Synthesis, Characterization and Application of Nanofluid — An Overview

Indranil Manna

Abstract | Nanofluids are quasi single phase medium containing stable colloidal dispersion of ultrafine or nanometric metallic or ceramic particles in a given fluid. Despite almost a negligible concentration (< 1 vol%) of the solid dispersoid, nanofluids register an extraordinarily high level of thermal conductivity, which largely depends on identity (composition), amount (volume percent), size and shape of the dispersoid and viscosity, density and related thermo-physical parameters of the base fluid. Nanofluids possess immense potential of application to improve heat transfer and energy efficiency in several areas including vehicular cooling in transportation, power generation, defense, nuclear, space, microelectronics and biomedical devices. In the present contribution, a brief overview has been presented to provide an update on the historical evolution of this concept, possible synthesis routes, level of improvements reported, theoretical understanding of the possible mechanism of heat conduction by nanofluid and scopes of application. The overview is supplemented with a summary of recent results from the author's own group to highlight certain simple approaches of synthesis and extent of enhancements achieved with those indigenous efforts. The biggest motivation for exploration and exploitation of nanofluid should come from the fact that the degree of consistently attained enhancement of thermal conductivity far exceeds the level predicted by the existing theory on the subject.

1. Introduction

Notwithstanding the publicity hype, nanotechnology has already or is soon likely to usher in several revolutionary changes that can significantly improve device performance, communication technology, sensor applications, drug delivery and several area of practical importance. Nanotechnology is considered to be one of the significant forces that could drive the next major industrial revolution of the century. The primary approach of nanotechnology is to manipulate the structure at the molecular or atomic aggregate level with the goal of achieving desired change in property with unprecedented precision.

Though exploits of nanotechnology mostly concerns engineering solids either for functional (electronic, magnetic, optical, catalytic, etc.) or structural (strength, hardness, wear/abrasion resistance, etc.) applications, the concept of nanofluid is rather new. About a decade back, researchers in Argonne National Laboratory, USA noticed that the fluid used for collecting nanometric alumina (Al_2O_3) particles synthesized by chemical vapor deposition showed usually large thermal

Department of Metallurgical & Materials Engineering, Indian Institute of Technology, Kharagpur 721302, India
imanna@metal.iitkgp.ernet.in

conductivity. Successful reproduction of this fluid with ultra fine particle dispersion in very small quantity and subsequent realization that the degree of increase in thermal conductivity was far above the level expected from the rule of average, created enough ripples to catch the imagination of scientific community and evoke a wide spread interest in synthesizing new type of nanofluids, exploring new areas of application and proposing plausible theories to explain the significant increase in thermal properties.

Efficient transfer of energy in the form of heat, from one body to another is often required in almost all industries. Thermal and nuclear power plant, refrigeration and air conditioning system, chemical and processing plants, electronic devices, space shuttles and rocket-launching vehicles, satellites are a few to name where the productivity as well as safety depends on efficient transfer of heat. Often a fluid is chosen as a medium for transferring heat and accordingly the mode of heat transfer is convection. The rate of heat transfer in convection is given by an apparently simple looking relationship; popularly known as Newton's law of cooling.

$$q = hA\Delta T$$

where the q is the rate of heat transfer, h is co-efficient of convective heat transfer, A is the surface area and ΔT is the temperature difference across which the transfer of thermal energy take place. It has been always the pursuit of the thermal engineers to maximize q for given ΔT or A. This can be done by increasing h. However, this is easier said than done. Heat transfer coefficient is a complex function of the fluid property, velocity and surface geometry. Out of different fluid properties, thermal conductivity influences the heat transfer coefficient in the most direct way as this is the property that determines the thermal transport at the micro-scale level.

It is well known that metals in solid form have much higher thermal conductivity than that of fluids. Heat transfer by conduction through solid is orders of magnitude larger than that by convection/conduction through a fluid. For example, the thermal conductivity of copper at room temperature is about 700 times greater than that of water and about 3000 times greater than that of engine oil [1]. Therefore, fluids containing suspended solid particles are expected to display significantly enhanced thermal conductivities relative to those of conventional heat transfer fluids [2]. In fact, numerous studies about the effective thermal conductivity of fluids that contain solid particles in suspension have been conducted. But these studies have been limited to the suspensions of millimeter or micrometer sized particles. However, there is no way to prevent solid particles from settling down from suspension when they are not in use/circulation. Moreover, the suspended particles pose the problem of maintenance by causing erosion of the prime mover and fouling of the heat transfer surface. Last but not least, the penalty of excess pressure drop often destroys the benefit of heat transfer augmentation. It is therefore, always beneficial to have the suspended particles in as small a size as possible. Apart from the other points discussed above, the small particles have a larger surface to volume ratio that favors the transport of thermal energy more efficiently.

Modern nanotechnology provides great opportunities to process and produce materials with average crystallite size below 50 nm. As already stated, the concept of nanofluid evolved in 1995 as an offshoot of synthesis of nanoparticles by chemical vapor deposition [1, 3]. These fluids with nanometer sized particle suspension in traditional heat transfer fluid offered significantly better thermal properties relative to those of conventional heat transfer fluids and liquids with no or micrometer-sized particles. The ratio of surface area to volume is 1000 times greater for particles with a 10 nm diameter than that for particles with 10 μm diameter. The much larger surface areas of nanoparticles relative to those of micro/macro-sized particles should not only improve heat transfer capabilities, but also increase the stability of the suspensions. These nanofluids have an unprecedented combination of the two features most highly desired for thermal engineering applications: extreme stability and high thermal conductivity.

Thus, 'nanofluid' is a new class of heat transfer fluid that utilizes dispersion of fine scale metallic particles in a heat transport liquid in appropriate size and volume fraction to derive a significant enhancement in the effective heat transfer coefficient of the mixture. In comparison to dispersing micron-size ceramic particles, nanofluids consist of suspension of ultra-fine or nanometric metallic particles with much smaller size and volume fraction, and yet offer a remarkably higher efficiency of heat transport.

2. Evolution of Nanofluid

Convective heat transfer can be enhanced passively by changing the flow geometry, boundary conditions, or by enhancing thermal conductivity of the fluid. It is obvious from a survey of thermal properties that all liquid coolants used today as heat transfer fluids exhibit rather poor thermal conductivity compared to solid metals.

Table 1: Thermal conductivities of various solids and liquids.

Material		Thermal conductivity (W/m-K)
Metallic solids	Copper	401
	Aluminum	237
Nonmetallic solids	Silicon	148
	Alumina (Al_2O_3)	40
Metallic liquids	Sodium (644 K)	72.3
Nonmetallic liquids	Water	0.613
	Ethylene glycol (EG)	0.253
	Engine oil (EO)	0.145

Supplementary efforts to increase heat transfer coefficient by agitation, increasing area, or adding solid dispersoids can achieve limited improvement if the thermal conductivity of the fluid itself is low. Thus, it is logical that efforts are made to increase the thermal conduction behavior of the cooling fluid itself. Earlier efforts have been made to increase the thermal conductivity of base fluids by suspending micro/macro-sized solid particles in fluids since the thermal conductivity of solid is typically 2–3 orders of magnitude higher than that of liquids (Table 1). However, adding micrometer size particles cause several problems arising out of sedimentation, clogging, pressure drop and erosion of channels/pipes/conduits.

That dispersion of solid enhances thermal conductivity or heat transfer coefficient of a fluid was known for ages. Maxwell [4] was a pioneer in this area who presented a theoretical basis for calculating the effective thermal conductivity of suspension. His efforts were followed by numerous theoretical and experimental studies, such as those by Hamilton and Crosser [5] and Wasp et al. [6]. These models work very well in predicting the thermal conductivity of slurries. However, nanofluid evoked particular interest principally because the enhancement achieved by dispersing only 1–2 vol% particles was far too greater than that anticipated by the rule of average. Furthermore, the number density of particles was insignificant if heat conduction was by physical collision or momentum transfer.

Modern materials technology provided the opportunity to produce nanometer-sized particles which are quite different from the parent material (coarse grained) in mechanical, thermal, electrical, and optical properties. Though every fluid possesses nanometric molecular chains and hence can be called nanofluid, the real justification of the name nanofluid comes from the fact that nanofluid is characterized by stable colloidal dispersion of ultrafine or nanometric solids in extremely small quantity (< 1 vol%) that is present together with the base fluid to form a pseudo-single phase medium with phenomenally greater thermal conductivity than that of the base fluid. It must be kept in mind that biologists have been using the term nanofluid for different types of particles, such as DNA, RNA, proteins, or fluids contained in nanopores [7].

Nanofluids possess a unique combination of the two most essential features desired in thermal engineering applications, namely, chemical and physical stability and high thermal conductivity. The attractive features which made nanoparticles probable candidates for suspension in fluids are the large specific surface area, less particle momentum and high mobility. With respect to conductivity enhancement, starting from copper, one can go up to multi-walled carbon nanotubes, which at room temperature exhibit 20,000 times greater conductivity than engine oil [8]. When the particles are properly dispersed, these features of nanofluids are expected to yield several benefits like: higher heat conduction due to large specific surface area and greater mobility (micro-convection) of tiny particles. It is already found that: (a) the thermal conductivity of nanofluids increases significantly with a rise in temperature [9], which may be attributed to the above reasons; (b) greater stability against sedimentation due to smaller size and weight; (c) more efficient heat transfer in micro-channels; (d) negligible friction and erosion of conduit surfaces.

The main excitement of using nanofluid arises due to the following features [10]: (a) Enhancement of thermal conductivity far beyond the level any theory could predict, (b) Dependence of thermal conductivity on particle size apart from concentration, (c) Greater stability of suspension using a stabilizing agent [11], and (d) Retention of Newtonian behavior at small concentration without much pressure drop.

The above mentioned potentials provided the thrust to begin research in nanofluids, with the expectation that these fluids will play an important role in developing the next generation of cooling technology. The result can be a highly conducting and stable nanofluid with exciting newer applications in the future. Before exploring how many of these dreams have been attained by the early results, it is necessary to say that this field of research is interdisciplinary, with inputs from chemistry, mechanical and chemical engineering, physics, and material science; hence, it is worth going into the details of not only applications but also synthesis and characterization.

3. Synthesis and Preparation of Nanofluid

Preparation of nanofluids is the first key step in experimental studies with nanofluids. Nanofluids are not just dispersion of solid particles in a fluid. The essential requirements that a nanofluid must fulfill are even and stable suspension, adequate durability, negligible agglomeration of particles, no chemical change of the particles or fluid, etc. Nanofluids are produced by dispersing nanometer-scale solid particles into base liquids such as water, ethylene glycol, oil, etc. In the synthesis of nanofluids, agglomeration is a major problem. There are mainly two techniques used to produce nanofluids: the single-step and the two-step method.

3.1. *The Single-step Process*

Various methods have been tried to produce different kinds of nanoparticles and nano-suspensions. Gleiter [12] provides a good overview of the synthesis methods. The initial materials tried for nanofluids were oxide particles, primarily because they were easy to produce and chemically stable in solution. Various investigators have produced Al_2O_3 and CuO nanopowder by an inert-gas condensation process [3, 13] that produced 2–200 nm-sized particles. The major problem with this method is its tendency to form agglomerates and its unsuitability to produce pure metallic nanopowders. The problem of agglomeration can be reduced to a good extent by using a direct evaporation condensation method. The latter method is a modification of the inert gas condensation process that has been adopted at Argonne National Laboratory, USA [1]. Even though this method has limitations of low vapor-pressure fluids and oxidation of pure metals, it provides excellent control over particle size and produces particles for stable nanofluids without surfactant or electrostatic stabilizers.

The single-step direct evaporation approach was developed by Akoh et al. [14] and is called the Vacuum Evaporation onto a Running Oil Substrate technique. The original idea of this method was to produce nanoparticles, but it was difficult to subsequently separate the particles from the fluids to produce dry nanoparticles. Eastman et al. [15] developed a modified vacuum evaporation onto oil technique, in which Cu vapor is directly condensed into nanoparticles by contact with a flowing low-vapor-pressure liquid ethylene glycol. Zhu et al. [16] presented a novel one-step chemical method for preparing copper nanofluids by reducing $CuSO_4 \cdot 5H_2O$ with $NaH_2PO_2 \cdot H_2O$ in ethylene glycol under microwave irradiation. Results showed that addition of $NaH_2PO_2 \cdot H_2O$ and the adoption of microwave irradiation are two significant factors which affect the reaction rate and properties of Cu nanofluids. Lo et al. [17] developed a vacuum-based submerged arc nanoparticle synthesis system to prepare CuO, Cu_2O, and Cu based nanofluids with different dielectric liquids. The morphologies of nanoparticles depended on the thermal conductivity of the dielectric liquids. An advantage of the one-step technique is that nanoparticle agglomeration is minimized, while the disadvantage is that only low vapor pressure fluids are compatible with such a process.

3.2. *The Two Step Process*

The two-step method is extensively used in the synthesis of nanofluids considering the available commercial nano-powders supplied by several companies. In this method, nanoparticles were first produced and then dispersed in the base fluids. Generally, ultrasonic equipment is used to intensively disperse the particles and reduce the agglomeration of particles. For example, Eastman et al. [15], Lee et al. [10], and Wang et al. [13] used this method to produce Al_2O_3 nanofluids. Also, Murshed et al. [18] prepared TiO_2 suspension in water using the two-step method. Other nanoparticles reported in the literature are gold (Au), silver (Ag), silica and carbon nanotubes. As compared to the single-step method, the two-step technique works well for oxide nanoparticles, while it is less successful with metallic particles. Except for the use of ultrasonic equipment, some other techniques such as control of pH or addition of surface active agents are also used to attain stability of the suspension of the nanofluids against sedimentation. These methods change the surface properties of the suspended particles and thus suppress the tendency to form particle clusters. It should be noted that the selection of surfactants should depend mainly on the properties of the solutions and particles. For instance, salt and oleic acid as dispersant are known to enhance the stability of transformer oil–Cu and water–Cu nanofluids, respectively [11]. Oleic acid and cetyltrimethylammoniumbromide (CTAB) surfactants were used by Murshed et al. [18] to ensure better stability and proper dispersion of TiO_2–water nanofluids. Sodium dodecyl sulfate (SDS) was used by Hwang et al. [19] during the preparation of water-based multi wall carbon nanotube dispersed nanofluids since the fibers are entangled in the aqueous suspension. In general, methods such as change of pH value, addition of dispersant and ultrasonic vibration aim at changing the surface properties of suspended particles and suppressing formation of particles-cluster to obtain stable suspensions. However, the addition of dispersants can affect the heat transfer performance of the nanofluids, especially at high temperature i.e. in the convective heat transfer and two-phase heat transfer regime.

4. Important Experimental Studies with Nanofluid

The heat transfer resistance of a flowing fluid is often represented by the Nusselt number and Prandtl number, which take into account the thermal conductivity of the fluid directly and indirectly, respectively. Thus, the first step to assess the heat transfer potential of a nanofluid is to measure its thermal conductivity. To date, majority of the research efforts concerning nanofluid were devoted to enhancing thermal conductivity of a given fluid than any other aspect of heat transfer, particularly with regards to application of nanofluid for automotive applications. Table 2 provides a chronological summary of selected important studies on nanofluid that reported significant enhancement of thermal conductivity.

5. Mechanism of Heat Conduction by Nanofluids

Besides carrying out experimental studies on the extent of increase in thermal conductivity of nanofluid possible with different combination of base fluid, dispersoids and surfactant, it is equally important to develop theories on mechanism of heat conduction and genesis of high enhancement of thermal properties of nanofluid by appropriate modeling and simulation exercises.

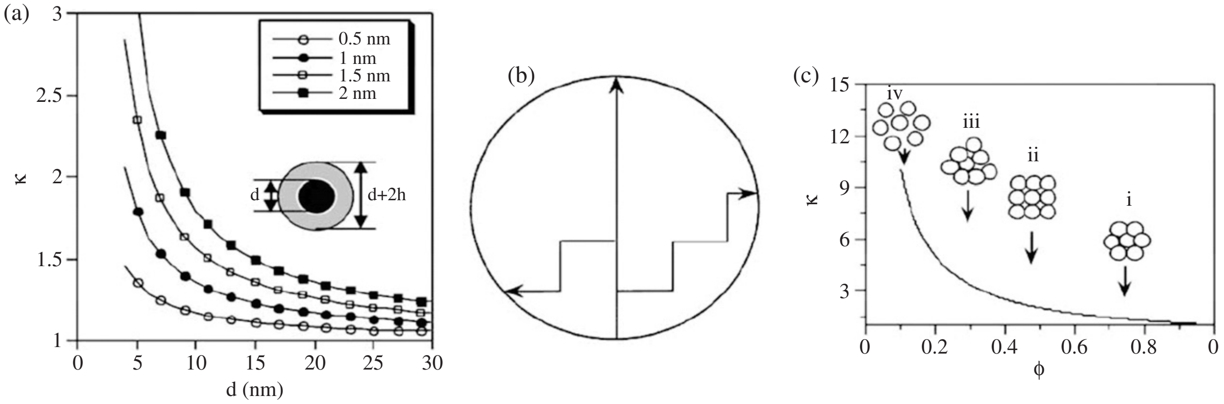
The conventional understanding of the effective thermal conductivity of mixtures originates from continuum formulations which typically involve only the particle size/shape and volume fraction, and assume diffusive heat transfer both in fluid and solid phases. This method can give a good prediction for micrometer or lager-size solid/fluid systems (say with macroscopic distribution), but fails to explain the unusual heat transfer characteristics of nanofluids. To explain the reasons for the unusual or anomalous increase of thermal conductivity in nanofluids, Keblinski et al. [27] and Eastman et al. [28] proposed four possible mechanisms e.g. Brownian motion of the nanoparticles, molecular-level layering of the liquid at the liquid/particle interface, anomalous nature of heat transport among the nanoparticles, and nanoparticle clustering. The possible mechanisms are schematically shown in Fig. 1. They postulated that the effect of Brownian motion can be ignored since contribution of thermal diffusion is much greater than Brownian diffusion. However, they only examined the cases of stationary nanofluids.

Wang et al. [13] argued that the thermal conductivities of nanofluids should be dependent on the microscopic motion (Brownian motion and inter-particle forces) and particle structure. Xuan and Li [11] also discussed several possible reasons for the improved effective thermal conductivity of nanofluids: the increased surface area due to suspended nanoparticles, the increased thermal conductivity of the fluid, the interaction and collision among particles, the intensified mixing fluctuation and turbulence of the fluid, and the dispersion of nanoparticles. Many researchers used the concept of liquid/solid interfacial layer to explain the anomalous improvement of the thermal conductivity in nanofluids.

Yu and Choi [29, 30] suggested models based on conventional theories which consider a liquid molecular layer around the nanoparticles. However, a study by Xue et al. [31] using molecular dynamic simulation showed that simple monoatomic liquids had no effect on the heat transfer characteristics both normal and parallel to the surface. This means that thermal transport in layered liquid may not be adequate to explain the increased thermal conductivity of suspensions of nanoparticles. Khaled and Vafai [32] investigated the effect of thermal dispersion on heat transfer enhancement of nanofluids. These results showed that the presence of the dispersive elements in the core region did not affect the heat transfer rate. However, the corresponding dispersive elements resulted in 21% improvement of Nusselt number for a uniform tube supplied by a fixed heat flux as compared to the uniform distribution for the dispersive elements. These results provide a possible explanation for the increased thermal conductivity of nanofluids which may determined partially by the dispersive properties.

Wen and Ding [33, 34] studied the effect of particle migration on heat transfer characteristics in nanofluids flowing through mini-channels ($D = 1$ mm) theoretically. They studied the effect of shear-induced and viscosity-gradient-induced particle migration and the self-diffusion due to Brownian motion. Their results indicated a significant non-uniformity in particle concentration and thermal conductivity over the tube cross-section due to particle migration. As compared to the uniform distribution of thermal conductivity, the non-uniform distribution caused by particle migration induced a higher Nusselt number. Koo and Kleinstreuer [35] discussed the effects of Brownian, thermo-phoretic, and osmo-phoretic motions on the effective thermal conductivities and demonstrated that the role of Brownian motion was much more important than the thermo-phoretic and osmo-phoretic motions. Furthermore, the particle interaction can be neglected when the nanofluid concentration is low ($< 0.5\%$). It was argued that liquid layering, phonon transport, and agglomeration could play more significant role in

Figure 1: Schematic diagrams of several possible mechanisms (after [27]): (a) Enhancement of k due to formation of highly conductive layer-liquid structure at liquid/particle interface; (b) Ballistic and diffusive phonon transport in a solid particle; (c) Enhancement of k due to increased effective ϕ of highly conducting clusters.



heat transport by nanofluid rather than Brownian motion. However, these findings have not been validated by experiment yet.

Recently, Evans et al. [36] suggested that the contribution of Brownian motion to the thermal conductivity of the nanofluid is very small and cannot be responsible for the unusual thermal transport properties of nanofluids. They also supported their argument using the molecular dynamic simulations and the effective medium theory. However, they just limited their discussion to stationary fluids, which weakens their results. Lee et al. [37] experimentally investigated the effect of surface charge state of the nanoparticle in suspension on the thermal conductivity. They showed that the pH value of the nanofluid strongly affected the thermal performance of the fluid. With further diverged pH value from the iso-electric point of the particles, the nanoparticles in the suspension got more stable so as to change the thermal conductivity. That may partially explain the disparities between different experimental data since many researchers used surfactants in nanofluids, but with insufficient descriptions.

Hence, there is no established mechanism to universally explain the strange behavior of nanofluids including the highly improved effective thermal conductivity, although many possible factors have been considered, including Brownian motion, liquid–solid interface layer, ballistic phonon transport, and surface charge state. Besides these microscale theories, there are still some other possible macro-scale explanations such as heat conduction, particle-driven natural convection, convection induced by electrophoresis, thermophoresis, etc.

6. Experimental Studies on Nanometric Al-alloy and Oxide Dispersed Nanofluids at IIT Kharagpur

It has recently been shown that two stage development of nanofluid by synthesizing nanometric Al-alloy (Al_2Cu and Ag_2Al) powder particles by mechanical alloying and subsequently dispersing the same in water/ethylene glycol could be a flexible method of producing nanofluid with greater scope of scaling up the process of synthesis [38–43]. The performance of this class of nanofluids critically depends upon the size and distribution of dispersoids and their ability to remain suspended and chemically un-reacted in the fluid. It is suggested that the uniformity and stability of suspension can be ensured by maintaining appropriate pH, using surface activators or surfactant and employing ultrasonic vibration. It may be pointed out that the maximum level of enhancement in conductivity ratio achieved by these nano-Al alloy dispersed nanofluids surpasses the earlier reported degree of improvement using other nanoparticles (Cu, CuO, Al_2O_3) in identical medium. The synthesis routine and relevant results of this development and their significance have been briefly discussed below.

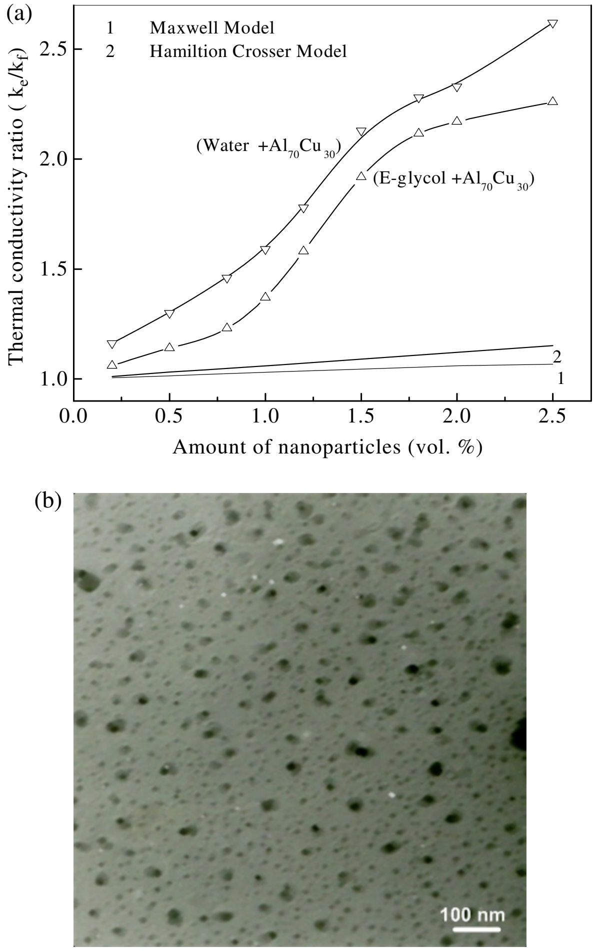
Al-30 at % Cu and Al-30 at % Ag dispersed nanofluids were prepared by a two-step method, in which Al-30 at % Cu and Al-30 at % Ag alloyed particles were first produced by mechanical alloying of elemental powder in appropriate proportion using a high energy planetary ball mill with WC media at 10:1 ball to powder weight ratio, followed by dispersing these submicron solid particles into ethylene glycol to produce nanofluids with different amount of particle dispersion. The

Table 2: Summary of Landmark Experimental Studies in Nanofluid.

Year	Nanofluid Used	Studies Conducted	Reference
1993	Al_2O_3, SiO_2 and TiO_2 dispersed water based nanofluid	Nanofluid prepared by two step method and temperature effect studied. 26%, 7% and 11% enhancement in thermal conductivity of water based nanofluid by dispersing 4.3 vol% Al_2O_3, SiO_2 and TiO_2 nanoparticles	Masuda et al. [20]
1999	CuO and Al_2O_3 nanoparticles dispersed in water and ethylene glycol	20% enhancement in thermal conductivity of ethylene glycol by dispersing 4 vol% CuO nanoparticles	Lee et al. [10]
1999	CuO and Al_2O_3 nanoparticles dispersed in water, ethylene glycol and vacuum pump oil	20% enhancement in thermal conductivity of water by dispersing 3 vol% Al_2O_3 nanoparticles	Wang et al. [13]
2000	Cu nanoparticles dispersed in water	Thermal conductivity ratio varies from 1.24 to 1.78 if volume percent of Cu nanoparticles increase from 2.5 to 7.5%	Xuan and Li [11]
2001	Cu nanoparticles dispersed in ethylene glycol	Effective thermal conductivity of ethylene glycol improved by up to 40% through the dispersion on 0.3% Cu nanoparticles	Eastman et al. [1]
2003	Ag and Au nanoparticles dispersed in water and toluene	0.011 vol% of Au nanoparticles dispersed toluene nanofluid shows enhancement in thermal conductivity 7% at 30°C and 14% at 60°C.	Patel et al. [21]
2003	CuO and Al_2O_3 nanoparticles dispersed in water (effect of temperature)	4 vol% Al_2O_3 dispersed water nanofluids thermal conductivity raise 9.4% to 24.3% with increase in Temperature from 21 to 51 °C	Das et al. [9]
2001	Carbon nanotube dispersed in oil	Thermal conductivity ratio exceeded 2.5 at 1 volume % nanotube	Choi et al. [2]
2003	Carbon nanotube dispersed in distilled water and ethylene glycol	At 1 volume %, the thermal conductivity enhancements are 12.7% and 7.0% for TCNT in ethylene glycol and distilled water, respectively	Xie et al. [22]
2004	MWCNT (sodium dodecyl sulfate) dispersed water based nanofluid	By dispersing 0.6 vol.% carbon nanotube in water 38% thermal conductivity enhancement. Also shown sonication and surfactant effect on thermal conductivity of nanofluid.	Assael et al. [23]
2005	Al_2O_3 nanoparticles dispersed in water (effect of temperature)	Dispersing 1 vol.% Al_2O_3 , 29% enhancement in water based nanofluid at 71°C	Chang et al. [24]
2005	Nano-Fe dispersed ethylene glycol based nanofluid	Shown sonication effect. 10% enhancement by dispersing 0.55 vol. Fe nanoparticles in ethylene glycol	Hong et al. [25]
2005	TiO_2(cetyl trimethyl ammonium bromide) nanoparticle in water	By dispersing 15 nm TiO_2sphere (5 vol%) 30% and 15–40 nm TiO_2 rod (5 vol.%) 33% enhancement in thermal conductivity	Murshed et al. [18]
2006	CuO-water based nanofluid SiO_2-water based nanofluid	Dispersing 1 vol.% CuO, 5% enhancement in water based nanofluid Dispersing 1 vol.% SiO_2, 3% enhancement in water based nanofluid	Hwang et al. [19]
	MWCNT-water based nanofluid	Dispersing 1 vol.% carbon nanotube, 7% enhancement in water based nanofluid	
	CuO-ethylene glycol based nanofluid	Dispersing 1 vol.% CuO, 9% enhancement in ethylene glycol based nanofluid	
	MWCNT-mineral oil based nanofluid	5 vol% carbon nanotube dispersed mineral oil based nanofluid have shown 9% enhancement in thermal conductivity	
2006	$A1_2O_3$ in water at 27.5°C to 37.7°C	2 and 10 vol.% of $A1_2O_3$ in water showed 8–22% enhancement in thermal conductivity	Li and Peterson [26]
	CuO in water at 28.9°C to 33.4°C	2 and 6 vol% CuO in water showed 35–51% enhancement in thermal conductivity	

particle and grain sizes of the milled product were varied by milling up to different hours. Milling was carried out in wet condition (using about 50 ml of toluene) to prevent undue oxidation, agglomeration of powders, changing the milling dynamics by smearing and coating the vials and ball surfaces with Al/Cu/Ag-powders, and ensuring sufficient output (alloyed powder) from the milling operation. Nano-ceramic dispersed nanofluids were also prepared by suspending spherical 3 mol.% Y_2O_3 partially-stabilized nanometric ZrO_2, Al_2O_3 and TiO_2 nanoparticles (Inframat Advanced Materials, USA) in water/ethylene glycol. Identity and particle/crystallite size of the phases were determined by X-ray diffraction (XRD). Average crystallite size and lattice strain were measured by separating the X-ray peak broadening contributions due to the Gaussian and Cauchian factors after subtracting the broadening due to strain and instrumental errors. Bright field transmission electron microscopy (TEM) studies were carried out to ascertain the size, distributions and morphology of powder particles in nanofluid. Solid particles were deagglomerated and homogenized in nanofluids by adding an appropriate surfactant (1 vol% oleic acid/tetramethyl ammonium hydroxide

Figure 2: (a) Thermal conductivity ratio (k_e/k_f) as a function of nanoparticle volume percent of $Al_{70}Cu_{30}$ dispersed water and ethylene glycol based nanofluid [40–41]; (b) TEM micrograph of mechanically alloyed (for 30 h) $Al_{70}Cu_{30}$ nanoparticles dispersed in ethylene glycol [40–41].



((CH$_3$)$_4$NOH, TMAH) and intensive ultrasonic vibration and magnetic stirring, respectively. To measure the thermal conductivity of nanofluids, we used an indigenously developed and improvised thermal comparator, based on the original concept of Powell [38]. Pool boiling heat transfer study with nanofluid has been conducted using a custom made pool boiling experimental facility [39].

6.1. *Al(Cu)-Nanoparticle Dispersed Nanofluid*

Fig. 2a shows the variation of normalized thermal conductivity ratio of nanofluid (to that of the base fluid) as a function of $Al_{70}Cu_{30}(Al_2Cu)$ nanoparticle volume percent. The results indicate that the nanofluids containing small volume percent of nanoparticles have significantly higher thermal conductivity (up to 2.4 times) than that of the base liquid without nanoparticles. Fig. 2b shows the size and distribution of $Al_{70}Cu_{30}(Al_2Cu)$ nanoparticles in ethylene glycol, as observed in the bright field TEM image of the powders fished on a polymer coated Cu-grid. It is evident that the particles are truly nanometric, isolated (not agglomerated) and uniformly distributed. The overall variation is sigmoidal with a nearly linear portion in the intermediate (0.75 to 1.5 vol%) concentration of particles. The increase in conductivity ratio is over 100% with merely 1.5 vol% particles present in the liquid. Though conductivity ratio increases further with greater amount of particles, stability of nanofluid is adversely affected due to sedimentation and inhomogeneity beyond 1.5 vol% of particles. Fig 2a also shows that the experimental results are significantly greater than the thermal conductivity predicted by the existing models as a function of nanoparticle amount [40]. It may be pointed out that synthesis of Al-based nano-dispersoids by mechanical alloying and dispersing the same in ethylene glycol to prepare nanofluid have been reported in the literature by our group for the first time. Furthermore, the maximum level of enhancement in conductivity ratio achieved in this study surpasses the earlier reported data in the literature [40, 41].

6.2. *Al(Ag)-Nanoparticle Dispersed Nanofluid*

The same two-stage method has been applied to prepare nanofluid comprising a small amount ($<$ 2 vol%) of nanocrystalline Ag_2Al nano-particles dispersed as a stable colloid in ethylene glycol and water. Thermal conductivity measurements, using the same indigenously designed thermal comparator device, show that the conductivity of this nanofluid is significantly greater (1.2–2.4 times) than that of the base fluid as well as that predicted by the existing models. Though conductivity ratio is proportional to the amount of nanoparticle concentration, loading above 2 vol% seems to adversely affect the stability and performance of nanofluid. In general, the increase in conductivity ratio is a function of identity/composition, size, volume percent, and thermal property of the nanoparticles or solid suspension [41, 42]. Ag_2Al-water nano-fluids show different performance and phenomena compared to pure water in terms of natural convection and nucleate boiling. The addition of Ag_2Al nano-particles causes a decrease in nucleate boiling heat transfer. The heat transfer coefficient decreases with increase in particle concentration. However, the present results deserve attention from the scientific community both as a source of new data and new trend that can be useful for modeling and comparison.

Figure 3: TEM image of (a) uniformly distributed, (b) chain distribution of mechanically alloyed (for 30 and 40 h) $Al_{70}Ag_{30}$ (Ag_2Al) nanoparticle dispersed ethylene glycol based nanofluid [40–41].

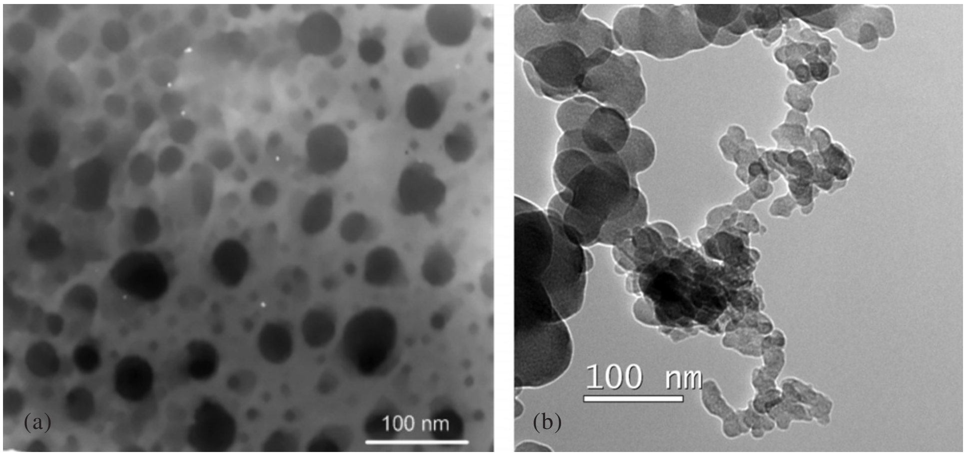


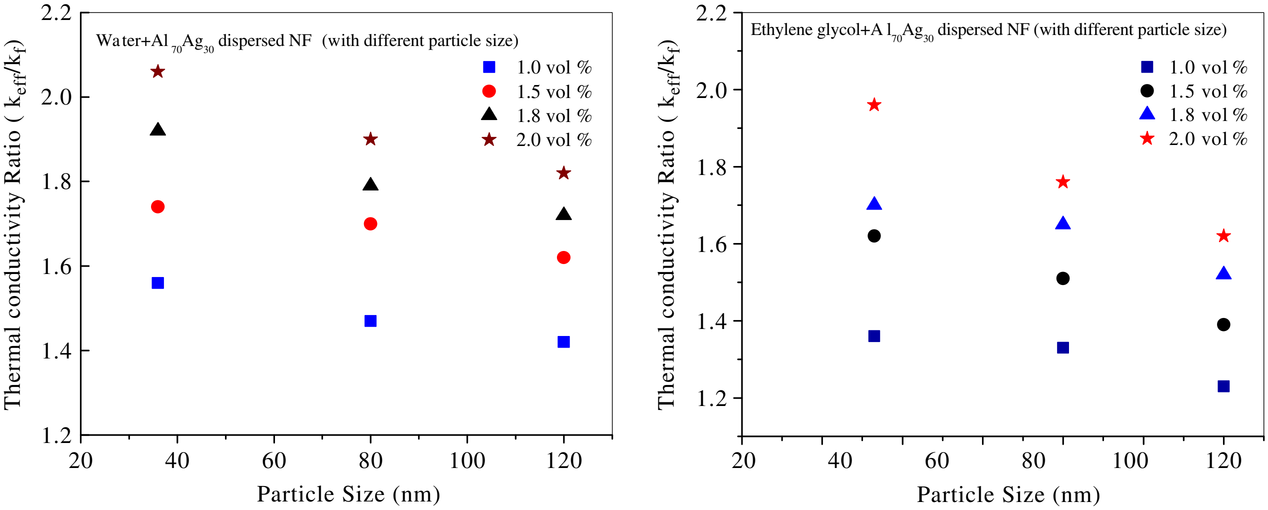
Fig. 3(a) and 3(b) show the size and distribution of nanoparticles in the ethylene glycol, as obtained in bright field TEM of powder particles collected/fished on carbon coated Cu grid, respectively. It is evident that the particles are truly nanometric (20–80 nm).

It is already noted that ethylene glycol based nanofluids containing small volume percent (< 2 vol%) of Ag_2Al nanoparticles induce significantly higher thermal conductivity than that of the base liquid without nanoparticles, (Fig. 4(a) and 4(b)). Fig. 4(a) suggests that enhancement in thermal conductivity follows a linear relationship both with the particle size and volume percent within the present range of investigation. 36 nm Ag_2Al dispersed water based nanofluid show 59 and 102% enhancement in thermal conductivity for 1 and 2 vol% of particles loading, respectively.

6.3. *Nano-ceramic Dispersed Nanofluid*

A systematic effort has been made to characterize commercially available (Y_2O_3 stabilized) ZrO_2, TiO_2 and Al_2O_3 nano particles, dispersed in ethylene glycol and water in very low volume percent following a special routine to prepare a new

Figure 4: Variation of thermal conductivity ratio (k_e/k_f) as a function of nanoparticle size. (a) Ag_2Al dispersed water based nanofluid (b) Ag_2Al dispersed ethylene glycol based nanofluid [42].



type of nanofluid and carry out characterization and thermal conductivity measurement of this nanofluid using an indigenously developed thermal comparator device [43]. Use of suitable surfactant and stirring routine ensured uniformity and stability of dispersion. Nucleate pool boiling of ZrO_2 based aqueous nanofluid has also been studied. Though enhancement in nucleate boiling heat transfer has been observed at low volume percent of solid dispersion, the rate of heat transfer falls with the increase in solid concentration and eventually becomes inferior even to pure water [39]. While surfactants increase the rate of boiling heat transfer, addition of surfactant to the nanofluid shows a drastic deterioration in nucleate boiling heat transfer. Furthermore, the boiling of nanofluid renders the heating surface smoother. Repeated runs of experiments with the same surface give a continuous decrease in the rate of boiling heat transfer.

Figure 5: (a) Boiling curves of pure water and nano ZrO_2 dispersed water based nanofluid without addition of surfactant [39]; (b) TEM micrographs showing 25–30 nm ZrO_2 particles dispersed in water [39, 43].

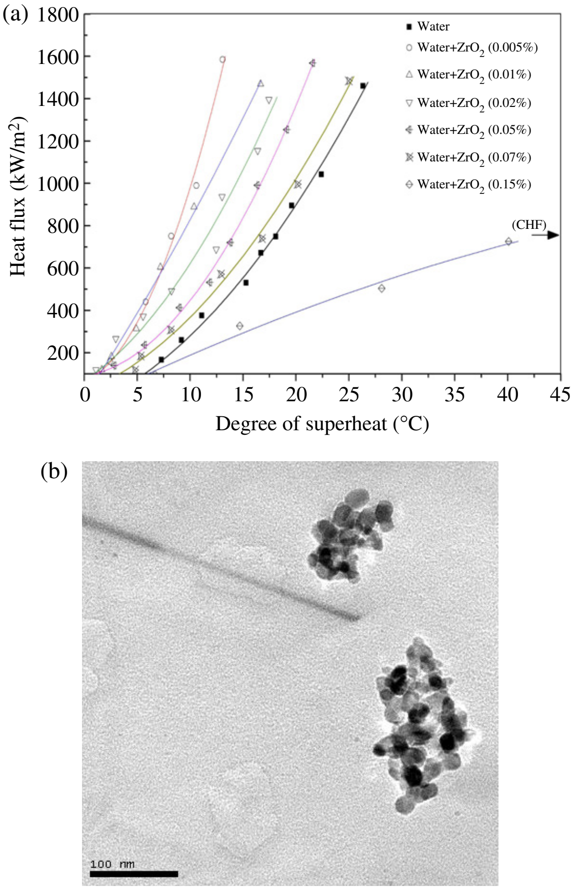


Fig. 5a depicts the boiling curves for pure water and nanofluid having different vol% of particle concentration in nucleate boiling regime. It is interesting to note that at the lowest concentration of nanoparticle (0.005 vol%) the coefficient of boiling heat transfer in the nucleate boiling region is substantially higher compared to that observed in pure water. However, there is a steady decrease in the heat transfer coefficient with the increase in ZrO_2 nanoparticle concentration further. At a concentration of 0.15 vol% of ZrO_2 the boiling curve falls much below that recorded for pure water. Fig. 5b shows the TEM image of ZrO_2 (20–30 nm, spherical) particles dispersed in water, after ultrasonic vibration and magnetic stirring.

6.4. *Summary of Achievements*

We have been able to prepare nanofluid by dispersing small amount (< 2 vol%) of nanocrystalline Al-30 at. %Cu, Al-30at. %Ag, partially stabilized nanometric ZrO_2 (with 3 mol.% Y_2O_3), TiO_2 and Al_2O_3 in deionized water and ethylene glycol. Use of 1–2 vol% of oleic acid and tetraethyl ammonium hydroxide as surfactant and appropriate stirring routine prevented agglomeration and ensured uniform dispersion of nanoparticles. Thermal conductivity of nanofluid, measured using an indigenously developed thermal comparator, recorded up to 1.2–2.0 times (20–100%) enhancement over that for concerned base fluid under comparable conditions. In general, thermal conductivity of nanofluids increases with volume percent of nanoparticles (within the present limit of 2 vol%). Besides amount, both specific size (surface area to volume) and shape (aspect ratio) significantly influence the thermal conductivity enhancement of nanofluids. The results for TiO_2 nanoparticle dispersed nanofluid show good agreement with Murshed et al. [18] data for TiO_2-water based nanofluids which indirectly support that measurement of thermal conductivity by thermal comparator is reliable and thermal comparator can serve as an alternate technique for transient hot wire method. Nucleating boiling heat transfer of aqueous nanofluids with different combinations of nanoparticles has been investigated covering a wide range of surface superheat. Boiling curve has also been constructed for nanofluids stabilized with appropriate surfactant. Some of observed results are interesting and are not in total conformity with those reported earlier. In general, the results appear quite promising for development of nanofluid for advanced thermal engineering applications. The level of thermal conductivity enhancement is significantly higher than that predicted by the existing models and experimental results reported in the literature.

7. Potential Scope of Application of Nanofluid

Nanofluids can be used to improve heat transfer and energy efficiency in a variety of thermal systems, including the important application of vehicle cooling or transportation, microelectronics, nuclear power generation, and rocket launching vehicles. Several studies conducted in academic institutions and national laboratories are now ready for field trials before commercial exploitation and implementation could be realized.

8. Concluding Remarks

Nanofluids are engineered colloids made of a base fluid and nanoparticles (1–100 nm) that can offer significant advantage in thermal managements of both large installation like heat exchanger, evaporator, radiators as well as miniature or micro electronics devices. The performance of nanofluid critically depends upon the size, quantity (volume percentage), shape and distribution of dispersoids, and their ability to remain suspended and chemically un-reacted in the fluid. Despite the exciting opportunities, lack of agreement among experimental results, poor characterization of suspension, inadequate theoretical understanding of the mechanisms of heat transfer by nanofluid are serious impediments against large scale commercial exploitation of nanofluids for thermal management in important fields such as electronics, transportation and thermal engineering. In summary, the next steps in the nanofluid research cycle are to concentrate on heat transfer enhancement and determine its physical mechanisms, taking into consideration such items as the optimum particle size and shape, particle volume concentration, fluid additive, particle coating, and base fluid. Precise measurement and documentation of the degree and scope of enhancement of thermal properties is extremely important. Better characterization of nanofluids is also important for developing engineering designs based on the work of multiple research groups, and fundamental theory to guide this effort should be improved. Important features for commercialization must be addressed, including particle settling, particle agglomeration, surface erosion, and large-scale nanofluid production at acceptable cost. Finally, it is pertinent to suggest that nanofluid research warrants a genuinely multi-disciplinary approach with complementary efforts from material scientists (regarding synthesis and characterization), thermal engineers (for measuring thermal conductivity and heat transfer coefficient under various regimes and conditions), chemists (to study the agglomeration behavior and stability of the dispersoid and liquid) and physicists (modeling the mechanism and interpretation of results).

Acknowledgement

The author is indebted to his students and colleagues associated with nanofluid research in his group (Prof P K Das, Mr Manoj Chopkar, Ms Gayatri Paul, Mr S Sudarshan, Mr V Vaikunthanathan). Most of the experimental results reported here are from the PhD thesis of Mr Manoj Chopkar. Partial financial support from ISAC-ISRO, IGCAR-Kalpakkam and DST-NSTI (Grant no. SR/S5/NM-04/2005) is gratefully acknowledged.

Received 02 October 2008; revised 09 November 2008.

References

1. J. A. Eastman, S. U. S. Choi, S. Li, W. Yu, and L. J. Thompson (2001) Anomalously Increased Effective Thermal Conductivity of Ethylene Glycol-Based Nanofluids Containing Copper Nanoparticles. Applied Physics Letters 78: 718–720.
2. S. U. S. Choi, Z. G. Zhang, W. Yu, F. E. Lockwood, and E. A. Grulke (2001) Anomalously Thermal Conductivity Enhancement in Nanotube Suspensions. Applied Physics Letters 79: 2252–2254.
3. S. U. S. Choi (1995), Enhancing Thermal Conductivity of Fluids with Nanoparticles, in Developments and Applications of Non-Newtonian Flows, eds. D. A. Singer and H. P. Wang, vol. FED 231, pp. 99–105, American Society of Mechanical Engineers, New York.
4. J. C. Maxwell, (1873). Treatise on Electricity and Magnetism. Oxford: Clarendon Press.
5. R. L. Hamilton, and O. K. Crosser (1962). Thermal Conductivity of Heterogeneous Two- Component Systems. Industrial & Engineering Chemistry Fundamentals 1: 187–191
6. E. J. Wasp, J. P. Kenny, and R. L. Gandhi (1977), Solid-Liquid Flow Slurry Pipeline Transportation, Series on Bulk Materials Handling, Trans. Tech. Publications, 1:4, Clausthal, Germany.
7. L. A. Pozhar (2000). Structure and Dynamics of Nanofluids: Theory and Simulations to Calculate Viscosity. Physical Review E 61: 1432–1446
8. J. Kim, C. K. Choi, Y. T. Kang, and M. G. Kim (2006). Effects of Thermodiffusion of Nanoparticles on Convective Instabilities in Binary Nanofluids. Nanoscale and Microscale Thermophysical Engineering 10: 29–39
9. S. K. Das, N. Putra, P. Thiesen, and W. Roetzel (2003). Temperature Dependence of Thermal Conductivity Enhancement for Nanofluids. Transactions of the ASME, Journal of Heat Transfer 125: 567–574.
10. S. Lee, S. U.-S. Choi, S. Li, and J. A. Eastman (1999). Measuring Thermal Conductivity of Fluids Containing Oxide Nanoparticles. Transactions of the ASME, Journal of Heat Transfer 121: 280–289.
11. Y. Xuan, and Q. Li (2000). Heat Transfer Enhancement of Nanofluids. International Journal of Heat and Fluid Flow 21: 58–64.
12. H. Gleiter (1989). Nanocrystalline Materials, Progress in Materials Science, vol. 33, no. 4, pp. 223–315.
13. X. Wang, X. Xu, and S. U. S. Choi (1999). Thermal Conductivity of Nanoparticle-Fluid Mixture. Journal of Thermophysics and Heat Transfer 13: 474–480.
14. H. Akoh, Y. Tsukasaki, S. Yatsuya, A. Tasaki (1978). Magnetic properties of ferromagnetic ultrafine particles prepared by vacuum evaporation on running oil substrate, Journal of Crystal Growth 45: 495–500.
15. J. A. Eastman, U. S. Choi, S. Li, L. J. Thompson, S. Lee (1997). Enhanced thermal conductivity through the development of nanofluids, Materials Research Society Symposium – Proceedings, Materials Research Society, Pittsburgh, PA, USA, Boston, MA, USA, vol. 457: pp. 3–11

16. H. –T. Zhu, Y.-S. Lin, and Y.-S. Yin (2004). A Novel One-Step Chemical Method for Preparation of Copper Nanofluids. Journal of Colloid and Interface Science 277: 100–103.
17. C. –H. Lo, T.-T. Tsung, L.-C. Chen, C.-H. Su, and H.-M. Lin (2005). Fabrication of Copper Oxide Nanofluid Using Submerged Arc Nanoparticle Synthesis System (SANSS). Journal of Nanoparticle Research 7: 313–320.
18. S. M. S. Murshed, K. C. Leong, and C. Yang (2005). Enhanced Thermal Conductivity of Ti02 — Water Based Nanofluids. International Journal of Thermal Sciences 44: 367–373.
19. Y. Hwang, H. S. Park, J. K. Lee, and W. H. Jung (2006). Thermal Conductivity and Lubrication Characteristics of Nanofluids. Current Applied Physics 6s 1: 67–71.
20. H. Masuda, A. Ebata, K. Teramae, and N. Fishinuma (1993). Alteration of Thermal Conductivity and Viscosity of Liquid by Dispersing Ultra-Fine Particles (Dispersion of y-A1203, SO2, and Ti02 Ultra-Fine Particles). Netsu Bussei 7: 227–233.
21. H. E. Patel, S. K. Das, T. Sundararajan, A. S. Nair, B. George, and T. Pradeep (2003). Thermal Conductivity of Naked and Monolayer Protected Metal Nanoparticle Based Nanofluids: Manifestation of Anomalous Enhancement and Chemical Effects. Applied Physics Letters 83: 2931–2933.
22. H. Xie, H. Lee, W. Youn, and M. Choi (2003). Nanofluids Containing Multiwalled Carbon Nanotubes and Their Enhanced Thermal Conductivities. Journal of Applied Physics 94: 4967–4971.
23. M. J. Assael, C.-F. Chen, I. Metaxa, and W. A. Wakeham (2004). Thermal Conductivity of Suspensions of Carbon Nanotubes in Water. International Journal of Thermophysics 25: 971–985.
24. H. Chang, T. T. Tsung, L. C. Chen, Y. C. Yang, H. M. Lin, C. K. Lin, and C. S. Jwo (2005). Nanoparticle Suspension Preparation Using the Arc Spray Nanoparticle Synthesis System Combined with Ultrasonic Vibration and Rotating Electrode. The International Journal of Advanced Manufacturing Technology 26: 552–558.
25. T. –H. Hong, H.-S. Yang, and C. J. Choi (2005). Study of the Enhanced Thermal Conductivity of Fe Nanofluids. Journal of Applied Physics 97: 064311.
26. C. H. Li and G. P. Peterson (2006). Experimental Investigation of Temperature and Volume Fraction Variations on the Effective Thermal Conductivity of Nanoparticle Suspensions (Nanofluids). Journal of Applied Physics 99: 0843 14.
27. P. Keblinski, S.R. Phillpot and S.U.S. Choi, J.A. Eastman (2000). Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids), International Journal of Heat and Mass Transfer 45: 855–863.
28. J. A. Eastman, S. R. Phillpot, S. U. S. Choi and P. Keblinski (2004). Thermal transport in nanofluids, Annu. Rev. Mater. Res. 34: 219–246.
29. W. Yu, and S. U. S. Choi (2004). The Role of Interfacial Layers in the Enhanced Thermal Conductivity of Nanofluids: A Renovated Hamilton-Crosser Model. Journal of Nanoparticle Research 6: 355–361.
30. W. Yu, and S. U. S. Choi (2005). An Effective Thermal Conductivity Model of Nanofluids with a Cubic Arrangement of Spherical Particles. Journal of Nanoscience and Nanotechnology 5: 580–586.
31. L. Xue, P. Keblinski, S. R. Phillpot, S. U. S. Choi, and J. A. Eastman (2004). Effect of Liquid Layering at the Liquid-Solid Interface on Thermal Transport. International Journal of Heat and Mass Transfer 47: 4277–4284.
32. A. R. A. Khaled and K. Vafai (2005). Heat Transfer Enhancement through Control of Thermal Dispersion Effects. International Journal of Heat and Mass Transfer 48: 2172–2185.
33. D. Wen, and Y. Ding (2005). Effect of Particle Migration on Heat Transfer in Suspensions of Nanoparticles Flowing through Mini-channels. Microfluidics Nanofluidics 1: 183–189.
34. D. Wen, and Y. Ding (2005). Experimental Investigation into the Pool Boiling Heat Transfer of Aqueous Based y-Alumina Nanofluids. Journal of Nanoparticle Research 7: 265–274.
35. J. Koo, and C. Kleinstreuer (2004). A New Thermal Conductivity Model for Nanofluids. Journal of Nanoparticle Research 6: 577–588.
36. W. Evans, J. Fish, and P. Keblinski (2006). Role of Brownian Motion Hydrodynamics on Nanofluid Thermal Conductivity. Applied Physics Letters 88: 093 116.
37. D. Lee, J.-W. Kim, and B. G. Kim (2006). A New Parameter to Control Heat Transport in Nanofluids: Surface Charge State of the Particle in Suspension. Journal of Physical Chemistry B 110: 4323–4328.
38. I. Manna, P. K. Das, M. Chopkar (2005). A Device for measuring the Thermal Conductivity of a fluid with dispersion of ultra-fine solid particles — An application for Indian patent (390/Kol/2005) filed in February 2005, under review.
39. M. Chopkar, I. Manna, P.K. Das (2008). Boiling heat transfer characteristics of ZrO_2–water nanofluids from a flat surface in a pool, Heat and Mass Transfer, vol 44: pp 999–1004.
40. M. Chopkar, P. K. Das and I. Manna (2006). Synthesis and Characterization of Nanofluid for Advanced Heat-Transfer Applications Scripta Materialia, Vol 55: pp 549–552.
41. M. Chopkar, P. K. Das and I. Manna (2007). Development and Characterization of Nanocrystalline Al2Cu/Ag2Al dispersed Water /Ethylene Glycol based Nano-fluid, Mater. Sci. Eng. B, vol 139: 141–148
42. M. Chopkar, S. Sudarshan, P. K. Das, I. Manna, Effect of particles size on thermal conductivity ratio of nanofluid, Metallurgical and Materials Transactions A, 2007 (Article in press) DOI: 10.1007/s11661-007-9444-7
43. M. Chopkar, P. K. Das, I. Manna (2007). Development and thermal characterization of nanocrysalline ZrO2 dispersed water and ethylene glycol based nanofluid, Philosophical Magazine vol 87: 4433–4444.

Professor Indranil Manna (born on 22.01.1961) received his Ph. D degree from the Indian Institute of Technology (IIT), Kharagpur in 1990. Earlier, he obtained his bachelor's (B. E.) and master's (M. Tech.) degree from Calcutta University and IIT-Kanpur in 1983 and 1984, respectively. Prof. Manna worked at the Mishra Dhatu Nigam, Hyderabad (an integrated superalloys plant) before joining IIT-Kharagpur in 1985. Since then, he has been at the same Institute as Lecturer (1985–1990), Assistant Professor (1990–1997), Associate Professor (1997–2003) and a Full Professor (2003–present). In between, he worked as guest scientist in different renowned Institutions and Universities abroad like Max Planck Institute at Stuttgart, Technical University of Clausthal, Nanyang Technological University, Liverpool University, University of Ulm for periods up to one year (on leave from IIT-Kharagpur). Prof. Manna teaches courses on phase transformation, surface engineering, X-ray diffraction, etc. His research interest concerns structure-property correlation in engineering materials including synthesis/application of nano-materials, surface coating/engineering, phase transition, oxide fuel cell, bainitic steel and modeling. His current activities on amorphous/nanocrystalline Al-alloys, nano-fluid and laser/plasma assisted surface engineering have evoked wide interest in the scientific community. He has published about 200 peer-reviewed papers, supervised 9 Ph.D, 25 M. Tech. and 35 B. Tech. theses, carried out about 30 sponsored projects worth over Rs. 100 million and recently obtained a patent on amorphous AlCuTi alloy. Prof. Manna won several prizes and awards in India and abroad including INSA Medal for Young Scientists, Young Metallurgist and Metallurgist of the Year Awards, MRSI Medal, AICTE career award and DAAD and Humboldt Fellowships, Acta Materialia Best

Referee Award (1999 and 2003). Currently, he is the Coordinator, Mission Project on Nano Science and Technology, and the Chairman, Central Research Facility, IIT, Kharagpur. Prof. Manna has been elected a Fellow (FNAE) of the Indian National Academy of Engineering (INAE), New Delhi, a Fellow (FNASc) of The National Academy of Sciences of India, Allahabad, and a Fellow (FASc) of the Indian Academy of Sciences, Bangalore. Recently, the German Academic Exchange Service (DAAD), Bonn has appointed him an Honorary DAAD Advisor for three years, INAE has awarded him INAE-AICTE Distinguished Industry Professorship for 2007-08, and Indian Institute of Metals (IIM) has conferred the GD Birla Gold Medal (2008) on him.

Prof. Manna is married (to Mrs Snigdha Manna) and has two children aged 18 (Oindrila, daughter), and 14 (Rudroneel, son).