates, the Navier-Stokes equations and the continuity equation are known to be represent-able thus Gosman et al [52] and Okhio [53]:

$$a_\varphi\left[\frac{\delta}{\delta z}\left(\varphi\frac{\delta\psi}{\delta r}\right)-\frac{\delta}{\delta r}\left(\varphi\frac{\delta\psi}{\delta z}\right)\right]-\frac{\delta}{\delta z}\left(b_\varphi r\frac{\delta}{\delta z}(c_\varphi\varphi)\right)-\frac{\delta}{\delta r}\left(b_\varphi r\frac{\delta}{\delta r}(c_\varphi\varphi)\right)+rd_\varphi=0 \quad (12)$$

The equation (12) above represents the main equation that is equivalent to all the equations of fluid momentum and heat transfer in which the pertinent variables are represented in the Table 1 below. Because all the above equations have the same form, when a solution has been found for one, others will become automatically solvable. The next task is to reduce them from their partial differential forms to finite difference approximations, which are then in a form suitable for programming on the digital desktop computer.

The equation (12) is general with ϕ standing for four variables ψ, ω, T and U_θ, and $a_\phi, b_\phi, c_\phi, d_\phi$ for coefficients represented in Table I below.

TABLE 1 - COEFFICIENTS

ϕ	a_ϕ	b_ϕ	c_ϕ	d_ϕ
$\frac{\omega}{r}$	r^2	r^2	μ_{eff}	$S_\omega^o - \frac{\partial}{\partial z}(\rho U_\theta^2)$
ψ	0	$\frac{1}{\rho r^2}$	1	$-\frac{\omega}{r}$
rU_θ	1	$\mu_{eff} r^2$	$\frac{1}{r^2}$	0
T	1	$\Gamma_{h,eff.}$	1	0

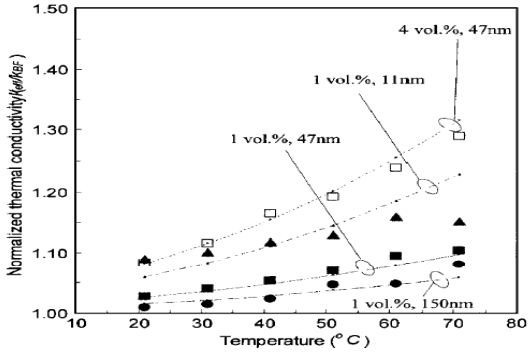

Fig. 5 Comparison of heat capacity formulas

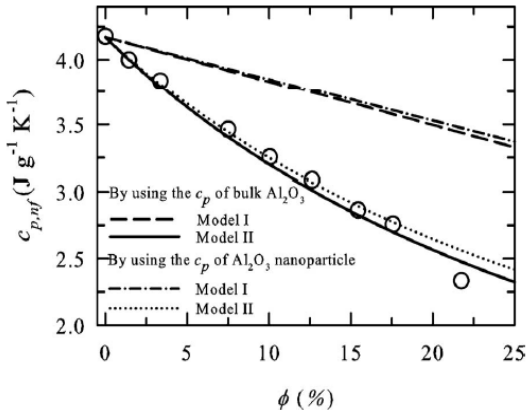

Fig. 6 Comparison of specific heat correlations

The comparisons between heat capacity formula and specific hear correlations are given in Figs. 5 and 6.

VIII. CONCLUSION

Nanofluids have extensive potential applications in engineering and science. Their anomalous properties have proven to be a pleasant surprise. With small additions of nanoparticles to a typical base liquid, it is found that a drastic increase in TC that is both highly temperature dependent and is found to increase non-linearly with the addition of more nanoparticles, results. Also, nanofluids have a higher CHF which is useful in many applications. However, a better understanding of how said properties work is critical. In order to obtain a better understanding of nanofluids' structures, both experimental and theoretical methods must be employed by researchers. A more elaborate understanding of nanofluids will only present to us the power to keep up with the high demand for cutting edge miniaturized technologies and will enable us to journey past the current limits that exist particularly in areas such as electronic packaging.

Having said the above, it is fair to conclude that current research have explored variations in Nanoparticle diameter size, nanoparticle volume fraction, nanofluid temperature, and free stream velocity in order to observe their effects on nanofluid characteristics and the heat transfer coefficient of different nano-fluid combinations under varying flow characteristics such as laminar forced convection over a flat plate. Of the parameters studied, observations show that the nanoparticle size and volume fraction affected the heat transfer coefficient and flow development the most. Full development of the flow has also been observed as it were in regular fluid flow, both for laminar as well as turbulent flows. In addition, increasing the free stream velocity for different types of nanofluids caused the velocity profile to develop a farther distance down the plate, as would be expected.

The literature has also shown that the nanoparticle volume fraction distribution has a large effect on the heat transfer coefficient. When nanoparticles are evenly dispersed throughout the fluid, the heat transfer coefficient was observed to increase by as much as 2 to 3 times compared to having a 1.5% volume fraction difference between the top and bottom. For water, the heat transfer coefficient increased as much as 130% and for ethylene glycol, the heat transfer coefficient increased by as much as 275%. These show the importance and the need for nanoparticles to stay suspended in the fluid even though the work reported by Yu, Singh, Timofeeva, and France in 2010[54] showed that larger particle nanofluid tended to provide better heat transfer properties in both laminar and turbulent flow regimes as is expected because of the large mass-fraction effects.

Also, from a nanometer to a picometer, the 16% increase in heat transfer coefficient for the water based nanofluid and about a 100% increase for the ethylene glycol based nanofluid has been attributed to the decrease in particle sizes. Decreasing the nanoparticle size also dispersed the volume fraction of the nanoparticles farther away from the solid boundary and lowered the temperature next to the solid boundary. The pleasant news from recent studies is that if sub nano sized particles could be mass produced for use in nanofluids, the heat transfer capabilities of

nanofluids could be improved by using smaller particles exhaustively.

We therefore conclude that many of the heat transfer enhancements observable in the works reported here were most noticeable when the nanoparticle size became smaller than a nanometer. Other improvements to the analysis of the literature include adding the effects of agglomeration, fluid nano-layers, and transition to turbulence [55 – 60]. Producing more experimental data in the future will enhance the studies on predictive and modeling tools for nanofluid calculations with or without heat transfer components.

ACKNOWLEDGMENT

The remarkable contributions of Ms. Jennifer Black B.Sc., the outgoing President of the **Southern Polytechnic State University, Undergraduate Research Club**, in the collection of research material for this publication, is hereby acknowledged and appreciated.

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