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A Study on Thermal Conductivity of Nanofluids

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Abstract – Nanofluids have been an area of interest since the past decade due to their number of potential applications in various fields. Their physical properties have been studied on a vast scale like thermal conductivity, viscosity etc. we present in this paper a study on the existing explanations on the mechanism of the anomalous thermal conductivity enhancement and varied experimental results put forward by the scientific community so far. The paper discovers that a much more deep study is needed both on experimental and theoretical platform in order to derive maximum from these emerging smart fluids.

Keywords: Nanofluids, Heat Transfer, Thermal Conductivity.

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1. INTRODUCTION

In this era of technological growth in industries, microelectronics, manufacturing and transportation, metrology and defense, there is a need to increase energy efficiency and reusability. However, the ability to rapidly cool the products being used needs to be increased dramatically because of increased loads and heat fluxes caused by increase in power and decrease in size of products i.e miniaturization. Consequently cooling is indispensible for maintaining the performance and reliability of the variety of products such as computers, power electronics, car engine and high powered lasers or x- rays (Wong & Leon, 2010. Nagar, et. al., 2013. Taylor, et. al., 2013). Air cooling is the most basic method for cooling electronics systems. However, higher heat flux over 10000Wm^{-2} in electronic devices and systems will necessitate the use of liquid cooling. In transportation industry, cooling is an important issue because of increasing trend towards higher engine power and exhaust-gas regulation or hybrid vehicles inevitably leads to larger radiators and increased frontal areas, resulting in increased fuel consumption (Wong & Leon, 2010). A pressing need for cooling also exists in ultra-high heat flux optical devices with brighter beams such as high powered x- rays.

A new approach to enhance heat transfer is necessary to meet cooling challenge caused by demand of more efficient heat transfer fluids in many industries such as transportation, electronics etc. The earlier technique was to disperse millimeter or micrometer sized particles in heat transfer fluids leading to increase in its cooling rate. The idea was to increase thermal conductivity behavior of cooling fluids. (Maxwell, 1891) first came out with theoretical basis for calculating effective thermal conductivity of suspension. The efforts were followed by Hamilton- Crosser [5] and wasp [6]. But on bitter side, such suspensions have following disadvantages.

1. The suspended particles settled rapidly (sedimentation) on the bottom surface of the container containing such suspensions, thereby reducing its heat transfer capability.

2. The sedimentation was reduced by increasing the circulation rate of the fluid but this led to increased corrosion or erosion of pipelines or containers carrying these fluids.

3. The millimeter or micrometer sized particles tend to clog the flow channels if cooling channels if cooling channels were taken narrow.

4. Pressure drop in fluid increased to considerable amount when large number of particles was suspended in the base fluid. This also required higher pumping power.

With the advent of nanotechnology in nineties, when it became possible to manufacture nano-sized particles, it was proposed that nanoparticles instead of micro-sized particles be used to form colloidal suspensions. These were quite stable with a very little settling in static conditions, the reason attributed to their extremely small size. Such stable colloidal suspensions were called ‘nanofluids’. This term was coined by S.U.S. Choi [7] at Argonne national laboratory which denoted this new class of engineered fluids. They had following advantages over microsized particle suspensions (Das, et. al., 2008):

1. More suspending time (more stability)

2. Higher surface area

3. Lower chances of erosion

4. Lesser clogging of channels

5. Higher thermal conductivity

6. Lower pumping power requirement

7. Energy saving efficiency

The unusually high effective thermal conductivity at small volume fraction of nanoparticles and increased heat flux intrigued the research community for several years. They were thought to be perfect for use as coolants and other cooling applications. Choi [7] quantitatively analyzed their potential benefits on thermal conductivity enhancement on reducing size and weight and reducing cost of thermal equipment.

1.1 SYNTHESIS OF NANOFLUIDS

a. Production of nanoparticles

The nanoparticles are the key building blocks of nanofluids so the available methods used to produce nanofluids are mechanical grinding, inert gas condensation technique, chemical vapor deposition, chemical precipitation, spray pyrolysis (Lee, et. al., 1999) etc.

b. Making of nanofluids

1. One-step technique

Direct evaporation one step method has been used to produce a nanofluid which combines making of nanoparticles and dispersing them into the base fluid into a single step. The nanoparticles which are initially in gas phase in the base fluid are solidified leading to a dispersion called nanofluid. This method prevents drying, storage, transportation and aggregation problem of nanoparticles (Yu & Xie, 2012) thereby increasing their stability. Sometimes residual impurities are left in the mixture owing to incomplete reaction which may adversely affect the conducting properties of nanofluids.

2. Two-step technique

In this step first nanoparticles are first produced as a dry powder by inert gas condensation technique, chemical vapor deposition etc. and then dispersed in the base fluid. This method has been used by Eastman et.al 1997 [11], Lee et.al 1999 [9], and Wang et.al 1999 [12]. This technique has advantages over the first one in terms of mass production of nanofluids. The main challenge is to obtain a fine dispersion as the nanoparticles tend to coagulate to form clusters. For that purpose addition of surfactant or process of thermal agitation is often used. The vacuum-SANSS (submerged arc nanoparticle synthesis system) is another efficient method to prepare nanofluids using different dielectric liquids

(Wong and Kurma, 2008), (Wong, et. al., 2007), Choi, et. al., 2004), (Hwang, et. al., 2006). One of other methods of synthesis nanofluid is laser ablation method (Tran and Soong, 2007). Both these are single step methods. There are four points that are necessary to be looked after for the synthesis of nanofluids which are dispersibility, stability, chemical compatibility and thermal stability of nanofluids.

1.2 NANOPARTICLE AND THE BASE FLUID

The various types of nanoparticles used for making nanofluids are

1. Oxide nanoparticles

In this category Al_2O_3, CuO, TiO_2, Fe_2O_3, SiO_2, ZrO_2 etc. have been used to makes various nanofluids.

2. Metallic nanoparticles

The different metal particles used for the purpose are copper, aluminium etc.

3. CNTs

The products of carbon such as carbon nanotubes (CNTs), graphenes etc. have been dispersed in base fluids to prepare nanofluids.

The most commonly used base fluids are water, ethylene glycol and engine oil. Refrigerants and lubricants have also been used to add nanoparticles to enhance their thermal conducting properties. Some surfactants like CTAB are also added in nanofluids for improving the stability of nanofluids. The variability of thermal conductivity values for different materials is evident from the table I. The solid nanoparticles including mettslic and nonmetallic particles exhibit higher thermal conductivity and when these are dispersed in base fluids, the resultant is expected to show better heat transfer properties.

Table I: Thermal Conductivity of Various Materials

	Material	Thermal conductivity ($Wm^{-1}.K^{-1}$)
Metallic solids	Silver (Ag)	429
	Copper (Cu)	401
	Aluminium (Al)	237
	Iron (Fe)	80

	Gold (Au)	318
Nonmetallic Solids	Diamond	3300
	Carbon nanotubes	3000
	Silicon	148
	Gold	315
	Alumina	40
	Copper oxide	17.64
Metallic liquids	Sodium at 644K	72.3
Nonmetallic liquids	Water	0.613
	Ethylene Glycol	0.253
	Engine Oil	0.145
	Toluene	0.133
	Poly (α-olefin) oil	0.117

1.3 DETERMINING EXPERIMENTALLY THE THERMAL CONDUCTIVITY OF NANOFLUIDS

Thermal conductivity is the most important parameter in deciding the heat transfer performance of the nanofluid. The methods which are being used to determine thermal conductivity of nanofluids are Transient hot wire method, and the steady state method. Temperature oscillation technique and hot strip method are seldom used methods. The basic equation in these methods is

$$k = c\frac{Q}{\Delta T}$$

In Transient Hot wire method, a thin metal wire (usually Platinum) immersed directly in the fluid under consideration. This acts as a heat source as well as a thermometer. This wire forms one arm of the wheatstone bridge with other known resistance arms. The principal behind is the observation of the rate at which temperature of the wire increases with time with a step up in voltage. It has proved to be the most reliable and accurate method to measure the effective thermal conductivity of the nanofluids with minimized effects of natural convection and high speed measurements.

1.4 EXISTING EXPERIMENTAL RESULTS ON THERMAL CONDUCTIVITY OF NANOFLUIDS

Experimental work so far in this area (Jeffrey, 1973, Koo and Kleinstreuer, 2004, Wang, et. al., 2003), (Xuan and Li, 2000, Hong, et. al., 2005, Putnam, et. al., 2006, Murshed, et. al., 2005, Murshed, et. al., 2009) has exhibited higher thermal conducting properties in nanofluids than the fluids without dispersion of nanoparticles or the conventional fluids used for heat transfer. For instance, Masuda et. al. (1993) [25] reported a 30 percent increase in thermal conductivity of water when 4.3 volume percent of aluminium oxide nanoparticles are added to it. The need for efficient cooling performances and the unexpected increase in thermal conductivity using nanofluids has aroused interest of research community to explore more about these fascinating colloidal suspensions.

Researchers have demonstrated that nanofluids consisting of CuO/Al_2O_3 nanoparticles in water or ethylene glycol exhibit increase in thermal conductivity to a considerable extent with addition of small volume fraction of nanoparticles. Wang et.al in 1999 [12] reported a maximum of 12 percent increase in thermal conductivity with a volume fraction of 3 percent for Al_2O_3/water nanofluid. The enhancement was found to be roughly proportional to volume fraction of nanoparticles. They also reported the effect of particle size on thermal conductivity enhancement.

Lee et.al [9] in 1999 studied Al_2O_3/EG and CuO/EG systems and a 20% increase was seen with 23.6nm of CuO nanoparticles in EG with a volume fraction of 4%. Zhou and Wang [26] saw a 17% increase in thermal conductivity in CuO/Water nanofluid system with just 0.4% volume fraction of CuO nanoparticles with the size of 50nm. M. Kole et.al [27] in 2011 show a 10.4% increase in thermal conductivity of gear oil with 2.5% volume fraction of CuO nanoparticles with the size of about 40nm. Eastman et.al (2001) [11] reported 40 percent enhancement of thermal conductivity of the base fluid with addition of 0.3 % Cu metallic nanoparticles. The base fluid used was ethylene glycol. Hong et. al [21] showed an enormous increase in thermal conductivity of nanofluids of 10nm size with 0.55% Fe nanoparticles suspended in ethylene glycol.

Das et.al [28] reported enhancement results for Al_2O_3 and CuO nanoparticles in water as the base fluid with temperature. They used temperature oscillation technique to measure thermal conductivity of these systems. They also studied the variation of thermal conductivity with size of the nanoparticles and suggested that smaller is the nanoparticle the higher is its mobility leading to a higher level stochastic motion. Similar to the above study Patel et.al [29] studied metal nanoparticles of Au and Ag in water and toluene coated with thiolate and citrate coating. They gave the polynomial variation of thermal conductivity with temperature and a linear variation of thermal conductivity with particle concentration. The nanoparticles which were coated using thiolate showed less thermal conductivity enhancement as compared to the nanoparticles with citrate coating. M. Yeganeh et.al [30] show an enhancement of 3%

in thermal conductivity of Diamond/water nanofluid. Xie et.al (2002) [31] studied SiC in water and ethylene glycol and reported a linear increase in enhancement of thermal conductivity with volume fraction of nanoparticles.

K. B. Anoop et.al [32] used Al_2O_3/water nanofluid to show the enhancement in thermal conductivity taking the size of the particles to be 45nm and 150nm. They studied experimentally the effect of particle size on the convective heat transfer in nanofluid in the developing region. TiO_2/water nanofluid has been studied by Abbasin et.al [33] taking the particle size to be 30nm. The effect of particle volume concentration and reynold number was seen on the Nusselt number. According to this paper higher Reynold number nanofluids are more beneficial than those having low Reynold number. Murshed et.al [24] also studied TiO_2/Water nanofluid system with both spherical and rod shaped nanoparticles predicting experimentally an enhancement of more than 30% with volume fraction ranging from 0.5% to 5%.

Enhancement in thermal conductivity in case of Carbon nanotubes has been found to be two orders of magnitude higher than the base fluid. Assael et.al 2005 [34] reported 34% for 0.6% volume for MWCNTs of around 130nm average diameter and average length of 40µm. Hwang et.al in 2005 [35] have reported similar results for MWCNTs in water and ethylene glycol. Nanofluid containing carbon nanotube (1% volume fraction) in oil exhibit 160% enhancement which is the greatest enhancement of thermal conductivity as shown by Choi et.al (2001) [36]. Kolade et.al [37] show a 10% increase in thermal conductivity of silicone oil with 0.2% of MWCNTs added to it. Jiang et.al in 2009 [38] studied CNTs in nanorefrigerants and tried to predict the thermal conductivity enhancement both theoretically and experimentally. They modified Yu and Choi model to give results with a mean deviation of 5.5%. They found a higher enhancement in case of CNT-R113 nanorefrigerant as compared to CNT water based nanofluid.

0.24 volume percent Polyaniline nanofibres have been dispersed in water to increase its thermal conductivity by 140% by M. Wan et.al [39]. Abareshi et.al [40] and A. Gavili et.al [41] have predicted the enhancement of thermal conductivity in case of Fe_3O_4/water nanofluid system as 11.5% and 200% with 3% and 5% volume fraction of nanoparticles. Usri et.al [42] have studied experimentally the thermal conductivity enhancement in Al_2O_3 nanoparticles suspended in base fluid which is a mixture of water and ethylene glycol and they have predicted 12.6% enhancement with 2% volume fraction of alumina nanoparticles. Esfe et.al [43] have investigated the effect of volume fraction and temperature on thermal conductivity of CNT-Al_2O_3/water hybrid nanofluid. CNTs having an outer diameter of 5-15nm were used along with 20nm sized alumina nanoparticles with water as the base fluid to form a hybrid nanofluid. They predicted a nonlinear increase in enhancement in effective thermal conductivity with solid volume fraction. Qing et.al [44] have found 80% enhancement in thermal conductivity at pH 9 in case of SiO_2- graphene nanoparticles added to naphthenic mineral oil. This hybrid nanofluid is found to be stable at pH 11 to improve the nanoparticle dispersion in transformer oil.

Pryazhikov et.al (2017) [45] have put forth the thermal conductivity enhancement of more than 50 nanofluid systems. On the basis of their experiments, they have predicted that the thermal conductivity coefficient is rather a complicated function of factors like particle concentration, size and material of the nanoparticle and the type of base fluid used. According to Pryazhnikov, there is no direct correlation between thermal conductivity of material of nanoparticle and thermal conductivity of nanofluids formed by these nanoparticles.

Various authors have performed different experiments which show variability in the thermal conductivity enhancement values for the same nanofluid system. Most of the above papers have used transient hot wire method to carry out the experimental work as it is one of the most accurate methods to measure thermal conductivity of nanofluids. The careful making of nanofluid i.e its preparation and management while making thermal conductivity measurements along with the stability conditions could be the possible reason for such varied results. Experiments done by good number of groups have certainly revealed that nanofluids have thermal properties superior to base fluids.

1.5 EXISTING THEORETICAL MODELS FOR THE EFFECTIVE THERMAL CONDUCTIVITY

Starting from Maxwell model 1892 many other classical models like Hamilton-Crosser [5], Davis model [46] and Jeffery model [17] etc. came up to explain the anomalous thermal conductivity of the nanofluids. Maxwell model considers the nanofluid to a uniform system with dispersion of spherical nanoparticles which are randomly placed.

$$\frac{k_{eff}}{k_f} = \frac{(k_p + 2k_f) + 2\phi(k_p - k_f)}{(k_p + 2k_f) - \phi(k_p - k_f)}$$

Hamilton Crosser model provides a modification to the Maxwell model using the shape factor for the two phase dispersions. Hamilton-crosser consider empirical shape factor η=3/ψ for spherical and cylindrical shaped particles. But this dealt with micrometer sized particles.

$$\frac{k_{eff}}{k_f} = \frac{(k_p + (\eta - 1)k_f) - (\eta - 1)\phi(k_f - k_p)}{(k_p + (\eta - 1)k_f) + \phi(k_f - k_p)}$$

Bruggemann model [47] considers interaction between inclusion phases in the host phase. This model gives the thermal conductivity of a mixture of homogeneous spherical inclusions as

$$k_{eff} = (3\phi - 1)k_p + [3(1 - \phi) - 1]k_f + \sqrt{\Delta}$$

Where Δ is a function of ϕ, k_f and k_p.

All classical models depend on the shape of particle, its volume fraction, nature of the base fluid and the particle thermal conductivity. However, these didn't include cluster formation, particle size, Brownian motion and interfacial layer formation etc.

Static models assumed the nanoparticles to be stationary in the base fluids and thermal transport is due to conduction. Maxwell- Garnet model [48] assumed that there are no interactions between the nanoparticles. This model is based on effective medium theory. Dynamic models accounted for Brownian motion nanoconvection as the mechanism for heat conduction. Jang and Choi [49] have given model based on conduction and convection caused by Brownian motion of particles. They presented four models of energy transport in the nanofluid, heat conduction in base fluid, heat conduction in nanoparticles, collisions between nanoparticles and micro-convection caused by random motion of the nanoparticles i.e. Brownian motion. Keblinski et.al [50] in 2002 have also used four factors responsible for the enhancement in thermal conductivity of nanofluids and used the concept of Kapitza resistance for explaining the fourth model of energy transport. But they conclude that ballistic heat transport still cannot explain the anomalous thermal conductivity enhancement.

Xie et.al [51] proposed a model which considered the average heat flux contribution from fluid, nanoparticle and the nanolayer. The thermal conductivity has been obtained using Fourier law of heat conduction and is given by

$$k = 1 + 3\Theta\phi_T + \frac{3\Theta^2\phi_T^2}{1 - \Theta\phi_T}$$

Where

$$\Theta = \frac{\beta_{lf}\{(1+\gamma)^3 - \frac{\beta_{pl}}{\beta_{lf}}\}}{(1+\gamma)^3 + 2\beta_{lf}\beta_{pl}}$$

β's are the functions of thermal conductivites of particle, fluid and the layer. The thermal conductivity inside the layer follows a linear variation. Pasrija et.al [52] proposed a semi- empirical model to predict the thermal conductivity enhancement of nanofluid systems using an exponential thermal conductivity profile of the interfacial nanolayer.

A brownian motion based model has been presented by Prasher etal [53] in 2006 which incorporates the effect of the localized convection caused by Brownian motion of nanoparticles. The brownian motion is the random motion of nanoparticles in the base fluid as shown in figure. It was assumed to be the key factor in enhancing the effective thermal conductivity of nanofluids.

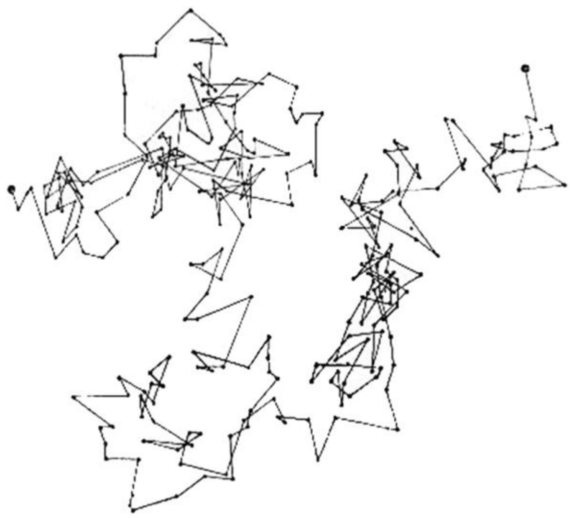

Figure 1 : Brownian motion [54]

According to Prasher, the effective thermal conductivity is given by

$$\frac{k_{eff}}{k_f} = (1 + A\mathrm{Re}^m \mathrm{Pr}^{0.333}\phi)\left[\frac{(k_p(1+2\alpha) + 2k_f) + 2\phi(k_p(1-\alpha) - k_f)}{(k_p(1+2\alpha) + 2k_f) - \phi(k_p(1-\alpha) - k_f)}\right]$$

In this expression, $\alpha = \frac{R_b k_f}{r_p}$, and is called the Biot Number. R_b is the interfacial thermal resistance between nanoparticles and base fluid. A is a constant found to be 4×10^4 [53] and Re is the reynold's number defined as

$$\mathrm{Re} = \frac{1}{\upsilon}\sqrt{\frac{9k_bT}{\pi\rho r_p}}$$

υ is the kinematic viscosity of the base fluid, ρ is the particle density and Pr is the Prandtl number. It gives the variation of effective thermal conductivity with the size of the nanoparticle as well as their volume fraction.

Yu and Choi [55] include the effect of interfacial nanolayer and gave a renovated Maxwell model. The ordered semi solid layer was thought to have an intermediate higher thermal conductivity between the nanoparticle and the base fluid.

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

Tillman et.al [56] in 2007 proposed a semi empirical approach to the thermal conductivity profile of the interfacial nanolayer and predicted the interfacial layer thickness of various nanofluid systems. Murshed et.al [57] in 2008 formulated a model which assumed the mixture to be composed of three components particle, interfacial layer and the liquid. Accordingly thermal conductivity is given by

$$k_{eff} = \frac{(k_p-k_{lr})\phi_p k_{lr}(2\gamma_1^3-\gamma^2+1)+(k_p+2k_{lr})\gamma_1^3(\phi_p\gamma^3(k_{lr}-k_f)+k_f)}{\gamma_1^3(k_p+2k_{lr})-(k_p-k_{lr})\phi_p(\gamma_1^3+\gamma^3-1)}$$

Where $\gamma = 1+\frac{h}{a}$ and $\gamma_1 = 1+\frac{h}{2a}$, a is particle radius, h is the interfacial layer thickness and k_{lr}, k_p, k_f are the thermal conductivities of the layer, the particle and the fluid respectively.

Patel et.al in 2008 [58] gave an improved model to study effective thermal conductivity of CNT nanofluids. According to this model the effective thermal conductivity is given by

$$\frac{k_{eff}}{k_f} = 1+\frac{k_s \varepsilon r_l}{k_f(1-\varepsilon)r_s}$$

where k_s , k_f, r_s , r_l are the thermal conductivities of solid nanoparticles and the fluid and r_s , r_l are radii of solid nanoparticles and the liquid or fluid.

Sohrabi et. al [59] put forward a semi analytical model based on thermal resistance approach. Their model considers simultaneous effect of nanolayer and the connective heat transfer caused by Brownian motion. The thermal conductivity is obtained as

$$k_{eff} = k_f(1-\sqrt[3]{\phi})\left[\frac{k_f}{k_l}\left(1-\frac{r_p}{r_o}\right)+\frac{2k_f r_p^2}{hd_p r_o^2}\right]^{-1}$$

where r_p/r_o is the ratio of outer and inner radius of the naoparticle. k_l is the overall heat conduction coefficient.

Hosseini et.al [60] formulated a model based on dimensionless groups to predict thermal conductivity of nanofluids. They used it to predict the thermal conductivity enhancement of the nanofluids containing carbon nanotubes. According to Hosseini the thermal conductivity is given as

$$k_{eff} = k_f\left[1+m\left(\frac{1}{d}\right)^{\alpha} a_R^{\beta}\phi_C^{\gamma}\right]$$

α, β and γ are empirical constants, a_R is the aspect ratio, d is the diameter of CNT nanoparticle and ϕ is its volume fraction. The values of the empirical constants have been determined by using method of least squares.

Liu et.al 2016 [61] gave reduced particle model by considering a thermal equivalent particle based on reducing the particle size by keeping thermal resistance constant . the reduced radius is given by

$$r_1 = \frac{(k_p-k_f)r_2^2}{(k_p-k_f)r_2+R_b k_p k_f}$$

where r_2 is the outer radius of the nanoparticle with a solid/liquid interface. R_b is the interfacial thermal resistance. The effective thermal conductivity is then obtained by using the existing Hamilton model based on effective medium theory (EMT). The model establishes that fact that particle size and aggregate size have positive effect on thermal conductivity enhancement.

A new theoretical model has been proposed by R chebbi [2017] recently. This model extends the Bridgman equation by adding the nanomaterial contribution to thermal conductivity. The following theoretical expression for effective thermal conductivity for small volume fraction is obtained as

$$k_{eff} = \frac{(1-\phi)^{1/3}k_f}{1+[(1-\phi)^{-1/3}-1](k_f/k_n)} + k_n[1-(1-\phi)^{2/3}]$$

where k_n is calculated as in Bridgman equation. The model does not include any fitting parameter and the model is applied to eight nanofluid systems. An ordered configuration structure lattice is considered and the result nearly supports the fact that transfer of energy takes place at the speed of sound in nanomaterial through collisions among nanoparticles.

Wang and Mujumdar 2007 [63] provided a review on different works on effective thermal conductivity of nanofluids. They compared experimental works by various researchers which described the forced and free convection flows and provided an insight into the ongoing research in this area. Most of the earlier classical models predicted a linear enhancement in thermal conductivity of nanofluids whereas experimental facts presented nonlinear variations with the volume fraction of nanoparticles.

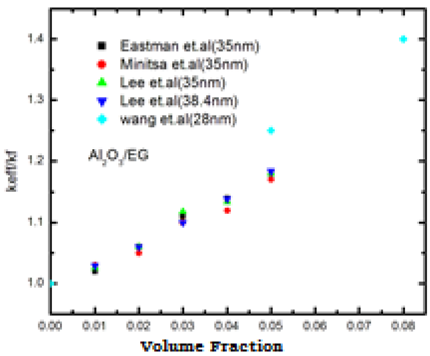

Figure 2: The experimental effective thermal conducitvity ratio for alumina/EG nanofluid

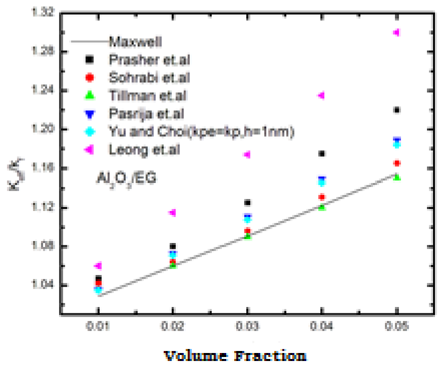

Figure 3: The theoretical results for alumina/EG nanofluid for particle size of 35nm

The collective observations of the literature show that many efforts have been put into in the past decade to find a proper explanation for the anomalous enhancement of thermal conductivity in nanofluids. The variation in different experimental results is as shown in figure 2 for Al_2O_3/EG nanofluid for similar sized diameters indicates that even for same sized nanoparticles dispersed in the base fluid may yield different enhancement. There are certain factors that need to be discussed like temperature, method of preparation, time for which the nanofluid remains stable etc. Figure 3 shows effective thermal conductivity ratio obtained by various models for Al_2O_3/EG nanofluid for particle size of 35nm. The different results are compared with the classical Maxwell model. Contributing factors are different for different models. Hence, still there is a need for a deeper insight as far as the factors affecting effective thermal conductivity is concerned. There needs to be an extensive and intensive research in this area for a fruitful outcome.

1.6 CONCLUSIONS

A strong demand exists that advanced heat transfer fluids with higher thermal conductivity be developed. It is a well-known fact that nanofluids have anomalous thermal conducting properties as compared to the base fluid values. They are potentially useful fluids which could be used for cooling in Microsystems. As a present scenario, there is a little inconsistency in the available experimental data as well as the measurement techniques available. Even a single model cannot explain all the properties of nanofluids as well as the wide dispersion in the experimental observations. The comprehensive outline of the ongoing research is that the nanofluids certainly are expected to be good champions as far as the heat transfer is concerned for the next generation of cooling devices. Further work is needed to explore the effect of all the contributing factors to gain more insight into the problem.

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