Defence Science Journal, Vol. 58, No. 5, September 2008, pp. 600-607

REVIEW PAPER

Thermal Conductivity of Nanofluids

A. K. Singh

Defence Institute of Advanced Technology, Pune-411 025

ABSTRACT

Nanofluids are suspensions of nanoparticles in base fluids, a new challenge for thermal sciences provided by nanotechnology. Nanofluids have unique features different from conventional solid-liquid mixtures in which mm or µm sized particles of metals and non-metals are dispersed. Due to their excellent characteristics, nanofluids find wide applications in enhancing heat transfer. Research work on the concept, heat transfer enhancement mechanism, and application of the nanofluids is still in its primary stage. This study provides a review of research in this field with focus on thermal conductivity studies of nanofluids.

Keywords: Nanofluids, enhanced heat transfer, effective thermal conductivity, diffusivity, Brownian motion, submerged arc nanosynthesis system, SANSS

1. INTRODUCTION

The concept of nanofluid is not new as in 1857 Michael Faraday first reported the study on the synthesis and colours of colloidal gold, but it was possible to put it into practice only after the tremendous development of nanotechnologies during the last decade[1]. The mixture of suspended nanoparticles in a base liquid is usually referred to as a nanofluid. Nature is full of nanofluids, like blood, a complex biological nanofluid where different nanoparticles (at molecular level) accomplish different functions, and functional components actively respond to their local environment. According to the types of liquids (organic and inorganic) and kinds of nanoparticles, one can get different types of nanofluids like process extraction nanofluids, environmental (pollution-controlling nanofluids), bio-, and pharmaceutical nanofluids. A new class of polymer nanofluids, drag-reducing nanofluids, aim at enhanced heat transfer, as well as, flow friction reduction. A wide range of active self-assembly mechanisms for nanoscale structures start from a suspension of nanoparticles in fluid. Addition of nanoparticles in liquid remarkably enhances energy transport process of the base liquid[2]. Modern nanotechnology allows one to process and produce materials with average crystallite size <50 nm. Nanofluid have some unique features that are quite different from conventional two-phase flow mixtures in which µm and/or mm particles are suspended. Pioneer works of Choi[1], Lee[3] *et al.*, Masuda[4] et al., and Eastman[5] introduced the thermal conductivity enhancement of nanofluids to the scientific community. Choi[1] made the first measurement of thermal conductivity of nanofluid. Since then, a large number of experimental and theoretical studies have been carried out by numerous researchers[6-11]. Compared to a conventional liquid and conventional two-phase mixture, the nanofluid has higher thermal conductivity, does not block flow channels, and induces a very small pressure drop. Solid particles are added as they conduct heat much better than a liquid. In addition, nanoparticles resist sedimentation, as compared to larger particles, due to Brownian motion and interparticle forces and possess much higher surface area (1,000-time) which enhances the heat conduction of nanofluids since heat transfer occurs on the surface of the fluid. Three properties that make nanofluids promising coolants are:(i) increased thermal conductivity,(ii) increased single-phase heat transfer, and (iii) increased critical heat flux. Research has shown that relatively small amounts of nanoparticles, of the order of 5 Vol.per cent or less, can enhance thermal conductivity of the base fluid to a large extent. Therefore, exploiting the unique characteristics of nanoparticles, nanofluids are created with two features very important for heat transfer systems:(i) extreme stability, and (ii) ultra-high thermal conductivity. This new class of heat transfer fluids has shown several distinct properties with large enhancements in thermal conductivity as compared to the base liquid[12], temperature and particle size dependence[13,14], reduced friction coefficient[15], and significant increase in critical heat flux[16].

2. SYNTHESIS OF NANOFLUIDS

Choi[1], *et al.* first prepared nanofluids by mixing nano particles with fluids. Since then, there has been rapid development in the systhesis techniques for nanofluids. However, there is not yet a standard preparation method for nanofluids. Different studies prepared nanofluids using different approaches. There are two fundamental methods to obtain nanofluids: (a) two-step process[17] in which nanoparticles are first produced as a dry powder, typically by an inert gas. The resulting nanoparticles are then dispersed into a fluid. This method may result in a large degree of

Received 06 June 2007, revised 19 March 2008

nanoparticle agglomeration.(b) chemical approach[18,19] using wet technology, a single-step approach, is emerging as a powerful method for growing nanostructures of different metals, semiconductors, non- metals, and hybrid systems. Advantages offered by nanochemistry are that surface-functionised nanoparticles and nanorods of metals or inorganic semiconductors, dispersible in wide variety of media such as water, can be readily prepared with precise control to produce monodispersed nanostructures[20]. Moreover, nanofluids made using this method showed higher conductivity enhancement than the ones made using 2-step method. Furthermore, the base fluids contain other ions and reaction products that are difficult or impossible to separate from the fluids.Using either of these two approaches, nanoparticles are inherently produced from processes that involve reduction reactions or ion exchange.

Laser ablation is another much sought, single-step technique that simultaneously makes and disperses nanoparticles directly in the base fluids. A variety of nanofluids have been prepared by laser ablation method[21-24] by ablating solid metals, semiconductors, etc which are submerged in the base fluid (water, lubrication oils, etc). By creating a nanofluid in this way, stable nanofluids resulted without using any property-changing dispersants. This method is also useful for further splitting of nanoparticles present in the nanofluids to study effect of particle size on thermal conductivity. Another one step approach adopted for nanofluids synthesis is based on microwave irradiation[25], and is a quick method of nanofluid systehesis. Submerged arc nano sysnthesis system(SANSS) is also used for preparing nanofluids[20,26].

A common difficulty encountered in nanofluid manufacture is nanoparticles tendency to agglomerate into larger particles, which limits the benefits of the high surface area nanoparticles. To counter this tendency, particle dispersion additives are often added to the base fluid with the nanoparticles. Unfortunately, this practice can change the surface properties of the particles, and nanofluids prepared in this way may contain unacceptable levels of impurities.

3. PARTICLE SIZE CHARACTERISATION

Imaging analysis of nanofluids is done using electron microscope (SEM/TEM, TEM being preferred over SEM for nanofluids) and most of the reported studies makes use of TEM for characterising nanofluids. Cryogenic transmission electron microscopy might provide a powerful characterisation method, but few laboratories are equipped to apply this technique. Sanning probe microsopy (SPM) has not found much use for characterising nanofluids. A simplistic approach makes use of particle size analyzer based on dynamic light scattering (DLS). Researchers have used DLS systems for particle size distribution to augment the results with TEM as main characterisation tool. Another valuable characterisation tool for the structure of suspensions at nanoscale is the small angle x-ray scattering (SAXS) and small angle neutron scattering (SANS)[27,28]. Under the approximation of a relatively monodisperse suspension, the scattering cross section can be related to the product of the particle form factor, which is determined by the shape of the particle, and the structure factor for correlations between different particles. A number of properties of the suspensions such as average particle size, gross characteristics of shape (e.g. round, or oblong, ratio of surface area to volume, thickness of the core and the shells of the particles), the poly dispersity and the extent to which particles remain isolated or have agglomerated can be obtained fairly easily.

4. THERMAL CHARACTERISATION OF NANOFLUIDS

Choi[1] established the field of nanofluids[1] in 1995, and in 2001 measured thermal conductivity enhancement of 160 per cent for MWCNT's dispersed in poly (a-olefin) oil. Several groups have measured thermal conductivities far in excess to those predicted by the Maxwell model, while it has been hypothesised that small particle size, and hence large surface area is important. Research conducted on copper oxide nanoparticles by two different groups reported that the nanofluid containing larger particles exhibited higher thermal conductivity. Das[10] *et al.* reported that nanofluids exhibit a strong dependence on temperature, with a correlation between higher conductivities and higher temperatures. The uniqueness of nanoparticles and nanofluids is that no current model, applicable to larger particles, can estimate the enhancement of nanoparticles because of the breakdown at continuum at the nano size.

4.1 Measurement of Thermal Conductivity of Nanofluids

There are steady state and transient methods for the measurement of thermal properties. Although steady-state methods are simple theoretically, these involve rather elaborate technique practically, including thermal guard to eliminate lateral heat flow and electronic control system to enable stable condition during the test. Transient methods provide fast measurement and reduce unwanted modes of heat transfer. Most thermal property measurements of nanofluids have been done using transient method of measurement. The measurement of thermal diffusivity and thermal conductivity is based on the energy equation for conduction. The thermal conductivity of nanofluid has been measured using the transient hot-wire method where the temperature increase of the platinum wire (referred as hot-wire) is related to the thermal conductivity K_{eff} of the fluid[29], widely employed to measure thermal conductivity of nanofluids[30-31]. Modified form of hot wire method referred as transient thermal probe method[32,33] is being used by the author to measure the thermal conductivity of nanofluids. Zhang[34], Zhang,[35] *et al.* have used transient short hot wire method to simultaneously measure thermal conductivity and thermal diffusivity of *Au/toluene*, Al_2O_3/H_2O, carbon nano fibre/H_2O[34] and ZrO_2/H_2O, TiO_2/H_2O CuO/H_2O[35]. Murshed[36] *et al.* have used double hot wire method to measure thermal diffusivity of nanofluids. Literature reported thermal conductivity for various nanofluids containing spherical or cylindrical solid particles is shown in Table 1.

Recently scanning thermal conductivity microscope (trade name Scanning Thermal Microscopy SThM) has been developed[37] to meet the need for thermally imaging devices and nanostructures. It aimed to directly measure thermal conductivity of microscopic structures and features such as fibres, fibre coatings, grain boundaries, grains and intergranular phases. While the spatial resolution of other thermometry techniques based on far-field optics are diffraction-limited to the order of several microns, spatial resolution of 50 nm has been demonstrated for SThM . SThM operates by raster scanning having a sharp temperature sensing tip on a solid surface. The temperature-sensing tip is usually mounted on a micro cantilever of an atomic force microscope (AFM) probe so that tip-sample constant contact force is maintained by the force feedback loop of the AFM. While the tip scans a sample, tip-sample heat transfer changes the tip temperature, which is measured and used to calculate the temperature or thermal properties of the sample at the tip-sample contact. This information in combination with probe position is used to construct a digital gray scale image of the surface with sub-micron resolution. SThM has been used to locate hot spots in electronic devices and to image contrast in thermal properties of composite thin film materials.

4.2 Theoretical Models

Increase in thermal conductivity depends on nanoparticle material, size and concentration. Nanoparticles have a large surface area-to-volume ratio; a 1 nm spherical particle has a surface area-to-volume ratio 1000 time greater than that of a 1 µm particle; Kapitza resistance becomes important for such large surface areas. Increase in thermal conductivity is beyond the classic Maxwellian model predictions. Literature survey reveals that there are large number of models for estimating thermal conductivity of nanofluids. The existing models can be categorised into two general groups:(i) Static models which assume stationary nanoparticles in the base fluid in which the thermal conductivity is predicted by conduction-based models such as Maxwell[45], Hamilton-Crosser[46], and others[47,48], using conductivity of phase constituents and volume fractions, (ii)Dynamic models[49,50]

Table 1. 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 0.613	$Al_2O_{3,}$ <50 nm, up to 4.3 vol%	2-step	1.08	[38]
Water 0.613	*CuO*, < 50 nm, up to 3.4 vol%	2-step	1.10	[38]
Water 0.613	*C*-MWNT 50 nm, 5 um 3 urn, 0.6 vol%	2-step	1.38	[39]
EG 0.252	*Fe*, <10 nm, 6.0 vol %	2-step	1.18	[40]
Water 0.613	TiO_2, 15 nm, < 5.0 vol %	2-step	1.30	[41]
Water 0.613	*Cu*, 18 nm, up to 5.0 vol%	1-step	1.60	[7, 42]
Thiolate	*Au*, 10-20 nm, 0.1 vol %	2-step	1.09	[43]
Cirate	*Ag*, 6-80 nm, 0.1 vol %	2-step	1.85	[43]
α- Olephin	CNT, 25x50000 nm, 1.0 vol %	2-step	2.50	[44]
EG 0.252	$Al_2O_{3,}$ <50 nm, up to 5.0vol%	2-step	1.18	[38]
EG 0.252	*CuO*, 35 nm, up to 4 vol%	2-step	1.21	[38]
EG 0.252	*Cu* 10 nm, up to 0.5 vol%	1-step	1.41	[42]
Oil (Trans.) 0.145	*Cu*, up to 100 nm, up to 7.6 vol%	2-step	1.43	[7]
Water 0.613	*Cu*, 75-100 nm, 1.0 vol %	1-step	1.23	[19]

based on random motion of the nanoparticles in fluid (Brownian motion) and responsible for transporting energy through collision between nanoparticles or micro liquid convection, mixing that enhances the transport of thermal energy. Modelling of nanofluid properties has been done through molecular diffusion simulation. Some of the basic models used to estimate the thermal conductivity based on above two approaches are shown in Table 2.

Heat transfer coefficient increase are on top of the thermal conductivity. Possible mechanisms considered for this increase are nanoparticle diffusion and boundary layer thinning, dispersion and enhanced turbulence. Increase in critical heat flux may be attributed to alteration of nucleation site by nanoparticle.

5. DISCUSSION

There has been vast interest about using nanofluids to meet new challenges in cooling and thermal management. Some of the literature reported results for various nanofluids with their thermal conductivity along with increase in nanofluid thermal conductivity over base fluid thermal conductivity and synthesis procedure used, have been shown in Table 1. The transient hot-wire method is one of the important means for measuring thermal conductivity. A number of studies have demonstrated anomalous enhancement of thermal conductivity when small amount of nanoparticles or nanofibres of oxides (Al_2O_3, ZrO_2, SiO_2, CuO), metals (Au, Ag, Cu), Carbon (PyC, diamond, C60) are suspended in common fluids (water, ethylene glycol, oils, etc). Das[10] *et al.* measured the conductivities of alumina and cupric oxide (in water) for different temperatures ranging from 20 °C to 50 °C for different loading conditions. They observed a linear increase in the conductivity ratio with temperature, however, for the same loading fraction, the rate of increase was higher for cupric oxide than for alumina. Patel[43]*et al.* have shown that even with the same surface-to-volume ratio, one can get different conductivities with different materials . This indicates that the quantum nature of transport phenomenon is significant. Similar trends have been seen with gold particles (4 nm) in toluene. At higher particle volume fraction, the conductivity enhancement varied more like temperature. Incidentally, an astonishing 11 per cent increase has been reported for almost vanishing concentration of 0.008 per cent for gold nanoparticles with thiolate covering.

These discussions highlight the complexity of the transport mechanism involved in nano dispersions. Choi[44] *et al*. tested a carbon nanotube-in-oil nanofluid and reported a dramatic enhancement in the effective thermal conductivity of the nanofluid (factor of 2.5 at a volume fraction of 1 per cent). Chopkar,[9] *et al*. has reported an increase of upto 2.4 time that of base fluids for Ag_2Al, and Al_2Cu nanofluid prepared in water and ethylene glycol for 0.2 to 1.5 Vol per cent nanoparticles.

Observations made from literature reviews are as follows: Thermal conductivity is enhanced by 30 per cent for Al_2O_3 water suspension at a volume of 4.3 per cent. In case of Cu-water nanofluid the thermal conductivity enhancement is 17 per cent for 4 per cent nanoparticle volume fraction.

Enhancement in thermal conductivity of CuO ethylene glycol nanofluid is 4 per cent and 22 per cent, respectively, for nanoparticle volume fraction of 1 per cent and 5 per cent. In case of CNT in ethylene glycol increase in thermal conductivity is 12.4 per cent for 1per cent volume and in synthetic oil increase is 30 per cent for a volume of 2 per cent.

Thermal conductivity increase is 11.3 per cent for MWCNT in water for 1 per cent volume fraction. Increase in thermal conductivity is 4 per cent for SiO_2–water nanofluid having 1per cent nanoparticles by volume fraction. The experimental studies on thermal conductivity with temperature using transient hot probe method for Ag, Fe and S for nanofluids being carried out by the author also indicate about 30-40 per cent increase in thermal conductivity for Ag and Fe nanofluids. A number of possible reasons for this behaviour have been proposed[8]. Several authors[49-50] have argued that large thermal conductivity increase is due to hydrodynamic effect of Brownian motion of nanoparticles. Keblinski[8] *et al*. put across four possible explanations for

Table 2. Basic thermal conductivity models, where K_{eff} is the effective thermal conductivity of solid-fluid mixture, $a = K_2/K_m$, K_m and K_2 are the thermal conductivities of base fluid and particle, respectively, n and υ are the particle shape factor and volume fraction, respectively; h is heat transfer coefficient, δ_T is thickness of layer

Expression	Remarks	Ref.
$\frac{K_{eff}}{K_m} = 1 + \frac{3(\alpha-1)\upsilon}{(\alpha+2)-(\alpha-1)\upsilon}$	Maxwell Model	[45]
$\frac{K_{eff}}{K_m} = \frac{\alpha+(n-1)-(n-1)(1-\alpha)\upsilon}{\alpha+(n-1)+(1-\alpha)\upsilon}$	Hamilton–Crosser Model	[46]
$\frac{K_{eff}}{K_m} = 1 + \frac{3(\alpha-1)\upsilon}{(\alpha+2)-(\alpha-1)\upsilon}\left[\upsilon + f(\alpha)\upsilon^2 + 0(\upsilon)^3\right]$	Davis model	[47]
$\frac{K_{eff}}{K_m} = \frac{(\alpha(1+2\beta)+2)+2\upsilon(\alpha(1-\beta)-1)}{(\alpha(1+2\beta)+2)-\upsilon(\alpha(1-\beta)-1)}$	Where $\beta = R_k K_m / R_2$ and R_k Kapitza resistance	[48]
$K_{eff} = K_m + (1-\upsilon) + K_2\upsilon + \upsilon h\delta_T$	Jang & choi model	[49]
$K_{eff}/K_m = \{1 + A\,R_e^{m}\,P_r^{\,0.333}\,\Phi\,[2(1-v)/(2+v)]\}$	Prasher et al model	[50]

the increase, i.e., Brownian motion of particles, molecular level layering of the liquid at liquid-particle interface, nature of heat transport in nanoparticles and effect of nanoparticle clustering. Particle aggregation and the formation of extended structures of linked nanoparticles may be responsible for much of the disagreement between experimental results and the predictions of effective medium theory. Simultaneous studies of thermal conductivity and viscosity may give additional insight into enhanced heat transfer. Surface modification or functionalisation may also lead to stronger thermal conductivity enhancements.

Key factors in understanding thermal properties of nanofluids are the ballistic nature of heat transport in the nanoparticles combined with direct or fluid mediated clustering effect that provide paths for rapid heat transport. Theoretical work, in the absence of a reliable experimental framework, has resulted in a large number of hypothesis, than systematic experimental results, to prove apparently anomalous phenomenon. Inspite of number of research studies on nanofluids, basic research remains at the initial stage, with results still to be reconfirmed and re-established. The size distribution of nanoparticles and nanoparticle aggregates in the suspensions is rarely reported. This lack of data can be attributed to the difficulty in properly characterising high-concentration suspensions of nanoparticles.

6. APPLICATIONS OF NANOFLUIDS

Very high thermal conductivity and extreme stability have always been desired for heat transfer fluids with particles. Fluids having this important combination of features did not exist till the advent of nanofluids. Nanofluid technology could make the process more energy efficient and cost-effective.These nanofluids could be used in a wide range of industrial applications. Demand for ultra-high-performance cooling in electronics has been increasing, and conventional enhanced surface techniques have reached their limit with regard to improving heat transfer. Since nanoparticles are relatively much smaller than the diameter of microchannel flow passages, smooth-flowing nanofluids could provide the solution. Since nanofluids can flow in microchannels without clogging, they would be suitable coolants. These could enhance cooling of MEMS under extreme heat flux conditions.

Engine coolants (ethylene glycol/water mixtures), engine oils, automatic transmission fluids, and other synthetic high-temperature heat transfer fluids currently possess inherently poor heat transfer capabilities, they could benefit from the high thermal conductivity offered by nanofluids. Nanofluids could be used as metalworking coolant fluids for grinding and polishing components. Solar energy systems could take advantage of nanofluids to enhance heat transfer from solar collectors to storage tanks. Nanofluids could improve the heat transfer capabilities of current industrial HVAC and refrigeration systems. Many innovative concepts are being considered; one involves the pumping of coolant from one location, where the refrigeration unit is housed to another location. Other potential nuclear applications include lightwater reactor coolants, standby safety system, spent-fuel storage pool, fusion diverters, etc.

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.

7. CONCLUSIONS

Most systems/processes whose performance is affected by heat generation could benefit from nanofluid coolants. Nanofluids have great potential for thermal management and control involved in a variety of applications such as electronic cooling, microelectro mechanical systems (MEMS) and spacecraft thermal management. The miniaturisation of mechanical and electrical components creates a need for heat transfer fluids with improved thermal characteristics over those of conventional coolants. The significant growth in performance and functionality of microelectronics combined with a miniaturisation trend in MEMS has resulted in an unprecedented increase in heat loads that presents a great challenge to thermal engineers. Nanofluids have the potential to meet these challenges. It is expected that nanofluids can be utilised in airplanes, cars, micro machines in MEMS, microreactors among others. Nanofluid spreading and adhesion on solid surface can yield materials with desirable structural and optical properties. Similarly, spreading behaviour of nanofluids containing surfactant micells has implications for soil remediation, oily soil removal, lubrication and enhanced soil recovery. Several investigations focused upon the energy transport enhancement inside stationary nanofluids show substantial augmentation of heat transport in the nanofluid consisting of copper or aluminium nanoparticles in water or mineral oils[2-4]. Such enhancement of energy transport is dependent on component fractions and physical properties of fluid.

Even though a large number of experiments have been conducted for measuring thermal conductivity, only a few were performed for evaluating other transport coefficients such as viscosity which is as critical as thermal conductivity in engineering systems that employ fluid flow. It is evident that the effects of viscosity and thermal conductivity should be considered together.

8. CURRENT RESEARCH DIRECTIONS AND FUTURE SCOPE

At present, fundamental and quantitative understanding of the thermal conductivity mechanisms in nanofluids is in the initial stage. Thus, current research is focused on theoretical and experimental studies to answer the question, "How does particle size affect thermal conductivity?" Researchers are working to build a structural model that can help explain the thermal conductivity of nanofluids.

In addition to particle size, particle motion induced by stochastic, inter particle, or other forces could be significant at the nanometer scale. Such motions may contribute significantly to energy transport at the nanometer scale. Another major task is analysing the microscopic motions in nanofluids and understanding their contribution to energy transport.

There are many variables involved, including nanoparticle size and shape, nanoparticle and base fluid materials, type and concentration of surfactant, concentration of nanoparticles, dispersion method, etc. There is a need for atomic and microscale-level understanding of heat transfer in nanofluids. It is expected that development of scanning thermal conductivity microscope shall detect differences in thermal conductivity of microscopic structures such as fibres, grains, particles, coatings, and intergranular phases. To accurately interpret a temperature map or a thermal property image obtained by SThM, a thorough understanding of heat transfer mechanisms at the tip-sample contact is required. The knowledge of heat transfer at micro or nanoscale contacts is, however, still limited.

Thermal conductivity has received the most attention, but several groups have recently initiated studies of other heat-transfer properties. Few studies have been conducted on the rheology of nanofluids, even though the viscosity of a nanofluid is as important as thermal conductivity when it comes to practical applications. Previous experimental results are not reproducible by other researchers, posing the question as to why nanofluids behave differently. Little is known about how nanofluids behave over time, at elevated temperatures, or what the ultimate physical limits are. The nanofluids have also shown that they do not follow the Einstein-Batchelor theory and exhibit a significantly rapid increase in viscosity than predicted. In most studies to date, sample sizes have been limited to less than a few hundred milliliter of nanofluid. Larger samples will be needed to test many properties of nanofluids in the future, particularly in assessing their potential for use in various applications. Robust techniques for large-scale production of stable nanofluids are needed. Large increases in the critical heat flux of boiling heat transfer have been reported within the past years, and this phenomenon deserves thorough study. Thermal conductivity is probably not a critical issue for critical heat flux, but the mechanisms that produce the increases in thermal conductivity are unknown at this point of time.

The future research should lead to the development of new experimental methods for characterising and understanding nanofluids in the lab and in nature, as well as to the development of computer-based models of nanofluids and functional, active nanofluid phenomena. This may lead to the development of diverse, complex nanofluids with polymer additives, including biological nanofluids, with potential for existing, new emerging, and critical applications, including energy production and conversion, transportation, environmental control, and cleanup, biomedical applications, directed self-assembly of nanostructures, and related fundamental nanoscale phenomena and processes in functional nanostructures.

A better understanding of the mechanisms behind the thermalconductivity enhancement would likely lead to recommendations for nanofluid design and engineering for industrial applications. On the basis of the promising results to date, nanofluid research could lead to a major breakthrough in solid/liquid composites for numerous engineering applications, such as coolants for automobiles, airconditioning, and supercomputers. The use of nanofluids in a wide variety of applications appears promising. Comprehensive and systematic experimental measurements will characterise heat transfer and flow friction properties on the macroscale, as well as chemistry, structure and dynamics on the nanoscale.

ACKNOWLEDGEMENTS

Author is thankful to Prof G.C.Pant, Chairman, Dept of Aerospace Engineering for encouragement and Vice Chancellor, Defence Institute of Advanced Technology, Pune, for granting permission to publish this work.

REFERENCES

1. Choi, S. Enhancing thermal conductivity of fluids with nanoparticles. *In* Development and applications of non-newtonian flows, edited by D.A. Siginer and H.P. Wang, New York: ASME, 1995, pp. 99-105.
2. Phelan, P.E.; Bhattacharya, P. & Prasher, R.S. Nanofluids for heat transfer applications. *Annu. Rev. Heat Transfer*, 2005, **14**, 255-75.
3. Lee, S.; Choi, S. U. S.; Li, S. & Eastman, J. A. Measuring thermal conductivity of fluids containing oxide nanoparticles., *J. Heat Transfer*, 1999, **121**, 280-289.
4. Masuda, H.; Ebata, A. ; Teramae, K. & Hishinuma, N. Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles (dispersion and Al_2O_3, SiO_2, and Tio_2 ultra-fine particles), Netsu Bussei (Japan), 1993, **7**(4) 227-33.
5. Eastman, J. A. ; Choi, S. U. S.; Li, S.; Thompson, L. J. & Lee, S. Enhanced thermal conductivity through the development of nanofluids. *Mater. Res. Soci. Symp. Proceedings*, Pittsburgh, PA, 1997, **457**, 3-11.
6. Xie, H.; Wang, J.; Xi, T., Liu, Y.; Ai, F. & Wu, Q. Thermal conductivity enhancement of suspensions containing nanosized alumina particles. *J. Appl. Phys.*, 2002, **91**(7), 4568-572.
7. Xuan, Y. & Le, Q. Heat transfer enhancement of nanofluids. *Int. J. Heat Fluid Flow*, 2000, **21**, 58-64.
8. Keblinski, P.; Phillpot, S. R.; Choi, S. U. S. & Eastman, J. A. Mechanisms of heat flow in suspensions of nano-sized particles nanofluids. *Int. J. Heat Mass Transfer*, 2002, **45**, 855-63.
9. Chopkar, M.; Kumar, S.; Bhandar, D.R.; Das, P.K. & Manna, I. Development and characterization of Al_2O_3 and Ag_2Al nanoparticle dispersed water and ethylene glycol based nanofluid., *Mat. Sci. Engg. B*, 2007, **139**, 141-48.
10. Das, S.K.; Putra, N.; Thiesen, P. & Roetzel, W. Temperature

dependence of thermal conductivity enhancement for nanofluids. *J. Heat Tr*., 2003, **125**, 567-74.

11. Patel, H.E.; Das, S.K.; Sundararajan, T. & Pradeep, T. A micro convection model for thermal conductivity of nanofluids. *Pramana-J. Phys*., 2005, **65**(5), 863-69.
12. Gandhi, K.S. Thermal properties of nanofluids:controversy in making. *Current Science*, 2007, **92**(6), 717-18.
13. Chon, C.H. & Kihm, K.D. Empirical correlation finding the role of temperature and particle size for nanofluid (Al_2O_3) thermal conductivity enhancement. *Appl. Phys. Lett*. 2005, **87**, 153107-1 to 3.
14. Yang, B. & Han, Z.H. Temperature dependent thermal conductivity of nanorod based nanofluids. *Appl. Phys. Lett*., 2006, **89**, 08311-1 to 3.
15. Kostic, K.M. Critical issues and application potentials in nanofluids research. *Proc. MN2006 , Multifunctional nanocomposites*. Honolulu, Hawaii. Sept 2006, 20-22.
16. Yulong, D.; Alias, H.; Wen, D. & Williams, R.A. Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids), *Int. J. Heat & Mass Tr.*, 2006, **49**, 240-50.
17. Xuan, Y.; Li, Q. & Hu, W. Aggregation structure and thermal conductivity of nanofluids. *AIChE J.*, 2003, **49**(4), 1038-043.
18. Zhu, H.; Lin, Y. & Yin, Y., A novel one-step chemical method for preparation of copper nanofluids. *J Collid & Int. Sci*., 2007, **277**, 100-03.
19. Liu, M.; Lin, M.C.; Tsai, C.Y. & Wang, C.C. Enhancement of thermal conductivity with *Cu* for nanofluids using chemical reduction method. *Int. J. Heat & Mass Trans*., 2006, **49**, 3028-033.
20. Lo, C. & Tsung, T. High thermal conductivity nanofluid fabrication by continuously controlled submerged arc nano synthesis system (CC-SANSS), *IEEE*, 2006, 686-89.
21. Phuoc, T. X.; Soong, Y. & Chyu, M. K. Synthesis of *Ag*-deionised water nanofluids using multi-beam laser ablation in liquids, optics and lasers in engineering, 2007, **45**(12), 1099-106.
22. Kim, S. H.; Choi, S. R. & Kim, D. Thermal conductivity of metal-oxide nanofluids: particle size dependence and effect of laser irradiation., *ASME Transactions*, 2007, **129**, 298-307.
23. Kabashin, A. V. & Meunier, M. Femto second laser ablation in aqueous solutions: a novel method to synthesize non-toxic metal colloids with controllable size. *J. Phys.: Conf. Series*, 2007, **59**, 354-59.
24. Hong, J.; Kim, S. H. & Kim, D. Effect of laser irradiation on thermal conductivity of ZnO nanofluids. *J. Phys.: Conf. Series*, 2007 **59**, 301-04.
25. Singh, A.K. & Raykar, V.S. Microwave synthesis of silver nanofluids with polyvinyl pyrrolidone (PVP) and their transport properties; colloid and polymer science, Accepted for publication, 2008.
26. Lo, Chih-Hung.; Tsung, Tsing-Tshih.; Chen, Liang-Chia.; Su, Chun-His. & Lin, Hong-Ming. Fabrication of copper oxide nanofluid using submerged arc nanoparticle synthesis system (SANSS). *J. Nanoparticle Res*., 2005, **7**, 313-20.
27. Hunter Robert, J. *Foundations of Colloid Sci*., Oxford University Press, Oxford, 1989.
28. Lurio, L. Report on initial XPCS and SAXS nanofluid structure testing, Energy Technology Division, Argonne National Laboratory, August 2004.
29. Jwo, C.S.; Teng; T.P. & Guo; Y.T. Research and development of measurement device for thermal conductivity of nanofluids. *J. Phys. Conf. Series*, 2005, **13**, 55-58.
30. Jwo, C. & Teng, T. Experimental study on thermal properties of brines containing nanoparticles. *Rev. Adv. Sci*. 2005, **10**, 79-83.
31. Murshed, S.M.S.; Leong, K.C. & Yang, C. Determination of the effective thermal diffusivity of nanofluids by the double hot wire technique., *J Phys. D: Appl. Phys.*, 2006, **39**, 5316-322.
32. Singh, A.K. & Reddy, N.S. Field instrumentation for thermal conductivity measurement. *Ind. J. Pure & Appl. Phys.*, 2003, **41**, 433-37.
33. Singh, A.K. A PC based transient method for thermal conductivity measurement. *Def. Sci. J.*, **50**(4), 2000, 244-54.
34. Zhang, X. Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles. *J. Appl. Phys.*, 2006, **100**, 044325-1 to5.
35. Zhang, X.; Gu, H. & Fujii, M. Experimental study on the effective thermal conductivity and thermal diffusivity of nanofluids. *Int J Thermophys.*, 2006, **27**(2),569-580.
36. Murshed, S.M.S.; Leong, K.C. & Yang, C. Determination of the effective thermal diffusivity of nanofluids by the double hot wire technique. *J. Phys. D: Appl. Phys.*,2006, **39**, 5316-322.
37. Shi, L. & Majumdar, A. Thermal transport mechanisms at nano scale point contacts. *ASME J. Heat Tranf.*, 2002, **124**, 329-37.
38. Choi, S.U.S. Nanofluid technology: Current status and future research. *Korea-U.S. Technical Conf. on Strategic Technologies*,Vienna, V.A. Oct.1998, pp. 22-24,
39. Assael, M.J.; Chen, C.F.; Metaxa, I. & Wakeham, W.A. Thermal conductivity of Suspensions of carbon nanotubes in water. *Int. J Thermophys.*, 2004, **25**, 971-85.
40. Hong, T; Yang, H. & Choi, C.J. Study of enhanced thermal conductivity of *Fe* nanofluids. *J. Appl. Phys.*, 2005, **97**, 064311-1 to 4.
41. Murshed, S. M. S.; Leong, K. C. & Yang, C. Enhanced thermal conductivity of Tio_2-water based nanofluids, *Int. J. of Therm. Sci*. 2005, **44**, 367-73.
42. Eastman, J.A.; Choi, S.U.S.; Li, S;. Soyez, G.; Thompson, L.J.& DiMelfi, R.J. Novel Thermal properties of nanostructured materials. *Int. Symp. Metastable Mechanically Alloyed & Nanocrystalline Materials*, Wollongong, Australia. Dec.1998, pp 7-12.
43. Patel, H. E.; Das, S. K.; Sundararajan, T.; Sreekumaran, A.; George, B. & Pradeep, T. Thermal conductivity of naked and monolayer protected metal nanoparticle based nanofluids: Manifestation of anomalous enhancement

and chemical effects. *Appl. Phys. Letts.*, 2003, **83**(14),2931-933.

44. Choi, S. U. S.; Zhang, Z. G.; Lockwood, F. E. & Grulke, E. A. Anomalous thermal conductivity enhancement in nanotube suspensions. *Appl. Phys. Letts*, 2001,**79**,. 2252-254.
45. Maxwell, J. C. A Treatise on Electricity and Magnetism. Oxford, NY, UK: Oxford: Clarendon, 1873.
46. Hamilton, R. & Crosser, O.K. Thermal conductivity of heterogeneous two-component systems. *IEC Fund.*, 1962, **1**(3), 187-91.
47. Davis, R.H. The effective thermal conductivity of a composite material with spherical inclusions. *Int. J. Thermophys.* 1986, **7**, 609-20.
48. Nan, C.W.; Birringer, R.; Clarke, D. R. & Gleiter, H. Effective thermal conductivity of particulate composites with interfacial thermal resistance. *J. Appl. Phys.*, 1997, **81**, 6692-699.
49. Jang, S. P. & Choi, S. U. S. Role of Brownian motion in the enhanced thermal conductivity of nanofluids. *Appl. Phys. Lett.*, 2004, **84**(21),4316-318.
50. Prasher, R. S.; Bhattacharya, P. & Phelan, P. E. Brownian motion based convective conductive model for the effective thermal conductivity of nanofluids. *Trans. ASME*, 2006, **28**, 588- 95.