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RESEARCH ARTICLE

REVIEW OF EXPERIMENTAL AND NUMERICAL METHODS TO DETERMINE THERMAL CONDUCTIVITY OF NANOFLUIDS

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Abstract

Study and research around heat conduction mechanisms of nanofluids and suspensions are active for a decade. Several models of effective thermal conductivity of nanofluids have been published. This review summarizes recent research for thermal conductivity of a solid/liquid suspension and unfolds the effects of interfacial layers, shells, and aggregate structure on this property. Basically, experimental, and numerical, both, ways to determine thermal conductivity are summarized here in respective sections along with an introductory section named preparation of nanofluids. Key parameters affecting the preparation and stability of nanofluids are reviewed here and further scope of research is assessed. Numerical or theoretical thermal conductivity models are validated against experimental ones by some of the authors, which are reviewed and summarized here. The effect of different parameters pertaining to both nanoparticles and base fluids are reviewed and summarized here for different combination of metal/oxides as particles and water/oils as base fluids. Other properties such as viscosity, convective heat transfer, boiling heat transfer of nanofluids and suspensions are equally important and will be reviewed in subsequent reports.

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Introduction:-

The heat transfer properties of various fluids can be enhanced actively or passively by changing different parameters such as boundary conditions of fluid, fluid flow geometry and thermal conductivity of fluids. In the process of achieving higher or better heat transfer properties of fluids, researchers have tried suspending micro and/ or nano sized solid particles of higher thermal conductivity in these fluids as mentioned in the Table-1. Maxwell's theoretical work formed the foundation in studying the heat transfer properties of fluids more than 100 years ago. Several researchers have conducted both theoretical and experimental investigations in assessing the heat transfer properties containing nano sized solid particles. The problem of solid particles or suspensions being settled down because of their large size and high density is not entirely solved. This stability problem of nanosuspensions creates the problem of additional flow resistance and eventually leads to problems of erosion. This can create troubles in commercializing the dispersed nano fluids containing the coarse-grained particles.

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Material	**Room Temperature Thermal Conductivity (W/m-K)**	
Metallic Solids	Silver Copper Aluminum	429 401 237
Non-metallic Solids	Diamond Silicon Alumina (Al2O3)	3300 148 40
Metallic Liquids	Sodium @ 644K	72.3
Non-metallic Liquids	Water Ethylene Glycol Engine Oil	0.613 0.253 0.145

Table 1:- Thermal Conductivities of Various Solids and Liquids.

The term nanofluid was proposed by Dr S.U.S Choi of Argonne National Laboratory in 1995 defining the fluid containing the nano particles of sizes 50 nm or below. The particles of this size can now be processed and produced with development of modern technologies. Nanofluids have the scope of having enhanced heat transfer properties compared to conventional or pure heat transfer fluids. The stability problem of solid particles can also be solved by using nano or micro sized particles since that increase the surface area for heat transfer and solves the problem of abrasion in nanofluids. The nanofluids will enable the design of lighter and smaller heat exchangers by extending the trend of miniaturization in upward direction. Review by Keblinski, et al. [12] discusses the heat transfer properties of nanofluids and scope of future research or challenges. Challenges such as little agreement between experimental and numerical studies, poor characterization of suspensions and limited understanding of the heat transfer mechanisms are still present. The sequence of content of this paper will give a review on recent developments on heat transfer mechanisms in nanofluids with a focus in thermal conductivity.

Nanofluids Preparation:-

The very first step in studying the heat conduction characteristics of nanofluids is their preparation. Different procedures have been identified by several researchers involving not just mixing of solid and liquid but meeting special requirements in order to obtain certain heat conduction characteristics. Some of the special requirements are stability and durability of the suspension, zero agglomeration of particles and essentially not changing the chemical composition of fluid. Agglomeration of particles is one of the major problems encountered during the preparation of nanofluids. The procedure of preparing nanofluids includes dispersion of nanometre scale solid particles in base fluids such as water, oil and ethylene glycol (EG) etc.

There are two techniques developed so far to produce the nanofluids, the first being single step method and second being the two step method. The very old and famous one step method named Vacuum Evaporation onto a Running Oil Substrate-(VEROS)[1]includes direct evaporation to produce nanoparticles. The difficulty with this procedure is the removal of particles from fluids in order to separate dry nanoparticles. Several modifications to this VEROShave been proposed by researchers. Eastman, et al. [8] suggested a modification involving the condensation of Cu vapour by keeping it in contact with the low-vapour-pressure liquid (EG). This condensation would result in formation of nanoparticles.

A novel one step method for producing the copper nanofluids was suggested by Zhu, et al. [40]. The method basically includes reduction of $CuSO_4.5H_2O$ with $NaH_2PO_2.H_2O$ in the fluid ethylene glycol under the atmosphere of microwave irradiation. The reaction rate of Cu nanofluids and their properties were found to be affected by the adoption of microwave irradiation. Also $NaH_2PO_2.H_2O$ addition also played a crucial role in producing and affecting the copper nanofluids. Figure 2 shows the TEM photographs of nanofluids prepared by the method.

Lo, et al. [18] employed a vacuum submerged arc nanoparticle synthesis system (SANSS) method. This method was also developed to produce the Cu based nanofluids. The authors used different dielectric liquids such as pure and 30-70% volume solutions of ethylene glycol and de-ionized water. The authors found that the thermal conductivity of dielectric liquid has the main influence over the different morphologies obtain for Cu nanofluids. The authors also concluded that Copper and Copper oxides both based nanofluids can be produced by the method. Minimization of agglomeration of nanoparticles was the main advantage with this method along with a disadvantage of only capable of being used with low vapour pressure fluids.

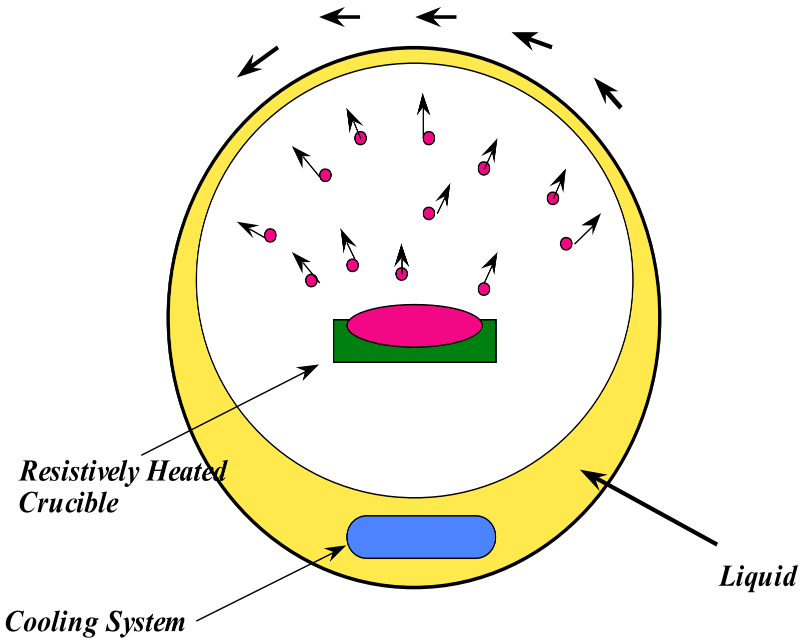

Figure 1:- Schematic diagram of nanofluid production system designed for direct evaporation/condensation of metallic vapor into low-vapor-pressure liquids[8].

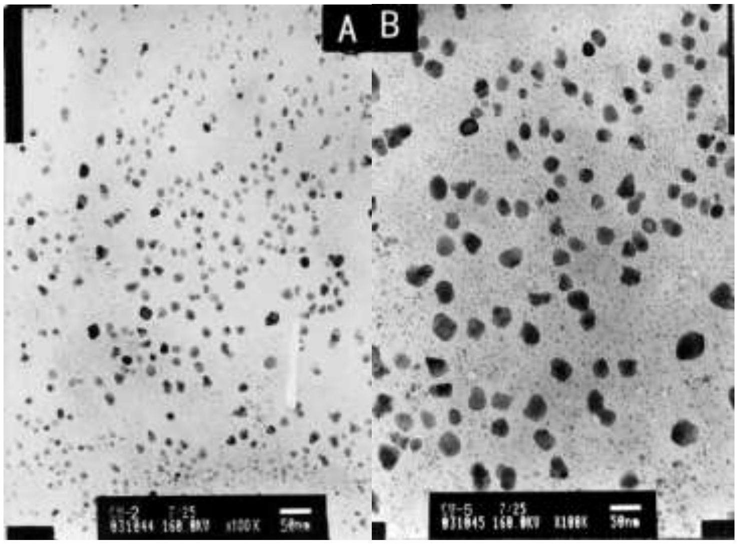

Figure 2:- TEM photographs[40] of Cu nanofluids prepared with different CuSO4 concentration: (A) 0.2 M, (B) 0.5 M.

The two step method is also being used extensively where availability of nanopowders is not an issue. The first step of this method is production of nanoparticles and second being the dispersion of nanoparticles. The agglomeration of particles is avoided by using ultrasonic equipment that enhances the dispersion of nanoparticles during the preparation of nanofluids.

Eastman, et al. [8]used the two step method to produce Al_2O_3 nanofluids.Murshed, et al. [22] also used the two step method in order to produce the nanofluids having TiO_2 suspension as nano-suspension and water as a base fluid. The two step method for producing the nanofluids turned out to be working well with oxides nanoparticles but was found not effective with metallic particles.

The problem of sedimentation while producing the nanofluids can also be solved with the help of several methods other than using ultrasonic equipment. Addition of surface agents and controlling the pH value helps achieving the stability of suspension against the sedimentation problem. The tendency of forming the clusters of particles is greatly reduced with these methods since suspended nanoparticles have their surface properties changed.

Xuan and Li [31] worked with salt as a stability agent or dispersant for transformer oil- Cu nanofluids and oleic acid for water-Cu nanofluids. Murshed, et al. [22] ensured the stability of TiO_2 nanofluids by using two stability agents or surfactants named as cetyltrimethylammoniumbromide and oleic acid in their studies. Heat transfer properties of nanofluids with the addition of dispersions are also found to be affecting at high temperatures.

Theoretical Models for Thermal Conductivity:-

Reliable theory or model to figure thermal conductivity of nanofluids is needed. Thermal conductivity of base fuel and nanoparticles must be considered for evaluation of thermal conductivity of nanofluids. The other three factors such as surface area, the shape of nanoparticles and volume fraction play a role too. The temperature of this nanofluids or suspension is also found to be dominant in some cases. Several empirical correlations are reviewed and summarized here to predict the conductivity of two-phase mixtures by researchers based on already known Maxwell and Hamilton and Crosser models.

The Maxwell model for thermal conductivity of solid/liquid mixture is as below. The effective thermal conductivity k_{eff}, is given by

$$k_{Maxwell} = \frac{k_p + 2k_l + 2(k_p - k_l)\emptyset}{k_p + 2k_l - (k_p - k_l)\emptyset} k_l \qquad (1)$$

whereK_p is the thermal conductivity of the particle, $K_l$is the thermal conductivity of the base fluid and φ is the particle volume fraction of the suspension.

The Hamilton and Crosser model take care of non-spherical particles by considering a shape factor n. Applicable to cases of mixtures where the thermal conductivity ratiois larger than 100 from solid to liquid.

$$k_{eff} = \frac{k_p + (n-1)k_b - (n-1)(k_b - k_p)\emptyset}{k_p + (n-1)k_b + (k_b - k_p)\emptyset} k_b \qquad (2)$$

wherenis the empirical shape factor given by n = Maxwell model is a special case of Hamilton and Crosser's model while taking sphericity equal to one.

Yu and Choi [39]modified Maxwell model and presented a modelcapable of predicting the presence of thin nanolayers. These nanolayers increase the effective volume fraction and hence thermal conductivity of nanofluids.

$$k_{pe} = \frac{[2(1-\gamma) + (1+\beta)^3(1+2\gamma)]\gamma}{-(1-\gamma) + (1+\beta)^3(1+2\gamma)} k_p \qquad (3)$$

The modified thermal conductivity of particles K_{pe} is given by equation (3) above where $\gamma = K_l/K_p$. $K_l$is the nano-layer thermal conductivity and K_p is the particle thermal conductivity and β = h/ris the nano-layer thickness to the original particle radius ratio. The modified Maxwell equation will be

$$k_e = \frac{k_{pe} + 2k_l + 2(k_{pe} - k_l)(1+\beta)^3\emptyset}{k_{pe} + 2k_l - (k_{pe} - k_l)(1+\beta)^3\emptyset} k_l \qquad (4)$$

The drawback with this model is that the thermal conductivity increases substantially with high particle concentration (>20 Vol %). Instead of increasing the volume fraction, one should consider adding the smaller particles.

Yu and Choi [38] also included the nonspherical particles by modifying Hamilton and Crosser model. The expression is as below.

$$k_e = \left(1 + \frac{n f_e A}{1 - f_e A}\right) k_l \qquad (5)$$

where the parameter A is defined by

$$A = \frac{1}{3} \sum_{j=a,b,c} \frac{k_{pj} - k_l}{k_{pj} + (n-1)k_l} \qquad (6)$$

and

$$f_e = \frac{\sqrt{(a^2+t)(b^2+t)(c^2+t)}}{abc} f = rf \qquad (7)$$

where the equivalent volume concentrationof the complex ellipsoids isf_e and f is the volume concentration of solid ellipsoid without surrounding layers. The nonlinear behavior of thermal conductivity of nanofluids needs to be explored further especially in case of general oxides and metal based.

Xue [37]considered the interface effect between particles and base fluid in nanofluids. The authors presented a novel model based on Maxwell and average polarization theory. The model is as below

$$9\left(1-\frac{\emptyset}{\lambda}\right)\frac{k_{eff}-k_b}{2k_{eff}+k_b}+\frac{\phi}{\lambda}\left[\frac{k_{eff}-k_{c,x}}{k_{eff}+B_{2,x}(k_{c,x}-k_{eff})}+4\frac{k_{eff}-k_{c,y}}{2k_{eff}+(1-B_{2,x})(k_{c,y}-k_{eff})}\right]=0 \tag{8}$$

whereλ= abc / [(a + t)(b + t)(c + t)] and (a, b, c) is the half radii of the assumed elliptical complex nanoparticles. $K_{c,j}$is the effective dielectric constant and $B_{2,x}$ is the depolarization factor along the x axis. The anomalous enhancement of thermal conductivity of oil nanofluids and its nonlinearity with nanotube loadings can now be interpreted well with this model.

Later onXue and Xu [36] developed another model based on Bruggeman model, taking into account the effect of interfacial shells by replacing the thermal conductivity of nanoparticles with the complex nanoparticles thermal conductivity.

$$\left(1-\frac{\emptyset}{\alpha}\right)\frac{k_{eff}-k_b}{2k_{eff}+k_b}+\frac{\phi}{\alpha}\left[\frac{(k_{eff}-k_2)(2k_2+k_1)-\alpha(k_1-k_2)(2k_2+k_{eff})}{(2k_{eff}+k_2)(2k_2+k_1)+2\alpha(k_1-k_2)(k_2-k_{eff})}\right]=0 \tag{9}$$

where Thermal conductivity of nanoparticle is k_1 and thermal conductivity of interfacial shell is k_2. α equals the volume ratio of spherical nanoparticle and complex nanoparticle.Comparing this model with conventional models, the new model also depends on the particle size and interfacial properties in addition to thermalconductivity of liquid and solid and their relative volume fraction.

Xuan, et al. [32]applied the theory of Brownian motion and the aggregation model to simulate the random motion of nanoparticles. This model considers the physical properties of both the base liquid and the nanoparticles. The effect of nanoparticles aggregation is considered and the thermal conductivity of nanofluids is found to be increasing with the fluid temperature. The model is as described below.

$$k_{eff}=\frac{k_p+2k_b-2(k_b-k_p)\emptyset}{k_p+2k_b+(k_b-k_p)\emptyset}k_b+\frac{\rho_p\emptyset C_p}{2}\sqrt{\frac{k_BT}{3\pi r_c\mu}} \tag{10}$$

where Boltzmann constant is$k_B$and apparent radius of clusters is r_c, which depends on the dimension of the cluster structure.

Xie, et al. [28]proposed a thermal conductivity model for nanofluids that would account for four parameters namely volume fraction of nanoparticles, size of nanoparticles, thickness of nanolayer and individual thermal conductivities of particles, fluid and nanolayer. The authors also took into account linear thermal conductivity distribution for the interfacial nanolayer. Their formula is

$$k_{eff}=(1+3\theta\emptyset_T+\frac{3\theta^2\emptyset_T^2}{1-\theta\emptyset_T})k_b \quad \text{and} \quad \theta=\frac{\beta_{lb}[(1+\gamma)^3-\frac{\beta_{pl}}{\beta_{bl}}]}{(1+\gamma)^3+2\beta_{lb}\beta_{pl}} \tag{11}$$

where

$$\beta_{lb}=\frac{k_l-k_b}{k_l+2k_b},\beta_{pl}=\frac{k_p-k_l}{k_p+2k_l},\beta_{bl}=\frac{k_b-k_l}{k_b+2k_l},\gamma=\frac{\delta}{r_p},\emptyset_T=\emptyset(1+\gamma)^3$$

where γ is the ratio of nanolayer thickness and nanoparticle thickness. $\emptyset_T$ equals the volume fraction of the original nanoparticle and nano-layer after modification.

Bhattacharya, et al. [4] used simulation technique to compute the effective thermal conductivity of nanofluid based on Brownian motion. The authors successfully combined the liquid conductivity with particle conductivity with the following relation.

$$K_{eff}=\emptyset K_p+(1-\emptyset)K_b \tag{12}$$

Where $k_p$is replaced by the effective contribution of the particles towards the overall thermal conductivity of the system,$k_p=\frac{1}{VT^2k_b}\sum_{j=0}^{n}<Q(0)Q(j\Delta t)>\Delta t$.

A theoretical model that includes four additional and important parameters was developed by Jang and Choi [11]. The authors considered the base fluid molecules collision by a term $(k_b(1-\emptyset))$ and thermal diffusion of nanoparticles in fluid by a term$(k_p\emptyset)$. The authors neglected collision of nanoparticles with one another explained by Brownian motion theory but considered the dynamic thermal interaction of nanoparticles with the base fluid molecules in nanofluids by adding a term ($fh\delta_T$). The expression for effective thermal conductivity for this model is as below.

$$k_{eff}=k_b(1-\emptyset)+(k_p\emptyset)+3C\frac{d_b}{d_p}k_bRe_{d_p}^2Pr\emptyset \tag{13}$$

where $h\sim(k_b/d_p)\,Re_{d_p}^2Pr^2)$ is the flow heat transfer coefficient for nanoparticles and $\delta=3d_p$ is the thickness of the thermal boundary layer.The model is not useful for high temperature analysis since the Brownian motion is neglected and most high temperature properties depend on Brownian motion in case of nanofluids. The advantages of this model are that it includes the effects of temperature, concentration, and particle size on thermal conductivity of nanofluids.

On the contrary, Prasher, et al. [25]took into account the Brownian motion of nanoparticles and mentioned that it causes the convection which helps in thermal conductivity enhancement of nanofluids. The authors introduced a correlation for the heat transfer coefficient h and modified the Maxwell model after considering the convection because of Brownian motion of nanoparticles past the liquid in nanofluids. The model is as described below,

$$k_{eff} = (1 + ARe^{m} Pr^{0.333} \emptyset)[\frac{k_p + 2k_b + 2(k_p - k_b)\emptyset}{k_p + 2k_b - (k_p - k_b)\emptyset}]k_b \qquad (14)$$

where $h = k_b/a(1 + ARe^{m} Pr^{0.333} \emptyset)$ and m and A are constants. The Reynolds number equation is given by following relation:

$$R_e = \frac{1}{\vartheta} \frac{18k_b T}{\pi d_p \rho_p}$$

Koo and Kleinstreuer [14, 15]developed a new model for thermal conductivity of nanofluids considering the effects of nanoparticle volume fraction and nanoparticle size. This model is temperature dependent, and the properties of nanoparticles and the base fluid is thought to be affected by Brownian motion of nanoparticles. The model is as described below

$$K_{eff} = \frac{k_p + 2k_b + 2(k_p - k_b)\emptyset}{k_p + 2k_b - (k_p - k_b)\emptyset} k_b + 5 * 10^4 \beta \emptyset \rho_p C_p \sqrt{\frac{T.k_B}{\rho_p.D}} f(T, \emptyset) \qquad (15)$$

It should be noted that only second term in above equation (14) accounts for Brownian motion making the effective thermal conductivity being dependent on the temperature. The first term is original Maxwell model. β is the parameter related to particle motion and the function in the second term accounts for the temperature dependence on the particle volume fraction ($\emptyset$).Therefore$f(T, \emptyset) = (-6.04\emptyset + 0.4705)T + (1722.3\emptyset - 134.63)$

The authors also investigated[14] the effects of pressure differentials and temperature profiles with the addition of CuO nanoparticles and using ethylene glycol and oils, which are high-Prandtl number base fluids. These parameters were found to increase the heat transfer properties of micro-heat sinks.

The thermal conductivity of Carbon nanotubes is difficult to predict theoretically since their aspect ratio is larger than general nanofluids. Nan, et al. [23] used the generalized Maxwell-Garnett approximation and came up with equation ($K_{eff} = 1 + \emptyset \frac{K_p}{3K_b}$) for the effective thermal conductivity of Carbon nanotubes-based composites. This model has a limitation of not considering the thermal resistance across the carbon nanotube-fluid interface. Later, Nan, et al. [24] modified their model and tried to describe the effect of the interface thermal resistance. However, the model still cannot explain the nonlinear phenomena of the effective thermal conductivity of nanotube suspensions with nanotube volume fractions.

Recently, to accountfor the geometric and physical anisotropy simultaneously, Gao and Zhou [9] proposed a differential effective medium theory based on Bruggeman's model to predict the effective thermal conductivity of nanofluids. Although their model involves the effect of aspect ratio of the nanotube, the size effect and temperature dependence have not be included. From the results, the prediction of the thermal conductivity of normal nanofluids rather than nanotube-based suspensions is not good.

Numerical Investigations for Thermal Conductivity of Nanofluids:-

Numerical method is basically a simulation approach adopted for investigating the heat transfer characteristics of nanofluids. There are two approaches developed and are reported by most of the researchers in this area. The first approach is based on an assumption that the continuum phenomenon is valid and works for fluids with suspended nano-sized particles. This is called single phase model. The single phase model is more efficient computationally. The second approach describes the solid and liquid phase in a better way by taking account a two phase model. This model is not openly discussed in literatures and research is still going on in these areas.Another method involves the consideration of taking into account the Boltzmann theory. Mathematically describing all the behaviours and properties of nanofluids might be challenging since several factors such as solid/liquid layering at the interface, Brownian motion, ballistic phonon transport through particles and nanoparticles clustering must be taken into account.

Maïga, et al. [19]initially studied the thermal and hydrodynamic properties of nanofluids flowing through a uniformly heated tube. Both laminar and turbulent flow regimes were taken into account for a single phase model carrying some adjusted properties. The thermal conductivity of nanofluids was found to be enhanced with the addition of nanoparticles compared to base fluid alone. Ethylene Glycol–γAl_2O_3 mixture nanofluids were found to be giving better heat transfer enhancement than water–γAl_2O_3. There are some drawbacks with this studies, found by the authors in their next studies and are summarized below.

Maïga, et al. [20]also numerically investigated the thermal and hydrodynamic characteristics of nanofluids for a laminar forced convection flow. The flow was considered to be taken inside a radial space between coaxial and heated disks in one case and inside a straight heated tube I other case. The simulations were run for two nanofluids namely Ethylene Glycol–$\gamma Al_2O_3$and water–γAl_2O_3. The authors found that the addition of nanoparticles has produced a remarkable increase in the heat transfer as compared to the base liquids. The heat transfer enhancement that appears to be more enhanced with the increase of the particle volume concentration butit does have an adverse effect on the wall shear stress. Ethylene Glycol–γAl_2O_3 mixture nanofluids were found to be giving better heat transfer enhancement than water–γAl_2O_3. Also Ethylene Glycol–γAl_2O_3induced a more drastic and adverse effect on the wall shear stress.

In case of tube flow[20], the augmentation of Reynolds number was found to be resulting in enhanced heat transfer properties due to nanoparticles suspension. The correlation was also derived for calculating the averaged Nusselt number of nanofluids in terms of Prandtl number and Reynolds number for the case where two thermal boundary conditions were considered.

In case of a radial laminar flow[20], where the range of governing parameters studied, it was found that heat transfer enhancement for nanofluids was not noticeable leading to believethat the two parameters, one being the flow Reynolds number and the other being the gap between disks have no or little effect.

Given the fact that Nusselt number or coefficient of heat transfer of nanofluids depend upon several factors such as thermal conductivityand heat capacity of nanoparticle and base fluid, the flow pattern and viscosity of nanofluid, volume fraction of suspended particles and the dimensions and shape of nanoparticles and flow structure. Several attempts have been made in deriving the correlations of convective heat transfer coefficient and Xuan and Roetzel [33] analysed the heat transfer performance of nanofluids and derived fundamental correlation for convective heat transfer of nanofluids. The authors used two models in order to explain the mechanism of the increased heat transfer rates namely single phase and two phase model.

The conventional[33] way or single phase model considered the ultrafine particles (<100 nm), which are easily fluidised and can be approximately considered to behave like a fluid. Assumption of no motion slip between the discontinuous phase of the dispersed ultrafine particles and the continuous liquid along with the thermal equilibrium among nanoparticles and fluids, the nanofluid can be taken as a pure fluid. All the equations of continuity, motion and energy for the pure fluid were extended to nanofluids.

The lattice Boltzmann equation is one of the solutions to the microscopic problems of describing the interactions between the suspended nanoparticles and base liquid particles as well as among the solid particles. Xuan and Yao [34]performed the simulation of nanoparticle distributions and flow of nanofluids taking into consideration the mechanical and thermal interactions among the nanoparticles and fluid molecules. The authors also considered the internal and external forces on the nanoparticles. The nanoparticle distribution is increased with the increased temperature of fluids responsible for mainly enhancing the heat transfer property of nanofluids.

Xue, et al. [35] used non-equilibrium molecular dynamics simulations to perform numerical investigation of nanofluids. The authors studied how the interfacial thermal resistance is affected by the solid-liquid interface and found that the simple monatomic liquid around the solid particle showed no influence on the thermal transport. There was no effect on thermal transport in either normal to the surface or parallel to the surface. The authors concluded that the thermal transport in interfacial layer of solid and liquid is unable to explain the large improvements in thermal conductivity of nanofluids.

It is indeed difficult to establish theory capable of predicting the heat transfer characteristics of nanofluids mathematically. The single-phase model is preferred over the two-phase mixture model by many researchers. In totality, the convective heat transfer performance of nanofluids is affected by factors such as the particle-liquid interaction and the relative movement between the particles and liquids.

MeasurementTechniques for Thermal Conductivity of Nanofluids:-

There are three main methods identified for measuring thermal conductivity of nanofluids and suspensions. The most widely accepted method is the transient hot wire method used by both the past researchers like Kestin and Wakeham [13] and present researchers like Murshed, et al. [21]. The transient hot wire method[13] works on the principle of determining the temperature rise of a heated wire from the measurements of change in the difference of resistance of two wires during their transient heating.

Basically the heat flux or generation can be calculated based on experimental measurements. The Figure-3 shows the setup of the transient hot wire method[21] with an addition of a refrigerating/heating circulator helping the authors to obtain different temperatures of nanofluids.

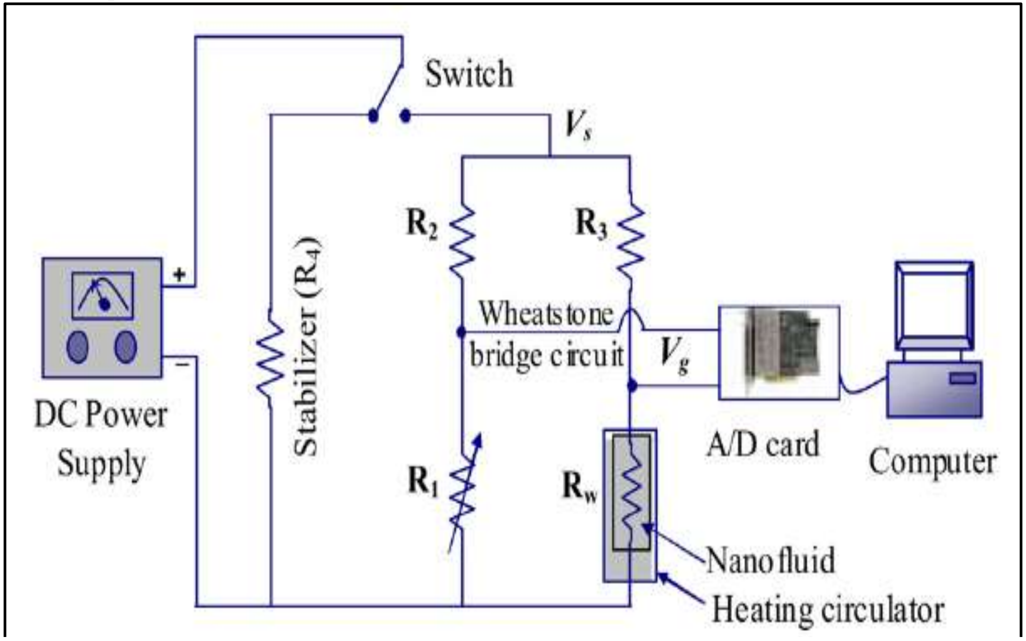

Figure 3:- Schematic of the transient hot wire experimental setup[21]

Several works has been done in order to find enhancement in thermal conductivity of nanofluids with these three methods by researchers and some of those works is reviewed here. The researchers mostly used Alumina (Al_2O_3) and copper oxide in experimental measurement of thermal conductivity.

The other two are the temperature oscillation technique[6] shown in Figure-4 and the steady state parallel- plate technique[27] shown in Figure-5.

The oscillation technique[6] measures the temperature of test cell containing the fluid, water cooler and the Peltier elements. The measurement data is fed, after amplification and proper filtering, to a data acquisition system and a computer for display. The Peltier elements take power from DC supply through a converter. The test cell temperature is controlled by cooling water from a thermostatic bath as shown in Figure-4.

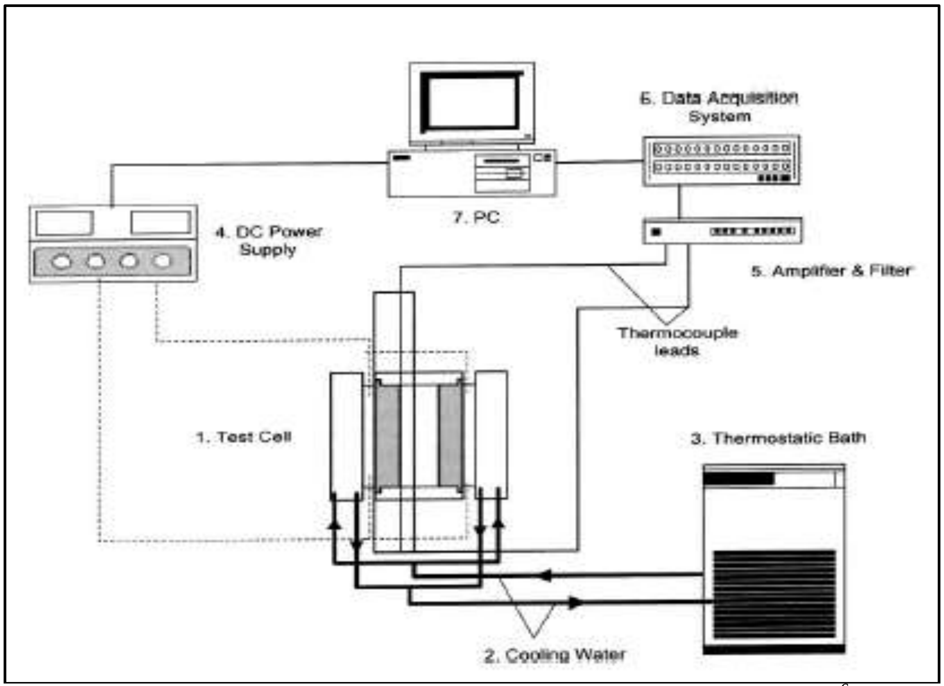

Figure 4:- Experimental Setup for Temperature Oscillation Technique[6].

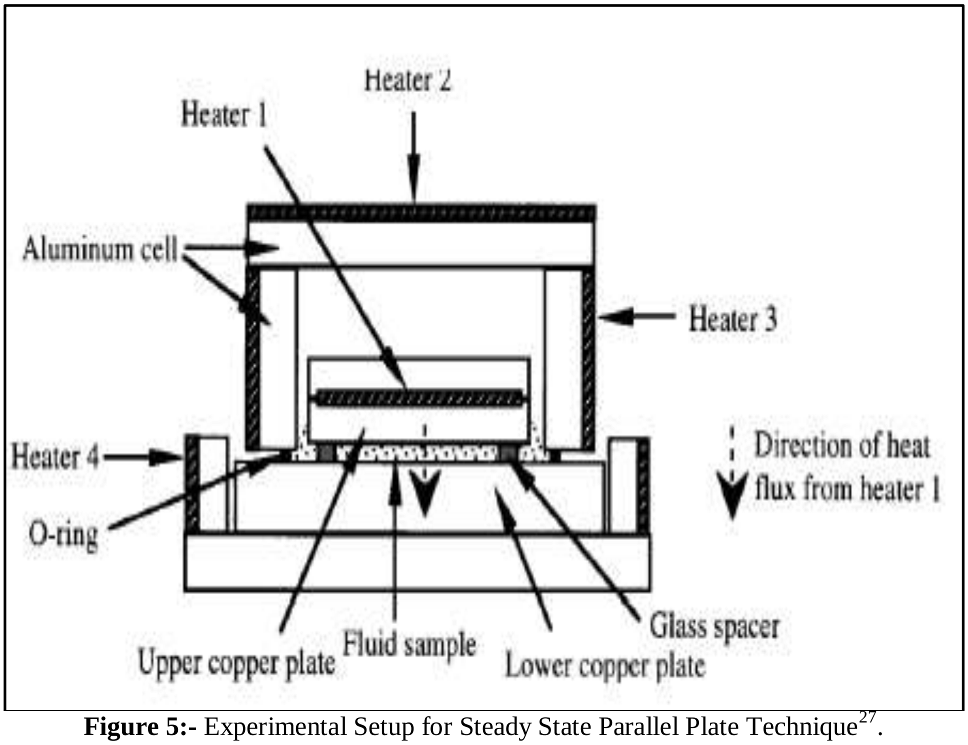

Figure 5:- Experimental Setup for Steady State Parallel Plate Technique[27].

The experimental apparatus for steady state parallel- plate technique[27] consists of a liquid contained between two high purity copper plates separated by three glass spacers. The top portion is accommodated into an aluminium cell.The increase in temperature is measured here instead of absolute temperature to find thermal conductivity of nanofluids. Four heaters are placed appropriately in order to heat the nanofluid and maintain the temperature in the cell. The heat supplied by heater 1 flow through the liquid from the upper copper plate to lower copper plate. The overall thermal conductivity of entire system containing fluid, copper plates and glass spacers can be calculated from one dimensional heat conduction mechanism.

Thermal Conductivity Measurements of Metal Oxides-Nanofluids:-

Eastman, et al. [8]used two different base fluids in order to measure thermal conductivity of nanofluids. The two base fluids are water and HE-200 oil. The nanoparticles were (Al_2O_3), CuO, and Cu which were added to these base fluids.The transient hot wire method was used to measure thermal conductivity of nanofluids. Two processes were used to prepare the nanofluids. In the first, powders of nanoparticles were prepared by Gas Condensation Process followed by dispersion in deionized water. The second procedure includes direct evaporation of nanoparticles into a low vapour pressure liquid. Thermal conductivity of nanofluids was found to be increased by 60 % as compared to corresponding base fluids for an addition of oxides 5 % by Volume. Experiment done with Cu particles in HE-200 oil produced larger enhancement in thermal conductivity of nanofluids.

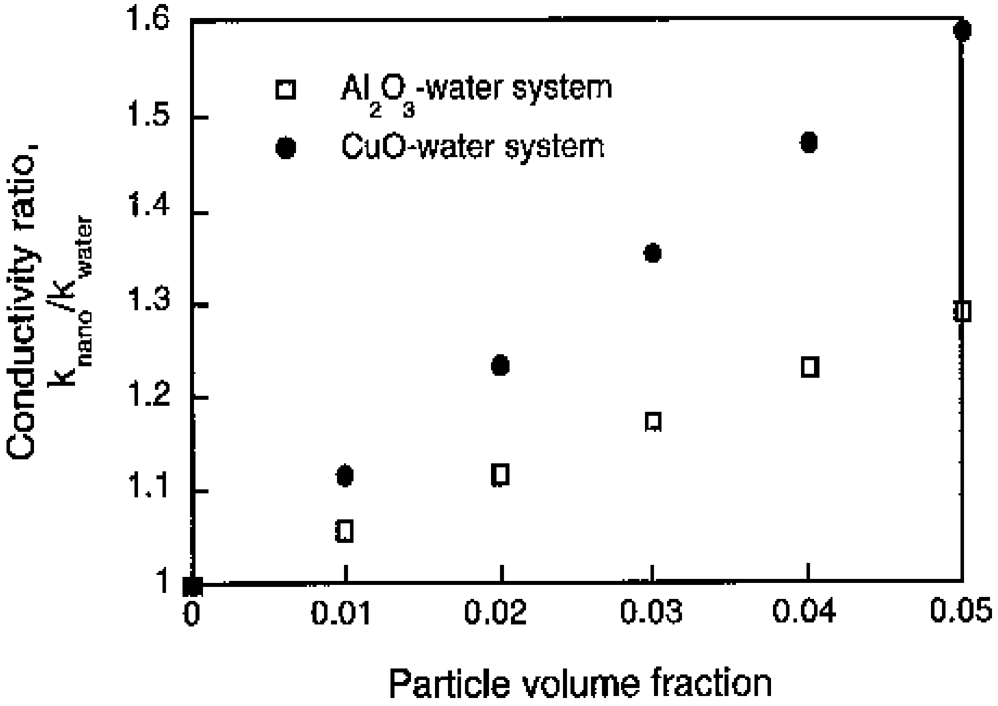

Figure 6:- Dramatic Improvements in Thermal Conductivity[8] of Deionized Water with Increasing Volume Fraction of dispersed Copper Oxide or Alumina Particles.

Xuan and Li [31]used water as a base fluid and investigated the effect of two nanoparticles Cu particles (100nm) and CuO particles of smaller dimension (36 nm). The thermal conductivity was found to be enhanced by same amount with addition of above two particles. The authors also evaluated the stability of suspension with selection of appropriate dispersants. The authors evaluated a dispersant-oleic acid for transformer oil-Cu nanofluids. One more dispersant named laurate salt was evaluated for water-Cu suspension. The stability of Cu particles in transformer oil was found to be better than the suspension of Cu particles in water.Theoretical analysis was also done and a parameter P_{eclet} number P_e is introduced in order to describe the effect of random movement and dispersion of nanoparticles on nanofluids. These two effects are equally important for evaluating the heat conduction mechanisms of nanofluids apart from thermal conductivity property. Some complicated phenomenons that coexist in the main flow of nanofluids are evaluated using the dispersion model in order to analyse the enhanced heat transfer mechanisms of nanofluids. Some of these phenomenons are Brownian diffusion and sedimentation, dispersion occurring in the main flow of nanofluids.

Xie, et al. [30] evaluated four different parameters found to affect thermal conductivity of nanofluids. The main parameter was pH value of the suspension. The isoelectric point of a particle is a pH value at which no electric charge is carried by its molecules. The authors found that thermal conductivity of nanofluids is enhanced by increasing the difference between isoelectric point and pH value of suspension. The suspension used was (Al2O3). The second parameter like specific surface area of dispersed particles was also found to be affecting the thermal conductivity of nanofluids. Some parameters like crystalline phase of nanoparticles are being investigated and not yet found to be affecting the thermal conductivity in a major way.

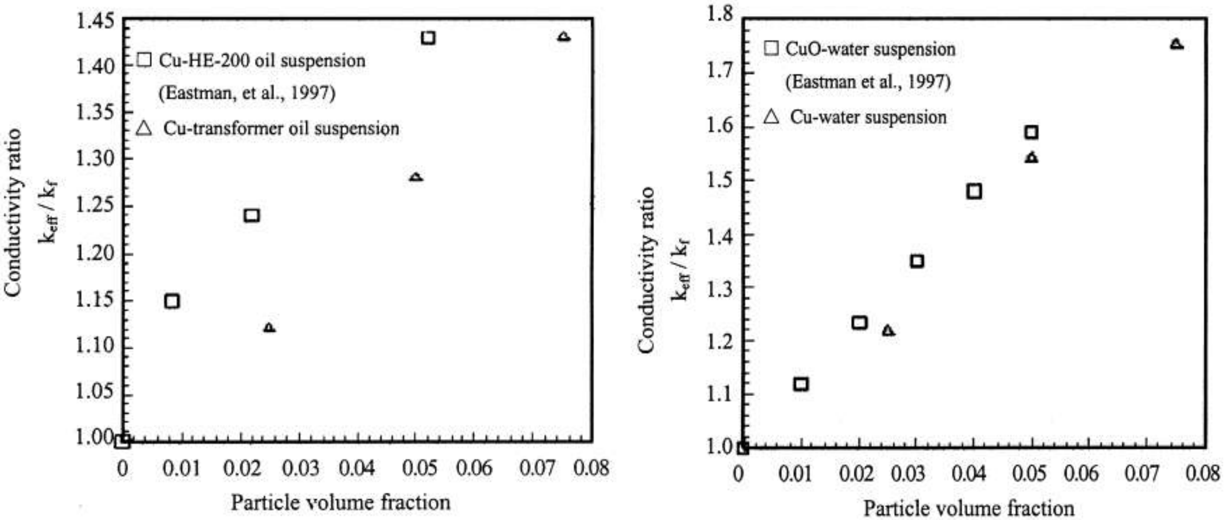

Figure 7:-The effects of particle volume fraction on the thermal conductivity[31]for the a) transformer oil±copper nanofluid and b) thewater±copper nanofluid.

Li and Peterson [16] basically used two water suspensions of CuO and Al_2O_3 of sizes 29 nm and 36 nm respectively. The authors investigated the effects of temperature and volume fraction variations on thermal conductivity of stated nanofluids or nanosuspensions. The authors found four parameters that affect the effective thermal conductivity of nanofluids or nanosuspensions. These include the material of nanoparticle followed by their diameters, volume fractions and bulk temperature. The 7.7°C increase in bulk temperature in case of Al_2O_3 and water suspension enhances the thermal conductivity of suspension by three times. The effect of bulk temperature on thermal conductivity of nanofluids needs to be explored deeper. The authors also formulated two-factor linear correlation for both the suspensions as mentioned below.

1. Al_2O_3/water: $(k_{eff}-k_b)/k_b = 0.764\varphi + 0.0187(T - 273.15) - 0.462$
2. CuO/water: $(k_{eff}-k_b)/k_b = 3.761\varphi + 0.0179(T - 273.15) - 0.307$

Murshed, et al. [22] used deionized water as base fluid and TiO_2 nanoparticles in two different shapes. The one being in rod shape of size Ø10×40 and the second being in spherical shape of size Ø15. The thermal conductivity of nanofluids was found to be affected by both the parameters. First the particle size and second the shape of particles.

Thermal Conductivity Measurements of Metallic Particles-Nanofluids:-

Eastman, et al. [7]investigated the effect of increasing the ratio of surface to volume along with decreasing the size of nanoparticles. Validity of Hamilton and Crosser's model for thermal conductivity was also investigated. It was found that the thermal conductivity enhancement for a two component mixture fluid from Hamilton's model was lower than experimental results. Reason being given is that Hamilton's model takes into account only the shape factor, which depends on the surface area of non-spherical particles. The shape factor does not depend on particle size meaning the increase in the ratio of surface to volume that accompanies the decrease in the particle size. This discrepancy between model's results and experimentally measured thermal conductivity is even larger for metallic nanofluids as compared to oxides nanofluids. They experimented with pure Cu nanoparticles of size less than 10 nm. The thermal conductivity of nanofluids was found to be increased by 40% even if the volume fraction was only 0.3% of dispersed solid in fluid ethylene glycol.

Hong, et al. [10]also used Ethylene glycol as base fluid and instead of using Cu particles; the authors used Fe nanoparticles of mean size of 10 nm. Chemical vapour condensation process was used to producethese Fe particles. The dispersion of Fe particles into the base fluid – ethylene glycol was enhanced by sonication of high powered pulses. The Comparison of Cu particle fluid with Fe particle fluid was done and found that the latter exhibits higher thermal conductivity enhancement. The suspension material's thermal conductivity effect was also evaluated and found that particles with higher thermal conductivity may not always turn out to be the best option. Volume fraction of solid particles does have an effect on thermal conductivity of nanofluids.The thermal conductivity of nanofluids was also found not to be enhanced with addition of stabilizing agent as predicted by Brownian motion of nanoparticles at molecular and nano-scale level. This is because of less dynamic motion of clustered particles as compared to individual particles; the thermal transport property is not enhanced in any manner. No thermal conductivity enhancement can be achieved with the stabilizing agent in any manner.

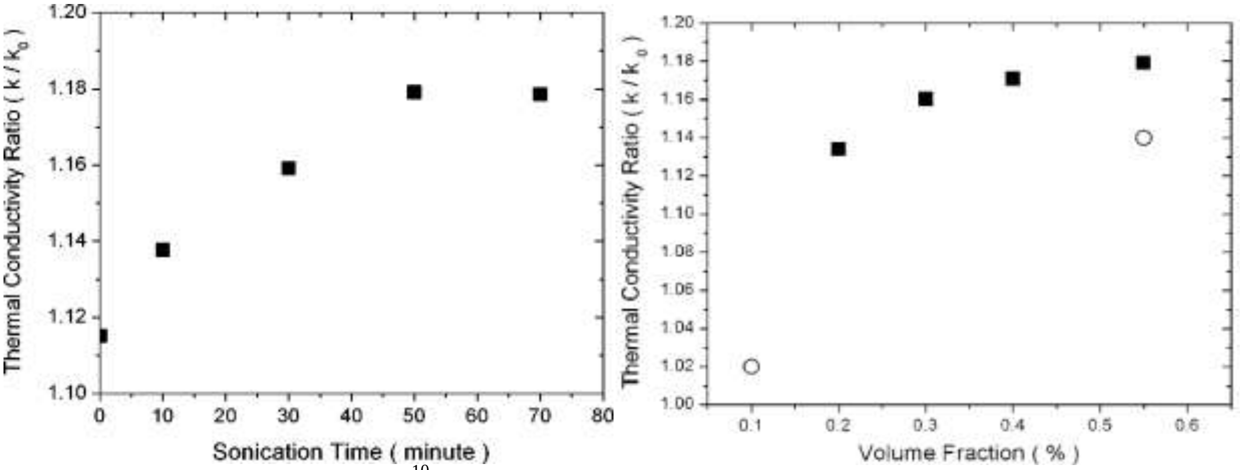

Figure 8:- a) Thermal conductivity[10] of 0.55 volume % Fe nanofluid as a function of the sonication time and b) Thermal conductivity of Fe nanofluids for different concentrations of Fe nanoparticles (filled squares) and Cu nanofluids (open circles).

The result of enhanced thermal conductivity with the small volume fraction of nanoparticles was not observed by Putnam, et al. [26] in their studies of nanofluids. The particles used in preparing the nanofluids were C60-C70 and Au ($\varphi \ll 1$). The result of getting 1.3% ± 0.8% enhancement in thermal conductivity with Au particle size of 4 nm contradicted the previous results of getting enhanced thermal conductivity with small volume fraction of nanoparticles. The authors believed in carrying out further quantitative measurements in this regard.

Thermal Conductivity Measurements of Carbon Nanotubes-fluids:-

The carbon nanotubes suspensions have been investigated for a long time and turned out to be enhancing the thermal conductivity of nanofluids very largely because of very high aspect ratios and thermal conductivity of nanotubes suspensions. Several researchers have investigated the use of carbon nanotubes in different ways by experimentation and one of them is presented here because of limit of number of references being reviewed and presented at this stage.

The effective thermal conductivity of nanotube- multiwall carbon nanotubes or MWNTs and oil (α olefin) mixtures was investigated by Choi, et al. [5]. The measured thermal conductivity of nanofluids was found to be nonlinear with nanotube loadings. The results were anomalously higher than the theoretical model results. The nanotubes give added advantages of effective management applications and higher conductivity enhancements.

Xie, et al. [29] used three different base fluids namely deionized water, decene and ethylene glycol for the purpose of producing nanosuspensions of multiwall carbon nanotubes. In order to form hydrophilic surfaces on carbon nanotubes surfaces, the authors created the oxygen concentrated functional group on these surfaces. The effective thermal conductivity of nanofluid was found to be decreasing with increase in thermal conductivity of base fluid and increasing with the increase in nanotube loading.

Assael, et al. [2] investigated the enhancement of thermal conductivity of nanofluid containing water as a base fluid and carbon-multiwall nanotubes as nanosuspensions. The authors reported the result of 38% enhancement in thermal conductivity with 0.6% by volume nanosuspensions in nanofluid. The authors also used a dispersant named sodium dodecyl sulphate 0.1 wt% in these nanofluids. The outer surface of carbon-multiwall nanotubes was found to be affected by the dispersant SDS used in their studies.

Later on Assael, et al. [3] used two different dispersants from what the authors used previously. These were hexadecyletrimethyl ammonium bromide (CTAB) and nanosphere AQ. The authors conducted experiments with carbon double walled nanotubes and carbon-multiwall nanotubes and found that for a 6% by volume suspensions of carbon multiwall nanotubes in water enhanced the thermal conductivity by 34%. Also CTAB was found to be better as a surfactant for both multiwall and double-walled nanotubes.

Liu, et al. [17]produced two nanofluids by dispersing the CNTs-(Carbon Nanotubes) in ethylene glycol and synthetic engine oil. The CNT with a base fluid of ethylene glycol produced up to 12.4% enhancement in thermal conductivity of nanofluids at 1% volume. The CNT with a base fluid of synthetic engine oil produced up to 30% enhancement in thermal conductivity of nanofluids at 2% volume. The two parameters such as structure of carbon nanotubes and clustering of carbon nanotubes needs to be explored further since the authors believe that the thermal conductivity depends on these. The need of generation of whole map of CNTs suspensions thermal conductivity is realized and should be explored deeper.

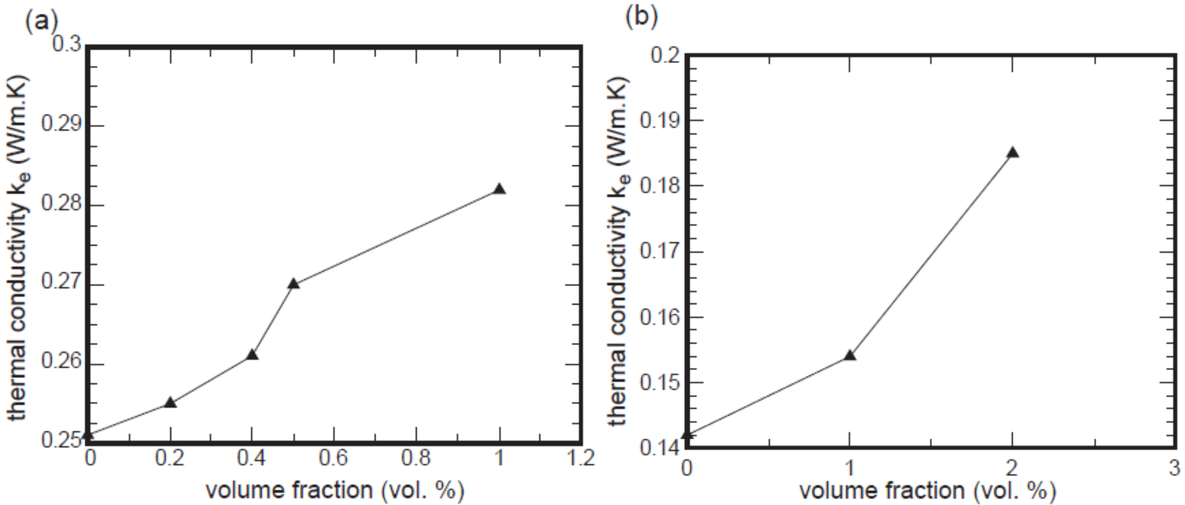

Figure 9:- (a) The thermal conductivity[17] of carbon nanotubes–ethylene glycol nanofluids as a function of volume fraction. (b) The thermal conductivity of carbon nanotubes–synthetic engine oil nanofluids as a function of volume fraction.

Conclusion:-

Both numerical models and experimental models for analyzing the thermal conductivity of nanofluids need to be explored deeper. To increase the understanding of the thermal conductivity of nanofluids and suspensions, parameters like size and shape of nanoparticles, interfacial contact resistance between nanoparticles and base fluids are explored deeper for numerical models of thermal conductivity. There are several experimental methods which include effect of temperature and volume variation of suspensions on thermal conductivity.

The major scope of research lies in carbon nanotubes that enhances the thermal conductivity in a large manner and often increases this property almost linearly with volume fraction of suspensions. The carbon nanotubes as suspensions can build a large three-dimensional CNT network that could potentially increase the thermal transport property of nanofluids.

Investigator	**Particles**	**Size (nm)**	**Fluids**	**Observations**
Eastman, et al. [8]	Al_2O_3/CuO/Cu	33/36/18	Water, HE-200 oil	5 vol% CuO particles in water gives 60% enhancements
Xie, et al. [30]	Al_2O_3	12.2–302	EG,Water and PO	pH value, SSA, crystalline phase
Li and Peterson [16]	Al_2O_3/CuO	36/29	Water	enhancement depends on volume fraction and temperature
Xuan and Li [31]	Cu	100	Water, oil	big metallic nanoparticles successfully suspended
Eastman, et al. [7]	Cu	<10	EG	0.3 vol% Cu-based nanofluids gives 40% enhancements
Hong, et al. [10]	Fe	10	EG	0.55 vol% Fe/EG nanofluids gives 18% enhancements

Murshed, et al. [22]	TiO_2	Ø10×40, Ø15	DW	5 vol% for Ø10 ×40 and Ø15 gives 33% and 30% enhancements
Choi, et al. [5]	MWNTs	Ø25×50 μm	Oil	1.0 vol% suspensions exceed 250% thermal conductivity
Xie, et al. [29]	TCNTs	Ø15×30 μm	DW, EG, DE	1.0 vol% leads to 19.6%, 12.7%, and 7.0% increase for fluids TCNT/DE, EG, and DW
Assael, et al. [2, 3]	MWNTs, DWNTs	Ø130× 10 μm	Water	0.6 vol% suspension leads to 34% enhancement
Liu, et al. [17]	CNTs	Ø20–30	EG, EO	12.4% for EG (1 vol%),30% for EO(2 vol%)

Table 2:- Summary of experimental studies on thermal conductivity of nanofluids.
Note: EG: ethylene glycol; PO: pump oil; EO: engine oil;DW: deionized water;CNTs: Carbon nanotubes

A need of very well-plannedexperiments is realized that should consider varying particle sizes keeping the total volume same and vice versa.Thermal transport property is also an area where further research is needed to provide explanation at a deeper level for computing thermal conductivity of two component mixture in effective way.

Other properties such as viscosity, convective heat transfer, boiling heat transfer of nanofluids and suspensions are equally important and must be considered while studying heat conduction mechanisms regarding nanofluids. This is also a potential area of further research.

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