

## A review on magnetic/nano fluids: Thermal phenomena in magnetic/nanofluids & It's Applications

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**Abstract:-** Interesting you know, Science of the very tiny one has become huge. It raises issues that are interesting and important to scientific understanding and seems to possess clues to the solution of knotty technological problems. The focus of the present work concerns thermal properties of suspensions of nanoparticles in fluids. They commonly referred to as nanofluids. In another explanation, nanofluids are nanoscale colloidal suspensions containing condensed nanomaterials. They are two-phase systems with one phase (solid phase) in another (liquid phase). Investigations of their thermal properties have thrown up many findings that are interesting and challenging to describe. The importance of thermal properties is in the context of heat removal from small spaces. It is a technological challenge arising from the need to cool high-speed microelectronic devices. And also , nanoparticle suspensions (nanofluids) have been recommended as a promising option for various engineering applications, due to the observed enhancement of thermophysical properties and improvement in the effectiveness of thermal phenomena. A number of investigations have been reported in the recent past, in order to quantify the thermo-fluidic behavior of nanofluids. Even if it is true that some review articles involving the progress of nanofluid investigations were published in the past several years], most of the reviews are concerned on the experimental and theoretical studies of the thermophysical properties or the convective heat transfer of nanofluids. The purpose of this paper will focuses on the importance of thermal properties, different techniques for measuring the thermal conductivity, thermal phenomena in nanofluids , especially the new application trends for nanofluids in addition to the heat transfer properties of nanofluids. And also this article will be used for researchers on nanofluids. We will try to find some challenging issues that need to be solved for future research based on the review on these aspects of nanofluids.

**Keywords and Pacs:-** Magnetic fluids, 47.65.Cb, Thermal diffusivity, 66.30.Xj, Heat transfer - convective, 44.25.+f, 44.27.+g, Convection, 44.25.+f, Thermal properties - of nanocrystals, and nanotubes 65.80.-g, Thermal instruments and apparatus 07.20.-n, Viscosity, diffusion, and thermal conductivity 51.20.+d

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### I. INTRODUCTION

Nanofluids have been searched to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, and convective heat transfer coefficients compared to those of base fluids like oil or water. It has demonstrated great potential applications in many fields.

Modern trends in process intensification and device miniaturization have resulted in the quest for effective heat dissipation methods from microelectronic systems and packages, owing to the increased fluxes and the stringent limits in operating temperatures. Conventional methods of heat removal have been found rather inadequate to deal with such high intensities of heat fluxes. A number of studies have been reported in the recent past, on the heat transfer characteristics of suspensions of particulate solids in liquids, which are expected to be cooling fluids of enhanced capabilities, due to the much higher thermal conductivities of the suspended solid particles, compared to the base liquids. However, most of the earlier studies were focused on suspensions of millimeter or micron sized particles, which, although showed some enhancement in the cooling behavior, also exhibited problems such as sedimentation and clogging. The gravity of these problems has been more significant in systems using mini or micro-channels.

A much more recent introduction into the domain of enhanced-property cooling fluids has been that of nanoparticle suspensions or nanofluids. Advances in nanotechnology have made it possible to synthesize particles in the size range of a few nanometers. These particles when suspended in common heat transfer fluids, produce the new category of fluids termed nanofluids. The observed advantages of nanofluids over heat transfer fluids with micron sized particles include better stability and lower penalty on pressure drop, along with reduced pipe wall abrasion, on top of higher effective thermal conductivity.

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It has been observed by various investigators that the suspension of nanoparticles in base fluids show anomalous enhancements in various thermophysical properties, which become increasingly helpful in making their use as cooling fluids more effective.

While the reasons for the anomalous enhancements in the effective properties of the suspensions have been under investigation using fundamental theoretical models such as molecular dynamics simulations, the practical application of nanofluids for developing cooling solutions, especially in miniature domains have already been undertaken extensively and effectively. Quantitative analysis of the heat transfer capabilities of nanofluids based on experimental methods has been a topic of current interest. The present article attempts to review the various experimental techniques used to quantify the thermal conductivity, as well as to investigate the thermal phenomena in nanofluids and the applications of nanofluids.

## II. THERMAL PROPERTIES OF NANOFLUIDS

The conventional approaches and designs have reached their limit and cooling threatens to be the limit to both further miniaturization and increased speeds. One of the conventional approaches is to circulate cooling fluids in microchannels incorporated in a device. Here, the limitation eventually arises from the ability of the fluid to conduct heat away from hot surfaces. Thermal conductivity reflects the ability of a medium to conduct heat. Typically, liquids are better conductors than gases and vapours. For example, while air has a conductivity of the order of 0.03 W/(m K), water has a conductivity of the order of 0.6 W/(m K).

However many solids are even better conductors than liquids. Thus, even common red brick has a conductivity of 60 W/(m K), while metals like silver and copper have a conductivity of 400 W/(m K). An exotic material like the carbon nanotube (CNT) has a conductivity of 3000 W/(m K). One obvious solution to the cooling problem is to boost the conductivity of a fluid by using a suspension of particles of a highly conducting solid in it. However, the size of the microchannels prevents the use of conventional 'fine' particles, which are typically micron-sized, since they can clog the channels.

Nanoparticles are the obvious substitute candidates and can make the solution feasible. Thus, studying the thermal properties of nanofluids has grabbed the attention of scientists and engineers. Three main experimental observations have been made during studies on thermal properties of nanofluids, and have been summarized by Eastman *et al.*1.

The salient features are as follows.

First and this is the most enigmatic feature, it was found that thermal conductivity of a fluid was enhanced by large factors when nanoparticles were added up to only a small volume fraction. Thus, Lee *et al.*2 found that addition of 4% of  $Al_2O_3$  particles increased thermal conductivity by a factor of 8%, while according to Eastman *et al.*1, particles of CuO at the same volume fraction enhance the conductivity by about 12%. This is interesting since conductivity of CuO is less than that of  $Al_2O_3$ . Metal particles have been found to be much more effective. Patel *et al.*3 found that even at as low a volume fraction of about 0.0001, thiol-protected gold particles increased thermal conductivity by 10%.

Other researchers have found greater enhancement with metal particles than with the lesser conducting oxide particles, though quantitatively less than that reported by Patel *et al.*3. Thus, ferrofluids containing 0.5% of iron particles were found4 to increase conductivity by 18%. Secondly, Das *et al.*5 found that thermal conductivity of nanofluids increased with increasing temperature. Clearly, this property is very advantageous in cooling applications.

Lastly, You *et al.*6 found that nanofluids exhibited three-fold increase in critical heat flux (CHF) over that of the liquid in which the particles were suspended. This parameter plays an important role in heat transfer where boiling is involved. All these features indicate the potential of nanofluids in applications involving heat removal. Issues concerning stability of nanofluids, since they do aggregate with ageing, have to be addressed before they can be put to use. Ironically, nanofluids of oxide particles are more stable but less effective in enhancing thermal conductivity in comparison with nanofluids of metal particles and CNTs. Though we will confine ourselves here to a discussion of enhancement of thermal conductivity, it is worthwhile to mention that enhancement of CHF may prove to be of wider utility.

**Table.** Nanofluids with their thermal conductivity, increase in nanofluid thermal conductivity over base fluid thermal conductivity and synthesis procedure used as reported in the literature

| Base fluid with conductivity | Nano particles, average diameter and concentration | Method used for synthesis | Max. thermal conductivity ratio | Ref. |
|------------------------------|--|---------------------------|---------------------------------|------|
| Water                        | $Al_2O_3$ , <50 nm, up to 4.3 vol%                 | 2-step                    | 1.08                            | [51] |

|                    |                                    |        |      |      |
|--------------------|------------------------------------|--------|------|------|
| 0.613              |                                    |        |      |      |
| Water              | $TiO_2$ , 15 nm, < 5.0 vol %       | 2-step | 1.30 | [52] |
| 0.613              |                                    |        |      |      |
| Cirate             | Ag, 6-80 nm, 0.1 vol %             | 2-step | 1.85 | [54] |
| $\alpha$ - Olephin | CNT, 25x50000 nm, 1.0 vol %        | 2-step | 2.50 | [53] |
| Thiolate           | Au, 10-20 nm, 0.1 vol %            | 2-step | 1.09 | [54] |
| EG                 | $Al_2O_3$ , <50 nm, up to 5.0 vol% | 2-step | 1.18 | [51] |
| 0.252              |                                    |        |      |      |

### III. TECHNIQUES EMPLOYED FOR MEASUREMENT OF THERMAL CONDUCTIVITY

The techniques employed for measurement of thermal conductivity can be broadly classified into transient and steady state methods. The transient measurement techniques frequently used are the hot wire method, the hot strip method, the temperature oscillation method and the  $3\omega$  method. Steady-state measurement using a 'cut-bar apparatus' has also been reported. These methods are reviewed below.

- **The short hot wire (SHW) method**

The transient short hot wire (SHW) method used to measure the thermal conductivity and thermal diffusivity of nanofluids has been described by Xie et al.. The technique is based on the comparison of experimental data with a numerical solution of the two-dimensional transient heat conduction applied to a short wire with the same length-to-diameter ratio and boundary conditions as in the experimental setup.

- **Temperature oscillation technique**

Das et al. proposed and demonstrated the temperature oscillation method for estimating thermal conductivity and thermal diffusivity of nanofluids. In this method, experimental setup shows a cylindrical fluid volume analyzed, with periodic temperature oscillations applied at surfaces A and B. The temperature oscillations are generated using Peltier elements attached to reference layer. The Peltier elements are powered by a DC power source. The real measurable phase shift and amplitude ratio of temperature oscillation can be expressed as,

$$\Delta G = \arctan \left( \frac{\text{Im}(B^*)}{\text{Re}(B^*)} \right) \dots\dots\dots[1]$$

and

$$\frac{u_L}{u_{L/2}} = \sqrt{\text{Re}(B^*)^2 + \text{Im}(B^*)^2}, \dots\dots\dots[2]$$

where G is the phase shift, u amplitude in Kelvin, and L thickness of fluid sample in meter.

The complex amplitude ratio between the mid-point of the specimen and the surface can be given by

$$B^* = \frac{2u_L e^{iG_L}}{u_L e^{iG_L} + u_0 e^{iG_0}} \cosh \left( \frac{L}{2} \left( \frac{i\omega}{\alpha} \right)^{1/2} \right), \dots\dots\dots[3]$$

where  $\alpha$  is the thermal diffusivity and the angular velocity,  $\omega$ , is given by

$$\omega = \frac{2\pi}{t_p} \dots\dots\dots[4]$$

The phase and amplitude of temperature oscillation at the two surfaces as well as at the central point C, gives the thermal diffusivity of the fluid, from Equations 1 or 2.

The temperature oscillation in the reference layer at the two boundaries of the test fluid yields the thermal conductivity. The frequency of temperature oscillation in the reference layer, in the Peltier element and that in the test fluid are the same.

The complex amplitude ratio at  $x = -D$  (D being the thickness of the reference layer) and  $x = 0$  is given by

$$B_R^* = \cosh(\zeta_D \sqrt{i}) - C \sinh(\zeta_D \sqrt{i}) \times \frac{(u_L/u_o)e^{i(G_L-G_o)} - \cosh(\zeta_L \sqrt{i})}{\sin(\zeta_L \sqrt{i})} \dots\dots[5]$$

where  $\zeta = x\sqrt{\frac{\omega}{\alpha}}$  and  $\zeta = x\sqrt{\frac{\omega}{\alpha_R}}$ . The subscript R represents the reference layer.

$$C = \frac{\lambda}{\lambda_R} \sqrt{\frac{\alpha}{\alpha_R}} \dots\dots\dots[6]$$

where  $\lambda$  is the thermal conductivity of the fluid.

The real phase shift and amplitude attenuation of the reference layer is given by

$$\Delta G_R = \arctan \frac{\text{Im}(B_R^*)}{\text{Re}(B_R^*)} \dots\dots\dots[7]$$

$$\frac{u_D}{u_o} = \sqrt{\text{Re}(B_R^*)^2 + \text{Im}(B_R^*)^2} \dots\dots\dots[8]$$

The thermal diffusivity of the reference layer being known either from above equations, the thermal conductivity of the specimen can be evaluated from Equation 6.

• **3 $\omega$  method**

The 3-Omega method used for measuring the thermal conductivity of nanofluids is a transient method. The device fabricated using micro electro-mechanical systems (MEMS) technique can measure the thermal conductivity of the nanofluid with a single droplet of the sample fluid.

• **Microlitre hot strip devices for thermal characterization of nanofluids**

A simple device based on the transient hot strip (THS) method used for the investigations of nanofluids of volumes as small as 20  $\mu$ L is reported in the literature by Casquillas et al. In this method[18], when the strip, in contact with a fluid of interest is heated up by a constant current, the temperature rise of the strip is monitored. Photolithography patterning of the strip was done using AZ5214 Shipley resist spin coated on a glass substrate. Electron beam evaporation deposition of Cr (5 nm)/Pt (50 nm)/Cr (5 nm) sandwich layer was followed by deposition of SiO<sub>2</sub> (200 nm) cover layer deposition by PECVD (plasma enhanced chemical vapor deposition). The electrical contact areas of the sample were obtained by photolithography and reactive ion etching of SiO<sub>2</sub> layer with SF<sub>6</sub> plasma, followed by chromium etching. The micro-reservoir for nanofluids was fabricated by soft lithography. The PDMS (polydimethylsiloxane) cover block was created from a 10:1 mixture of PDMS-curing agent. The PDMS was degassed at room temperature for 2 h and cured at 80°C for 3 h. A PDMS block of 20 mm long, 10 mm large, and 3 mm thick was cut and a 5 mm diameter hole was drilled in the center for liquid handling. The PDMS block and the glass substrates were exposed to O<sub>2</sub> plasma, before the device was baked at 80°C for 3 h for irreversible bonding. THS device, with a water droplet confined in the open hole is shown in Figure 5. The current and voltage measurements were performed using a voltmeter (Agilent 34410A) and a function generator (Agilent 33220A) linked to a current source. The temperature variation of the strip was recorded by applying a constant current and monitoring the resistivity change with time from which the liquid thermal conductivity was deduced.

The transient response of the platinum strip temperature can be described by the following expression for  $t > 0.2$  s:

$$T = T_o + \alpha_f \ln(t),$$

Where  $T_o$  is the intercept on the temperature axis of the T vs. ln(t) graph. The thermal diffusivity,  $\alpha_f$  depends on the thermal conductivity k, the density, and the specific heat capacity of the fluid. As a first-order approximation, it is possible to obtain the thermal conductivity from the measurement of  $\alpha_f$ .

• **Steady state measurement using cut-bar apparatus**

Steady-state measurement of the thermal conductivity of nanofluids using a cut-bar apparatus has been reported by Sobhan and Peterson [20]. The steady state thermal conductivity of the nanofluid can be modeled as shown in Figure 6. The apparatus consists of a pair of copper rods (2.54 cm diameter) separated by an O-ring to form the test cell. Several thermocouples are soldered into the copper bars to measure surface temperatures and the heat flux. The test cell is placed in a vacuum chamber maintained at less than 0.15 Torr. The external convection and/or radiation losses are thus minimized, and hence neglected. The size of the test cell is kept small, such that convection currents do not set in, as indicated by an estimation of the Rayleigh number. The heat flux in the cut-bar apparatus is the average of the heat fluxes from Equation below, calculated from the temperature differences between the upper and lower copper bars:

$$q = k_{\text{copper}} \Delta T_{\text{bar}} / \Delta Z_{\text{bar}}$$

where  $q$  is the heat flux,  $k_{\text{copper}}$  the thermal conductivity of copper bars,  $\Delta T_{\text{bar}}$  the temperature difference along the copper bars, and  $\Delta Z_{\text{bar}}$  the distance along the copper bars.

The effective thermal conductivity of the nanoparticle suspension contained in the test cell can be calculated as:

$$k_{\text{eff}} = [q(\Delta Z_{\text{cell}} / \Delta T_{\text{cell}}) - k_{\text{O-ring}} A_{\text{O-ring}}] / A_{\text{cell}}$$

where  $k_{\text{eff}}$  is the effective thermal conductivity of the nanofluid,  $q$  the heat flux,  $\Delta T_{\text{cell}}$  the average temperature difference between the two surfaces of the test cell,  $\Delta Z_{\text{cell}}$  the distance between the two cell surfaces,  $k_{\text{O-ring}}$  the thermal conductivity of the rubber O-ring,  $A_{\text{O-ring}}$  the cross-sectional area of the rubber O-ring, and  $A_{\text{cell}}$  the cross-sectional area of the test cell. Baseline experiments using ethylene glycol and distilled water showed an accuracy of measurement within +/-2.5%.

#### IV. FORCED CONVECTION IN NANOFLUIDS

Forced convection heat transfer is one of the most widely investigated thermal phenomena in nanofluids [23-35], relevant to a number of engineering applications. Due to the observed improvement in the thermal conductivity, nanofluids are expected to provide enhanced convective heat transfer coefficients in convection. However, as the suspension of nanoparticles in the base fluids affect the thermophysical properties other than thermal conductivity also, such as the viscosity and the thermal capacity, quantification of the influence of nanoparticles on the heat transfer performance is essentially required. As the physical mechanisms by which the flow is set up in forced convection and natural convection are different, it is also required to investigate into the two scenarios individually. The case of the natural convection (thermosyphon) loops is another problem in itself, because the characteristic of the flow is similar to that of the forced convection loop, though the mechanism is buoyancy drive. Some of the important investigations on forced convection in nanofluids are reviewed here. Studies on free convection and thermosyphon loops will be discussed here.

##### • Convective heat transfer in fully developed laminar flow

Experimental investigations on the convective heat transfer coefficient of water-Al<sub>2</sub>O<sub>3</sub> nanofluids in fully developed laminar flow regime have been reported by Hwang et al. [29]. Their experimental setup consisted of a circular tube of diameter 1.812 mm and length 2500 mm, with a test section having an externally insulated electrical heater supplying a constant surface heat flux (5000 W/m<sup>2</sup>), a pump, a reservoir tank, and a cooler, as shown in Figure 8. T-type thermocouples were used to measure the tube wall temperatures,  $T_s(x)$ , and the mean fluid temperatures at the inlet ( $T_{m,i}$ ) and the exit. A differential pressure transducer was used to measure the pressure drop across the test section. The flow rate was held in the range of 0.4 to 21 mL/min. With the measured temperatures, heat flux, and the flow rate, the local heat transfer coefficients were calculated as follows:

$$h(x) = \frac{q''}{T_s(x) - T_m(x)},$$

where  $T_m(x)$  and  $h(x)$  are the mean temperature of fluid and the local heat transfer coefficient. The mean temperature of fluid at any axial location is given by,

$$T_m(x) = T_{m,i} + \frac{q' P}{\dot{m} C_p} x$$

where  $P$ ,  $\dot{m}$ , and  $C_p$  are the surface perimeter, the mass flow rate, and the heat capacity, respectively.

The darcy friction factor for the flow of Al<sub>2</sub>O<sub>3</sub>-water nanofluids was calculated using the measured pressure drop in the pipe and plotted against the Reynolds number. The result was found to agree with the theoretical value for the fully developed laminar flow obtained from  $f = 64/\text{Red}$ . The measured heat transfer coefficient for water was found to provide an accuracy of measurement with less than 3% error when compared to the Shah equation. The convective heat transfer coefficient for nanofluids was found to be enhanced by around 8%, compared to pure water. It was proposed that the flattening of the fluid velocity profile in the presence of the nanoparticles could be one of the reasons for enhancement in the heat transfer coefficient.

- **Convective heat transfer under constant wall-temperature condition**

Heris et al. [30] measured convective heat transfer in nanofluids in a circular tube, subjected to a constant wall temperature condition. The test section consisted of a concentric tube assembly of 1 m length. In this, the inner copper tube was of 6 mm diameter and 0.5 mm thickness, and the outer stainless steel tube was of 32 mm diameter, which was externally insulated with fiber glass. The constant wall temperature condition was maintained by passing saturated steam through the annular section. The nanofluid flow rate was controlled by a reflux line with a valve. K-type thermocouples were used to measure the wall temperatures ( $T_w$ ) and bulk temperatures of the nanofluid at the inlet and the outlet ( $T_{b1}$  and  $T_{b2}$ ). A manometer was used to measure the pressure drop along the test section. From a measurement of the time required to fill the glass vessel, the flow rate was calculated. The uncertainties associated with the measurement of the temperature and the flow rate measurements were found to be 1.0 and 2.0%, respectively. The convective heat transfer coefficient and the Nusselt number were calculated as follows:

$$\overline{h_{nf}}(\text{exp}) = \frac{C_{p,ref} \cdot \rho_{ref} \cdot \overline{U} \cdot A (T_{b2} - T_{b1})}{\pi D L (T_w - T_b)_{LM}},$$

$$\overline{Nu_{nf}}(\text{exp}) = \frac{\overline{h_{nf}}(\text{exp}) \cdot D}{k},$$

Where  $(T_w - T_b)_{LM}$  is the logarithmic mean temperature difference,  $A$ ,  $D$ , and  $L$  cross-sectional area, diameter, and heated length of the pipe and  $\overline{U}$  is the average flow velocity. The uncertainties of the calculated heat transfer coefficient, pressure drop, Peclet number, Nusselt number, and Reynolds number were 3, 3, 3, 4, and 2.5%, respectively. The convective heat transfer coefficient was measured for nanofluids in the laminar flow regime at constant wall temperature condition, for the volume concentration in the range of 0.2 to 2.5%. The experimental results were compared with the Sieder-Tate correlation. Addition of nanoparticles showed a deviation from the values obtained by the correlation, which was particularly significant at higher values of the Peclet number. Typically, at a Peclet number of 6000, the heat transfer coefficient was found to be enhanced by 1.16 times for 0.2% concentration and 1.41 times for 2.5% concentration.

- **Convective heat transfer in thermally developing region**

Anoop et al. [31] investigated the effect of the size of nanoparticles on forced convection heat transfer in nanofluids, focusing the study on the thermally developing region. The experimental forced circulation loop consisted of a pump, a heated test section (copper tube, 1200 mm length,  $4.75 \pm 0.05$  mm inner diameter, 1.25 mm thickness), a cooling section, and a collecting tank. A constant laminar flow rate was maintained in the loop. A variable transformer connected to the electric circuit of the pump was used to vary the flow rates. The DC power source connected to the electrically insulated Ni-Cr wire, uniformly wound around the pipe dissipated a maximum power of 200 W. T-type thermocouples were used to measure the wall temperatures as well as the fluid inlet and exit temperatures.

Plug flow was maintained at the entrance using a series of wire meshes. A precise measuring jar and stop watch is used to measure the flow rates. The local heat transfer coefficient and local Nusselt number are defined by using above Equations. The thermal conductivity value used was at the bulk mean temperature. The density and specific heat of the nanofluid dependent on the volume fraction,  $\phi$ , was given by,

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

$$(\rho C_p)_{nf} = (1 - \phi)(\rho C_p)_{bf} + \phi(\rho C_p)_p.$$

The convective heat transfer coefficient was measured with nanofluids mixed with Al<sub>2</sub>O<sub>3</sub> nanoparticles of average sizes 45 and 150 nm. In the developing flow region and for a Reynolds number of 1500, the 45-nm sized particles gave 25% enhancement in heat transfer compared with 11% by the 150-nm particles, for a concentration of 4% by weight. The enhancement in heat transfer coefficient was also found to decrease, from the developing to fully developed region. For a concentration of 4% (by weight) of 45 nm

particles and an approximate Reynolds number of 1500, the enhancement in heat transfer coefficient was 31% at  $x/D = 63$ , while it was 10% at  $x/D = 244$ . The uncertainty in the measurement of thermal conductivity was found to be less than 2%, and that for viscosity was 0.5%. A systematic uncertainty analysis yielded the maximum error in the Reynolds number and the Nusselt number to be around 3.24 and 2.45%, respectively. Variation of heat transfer coefficient with particle size and Reynolds number were described by Anoop et al. [31].

- **Single-phase and two-phase heat transfer in microchannels**

Lee et al. [32] investigated on the use of nanofluids for single-phase and two-phase heat transfer in microchannels. The channels were fabricated by milling rectangular grooves, 215  $\mu\text{m}$  wide and 821  $\mu\text{m}$  deep, into the top surface of an oxygen-free copper block. The block was inserted into a G-7 plastic housing and sealed on top with a polycarbonate cover plate. The method produced 21 parallel microchannels, each with a hydraulic diameter of 341  $\mu\text{m}$ , occupying a total substrate area with 1 cm width and 4.48 cm length. Heating was provided by 12 cartridge heaters embedded in the bottom of the copper block. The fluid temperature and pressure were measured at the inlet and exit plenums of the housing. The bottom wall temperature was also measured using K-type thermocouples inserted along the flow direction. A Yokogawa WT210 power meter was used to measure the electric power input to the copper block. A bypass was included immediately downstream of the flow-meters to calibrate the flow meters. An HP 3852A data acquisition system was utilized in the setup. Heat loss from the copper block was estimated as less than 5% of the electrical power input. The single phase flow experiments in the laminar regime showed an enhancement in heat transfer with the nanoparticle concentration. The fluid and pipe wall temperatures were found to increase with the nanoparticle concentration, which was interpreted as due to the reduced specific heat of nanofluids. The enhancement in heat transfer was found to be lesser in the turbulent flow regime than in the laminar regime. In the case of two phase heat transfer using nanofluids, it was observed that the chances of particles separating, getting deposited as clusters and thus clogging passages in micro-channels could make the method less preferable.

- **Convective heat transfer in confined laminar radial flows**

Impinging jets with or without confinement as well as fluid flow between fixed or rotating disks with axial injection have applications in turbomachinery and localized cooling. Gherasim et al. [33] experimentally investigated the heat transfer enhancement capabilities of coolants with  $\text{Al}_2\text{O}_3$  nanoparticles suspended in water inside a radial flow cooling system. The test rig was as shown in Figure 14. Parametric studies were performed on heat transfer inside the space delimited by the nozzle and the heated disk (Aluminum, 30 cm diameter, 7.5 cm thick), with and adjustable separating distance between them. The disk was heated with seven symmetrically implanted 200 W cartridge heating elements, one at the center of the disk, and the other six spaced at  $60^\circ$  from each other at approximately half the radial distance. Thermally insulated K-type thermocouples were used to measure the temperatures. The heated disk was insulated using a 1.5-cm Teflon disk and a 3-cm thick insulating foam board. The periphery of the test section was surrounded by insulating foam. The concentric inlet and outlet tubes were insulated from each other using a plastic sleeve and a layer of air. From the time required to accumulate a certain quantity of fluid, the fluid mass flow rate was calculated. The heat flux was varied by changing the tension applied to the heating elements. The applied power was calculated from the measured voltage and current. The Reynolds number, as defined in Equation, and the Nusselt number (Above Equation) were calculated:

$$\text{Re} = \frac{\bar{U}_{\text{inlet}} \cdot D_h \cdot \rho_{\text{nf}}}{\mu_{\text{nf}}},$$

where  $\bar{U}_{\text{inlet}}$  is the mean inlet fluid velocity and  $D_h$  is given by  $2\delta$ , where  $\delta$  is the distance separating the disks. The local heat transfer coefficient  $h_r$  is obtained as:

$$h(r) = \frac{q''}{T_{w,r} - T_{b,r}}.$$

The bulk temperature at a given radial section ( $T_{b,r}$ ) was calculated as:

$$T_{b,r} - T_{b,i} = \frac{q'' \pi r^2}{\dot{m} C_p},$$

where  $T_{b,r}$  and  $T_{b,i}$  are the bulk temperatures at a given radius and at the inlet.

Considering all the uncertainties on experimental measurements, the average relative errors on Nusselt number calculations were estimated as 12.1, 11.5, and 11% for cases with particle volume concentrations of 2, 4, and 6%, respectively. The experiments were aimed at investigating the effect of nanofluids in a steady laminar flow between the disk and a flat plate, with axial entry and radial exit. The heat transfer coefficient was found to increase with the particle concentration and the flow rate and decrease with an increasing gap between disks.

## V. NATURAL CONVECTION LOOPS USING NANOFLUIDS

Many of the investigations on natural convection phenomena in nanofluids deal with stagnant columns of the liquid, and in these studies, a possibility of reduction of the heat transfer coefficient has been observed [43]. Some investigators have discussed on the reasons for this behavior, and have suggested that this may be due to the reduction in the gradients of temperature within the fluid, resulting from the enhancement of the fluid thermal conductivity. However, natural circulation loops present a different scenario compared to convection in liquid columns, as the circulation is developed due to thermosyphon effect. It is of interest to look into some of the investigations on natural circulation loops with nanofluids, and understand the heat transfer performance under the influence of the nanoparticles. A few important articles on this topic are reviewed below. Some investigations on natural convection in stagnant fluid columns and pool boiling heat transfer are also reviewed.

Noie et al. [43] reported an enhancement in heat transfer when nanofluids were used in a two-phase closed thermosyphon (TPCT). The TPCT was made of a copper tube (20 mm internal diameter, 1 mm thick, 1000 mm long) and, the evaporator (300 mm long) and condenser (400 mm long) sections. Heating was provided by a Nickel-Chrome wire electric heater wound around the evaporator section, with a nominal power of 1000 W.

The input power is given by:

$$Q_{in} = VI - Q_{loss}$$

Where  $Q_{loss}$  is the total heat loss from the evaporator section by radiation and free convection:

$$Q_{loss} = Q_{rad} + Q_{conv}$$

The radiation and free convection heat transfer rates were calculated as follows:

$$Q_{rad} = \varepsilon A \sigma (T_{ins}^4 - T_{surr}^4)$$

$$Q_{conv} = h_{conv} \cdot A (T_{ins} - T_{surr}).$$

In the above, the free convection heat transfer coefficient was determined using the expression:

$$Nu = \frac{h_{conv} \cdot L_t}{k_{surr}} = \left\{ 0.825 + \frac{0.387 \cdot Ra^{1/6}}{\left[ 1 + \left( \frac{0.492}{Pr} \right)^{9/16} \right]^{8/27}} \right\}^2.$$

The total heat loss was estimated to be about 2.49% of the input power to the evaporator section. As seen here, LM35 thermocouples were mounted on the TPCT, evaporator section, adiabatic section, and condenser section. Precise thermometers were used in the condenser section to read the input and output temperature of the coolant water. All the measured data were monitored using a data acquisition system. The quantity of heat transferred to the coolant water was calculated as:

$$Q_{out} = m C_p (T_{out} - T_{in}).$$

The efficiency of the TPCT was expressed as a ratio of the output heat by condensation to the input heat by evaporation:

$$\eta = \frac{Q_{out}}{Q_{in}}$$

Considering the measurement errors of the parameters such as the current, the voltage, the inlet and outlet temperature of cooling water, and the mass flow rate, and neglecting the effect of  $Q_{loss}$ , the maximum uncertainty of the efficiency was calculated as 5.41%. For an input power of 97.1 W, the 1% nanofluid gives an efficiency of 85.6% as compared to 75.1% given by pure water.

Nayak et al. [44] investigated the single phase natural circulation behavior of nanofluids in a rectangular loop. The test facility was made of glass tubes with 26.9 mm inner diameter, and had a heating section at the bottom and a cooling section at the top. The volumetric expansion of the fluid was accommodated by the expansion tank which also ensured that the loop remains full of water. Thermocouples were used to measure the instantaneous local temperature, and a pressure transducer installed in the horizontal leg of the loop measured the flow rate. The loop was insulated to minimize the heat losses to the ambient. The measurement accuracy was 0.4% (+1.1°C) for the thermocouples, +0.25% for the flow rate measurement and +0.5% of the range (0 to 1250 W) for power and pressure drop (-100 to +100 Pa). Experimental results have shown that the steady-state flow rate of nanofluids in the thermosyphon loop is higher compared to pure water. The flow rate is increased by 20 to 35% depending on the nanoparticle concentration and the heat input.

Khandekar et al. [45] reported investigations on the thermal performance of a closed two-phase thermosyphon system, using pure water and various water-based nanofluids of Al<sub>2</sub>O<sub>3</sub>, CuO, and laponite clay as working fluids. The setup has a pressure transducer fitted to the thermosyphon to monitor proper initial vacuum level and subsequent saturation pressure profiles. Four mica insulated surface heaters (116 mm × 48 mm) were mounted on the outer surface of a copper heating block (120 mm × 50 mm × 50 mm) with a center bore to accommodate the thermosyphon container which acts as the evaporator. The finned tube condenser was made of 40 square copper fins (70 mm × 70 mm × 1 mm), brazed at a pitch of 6.5 mm. The inlet and outlet of the shell side were designed so as to produce cross-flow conditions over the condenser fins. K-type thermocouples were used to measure the temperature at important axial locations on the thermosyphon tube. A PC based data acquisition system (NI-PCI-4351, National Instruments) was used to acquire the data.

The thermal resistance is defined as:

$$R_{th} = (T_e - T_c) / \dot{Q}$$

where  $T_e$  and  $T_c$  are average values of the temperatures measured by the thermocouples.

The basic mechanisms of heat transfer, in a gravity-assisted thermosyphon, are nucleate pool boiling in the evaporator and film-wise condensation in the condenser section [20]. The boiling and condensation heat transfer rates are influenced by the thermophysical properties of the working fluid and the characteristic features of the solid substrate. Major limitations of the gravity assisted thermosyphon are the dry-out limitation, counter current flow limitation (CCFL) or flooding, and the boiling limitation. It was noticed that if the filling ratio (FR) is more than 40%, dry out phenomenon is not observed and the maximum heat flux is limited by the CCFL/flooding or the boiling limitation (BL).

The thermal performance of the system was found to be deteriorating when nanofluids were used as working fluids. The deterioration was maximum with laponite and minimum for aluminum oxide suspended nanofluids. Increased thermal conductivity of the nanofluids showed no effect on the nucleate pool boiling heat transfer coefficient. It was suggested that physical interaction of nanoparticles with the nucleating cavities has been influencing the boiling characteristics of the nanofluids. The deterioration of the thermal performance of the nanofluid in closed two-phase thermosyphon was attributed to the improvement in wettability due to entrapment of nanoparticles in the grooves present on the surface. Improved critical heat flux values were also observed, which effect was also attributed to the increased wettability characteristics of nanofluids.

Natural convection heat transfer is a preferred mode as it is comparatively noise less and does not have pumping power requirement. The use of Al<sub>2</sub>O<sub>3</sub>/water nanofluids in closed two-phase thermosyphon systems [44] has shown to increase its efficiency by 14.7% when compared to water. In rectangular loops [45] with water-based nanofluids, the flow instabilities were found to decrease and the circulation rates improved, compared to the base fluid. At the same time, there have been observations [46] that in two-phase thermosyphon loops, water-based nanofluids with suspended metal oxides have inferior thermal performance compared to the base fluids, which was explained as due to the increased surface wettability of nanofluids.

Putra et al. [46] experimentally investigated the natural convection inside a horizontal cylinder heated from one side and cooled from the other. The effects of the particle concentration, the material of the particles, and the geometry of the containing cavity on natural convection were investigated. A systematic and definite deterioration of natural convection was observed and the deterioration increased with particle concentration.

Copper oxide nanofluids showed larger deterioration than aluminum oxide nanofluids. With 4% Al<sub>2</sub>O<sub>3</sub> concentration, an L/D ratio of 1.5 showed a higher value of Nusselt number compared to an L/D ratio of 0.5.

Liu et al. [47] studied the boiling heat transfer characteristics of nanofluids in a flat heat pipe evaporator with a micro-grooved heating surface. The nucleate boiling heat transfer coefficient and CHF of water-CuO nanofluids at different operating pressures and particle concentrations were measured. For a nanoparticle mass concentration less than 1%, the heat transfer coefficient and CHF were found to increase. Above 1% by weight, the CHF was almost constant and the heat transfer coefficient deteriorated. This was explained to be due to a decrease in the surface roughness and the solid-liquid contact angle. Heat transfer coefficient and CHF of nanofluids were found to increase with a reduction in the pressure. At the atmospheric pressure, the heat transfer coefficient and CHF showed 25 and 50% enhancement, respectively, compared to 150 and 200% enhancement at a pressure of 7.4 kPa.

Boiling heat transfer on a high-temperature silver sphere immersed in TiO<sub>2</sub> nanofluid was investigated by Lotfi et al. [48]. A 10 mm diameter silver sphere heated to 700°C was immersed in the nanofluid at 90°C to study the boiling heat transfer and quenching capabilities. Film boiling heat flux in the TiO<sub>2</sub> nanofluid was found to be lower than that in water. The accumulation of nanoparticles at the liquid-vapor interface was found to reduce the vapor removal rate from the film, creating a thick vapor film barrier which reduced the minimum film boiling heat flux. Experiments by Narayan et al. showed that surface orientation has an influence on pool boiling heat transfer in nanoparticle suspensions. A smooth heated tube was suspended at different orientations in nanofluids to study the pool boiling performance. The pool boiling heat transfer was found to be maximum for the horizontal inclination. Al<sub>2</sub>O<sub>3</sub>-water nanofluids of 47 nm particles and 1% by weight concentration showed enhancement in pool boiling heat transfer performance, over that of water. With increase in concentration and particle size, the performance decreased for nanofluids. For vertical and 45° inclination orientations, nanofluids showed inferior performance compared to pure water. Coursey and Kim [50] investigated the effect of surface wettability on the boiling performance of nanofluids. In the experiments, heater surfaces altered to varying degrees by oxidization or by depositing metal were investigated by measuring the surface energy measurements and boiling heat transfer (CHF). It was found that the CHF of poorly wetting systems could be improved by up to 37% by the use of nanofluids, while surfaces with good wetting characteristics showed less improvement.

## VI. APPLICATION OF NANOFUIDS

Nanofluids are having best thermal nanofluids for ex., MgO-EG nanofluid, it was found to have superior features with the highest thermal conductivity and lowest viscosity. In this part, we will discuss the applications of nanofluids in heat transfer enhancement.

- **Electronic applications**

Nanofluids with higher thermal conductivities are predicated convective heat transfer coefficients compared to those of base fluids. Researches illustrated that nanofluids could increase the heat transfer coefficient by increasing the thermal conductivity of a coolant. Advanced electronic devices face thermal management challenges from the high level of heat generation and the reduction of available surface area for heat removal. So, the reliable thermal management system is vital for the smooth operation of the advanced electronic devices.

Nanofluids reduced both the thermal resistance and the temperature difference between the heated microchannel wall and the coolant. A combined microchannel heat sink with nanofluids had the potential as the next generation cooling devices for removing ultra-high heat flux. It was found nanofluids could enhance the performance as compared with that using pure water as the coolant.

The thermal requirements on the personal computer become much stricter with the increase in thermal dissipation of CPU. One of the solutions is the use of heat pipes. Nanofluids, employed as working medium for conventional heat pipe, have shown higher thermal performances, having the potential as a substitute for conventional water in heat pipe.

The thermal performance investigation of heat pipe indicated that nanofluids containing silver or titanium nanoparticles could be used as an efficient cooling fluid for devices with high energy density. These positive results are promoting the continued research and development of nanofluids for such applications.

- **Transportation**

Nanofluids have great potentials to improve automotive and heavy-duty engine cooling rates by increasing the efficiency, lowering the weight and reducing the complexity of thermal management systems. The improved cooling rates for automotive and truck engines can be used to remove more heat from higher horsepower engines with the same size of cooling system. Alternatively, it is beneficial to design more compact cooling system with smaller and lighter radiators. It is in turn benefit the high performance and high fuel

economy of car and truck. From the thermal performance viewpoint, the use of nanofluid in the transmission has a clear advantage.

The researchers of Argonne National Laboratory have assessed the applications of nanofluids for transportation. The use of high-thermal conductive nanofluids in radiators can lead to a reduction in the frontal area of the radiator up to 10%. The fuel saving is up to 5% due to the reduction in aerodynamic drag. By reducing the size and changing the location of the radiator, a reduction in weight and wind resistance could enable greater fuel efficiency and subsequently lower exhaust emissions.

In USA, car manufacturers GM and Ford are running their own research programs on nanofluid applications. A €8.3 million FP7 project, named NanoHex (Nanofluid Heat Exchange), began to run. It involved 12 organizations from Europe and Israel ranging from Universities to SME's and major companies. NanoHex is overcoming the technological challenges faced in development and application of reliable and safe nanofluids for more sophisticated, energy efficient, and environmentally friendly products and services.

- **Industrial cooling applications**

The application of nanofluids in industrial cooling will result in great energy savings and emissions reductions.. For the US electric power industry, using nanofluids in closed loop cooling cycles could save about 10-30 trillion Btu per year (equivalent to the annual energy consumption of about 50,000–150,000 households). The thermal conductivity of the liquid-metal fluid can be enhanced through the addition of more conductive nanoparticles.

- **Heating buildings and reducing pollution**

Nanofluids in heat exchangers could reduce volumetric and mass flow rates, resulting in an overall pumping power savings. Nanofluids necessitate smaller heating systems, which are capable of delivering the same amount of thermal energy as larger heating systems, but are less expensive. This lowers the initial equipment cost excluding nanofluid cost. This will also reduce environmental pollutants because smaller heating units use less power, and the heat transfer unit has less liquid and material waste to discard at the end of its life cycle.

- **Nuclear systems cooling**

The Massachusetts Institute of Technology has established an interdisciplinary center for nanofluid technology for the nuclear energy industry. The researchers are exploring the nuclear applications of nanofluids, specifically the following three:

- 1) main reactor coolant for pressurized water reactors (PWRs). It could enable significant power uprates in current and future PWRs, thus enhancing their economic performance. Specifically, the use of nanofluids with at least 32% higher critical heat flux (CHF) could enable a 20% power density uprate in current plants without changing the fuel assembly design and without reducing the margin to CHF;
- 2) coolant for the emergency core cooling systems (ECCSs) of both PWRs and boiling water reactors. The use of a nanofluid in the ECCS accumulators and safety injection can increase the peak-cladding-temperature margins (in the nominal-power core) or maintain them in uprated cores if the nanofluid has a higher post-CHF heat transfer rate;
- 3) coolant for in-vessel retention of the molten core during severe accidents in high-power-density light water reactors. It can increase the margin to vessel breach by 40% during severe accidents in high-power density systems such as Westinghouse APR1000 and the Korean APR1400. While there exist several significant gaps, including the nanofluid thermal-hydraulic performance at prototypical reactor conditions and the compatibility of the nanofluid chemistry with the reactor materials. Much work should be done to overcome these gaps before any applications can be implemented in a nuclear power plant.

- **Space and defense**

Due to the restriction of space, energy and weight in space station and aircraft, there is a strong demand for high efficient cooling system with smaller size. Researchers have reported order of magnitude increases in the critical heat flux in pool boiling with nanofluids compared to the base fluid alone. Further research of nanofluids will lead to the development of next generation of cooling devices that incorporate nanofluids for ultrahigh-heat-flux electronic systems, presenting the possibility of raising chip power in electronic components or simplifying cooling requirements for space applications. A number of military devices and systems require high-heat flux cooling to the level of tens of MW/m<sup>2</sup>. At this level, the cooling of military devices and system is vital for the reliable operation. Nanofluids with high critical heat fluxes have the potential to provide the required cooling in such applications as well as in other military systems, including military vehicles, submarines, and high-power laser diodes. Therefore, nanofluids have wide application in space and defense fields where power density is very high and the components should be smaller and weight less.

## VII. MORE ON APPLICATIONS OF MAGNETIC FLUIDS

Nanofluids could also be designed for properties other than industrial heat transfer. For example, the biomedical field could disperse magnetic nanoparticles into blood, guide these magnetically to a cancerous tumor, and then use a laser or magnetic field that transfers energy to the particles to destroy the tumor without significantly heating the blood or damaging healthy tissue nearby. Targeted local delivery of drugs or radiation would also be possible using magnetically-guided nanoparticles in the bloodstream.

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