ISSN: 2395-6607, Vol. 1, No. 1 March 2015, pp. 41–49

NANOFLUIDS–SMART COOLANTS: MILESTONES AND APPLICATIONS

Julie Andrews[1], Alphonsa Mathew[2] and S.P. Anjali Devi[3]
[1,2]Department of Mathematics,
St. Thomas' College (Autonomous), Thrissur, Kerala, India
[3]Department of Applied Mathematics,
Bharathiar University, Coimbatore–46, India
E-mail: [1]srjulia_cmc@yahoo.com, [2]alphonsastc@gmail.com

Abstract—*Nanofluids, in which nano-sized particles (typically less than 100 nanometers) are suspended in liquids, have emerged as a potential candidate for the design of heat transfer fluids. The different processes and materials for the synthesis of nanofluids are discussed in brief. The diverse application side of nanofluids, giving special emphasis to the cooling applications is mentioned in this paper. The work discloses the fascinating thermal and physical properties of nanofluids with efficient heat transfer characteristics. It is found out that the heat transfer enhancement is caused by the suspending nanoparticles and it becomes more pronounced with the increase of the particle volume fraction. This paper is an eye opener to the recent studies happening in the interesting and venturing world of nanofluids which are likely to be the smart coolants of the next generation and clarifies the use of nanofluids in industries instead of ordinary coolants.*

Keywords: *Nano Fluids, Nano Materials, Thermal Conductivity, Coolants, Applications*

INTRODUCTION

Nanofluid is a suspension of solid nanoparticles (1-100nm diameter) in conventional liquids like water, oil or ethylene glycol. The emergence of nanofluids as a new field of nano scale heat transfer in liquids is related directly to miniaturization trends and nanotechnology. Nanofluids owe its history to the Advanced Fluids Program (AFP) at Argonne National Laboratory (ANL) that encompassed a wide range (meters to nanometers) of size regimes and eventually the wide research road became narrow, starting with large scale and descending through micro scale to nano scale, culminating in the invention of nanofluids. The goal of nanofluids is to achieve the highest possible thermal properties at the smallest possible concentrations by uniform dispersion and stable suspension of nanoparticles in host fluids. When used as coolants, nanofluids can provide dramatic improvements in the thermal properties of host fluids. The novel nanofluids enable a more efficient, effective and uniform heat removal capability for systems requiring highly accurate temperature control at high heat fluxes.

In the development of energy-efficient heat transfer fluids, the thermal conductivity of the heat transfer fluids has a specific role to play. Though numerous development efforts and considerable previous research have took place, major improvements in cooling capabilities have been constrained because traditional heat transfer fluids used in today's thermal management systems, such as, water, oils, and ethylene glycol, have inherently poor thermal conductivities, orders-of-magnitude smaller than those of most solids. It is well known that at room temperature, metals at room temperature in solid form have higher thermal conductivities than those of their fluids as illustrated by Touloukian *et al.* (1970). The thermal conductivity of metallic liquids is much higher than those of non metallic liquids. As a consequence, the thermal conductivities of fluids that contain suspended solid metallic particles could be expected to be significantly higher than those of conventional heat transfer fluids.

Compositions of solid and liquid particles have been studied since the 1970's, but not until the incorporation of nanometer sized particles have these compositions attracted significant attention from the thermo-fluids research community. Anomalous enhancement in thermo-physical properties have been reported in the literature when the particles used to seed the base fluids were changed from micro meter sized particles to nanometer-sized particles. The mechanical, optical, electrical, magnetic and thermal properties of nanoparticles are superior to those of conventional bulk materials with coarse grain structures. Recognizing an excellent opportunity to apply nanotechnology to thermal engineering, Choi conceived the novel concept of nanofluids by hypothesizing that it is possible to break through these century-old technical barriers by exploiting the unique properties of nanoparticles.

It is known that suspension of solid particles has a great potential in improving heat transfer properties of conventional fluid as narrated by Ahuja (1975), Liu *et al.* (1988) and Webb (1993). Practical application of these coolants with suspended particles of the magnitude millimeter or micrometer sized in them shows some problems such as instability of particles, erosion, and flow channel clogging and extra pressure drop in flow channel. New advances in producing nano-sized metallic or nonmetallic particles have allowed producing new kind of fluid named as nanofluid. Nanofluids due to their excellent properties including better stability and increased thermal conductivity have been investigated by several researchers like Lee *et al.* (1999), Choi *et al.* (2001), Eastman *et al.* (2001), Keblinski *et al.* (2001), Das *et al.* (2003a, b, c), Murshed *et al.* (2005), Vadasz *et al.* (2005), Wang *et al.* (2003), Xue and Xu (2005), and Yu and Choi (2003). For example, Eastman *et al.* (2001) reported that the Cu/ethylene glycol nanofluid with 0.3% volume of Cu nanoparticles can enhance thermal conductivity up to 40%.

SYNTHESIS OF NANOFLUIDS

Nanofluid is defined as a colloidal solvent containing dispersed nanometer-sized particles (~1-100 nm). Researchers have found out many materials that can be used as base fluids and nano particles. Stable and highly conductive nanofluids are produced by one step and two step production methods. Both approaches for creating nano particle suspensions suffer from agglomeration of nano particles, which is a key issue in all the technology involving nano powder. Therefore, synthesis and suspension of nearly non agglomerated or mono dispersed nanoparticles in liquids is the key to significant enhancement in thermal properties of nanofluids.

Nano structured or nano phase materials made of nanometer sized particles enhanced physical properties not exhibited by conventional bulk solids. All physical mechanisms have a critical length scale below which the physical properties of materials are changed. Thus the particles smaller than 100 nm exhibit properties different from those of conventional solids. The noble properties of nanophase materials come from the relatively high surface area or volume ratio which is due to high proportion of constituent atoms residing at the grain boundaries. The thermal, mechanical, optical, magnetic and electric properties of nanophase materials are superior to those of conventional materials with coarse grain structures.

Nanoparticles used in nanofluids have been made of various materials such as oxide ceramics (Al_2O_3, CuO), nitride ceramics (AlN, SiN), carbide ceramics (SiC, TiC), metals (Cu, Ag, Au), semiconductors (TiO_2, SiC), carbon nanotubes, and composite materials such as alloyed nanoparticles $Al_{70}Cu_{30}$ or nanoparticle core-polymer shell composites. In addition to the nonmetallic, metallic and other materials for nanoparticles, completely new materials and structures such as materials 'doped' with molecules in their solid liquid interface structure, may also have desirable characteristics.

Many types of liquids like water, ethylene glycol and oil have been used as host liquids in nanofluids.

Fabrication of nanoparticles can be classified into two broad categories:

1. Physical processes
2. Chemical processes

Currently a number of methods exist for the manufacture of nanoparticles. Physical method includes inert-gas condensation (IGC) developed by Granquist and Buhrman (1976) and mechanical grinding. Chemical method includes chemical vapour deposition (CVD), chemical precipitation, micro emulsions, thermal spray and spray pyrolysis.

The current processes for making metal nanoparticles include IGC, mechanical grinding, chemical precipitation, thermal spray and spray pyrolysis. Sonochemical method makes suspensions of iron nanoparticles stabilized by Oleic acid. Most recently, Chopkar *et al.* (2006) produced alloyed nanoparticles $Al_{70}Cu_{30}$ using ball milling. In ball milling, balls impart a lot of energy to a slurry of powder, and in most cases some chemicals are used to cause physical and chemical changes. These nanosized materials are most commonly produced in the form of powders. In powder form, nanoparticles are dispersed in aqueous or organic host liquids for specific applications.

Although nanoparticles often refer to spherical shapes, there are also various anisotropic shapes. These refer to all shapes other than spherical. Such shapes require more than one parameter to describe their shapes. The most common ones are nano rods and nano triangles. Several other shapes, such as tripods, tetra pods, stars, flowers and sheets are known, and in several cases synthetic flexibility does not exist. However, it is not possible to get most of these in the solution phase and so out of the discussion range.

Stable suspensions of nanoparticles in conventional heat transfer fluids are produced by two methods: single-step technique and two-step technique. The single-step method simultaneously makes and disperses nanoparticles into base fluids. In two-step method, we first make nanoparticles using one of the above-described nanoparticle processing techniques and then disperse them into base fluids. Most nanofluids containing oxide nanoparticles and carbon nanotubes reported in the open literature are produced by two-step process. Although the two-step method works well for oxide nanoparticles, it is not as effective for metal nanoparticles such as copper. For nanofluids containing high-conductivity metals, it is clear that the single-step technique is preferable to the two-step method.

MILESTONES IN EXPERIMENTAL DISCOVERIES ON NANOFLUIDS

Experimental work in nanofluids research groups world-wide has discovered that nanofluids exhibit thermal properties superior to those of base fluids or conventional solid-liquid suspensions. Studies by Choi *et al.* (2001) and Eastman *et al.* (2001) have shown that copper and carbon nano tube (CNT) nanofluids possess extremely high thermal conductivities compared to those of their base liquids without dispersed nanoparticles and CNT nanofluids have a nonlinear relationship between thermal conductivity and concentration at low volume fractions of CNTs as found out by Choi *et al.* (2001). The distinctive features like strong temperature-dependent thermal conductivity discussed by Das *et al.* (2003b) and strong size-dependent thermal conductivity studied by Choi *et al.* (2005) were contributed by thermal conductivity measurement experiments of nanofluids.

Compared to the studies on conduction, there are only a few works on convection and boiling heat transfer in nanofluids. The revolutionary discoveries by Faulkner *et al.* (2004) and You *et al.* (2003) such as a two fold increase in the laminar convection heat transfer coefficient and a threefold increase in the critical heat flux in pool boiling were really unexpected as the discoveries related to conduction. Xuan and Li (2003) were the first to show a significant increase in the turbulent heat transfer coefficient. The potential impact of these discoveries on heat transfer applications made nanofluids promising coolants for the industrial and electronic world. As a consequence of these discoveries, research and development on nanofluids has drawn caring attention from industry and academia over the past several years.

APPLICATIONS OF NANOFLUIDS

Nanofluids find most of their applications in thermal management of industrial and consumer products as efficient cooling is vital for realizing the functions and long-term reliability of the same. There are a large number of tribological and medical applications for nanofluids. Recent studies have demonstrated the ability of nanofluids to improve the performance of real-world devices and systems such as automatic transmissions. This paper specifically discusses the cooling applications of nanofluids.

Cooling Applications

The cooling applications of nanofluids include Crystal Silicon Mirror Cooling, Electronics cooling, Vehicle cooling, Transformer cooling, Space and Nuclear systems cooling, Defense applications and so on.

One of the first applications of research in the field of nanofluids is for developing an advanced cooling technology to cool crystal silicon mirrors used in high-intensity x-ray sources as discussed by Lee and Choi (1996). As nanofluids remarkably reduce the thermal resistances and increase the power densities, the superiority of nanofluid-cooled silicon micro channel heat exchanger compared with water and liquid nitrogen is obvious. The benefits of using nanofluids as a room-temperature coolant are clear, including dramatic enhancement of cooling rates while operating the advanced cooling system at room temperature. Moreover, the possibility of thermal distortion and flow-induced vibration will be eliminated by passing the nanofluids through micro channels within the silicon mirror itself. The advanced cooling technology developed by Lee and Choi (1996) employs micro channel filled with nanofluids. The advanced cooling technology could provide more efficient cooling than that of other cooling technologies because the micro channels increase the effective heat transfer area, and the metallic nanoparticles increase the effective thermal conductivity of coolants. The advanced cooling technology may be used in cooling engines, superconducting magnets, and densely packed computer chips. Lee and Choi (1996) estimated that for high-aspect-ratio micro channels, power densities of approximately 3000 W/cm^2 is achievable using nanofluids. Therefore, future experimental work on nanofluid-cooled micro channel heat exchangers will advance the art of cooling high-heat-load devices.

Nano electronics refer to the use of nano technology on electronic components, especially transistors. Although the term nano technology is generally defined as utilizing technology less than 100nm in size, nano electronics often refer to transistor devices that are so small that inter atomic interactions and quantum mechanical properties need to be studied extensively. The aim of nano electronics is to process, transmit and store information by taking advantage of properties of matter that are distinctly different from macroscopic properties. The last few decades has seen an exponential growth in micro chip capabilities due to primarily a decrease in the minimum feature sizes. Nano Electronics thus needs to be understood as a general field of research aimed at developing an understanding of the phenomenal characteristics of nanometer sized objects with the aim of exploiting them for information processing purposes.

It was experimentally proved by Chein *et al.* (2003) that the thermal performance of heat pipes can be enhanced by nearly a factor of two when nanofluids are used. Tsai *et al.* (2004) used gold nanofluids as the working fluid for a conventional meshed circular heat pipe and the results show that at the same charge volume, there is significant reduction in the thermal resistance of heat pipe with nanofluid compared with DI water. The work clarifies the advantages of a conventional circular heat pipe with nanofluids over that with DI water. Kang *et al.* (2006) observed that the measured wall temperature of the heat pipe with water-based nanofluids containing a tiny amount of silver nano particles is lower than with DI water and decreases with increasing concentration of silver nanoparticles.

Ma *et al.* (2006) were the first to develop an ultrahigh-performance chip cooling device called the nanofluid oscillating heat pipe (OHP). It was Ma *et al.* (2006) who proposed the novel concept of combined nanofluids and OHPs for the breakthrough of chip cooling as they established that an OHP with water-based nanofluids containing Al_2O_3 nanoparticles has the ability to remove heat in excess of $1000 W/cm^2$. This innovative and interesting discovery will surely advance the state of the art in nanofluid applications and accelerate development of a highly efficient cooling device for ultra high-heat-flux electronic systems.

Silicon micro channel heat sink (MCHS) performance using nanofluids as the coolant was numerically investigated by Chein and Huang (2005) and it was clarified that nanofluids have the potential to enhance MCHS performance. Moreover, Koo and Kleinstreuer (2005) simulated and analyzed steady laminar flow of nanofluids in micro channels and were able to conclude that copper nanoparticles at low volume fractions to high-Prandtl number fluids significantly increases the heat transfer performance of a micro channel heat sink. The analytical and the experimental work on MCHS performance by Chein and Chuang (2007) finalized with the result that when the flow rate is low, the amount of heat absorbed by water-based nanofluids containing CuO nanoparticles is greater than that absorbed by water and the MCHS wall temperature is lower with nanofluids than with water.

Furthermore, Roy *et al.* (2004) found out that the use of a temperature-dependent property model predicts much better thermal and hydraulic performance than that in previous predictions using constant properties. The results from the work of Palm *et al.* (2006) which dealt with heat transfer enhancement capabilities of nanofluids inside typical radial flow impingement jet cooling systems show that nanofluids can increase the average wall heat transfer coefficient significantly and decrease the wall shear stress. This is an encouraging milestone for the use of nanofluids in impinging jet cooling systems. Zhou (2004) investigated the heat transfer characteristics of copper nanofluids with acoustic cavitation bubbles and this significant work is capable of accelerating the practical applications of nanofluids.

It is quite interesting to note that nanoparticles can be dispersed not only in coolants and engine oils, but also in transmission fluids, gear oils, and other fluids and lubricants. Actually nanofluids provide better overall thermal management and better lubrication. The results from the first application of nanofluid research in cooling a real- world automatic power transmission system by Tzeng *et al.* (2005) on the experimental platform of the real rotary blade coupling (RBC) of a power transmission system of a real-time four-wheel-drive vehicle show that CuO nanofluids have the lowest temperature distribution at both high and low rotating speed and accordingly the best heat transfer effect. Really, it shows a real-world application of nanofluids and as a consequence represents a gaint step forward for industrial applications of nanofluids.

The power generation industry is interested in transformer cooling application of nanofluids for reducing transformer size and weight. The ever-growing demand for greater electricity production will require upgrades of most transformers at some point in the near future at a potential crest of millions of dollars in hardware retrofits. If the heat transfer capability of existing transformers can be increased, many of the upgrades may not be necessary. It was demonstrated by Xuan and Li (2000) and Yu *et al.* (2007) that the heat transfer properties of transfer oils can be improved by using nanoparticle additives specially, nanofluid-based transformer oil is likely to be the next-generation cooling fluid in transformers. The first key element in nanofluid technology which is the uniform dispersion of non agglomerated nanoparticles is still challenging for new combination of nanoparticle-based fluid and more focus is needed on the study of dynamic interactions between nanoparticles and liquid molecules and interface structure and chemistry.

It was Yu *et al.* (2003) and Vassallo *et al.* (2004) who discovered the unprecedented phenomenon that nanofluid can double or triple the CHF in pool boiling. Kim *et al.* (2006) found that the high surface wetability caused by nanoparticle deposition can explain these remarkable thermal properties of nanofluids. The capability of nanofluids for the tremendous increase in CHF and the upper heat flux limit in nucleate boiling systems is of paramount practical importance to ultrahigh heat-flux devices that use nucleate boiling such as high power lasers and nuclear reactor components. Thus, actually nanofluids have opened up exciting offers for raising chip power in electronic devices or simplifying cooling requirements for space applications. Leading nuclear researchers are very much interested in the use of nanofluids with dramatically increased CHF values because it could enable very safe operation of commercial or military nuclear reactors. Currently many evaluations on the potential impact of the use of nanofluids on the safety neutronic and economic performance of nuclear systems are done in the Massachusetts institute of technology which has established an interdisciplinary center for the nanofluid technology for the nuclear energy industry.

There are a number of military devices and systems such as high-powered military electronics, military vehicle components, radars and lasers which require high-heat-flux cooling. In reality, cooling with conventional heat transfer fluid is difficult for such conditions. Some specific examples of potential military applications include power electronics and directed-energy weapons cooling. Nanofluids provide advanced cooling technology for military vehicles, submarines and high-power laser diodes.

Nanofluid research for defense application considers multifunctional nanofluids with added thermal energy storage or energy harvesting through chemical reactions.

The novel projected applications of nanofluids include sensors and diagnostics that instantly detect chemical warfare agent in water or water or food borne contamination; biomedical applications include cooling medical devices, deleting unhealthy substances in the blood, cancer treatment or drug delivery; and development of advanced technologies such as advanced vapour compression refrigeration systems. It is clear that nanofluids will be increasingly important for high-value added niche applications as well as for high- volume applications.

ESTABLISHING NANOFLUID PROPERTIES

The viscosity, specific heat capacity, density and thermal conductivity of the nanofluids depend on the volume fraction ϕ of the nanoparticles used.

The dynamic viscosity of the nanofluid as given by Brinkman (1952) is as follows:

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2..5}} \quad (1)$$

Where, μ_f the dynamic viscosity of the base fluid and ϕ solid volume fraction.

The effective density of the nanofluid is given by

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_s \quad (2)$$

Where, ρ_f and ρ_s are density of the base fluid and solid particle respectively.

The heat capacity of the nanofluid is given by

$$\left(c_p\right)_{nf} = (1-\phi)(c_p)_f + \phi(c_p)_s \quad (3)$$

as given by Santra *et al.* (2009), where $(c_p)_f$ and $(c_p)_s$ are heat capacitances of the base fluid and solid particle respectively.

The majority of nanofluid research has been on establishing the thermal conductivity of nanofluids, which was discussed more extensively on heat transfer variables of nanofluids. Some researchers have found moderate enhancements in thermal conductivity, but many have observed large enhancements. For instance, Garg *et al.* (2008) found from testing copper/ethylene glycol nanofluid, that the thermal conductivity was twice the amount as what is predicted by the Maxwell effective medium theory.

CONCLUSION

One of the goals of theoretical research on nanofluids is to develop a theory of nanofluids to explain how nanoparticles change the thermal properties of nanofluids. A theory of nanofluids would also provide a theoretical foundation for physics and chemistry based predictive models.

There are several reasons why the theory behind the thermal conductivity of nanofluids has not yet emerged. First, the thermal behaviour of nanofluids is quite different from that of solid-solid composites or solid-liquid suspensions. For example, the thermal conductivity of solid composites is reduced when the size of the grain is reduced. In contrast the effective thermal conductivity of nanofluids is increased when the nanoparticle size is reduced. Second, nanofluids and conventional solid-liquid suspensions are quite different not only in the magnitude of the thermal conductivity, but also in the dependence of thermal conductivity on temperature and particle concentration, and size. Third, nanofluids comprises an emerging, highly interdisciplinary field combining some aspects of such traditional fields as material science, colloidal science, physics, chemistry and engineering. So a full understanding of nanofluids requires some knowledge of each field. Therefore developing a theory of nanofluids is very challenging.

Numerous studies conducted on nanofluids have made scientific breakthrough not only in discovering unexpected thermal properties of nanofluids, but also in proposing new mechanisms behind the enhanced thermal properties of nanofluids and thus identifying unusual opportunities to develop them as next generation coolants for computers and safe coolants for nuclear reactors. Applied research in nanofluids has demonstrated in the laboratory that nanoparticles can be used to enhance the thermal conductivity and heat transfer performance of conventional heat transfer fluids. Some researchers took the concept one step into practical applications and demonstrated the ability of nanofluids to improve the performance of real world devices and systems such as automatic transmissions. Thus, nanofluid research has made the initial transition from our laboratory to industrial research laboratories. This important work has provided guidance as to the right direction, the first step in the development of commercial nanofluid technology. With continued collaboration between basic and applied nanofluid researchers in academia and industry on thermal properties, performance, theory, mechanisms, modeling, development and eventual commercialization of nanofluids, nanofluid research is expected to bring breakthroughs in nanotechnology-based cooling technology and have a strong impact on a wide range of engineering and biomedical applications. In future, promising nanofluids should be studied not only under real- world conditions of use, but also over a longer period of time. Nanofluids will be in number one position for the contribution of the humanity to the newer horizons. Concluding, we can remark that surely, coming days are for the nanofluids.

REFERENCES

Ahuja, A. (1975) *J. Appl. Phys.,* 46, 3408.

Brinkman, H.C. (1952) *J. Chem. Phys.,* 20, 571.

Chein,R. and Chuang, J. (2007) *Int. J. Thermal Sciences,* 46, 57.

Chein,R. and Huang, G. (2005) *Appl. Therm. Eng.*, 25, 3104.

Chein,H.T., Tsai,C.I. and Chen, P.H. (2003) *Proceedings of International Conference on Electronics Packaging Technology*, IEEE, Piscataway, NJ, 389.

Choi, S.U.S. (1995) *Enhancing thermal conductivity of fluids with nanoparticles,* American Society of Mechanical Engineers, Fluids Engineering Division (Publication) FED, New York

Choi, S.U.S., Zhang, Z.G. and Yu, W. (2001) *Appl. Phys. Lett.*, 79, 2252.

Chon, C. H., Kihm, K. D. and Lee, S. P. (2005) *Appl. Phys. Lett.*, 87, 153107.

Chopkar, M., Das, P.K. and Manna,I. (2006) *Scr. Mater*, 55, 549.

Das, S.K., Choi, S.U.S. and Yu, W. (2008) *Nanofluids: Science and Technology*, John Wiley & Sons,Inc., Hoboken, New Jersey.

Das, S.K., Putra, N. and Roetzel, W. (2003a) *Int. J. Heat Mass Transfer*, 46, 851.

Das, S.K.,Putra,N. and Thiesen, P. (2003c) *J. Heat Transfer*, 125, 567.

Eastman, J.A., Choi, U.S. and Li, S. (1999) *Mater Sci. Forum,* 312, 629.

Evans, W., Fish, J. and Keblinski, P. (2006) *Appl. Phys.Lett.*, 88, 093116.

Garg, J. *et al.* (2008) *J. Appl. Phys.*, 103, 074301.

Gosselin, L. and Silva, A.K. (2004) *Appl. Phys.Lett.,* 85*,* 4160.

Granqvist, C.G. and Buhrman, R.A. (1976) *J. Appl. Phys.*, 47, 2200.

Hamilton, R.L. and Crosser, O.K. (1962) *Ind. Eng. Chem. Fundam.,* 1, 187

Jordan, A. *et al.* (1999) *J. Magn. Mater.*, 201, 413.

Kang, S.W. *et al.* (2006) *Appl. Therm. Eng.*, 26, 2377.

Karthikeyan, N. R. *et al.* (2008) *Materials Chemistry and Physics*, 109, 50.

Kim, S.J. *et al.* (2006) *Appl. Phys. Lett.*, 89, 153107.

Keblinski, P. *et al.* (2001) *Int. J. Heat Mass Transfer*, 45, 855.

Keblinski, P., Eastman, J. A. and Cahill, D. G. (2005) *Materials Today*, June, 36.

Ki, J., Kang, Y. T. and Choi, C. K. (2004) *Physics of Fluids,* 16, 2395.

Koo, J. and Kleinstreuer, C. (2005) *Int. J. Heat Mass Transfer*, 48, 2652.

Lee, S. and Choi, S.U.S. (1996) Proceedings of International Mechanical Engineering Congress and Exhibition, Atlanta, USA.

Lee, S. *et al.* (1999) *J. Heat Transfer*, 121, 280.

Li, J.F. *et al.* (2004) *Tribol. Int.*, 37, 77.

Liu, K.V., Choi, S.U.S. and Kasza, K.E. (1988) Argonne National Laboratory Report, ANL-88-15.

Ma, H.B. *et al.* (2006) *Appl.Phys.Lett.*, 88, 143116.

Maxwell, J.C. (1873) *Treatise on electricity and magnetism*, Clarendon Press, Oxford.

Murshed, S.M.S., Leong, K.C. and Yang, C. (2005) *Int. J. Therm. Sci.*, 44, 367.

Palm, S.J., Roy,G. and Nguyen C.T. (2006) *Appl. Therm. Eng.*, 26, 2209.

Patel, H.E. *et al.* (2005) *Pramana - J. Phys.,* 65*,* 863.

Prakash, M. and Giannelis, E. P. (2007) *J. Comp. Mat. Des*., 14, 109.

Prasher, R., Bhattacharya, P. and Phelan, P. E. (2006) *J. Heat Transfer*, 128, 588.

Que, Q., Zhang, J. and Zhang, Z. (1997) *Wear,* 209, 8.

Ren, Y., Xie, H. and Cai, A. (2005) *J. Phys. D: Appl. Phys.*, 38, 3958.

Santra, A.K., Sen, S. and Chakraborty, N. (2009) *Int. J. Thermal Sciences.,* 48, 391.

Touloukian, Y.S. (1970) *Thermophysical Properties of Matter,* Vol 2, Plenum Press, New York.

Tsai, C.Y.*et al.* (2004) *Mater. Lett.*, 58, 1461.

Tzeng, S.C., Lin,C.W. and Huang, K.D. (2005) *Acta Mech.*, 179, 11.

Vadasz, J.J., Govender, S. and Vadasz, P. (2005) *Int. J. Heat Mass Transfer*, 48, 2673.

Vassallo, P., Kumar, R. and D'Amico, S. (2004) *Int. J. Heat Mass Transfer*, 47, 407.

Wang, B.X., Zhou, L.P. and Peng, X.F. (2003) *Int. J. Heat Mass Transfer*, 46, 2665.

Xuan,Y. and Li, Q. (2000) *Int. J. Heat Fluid Flow*, 21, 58.

Xuan, Y. and Roetzel, W. (2000) *Int. J. Heat Mass Transfer*, 43, 3701.

Xue, Q. and Xu, W.M. (2005) *Mater Chem Phys*, 90, 298.

You, S.M., Kim, J.H. and Kim, K.M. (2003) *Appl. Phys. Lett.*, 83, 3374.

Yu, C. J. *et al.* (1999) *Phys. Rev. Lett.*, 82, 2326.

Yu, W. and Choi, S.U.S. (2003) *J. Nano. Res.*, 5, 167.

Yu, W., Choi, S.U.S. and Dronbik, J. (2007) ECI Conference on Nanofluids: Fundamental and Applications, Copper Mountain, CO, Sept. 16-20.

Yu, W.*et al.* (2008) *Heat Transfer Engineering*, 29, 432.