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CHAPTER 1

1.1 INTRODUCTION

Thermal properties of liquids play a decisive role in heating as well as cooling applications in industrial processes. Thermal conductivity of a liquid is an important physical property that decides its heat transfer performance. Conventional heat transfer fluids have inherently poor thermal conductivity which makes them inadequate for ultra-high cooling applications. Scientists have tried to enhance the inherently poor thermal conductivity of these conventional heat transfer fluids using solid additives following the classical effective medium theory (Maxwell, 1873) for effective properties of mixtures. Fine tuning of the dimensions of these solid suspensions to millimeter and micrometer ranges for getting better heat transfer performance have failed because of the drawbacks such as still low thermal conductivity, particle sedimentation, corrosion of components of machines, particle clogging, excessive pressure drop etc. Downscaling of particle sizes continued in the search for new types of fluid suspensions having enhanced thermal properties as well as heat transfer performance.

All physical mechanisms have a critical scale below which the properties of a material changes totally. Modern nanotechnology offers physical and chemical routes to prepare nanometer sized particles or nanostructured materials engineered on the atomic or molecular scales with enhanced thermo-physical properties compared to their respective bulk forms.

Choi (1995) and other researchers (Masuda et al., 1993; Lee et al., 1999) have shown that it is possible to break down the limits of conventional solid particle suspensions by conceiving the concept of nanoparticle-fluid suspensions. These nanoparticle-fluid suspensions are termed nanofluids, obtained by dispersing nanometer sized particles in a conventional base fluid like water, oil, ethylene glycol etc. Nanoparticles of materials such as metallic oxides (Al2O3, CuO), nitride ceramics (AlN, SiN), carbide ceramics (SiC, TiC), metals (Cu, Ag, Au), semiconductors (TiO2, SiC), single, double or multi walled carbon nanotubes (SWCNT, DWCNT, MWCNT), alloyed nanoparticles (Al70Cu30) etc. have been used for the preparation of nanofluids. These nanofluids have been found to possess an enhanced thermal conductivity (Shyam et al., 2008; Choi et al., 2001; Eastman et al., 2001) as well as improved heat transfer performance (Xuan et al., 2003; Yu et al., 2003; Vassalo et al., 2004; Artus, 1996) at low concentrations of nanoparticles. Even at very low volume fractions (< 0.1%) of the suspended particles, an attractive enhancement up to 40% in thermal conductivity has been reported on these nanotechnology based fluids (Wang et al., 1999) and the percentage of enhancement is found to increase with temperature (Das et al., 2003) as well as concentration of nanoparticles.

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The effective thermal conductivity of these nanofluids are usually expressed as a normalized thermal conductivity value obtained by dividing the overall thermal conductivity of the nanofluid by the base fluid thermal conductivity or sometimes as a percentage of the effective value with respect to the base fluid value.

Structure of Nanofluids

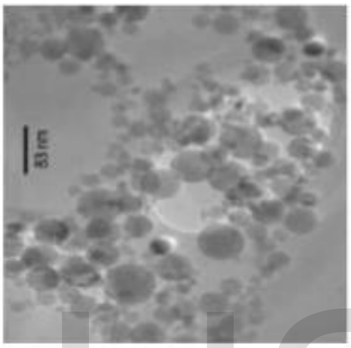

Figure 1: ZrO_2 in water that produced
with Two Step method

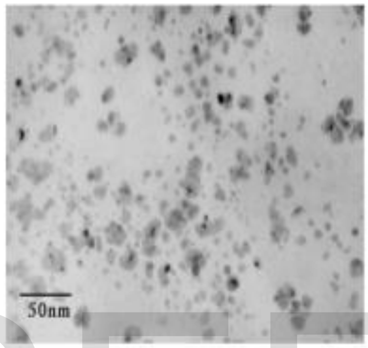

Figure 2: Cu nanoparticles in ethylene glycol produced with One Step method

The enhanced thermal behaviour of nanofluids could provide a basis for an enormous innovation for heat transfer intensification, which is of major importance to a number of industrial sectors including transportation, power generation, micro manufacturing, thermal therapy for cancer treatment, chemical and metallurgical sectors, as well as heating, cooling, ventilation and air-conditioning. Nanofluids are also important for the production of nanostructured materials for the engineering of complex fluids as well as for cleaning oil from surfaces due to their excellent wetting and spreading behavior (Ding et al. [14]). Another application of the nanofluid flow is in the delivery of nano-drug as suggested by Kleinstreuer et al.

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1.2 Classification Nanofluids

The enhancement of the thermal conductivity of nanofluids depends on the selection of nanomaterial and the base fluid. Until now, the base fluids used include water, ethylene glycol, transformer oil, and toluene.

The nanoparticles that are used can be broadly divided into three groups:

- Ceramic
- Pure metallic particles
- Carbon nanotubes (CNTs).

Different combinations of the above particles and fluids give different nanofluids.

Ceramic nanofluids : The first type of nanofluid investigated by the ANL group was ceramic nanoparticle nanofluid. The first research in this area showcased conductivity measurements on fluids that contained Al2O3 and CuO nanoparticles in water and ethylene glycol.

Metallic nanofluids : The potential of nanofluids was explored from the experiments carried out with ceramic nanofluids. However, with the emergence of metallic particlebased nanofluids was a crucial step. However, the real breakthrough came when the ANL group reported a 40% enhancement of conductivity with only 0.3% concentration of 10 nm-sized copper particles suspended in ethylene glycol. When gold and silver were used for the first time to prepare nanofluids, the most important observation in their study was a significant enhancement in thermal conductivity for even small concentrations.

Carbon Nanotube nanofluids : The greatest enhancement of thermal conductivity was achieved when Carbon nanotubes and polymer nanotubes were used with suitable base fluids. They were found to be most promising nanomaterials for their superior thermal features. CNTs have a very high aspect ratio and thus have extraordinary heat transfer properties.

The thermal conductivity of nanofluids depends on the thermal conductivity of the base fluid, the characterizations of the dispersed nanomaterial (structure, shape, and size), the concentration, additives, and interactions between the nanomaterials and base fluid etc. These dependence factors affect the thermal conductivity enhancement of CNTs-nanofluids with different contributions. Currently, there

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are two main types of carbon nanotubes: single-walled nanotubes (SWNTs) and multiwalled nanotubes (MWNTs) that can be used to make nanofluids with different base fluids. Their different structures and sizes, create differences in aspect ratios thus enhancing the thermal conductivity enhancement of CNTsnanofluids.[Meibo Xing, et al, 2015] obtain higher thermal conductivity values than that of the base fluid.

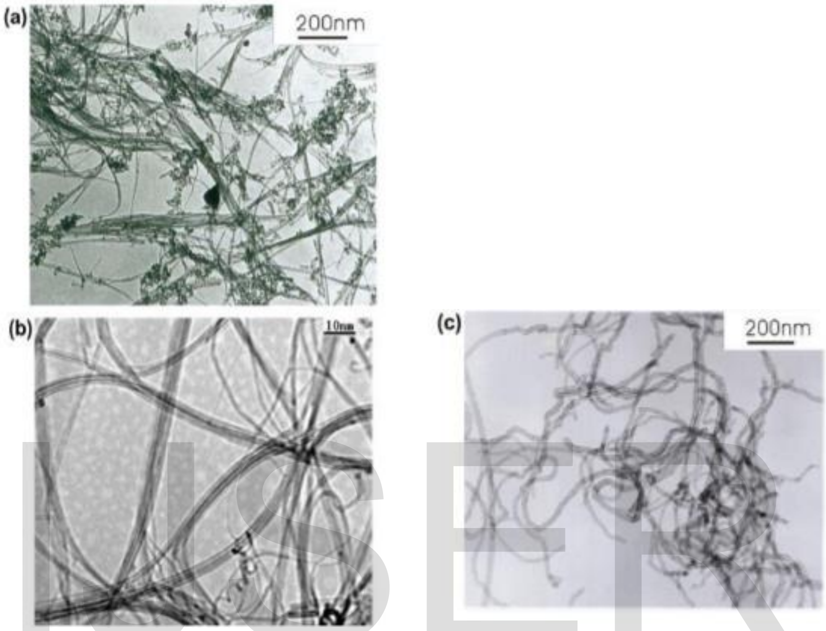

Fig.3 The TEM images of (a))S-SWNTs, (b)L-SWNTs, (c)MWNTs

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CHAPTER 2

REVIEW OF LITERATURE

2.1 Review on Nanofluids: Preparation, Stability Mechanisms, and Applications- Wei Yu and Hua Qing Xie, *School of Urban Development and Environmental Engineering, Shanghai Second Polytechnic University, Shanghai 201209, China*

Nanofluids, the fluid suspensions of nanomaterials, have shown many interesting properties, and the distinctive features offer unprecedented potential for many applications. This paper summarizes the recent progress on the study of nanofluids, such as the preparation methods, the evaluation methods for the stability of nanofluids, and the ways to enhance the stability for nanofluids, the stability mechanisms of nanofluids, and presents the broad range of current and future applications in various fields including energy and mechanical and biomedical fields. At last, the paper identifies the opportunities for future research.

2.1.1.Introduction

Nanofluids are a new class of fluids engineered by dispersing nanometer-sized materials. They are two-phase systems with one phase (solid phase) in another (liquid phase). Nanofluids have been found to possess enhanced thermophysical properties such as thermal conductivity, thermal diffusivity, viscosity, and convective heat transfer coefficients compared to those of base fluids like oil or water. It has demonstrated great potential applications in many fields. In this paper, the new progress in the methods for preparing stable nanofluids is discussed and summarizes the stability mechanisms. The purpose of this paper will focus on new preparation methods and stability mechanisms, especially the new application trends for nanofluids in addition to the heat transfer properties of nanofluids. We will try to find some challenging issues that need to be solved for future research based on the review on these aspects of nanofluids.

2.1.2. The Stability of Nanofluid

The agglomeration of nanoparticles results in not only the settlement and clogging of microchannels but also the decreasing of thermal conductivity of nanofluids. So, the investigation on stability is also a key issue that influences the properties of nanofluids for application, and it is necessary to study and analyze influencing factors to the dispersion stability of nanofluids.

- The Stability Evaluation Methods for Nanofluids
    - Sedimentation and Centrifugation Methods.
    - Zeta Potential Analysis
    - Spectral Absorbency Analysis.

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TABLE 1: Properties of oxides and their nanofluids.

	Thermal conductivity* W/(m·K)	Density (g/cm^3)	Crystalline	Viscosity (Cp) with 5.0 vol. % 30	Thermal conductivity enhancement of nanofluids (%) with 5.0 vol. %
MgO	48.4	2.9	Cubic	17.4	40.6
TiO_2	8.4	4.1	Anatase	31.2	27.2
ZnO	13.0	5.6	Wurtzite	129.2	26.8
Al_2O_3	36.0	3.6	γ	28.2	28.2
SiO_2	10.4	2.6	noncrystalline	31.5	25.3

*Thermal conductivities of the oxides are for the corresponding bulk materials

- The Ways to Enhance the Stability of Nanofluids
  - Surfactants Use in Nanofluids.
  - Surface Modification techniques.

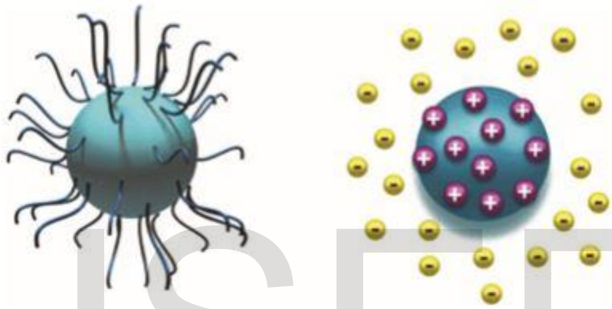

Fig4 Types of colloidal stabilization.

2.2. Heat transfer enhancement of nanofluids - Yimin Xuan , Qiang Li, *School of Power Engineering, Nanjing University of Science and Technology, Nanjing 210094, People's Republic of China.*

This paper presents a procedure for preparing a nanofluid which is a suspension consisting of nanophase powders and a base liquid. By means of the procedure, some sample nanofluids are prepared. Their TEM photographs are given to illustrate the stability and evenness of suspension. The theoretical study of the thermal conductivity of nanofluids is introduced. The hot-wire apparatus is used to measure the thermal conductivity of nanofluids with suspended copper nanophase powders. Some factors such as the volume fraction, dimensions, shapes and properties of the nanoparticles are discussed. A theoretical model is proposed to describe heat transfer performance of the nanofluid flowing in a tube, with accounting for dispersion of solid particles

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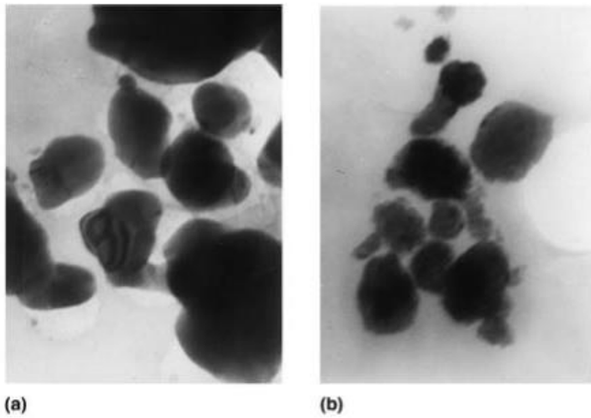

Fig 5 TEM micrographs of nano Cu particles transformer oil at pHˆ6.3. (a) 2 vol% suspension (scale times: 100,000). (b) 5 vol% suspension (scale times: 100,000).

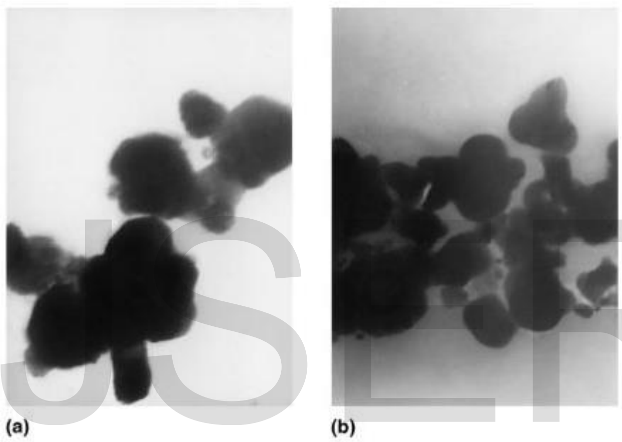

Fig 6 TEM micrographs of nano Cu particles±deionized water at pHˆ6.8. (a) 5 vol% suspension (scale times: 50,000). (b) 7.5 vol% suspension (scale times: 30,000).

The enhanced performance of the nanofluid results from not only its high thermal conductivity, but also from the random movement and dispersion effect of the nanoparticles. The Peclet number Pe is a comprehensive parameter to describe such effects.

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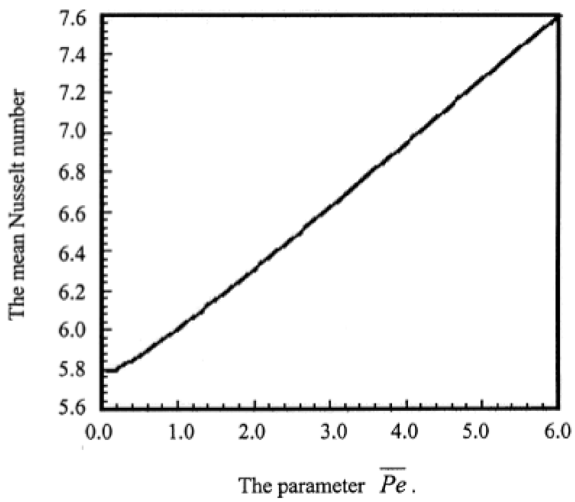

Fig. 6. The mean Nusselt number vs the parameter $\overline{Pe}$.

Experiment is necessary to determine this parameter. Compared to Choi's primitive analysis (Choi, 1995), which just accounted for the effect of high thermal conductivity of the nanofluid, the aforementioned expressions provide a sophisticated way to analyze the enhanced heat transfer mechanism of the nanofluid. It is emphasized that these expressions are theoretical and experimental work is needed to further reveal the enhanced mechanism and to improve the heat transfer performance of the nanofluid.

2.3 A Review: Enhancement of Heat Transfer with Nanofluids - S. Kumar Department of Mechanical Engineering, Heritage Institute of Technology, Kolkata, India,

S. Chakrabarti Department of Mechanical Engineering, Indian Institute of Engineering Science and Technology, Shibpur, India.

The performance of industrial and practical appliances can be improved to perform some important heat transfer duty by heat transfer enhancement techniques. The enhancement of heat transfer using nanofluids have been used as one of the passive heat transfer techniques in several heat transfer applications. It is considered to have great potential for heat transfer enhancement and are highly suited to application in heat transfer processes. In recent years, several important research works have been carried out to understand and explain the causes of the enhancement or control of heat transfer using nanofluids. This review addresses the unique features of nanofluids, such an enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Brownian motion, etc. From the studies of literatures it has been found that the heat transfer coefficient increases with an increase in the concentration of solid particles. Certain studies with a smaller particle size indicate an increase in the heat transfer enhancement when is compared to values obtained with a larger size. The significant applications in the engineering field explain why so many investigators have studied heat

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transfer with augmentation by a nanofluid in the heat exchanger. This article presents a review of the heat transfer applications of nanofluids to develop directions for future work. Future heat transfer studies can be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulence regions. There appears to be hardly any research in the use of nanofluids as refrigerants. Nanoparticle-refrigerant dispersions in two-phase heat transfer applications can be studied to explore the possibility of improving the heat transfer characteristics of condensers and evaporators used in refrigeration and air conditioning systems.

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CHAPTER 3

Preparation Methods for Nanofluid

3.1 Two-Step Method

Two-step method is the most widely used method for preparing nanofluids. Nanoparticles, nanofibers, nanotubes, or other nanomaterials used in this method are first produced as dry powders by chemical or physical methods. Then, the nanosized powder is dispersed into a fluid in the second processing step with the help of intensive magnetic force agitation, ultrasonic agitation, high-shear mixing, homogenizing, and ball milling. Two-step method is the most economic method to produce nanofluids in large scale, because nanopowder synthesis techniques have already been scaled up to industrial production levels. Due to the difficulty in preparing stable nanofluids by two-step method, several advanced techniques are developed to produce nanofluids, including one-step method.

3.2 One Step Method

To reduce the agglomeration of nanoparticles, Eastman et al. developed a one-step physical vapor condensation method to prepare Cu/ethylene glycol nanofluids. The one-step process consists of simultaneously making and dispersing the particles in the fluid. In this method, the processes of drying, storage, transportation, and dispersion of nanoparticles are avoided, so the agglomeration of nanoparticles is minimized, and the stability of fluids is increased. The one-step processes can prepare uniformly dispersed nanoparticles, and the particles can be stably suspended in the base fluid. The method avoids the undesired particle aggregation fairly well. One-step physical method cannot synthesize nanofluids in large scale, and the cost is also high, so the one-step chemical method is developing rapidly.

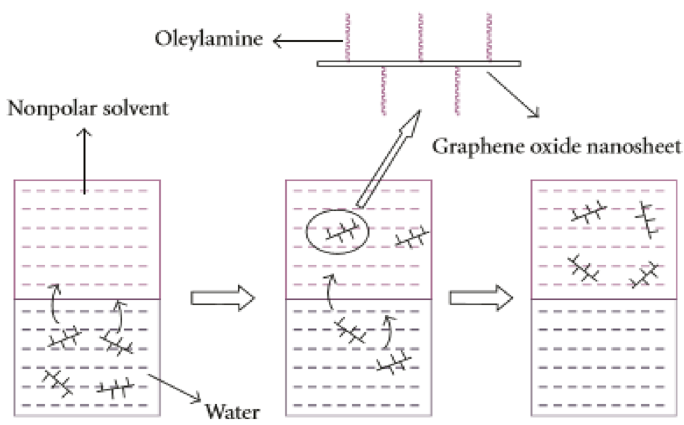

Fig 7 Schematic illustration of the phase transfer process.

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CHAPTER 4

Properties of Nanofluids

It may be noted that particle size is an important physical parameter in nanofluids because it can be used to tailor the nanofluid thermal properties as well as the suspension stability of nanoparticles. Researchers in nanofluids have been trying to exploit the unique properties of nano particles to develop stable as well as highly conducting heat transfer fluids. The key building blocks of nanofluids are nanoparticles; so research on nanofluids got accelerated because of the development of nanotechnology in general and availability of nanoparticles in particular. Compared to micrometer sized particles, nanoparticles possess high surface area to volume ratio due to the occupancy of large number of atoms on the boundaries, which make them highly stable in suspensions. Thus the nano suspensions show high thermal conductivity possibly due to enhanced convection between the solid particle and liquid surfaces. Since the properties like the thermal conductivity of the nano sized materials are typically an order of magnitude higher than those of the base fluids, nanofluids show enhancement in their effective thermal properties. Due to the lower dimensions, the dispersed nanoparticles can behave like a base fluid molecule in a suspension, which helps us to reduce problems like particle clogging, sedimentation etc. found with micro particle suspensions. The combination of these two features; extra high stability and high conductivity of the dispersed 'nanospecies' make them highly preferable for designing heat transfer fluids. The stable suspensions of small quantities of nanoparticles will possibly help us to design lighter, high performance thermal management systems.

Cooling is indispensable for maintaining the desired performance and reliability of a wide variety of industrial products such as computers, power electronic circuits, car engines, high power lasers, X-ray generators etc. With the unprecedented increase in heat loads and heat fluxes caused by more power in miniaturized products, high tech industries such as microelectronics, transportation, manufacturing, metrology and defense face cooling as one of the top technical challenges. For example, the electronics industry has provided computers with faster speeds, smaller sizes and expanded features, leading to ever increasing heat loads, heat fluxes and localized hot spots at the chip and package levels. Such thermal problems are also found in power electronics, optoelectronic devices etc. So the enhanced heat transfer characteristics of nanofluids may offer the development of high performance, compact, cost effective liquid cooling systems.

4.1 Nanofluid thermal conductivity

Practical applications of nanofluids discussed above are decided by the thermophysical characteristics of nanofluids. In the last decade, significant amounts of experimental as well as theoretical research were done to investigate the thermophysical behavior of nanofluids. All these studies reveal the fact that micro structural characteristics of nanofluids have a significant role in deciding the effective thermal conductivity of nanofluids. Experimental work done by a good number of research groups worldwide has revealed that nano fluids exhibit thermal properties superior to base fluid or conventional micrometer sized particle-fluid suspensions. Choi et al. (2001) and Eastman et al. (2001)

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have shown that copper and carbon nanotube (CNT) nano fluid suspensions possess much higher thermal conductivities compared to those of base fluids and that CNT nanofluids have showed a non linear relationship between thermal conductivity and concentration at low volume fractions of CNTs (Choi et al., 2001).

Most of the experimental studies on effective thermal conductivities of nanofluids have been done by using a transient hot wire (THW) method, as this is one of the most accurate methods to measure the thermal conductivities of fluids. Another method generally employed is the steady state method. All the experimental results obtained by these methods have shown that the thermal conductivity of nanofluids depend on many factors such as particle volume fraction, particle material, particle size, particle shape, base fluid properties and temperature.

More detailed descriptions about the effect of these parameters on effective thermal conductivity of nanofluids are discussed below.

4.1.1. Effect of particle volume fraction

Particle volume fraction is a parameter that has been investigated in almost all of the experimental studies and most of the results are generally in agreement qualitatively. Most of the research reports show an increase in thermal conductivity with an increase in particle volume fraction and the relation found is, in general, linear.

There are many studies in literature on the effect of particle volume fraction on the thermal conductivity of nanofluids. :

- Masuda et al. (1993) measured the thermal conductivity of water based nanofluids consisting of Al2O3 (13nm), SiO2 (12nm) and TiO2 (27nm) nanoparticles, the numbers in the parenthesis indicating the average diameter of the suspended nanoparticles. An enhancement up to 32.4% was observed in the effective thermal conductivity of nanofluids for a volume fraction about 4.3% of Al2O3 nanoparticles.
- Lee et al. (1999) studied the room temperature thermal conductivity of water as well as ethylene glycol (EG) based nanofluids consisting of Al2O3 (38.5nm) and CuO (23.6nm) nanoparticles.
- Measurements on other nanofluid systems such as TiO2 in deionized water (Chopkar et al., 2008) and multi walled carbon nanotube (MWCNT) in oil (Choi et al., 2001) show a non linear relation between the effective thermal conductivity and particle volume fraction which indicate the interactions between the particles in the system.

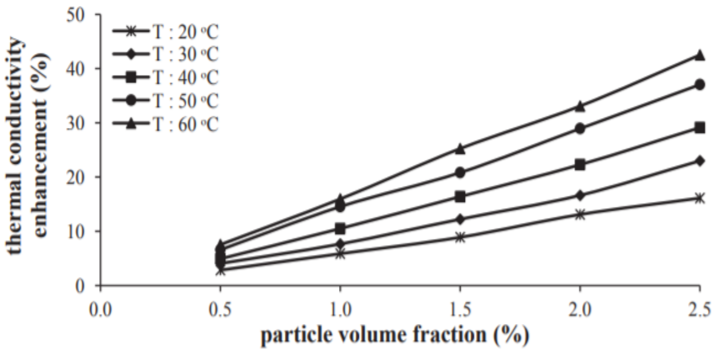

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Fig 8. Percentage of enhancement of thermal conductivity of maghemite nanofluids at various particle volume fractions

4.1.2. Effect of particle material

Most of the studies show that particle material is an important parameter that affects the thermal conductivity of nanofluids.

- Lee et al. (1999) considered the thermal conductivity of nanofluids with Al2O3 and CuO nanoparticles. They found that nanofluids with CuO nanoparticles showed better enhancement compared to the nanofluids prepared by suspending Al2O3 nanoparticles in the same base fluid. It may be noted that as a material Al2O3 has higher thermal conductivity than CuO. Authors explain this behavior as due to the formation clusters of Al2O3 nanoparticles in the fluid.
- Chopkar et al. (2008) made room temperature measurements in water and EG based nanofluids consisting of Ag2Al as well as Ag2Cu nanoparticles and it was found that the suspensions of Ag2Al nanoparticles showed enhancement in thermal conductivity slightly more than Ag2Cu nanoparticle suspensions. This was explained as due to the higher thermal conductivity of Ag2Al nanoparticles.

4.1.3 Effect of base fluid

According to the conventional effective medium theory (Maxwell, 1873), as the base fluid thermal conductivity decreases, the effective thermal conductivity of a nanofluid increases.

- As per Wang et al.'s (1999) results on the thermal conductivity of suspensions of Al2O3 and CuO nanoparticles in several base fluids such as water, ethylene glycol, vacuum pump oil and engine oil, the highest thermal conductivity ratio was observed when ethylene glycol was used as the base fluid. EG has comparatively low thermal conductivity compared to other base fluids. Engine oil showed somewhat lower thermal conductivity ratios than Ethylene Glycol. Water and pump oil showed even smaller ratios respectively. However, CuO/EG as well as CuO/water nanofluids showed exactly same thermal conductivity enhancements at the same volume fraction of the nanoparticles.
- Chopkar et al. (2008) contradicted the above results based on mean field theory statement by reporting higher thermal conductivity enhancement for nanofluids with a base fluid of higher thermal conductivity.
- The theoretical analysis made by Hasselmann and Johnson (1987) have shown that the effective thermal conductivity of fluid-particle mixtures were nearly independent of base fluid thermal conductivity.

4.1.4 Effect of particle size

The advent of nanofluids offers the processing of nanoparticles of various sizes in the range of 5-500 nm. It has been found that the particle sizes of nanoparticles have a significant role in deciding the effective thermal conductivity of nanofluids.

- Chopkar et al. (2006) studied the effect of the size of dispersed nanoparticles for Al70Cu30 /EG nanofluids by varying the size of Al70Cu30 nanoparticles in the range from 9 nm to 83 nm.

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- In another study on water and EG based nanofluids consisting of Al2Cu and Ag2Al nanoparticles, Chopkar et al. (2008) also investigated the effect of particle size on effective thermal conductivity of nanofluids.
  In all these cases it has been found that the effective thermal conductivity of a nanofluid increases with decreasing nanoparticle size.
- In another study of the effect of particle size on the thermal conductivity of nanofluids, reported by Beck et al. (2009) in water as well as EG based nanofluids consisting of Al2O3 nanoparticles, the normalized thermal conductivity of nanofluids vary in such a way that it decreases with decreasing the nanoparticle size.

Thus, conflicting reports have appeared in literature on the dependence of particle size on the thermal conductivity of nanofluids.

4.1.4. Effect of particle shape

For experimentation, spherical as well as cylindrical shaped nanoparticles are commonly used for nanofluid synthesis. The cylindrical particles have larger aspect ratio (length to diameter ratio) than spherical particles. The wide differences in the dimensions of these particles do influence the enhancement in effective thermal properties of nanofluids.

A general observation is that nanotube suspensions show a higher enhancement than the spherical particle suspension due to rapid heat transfer along a larger distance through a cylindrical particle since it has a length of the order of a micrometer. However, the cylindrical particle suspension need higher pumping power due to its enhanced viscosity which limits its usage, possible application as a heat transfer fluid.

4.1.5 Effect of temperature

The temperature of a two component mixture, such as a nanofluid, depends on the temperature of the solid component as well as that of the host media. In a nanofluid the increase in temperature enhances the collision between the nano particles (Brownian motion) and the formation of nanoparticle aggregates , which result in a drastic change in the thermal conductivity of nanofluids.

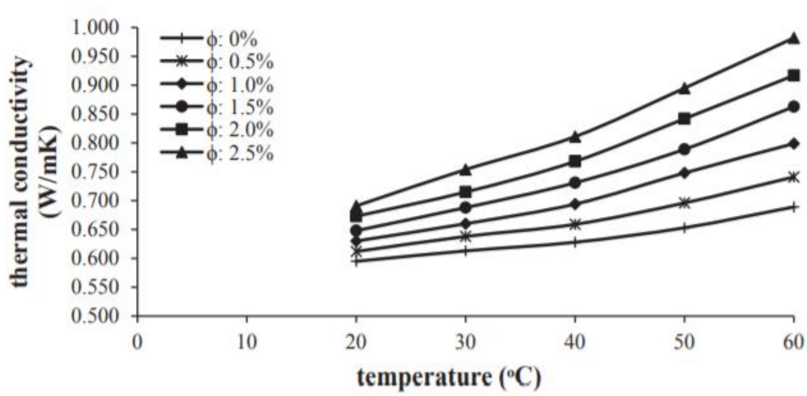

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Fig 9. Thermal conductivity of maghemite nanofluids at various temperatures

- Masuda et al. (1993) measured the thermal conductivity of water-based nanofluids consisting of Al2O3, SiO2, and TiO2 nanoparticles at different temperatures.
  It was found that thermal conductivity ratio decreased with increasing temperature.
- The temperature dependence of the thermal conductivity of Al2O3 /water and CuO/water nanofluids, measured by Das et al. (2003), have shown that for 1 vol.% Al2O3/water nanofluid, thermal conductivity enhanced from 2% at 210C to 10.8% at 510C. Temperature dependence of 4 vol. % Al2O3 nanofluid was much more significant, an increase from 9.4% to 24.3% at 510C.
- The investigations of Li et al. (2006) in CuO/water as well as Al2O3/water reveal that the dependence of thermal conductivity ratio on particle volume fraction get more pronounced with increasing temperature.
- The theoretical results based on Hamilton-Crosser model (1962) do not support the argument of any significant variation in thermal conductivity with temperature.

Researchers have explained the enhancement in thermal conductivity with temperature in terms of the Brownian motion of particles since it increases the micro convection in nanoparticle suspensions.

4.1.6 Effect of sonication time

The ultrasonic vibration technique is the most commonly used technique for producing highly stable, uniformly dispersed nano suspensions by two step process. It has been found that the duration of the application of the ultrasonic vibration has a significant effect on the thermal conductivity of nanofluids since it helps to reduce the clustering of nanoparticles.

4.1.7 Effect of the preparation method followed

The nanofluids employed in experimental research need to be well characterized with respect to particle size, size distribution, shape and clustering of the particles so as to render the results most widely applicable. As per the application, either a low or high molecular weight fluid can be used as the host fluid for nanofluid synthesis. The dispersion of nanoparticles in a base fluid has been done either by a two step method or by a single step method. In either case, a well-mixed and uniformly dispersed nanofluid is needed for successful reproduction of properties and interpretation of experimental data. As the name implies the two step method involves two stages, first stage is the processing of nanoparticles following a standard physical or chemical method and in the second step proceeds to disperse a desired volume fraction of nanoparticles uniformly in the base fluid. The single-step method provides a procedure for the simultaneous preparation and dispersion of nanoparticles in the base fluid.

- Most of the metallic oxide nanoparticle suspensions are prepared by the two step method . The two step method works well for oxide nanoparticles as well, but it is not as effective for metallic nanoparticles such as copper.

- Zhu et al. (2004) developed a one step chemical method for producing stable Cu-in ethylene glycol nanofluids and have shown that the single step technique is preferable over the two step method for preparing nanofluids containing highly thermal conducting metals.

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CHAPTER 5

Characterization of Nanofluids

5.1. The Stability Evaluation Methods for Nanofluids

5.1.1. Sedimentation and Centrifugation Methods Many methods have been developed to evaluate the stability of nanofluids. The simplest method is sedimentation method. The sediment weight or the sediment volume of nanoparticles in a nanofluid under an external force field is an indication of the stability of the characterized nanofluid. The variation of concentration or particle size of supernatant particle with sediment time can be obtained by special apparatus. The nanofluids are considered to be stable when the concentration or particle size of supernatant particles keeps constant. For the sedimentation method, long period for observation is the defect. Therefore, centrifugation method is developed to evaluate the stability of nanofluids. It has been found that the obtained nanofluids are stable for more than 1 month in the stationary state and more than 10h under centrifugation at 3,000 rpm without sedimentation.

5.1.2 Zeta Potential Analysis Zeta potential is electric potential in the interfacial double layer at the location of the slipping plane versus a point in the bulk fluid away from the interface, and it shows the potential difference between the dispersion medium and the stationary layer of fluid attached to the dispersed particle. The significance of zeta potential is that its value can be related to the stability of colloidal dispersions. So, colloids with high zeta potential (negative or positive) are electrically stabilized, while colloids with low zeta potentials tend to coagulate or flocculate. .The colloids with zeta potential from 40 to 60 mV are believed to be good stable, and those with more than 60 mV have excellent stability.

5.1.3 Spectral Absorbency Analysis Spectral absorbency analysis is another efficient way to evaluate the stability of nanofluids. In general, there is a linear relationship between the absorbency intensity and the concentration of nanoparticles in fluid. *Huang et al.* evaluated the dispersion characteristics of alumina and copper suspensions using the conventional sedimentation method with the help of absorbency analysis by using a spectrophotometer after the suspensions deposited for 24 h. The stability investigation of colloidal FePt nanoparticle systems was done via spectrophotometer analysis. If the nanomaterials dispersed in fluids have characteristic absorption bands in the wavelength 190–1100nm, it is an easy and reliable method to evaluate the stability of nanofluids using UV-vis spectral analysis. The variation of supernatant particle concentration of nanofluids with sediment time can be obtained by the measurement of absorption of nanofluids, because there is a linear relation between the supernatant nanoparticle concentration and the absorbance of suspended particles.

5.2 Features of Nanofluids

When the particles are properly dispersed, these features of nanofluids are expected to give the following benefits:

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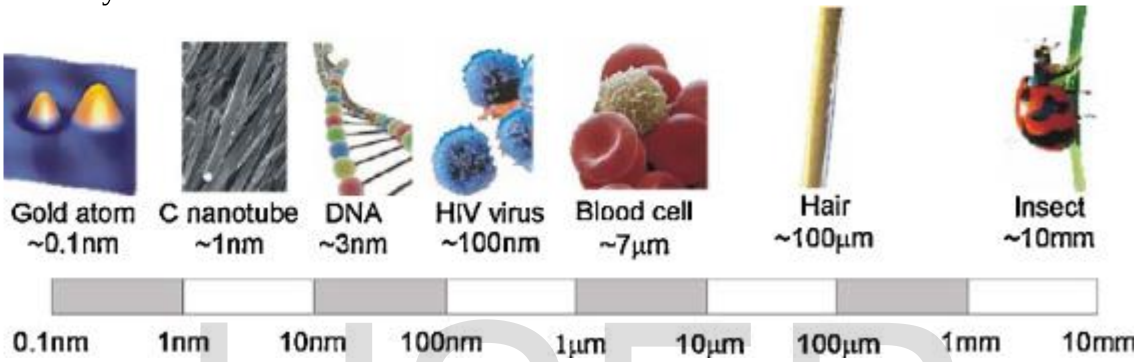
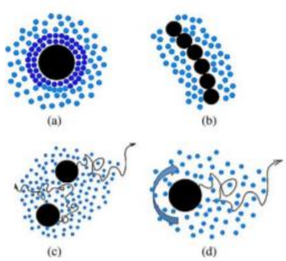
- Higher heat conduction: The nanoparticles have a large surface area which allows more heat transfer. Due to their tiny size, they are mobile and may bring about micro convection. The abnormal increase in thermal conductivity of nanofluids can be attributed to the above reasons.
- Stability: The problem of sedimentation is resolved because the particles are small, they weigh less, thus making the chances of sedimentation less. Reduced sedimentation can help overcome one of the major drawbacks of suspensions
- Reduced chances of erosion: Nanoparticles are very small hence the momentum they impart on a solid wall is very small. This causes reduced erosion of materials they are in contact with.
- Reduction in pumping power: To increase the heat transfer in a conventional fluid by a factor or two, pumping power must be increased by a factor of ten. In the case of nanofluids, the required increase in pumping power will be very moderate unless there is a very sharp increase in viscosity.



5.3 Mechanism of Heat Transfer

The researchers have been analyzing several mechanisms, in order to analyze the increase in heat transfer. Listed below are the possible mechanisms:

- Liquid-layering
- Particle aggregation
- Particle Brownian motion
- Brownian-motion-induced convection.



Sketch of four potential mechanisms responsible for the reported conductivity enhancement: (a) liquid layering, (b) particle aggregation, (c) particle Brownian motion and (d) Brownian-motion-induced convection

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CHAPTER 6

APPLICATIONS OF NANOFLUIDS

6.1 Heat Transfer Applications

Industrial Cooling Applications . Routbort et al. started a project in 2008 that employed nanofluids for industrial cooling that could result in great energy savings and resulting emissions reductions. For U.S. industry, the replacement of cooling and heating water with nanofluids has the potential to conserve 1 trillion Btu of energy. For the U.S. electric power industry, using nanofluids in closedloop cooling cycles could save about 10–30 trillion Btu per year (equivalent to the annual energy consumption of about 50,000–150,000 households).

Smart Fluids. In this new age of energy awareness, our lack of abundant sources of clean energy and the widespread dissemination of battery operated devices, such as cellphones and laptops, have accented the necessity for a smart technological handling of energetic resources. Nanofluids have been demonstrated to be able to handle this role in some instances as a smart fluid.

In a recent paper published in the March 2009 issue of Physical Review Letters, Donzelli et al. showed that a particular class of nanofluids can be used as a smart material working as a heat valve to control the flow of heat. The nanofluid can be readily configured either in a "low" state, where it conducts heat poorly, or in a "high" state, where the dissipation is more efficient. To leap the chasm to heating and cooling technologies, the researchers will have to show more evidence of a stable operating system that responds to a larger range of heat flux inputs.

Nuclear Reactors. Kim et al. at the Nuclear Science and Engineering Department of the Massachusetts Institute of Technology (MIT), performed a study to assess the feasibility of nanofluids in nuclear applications by improving the performance of any water-cooled nuclear system that is heat removal limited. Possible applications include pressurized water reactor (PWR) primary coolant, standby safety systems, accelerator targets, plasma divertors, and so forth, In a pressurized water reactor (PWR) nuclear power plant system, the limiting process in the generation of steam is critical heat flux (CHF) between the fuels rods and the water—when vapor bubbles that end up covering the surface of the fuel rods conduct very little heat as opposed to liquid water. Using nanofluids instead of water, the fuel rods become coated with nanoparticles such as alumina, which actually push newly formed bubbles away, preventing the formation of a layer of vapor around the rod and subsequently increasing the CHF significantly. After testing in MIT's Nuclear Research Reactor, preliminary experiments have shown promising success where it is seen that PWR is significantly more productive. The use of nanofluids as a coolant could also be used in emergency cooling systems, where they could cool down overheat surfaces more quickly leading to an improvement in power plant safety.

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6.2 Automotive Applications

Engine oils, automatic transmission fluids, coolants, lubricants, and other synthetic high-temperature heat transfer fluids found in conventional truck thermal systems— radiators, engines, heating, ventilation and air-conditioning (HVAC)—have inherently poor heat transfer properties. These could benefit from the high thermal conductivity offered by nanofluids that resulted from addition of nanoparticles.

Nanofluid Coolant. In looking for ways to improve the aerodynamic designs of vehicles, and subsequently the fuel economy, manufacturers must reduce the amount of energy needed to overcome wind resistance on the road. At high speeds, approximately 65% of the total energy output from a truck is expended in overcoming the aerodynamic drag. This fact is partly due to the large radiator in front of the engine positioned to maximize the cooling effect of oncoming air.

The use of nanofluids as coolants would allow for smaller size and better positioning of the radiators. Owing to the fact that there would be less fluid due to the higher efficiency, coolant pumps could be shrunk and truck engines could be operated at higher temperatures allowing for more horsepower while still meeting stringent emission standards.

that the use of high-thermal conductive nanofluids in radiators can lead to a reduction in the frontal area of the radiator by up to 10%. This reduction in aerodynamic drag can lead to a fuel savings of up to 5%. The application of nanofluid also contributed to a reduction of friction and wear, reducing parasitic losses, operation of components such as pumps and compressors, and subsequently leading to more than 6% fuel savings.

Nanofluid in Fuel The aluminium nanoparticles, produced using a plasma arc system, are covered with thin layers of aluminium oxide, owing to the high oxidation activity of pure aluminium, thus creating a larger contact surface area with water and allowing for increased decomposition of hydrogen from water during the combustion process. During this combustion process, the alumina acts as a catalyst and the aluminium nanoparticles then serve to decompose the water to yield more hydrogen. It was shown that the combustion of diesel fuel mixed with aqueous aluminium nanofluid increased the total combustion heat while decreasing the concentration of smoke and nitrous oxide in the exhaust emission from the diesel engine.

6.3 Electronic Applications

Nanofluids are used for cooling of microchips in computers and elsewhere. They are also used in other electronic applications which use microfluidic applications.

Cooling of Microchips. A principal limitation on developing smaller microchips is the rapid heat dissipation. However, nanofluids can be used for liquid cooling of computer processors due to their high thermal conductivity. It is predicted that the next generation of computer chips will produce

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localized heat flux over 10MW/m^2, with the total power exceeding 300W. In combination with thin film evaporation, the nanofluid oscillating heat pipe (OHP) cooling system will be able to remove heat fluxes over 10MW/m^2 and serve as the next generation cooling device that will be able to handle the heat dissipation coming from new technology.

Microscale Fluidic Applications. The manipulation of small volumes of liquid is necessary in fluidic digital display devices, optical devices, and microelectromechanical systems (MEMS) such as lab-on-chip analysis systems. This can be done by electrowetting, or reducing the contact angle by an applied voltage, the small volumes of liquid. Electrowetting on dielectric (EWOD) actuation is one very useful method of microscale liquid manipulation.

6.4 Biomedical Applications.

Nanodrug Delivery. Most bio-MEMS studies were done in academia in the 1990s, while recently commercialization of such devices have started. Examples include an electronically activated drug delivery microchip, a controlled delivery system via integration of silicon and electroactive polymer technologies; a MEMS-based DNA sequencer and arrays of in-plane and out of plane hollow micro-needles for dermal/transdermal drug delivery as well as nanomedicine applications of nanogels or gold-coated nanoparticles. An objective of the advanced endeavours in developing integrated micro- or nano-drug delivery systems is the interest in easily monitoring and controlling target-cell responses to pharmaceutical stimuli, to understand biological cell activities, or to enable drug development processes.

Cancer Therapeutics. There is a new initiative which takes advantage of several properties of certain nanofluids to use in cancer imaging and drug delivery. This initiative involves the use of iron-based nanoparticles as delivery vehicles for drugs or radiation in cancer patients. Magnetic nanofluids are to be used to guide the particles up the bloodstream to a tumor with magnets. It will allow doctors to deliver high local doses of drugs or radiation without damaging nearby healthy tissue, which is a significant side effect of traditional cancer treatment methods. In addition, magnetic nanoparticles are more adhesive to tumor cells than non-malignant cells and they absorb much more power than microparticles in alternating current magnetic fields tolerable in humans; they make excellent candidates for cancer therapy.

Sensing and Imaging. Colloidal gold has been used for several centuries now, be it as colorant of glass ("Purple of Cassius") and silk, in medieval medicine for the diagnosis of syphilis or, more recently, in chemical catalysis, non-linear optics, supramolecular chemistry, molecular recognition and the biosciences. Colloidal gold is often referred to as the most stable of all colloids.

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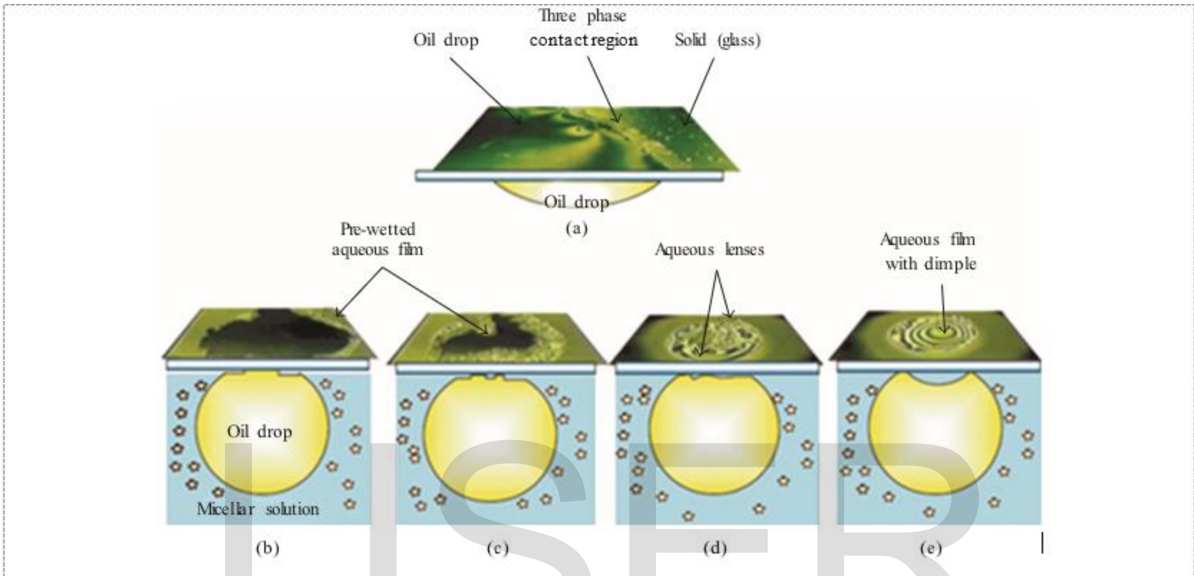
6.5 Other Applications

Nanofluid Detergent. Nanofluids do not behave in the same manner as simple liquids with classical concepts of spreading and adhesion on solid surfaces. This fact opens up the possibility of nanofluids being excellent candidates in the processes of soil remediation, lubrication, oil recovery and detergency. Future engineering applications could abound in such processes.



: (a) Photomicrograph showing the oil drop placed on a glass surface and differential interference patterns formed at the threephase contact region(b), Photomicrographs taken after addition of the nanofluid at (b), 30s; 2 minutes; (d), 4 minutes; (e), 6 minutes region.

Overall, this phenomenon which involves the increased spreading of the detergent surfactants, which are not only limited to polystyrene nanoparticles, and enhanced oil removal process offers a new way of removing stains and grease from surfaces. This type of nanofluid also has potential in the commercial extraction of oil from the ground as well as the remediation of oil spills.

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CHAPTER 7

7.1 Challenges of nanofluids

Many interesting properties of nanofluids have been reported in the review. In the previous studies, thermal conductivity has received the maximum attention, but many researchers have recently initiated studies on other heat transfer properties as well. The use of nanofluids in a wide variety of applications appears promising. But the development of the field is hindered by-

(i) lack of agreement of results obtained by different researchers;
(ii) poor characterization of suspensions;
(iii) lack of theoretical understanding of the mechanisms responsible for changes in properties.

Experimental studies in the convective heat transfer of nanofluids are needed. Many issues, such as thermal conductivity, the Brownian motion of particles, particle migration, and thermophysical property change with temperature, must be carefully considered with convective heat transfer in nanofluids.

Future convective studies must be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulent regions. The use of nanofluids in heat pipes has shown enhancement in performance and considerable reduction in thermal resistance.

However, recent studies indicate particle aggregation and deposition in micro-channel heat sinks. Further study is required in these areas to identify the reasons for and the effects of particle deposition. Finally, there appears to be hardly any research in the use of nanofluids as refrigerants. Nanoparticle refrigerant dispersions in two-phase heat transfer applications can be studied to explore the possibility of improving the heat transfer characteristics of evaporators and condensers used in refrigeration and air-conditioning appliances.

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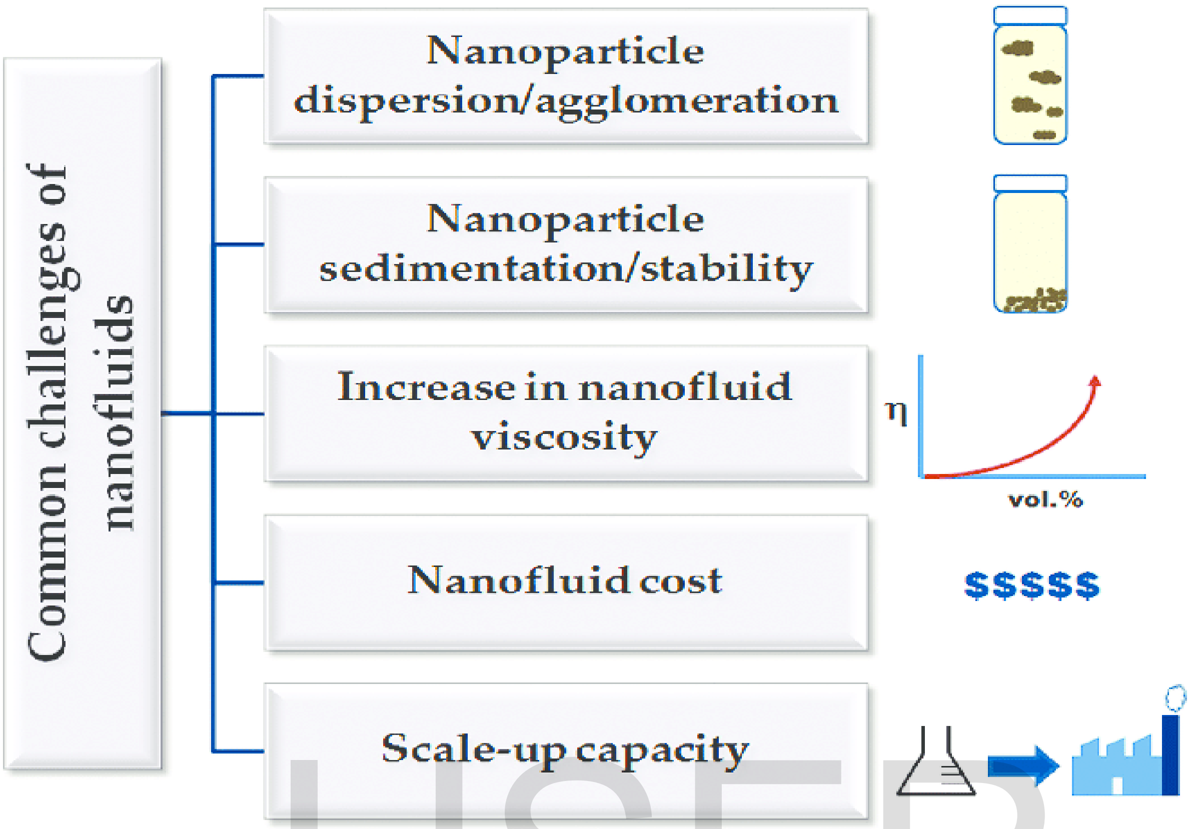

7.2 Conclusion

- Nanofluids are important because they can be used in numerous applications involving heat transfer, and other applications such as in detergency. Colloids which are also nanofluids have been used in the biomedical field for a long time, and their use will continue to grow. Nanofluids have also been demonstrated for use as smart fluids. Problems of nanoparticle agglomeration, settling, and erosion potential all need to be examined in detail in the applications. Nanofluids employed in experimental research have to be well characterized with respect to particle size, size distribution, shape and clustering so as to render the results most widely applicable. Once the science and engineering of nanofluids are fully understood and their full potential researched, they can be reproduced on a large scale and used in many applications. Colloids which are also nanofluids will see an increase in use in biomedical engineering and the biosciences.

- Based on literatures, it has been found that the improved thermal conductivities of nanofluids are the one of the driving factors for improved performance in different applications. It was found that thermal conductivity of nanofluids with MWCNT can be increased up to 150%.

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- As heat transfer (i.e. conduction, convective, boiling) can be enhanced by nanofluids, heat exchanging devices can be made energy efficient and compact. Reduced or compact shape may results in reduced drag for example in automobile and similar applications.

- It was also found that there are inconsistencies in the reported results published by many researchers. Few researchers reported the inconsistencies between model and experimental results of thermal conductivity of nanofluids.

- Exact mechanism of enhanced heat transfer for nanofluids is still unclear as reported by many researchers.

- Nanofluids stability and its production cost are major factors that hinder the commercialization of nanofluids. By solving these challenges, it is expected that nanofluids can make substantial impact as coolant in heat exchanging devices.

7.3 Recommendations for future work

This work focused on the characterization and the convection of various nanofluids, however further research is required for better understanding of nanofluids. The current results imply most of the oxide nanofluids are ineffective as heat transfer liquids and certain CNT nanofluids are effective. A traditional effective medium theory failed to explain the results. More research on the oxide nanofluids may not be needed but there may be some controlling parameter which increases the thermal conductivity we did not recognize.

Future research needs to focus on finding out the main parameters affecting the thermal conductivity of nanofluids. The thermal conductivity of nanofluids can be a function of parameters such as particle shape, particle agglomeration, particle polydispersity, etc. In order to clarify these variables, a number of experiments will be necessary as varying only one parameter among the selected parameters. The possible main parameters are the aspect ratio of the particle and the polydispersity of particles based on the results of CNT nanofluids in this work. We acquired significantly higher thermal conductivity with CNT nanofluids consisting of long, monodisperse tube shapes and no change in the thermal conductivity with CNT nanofluids with short, irregular tube shape. The thermal conductivity of oxide nanofluids may also be affected by the particle shapes. The challenging point is to obtain the desirable

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nanoparticle product. Currently, the available nanoparticles are limited and their specifications are not accurate. The development of the nanoparticle production technique will be very helpful for the nanofluid research. Finally, a theoretical model needs to be developed which explains the empirical data.

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