STUDY ON THERMOPHYSICAL PROPERTIES OF FLUIDS CONTAINING CARBON NANOTUBES

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ABSTRAK

Di kala permintaan yang akut terhadap tenaga, cecair pemindah haba adalah diperlukan untuk mengubahsuai dan menbangunkan cecair berprestasi tinggi dikenali sebagai cacair-nano. Ciri-ciri cecair ini masih lagi belum di perolehi sepenuhnya. Karbon nanotiub(CNT) didapati mampu untuk meningkatkan dayaupaya termal bagi cecair pemindah haba kenvensional. Walaupun begitu kebanyakkan penyelidikan terdahulu telah memfokuskan kesan konsentrasi bahan ini terhadap curi-ciri termal-fizikal cecair-nano. Tiada penyelidikan yang mendalam dilakukan untuk menentukan secara terus kesan keadah penyediaan terhadap kestabilan, konduktiviti termal dan kelikatan CNT terampai. Ciri –ciri termal cacair mengandingi CNT berbeza bergantung kepada teknik penyediaan yang berbeza dan pengukuran jitu telah dilakukan pada experimen ini untuk menentukan kesan keadah-kaedah ini. Kesan variasi masa ultrasonikasi dan sufaktan yang berlainan terhadap ciri-ciri termal-fizikal multi dinding karbon nanotiub (MWCNTs) telah dikaji. Ciri-ciri termal-fizikal yang diukur adalah konduktivi termal dan kelikatan pada suhu yang berlainan. Gam Arabic (GA), Sodium dodecylbenzene sulfonate (SDBS) and Sodium dodecyl sulfate (SDS) telah digunakan sebagai surfaktan. Penggunaan GA menujukkan konduktiviti termal yang lebih tinggi berbanding SDBS and SDS. Sampel yang mengandungi 0.5 wt% MWCNT, 0.25% GA mengikut peratusan berat dan air tersuling sebagai cacair asas telah di sediakan pada masa ultrasonikasi yang berbeza dalam kajian ini. Pengimejan telah dilakukan menggunakan teknik TEM untuk melihat ciri-ciri penyebaran sampel dan melihat pengurangan penggumpalan CNT serta panjang. Pengurangan penggumpalan didapati lebih penting dari panjang. Hasil kajian menunjukkan ultrasonikasi memberi kesan terhadap konduktiviti termal, kelikatan dan penyebaran. Peningkatan maksimum kondutiviti termal adalah sebanyak 22.31% (nisbah sebanyak 1.22) pada suhu 45 darjah celsius bagi sampel yang mengalami sonikasi selama 200minit. Konduktiviti

termal meningkat dengan peningkatan suhu dan masa sonikasi. Pertimbangan terhadap kelikatan mendapati cacair-nano diklasifikasikan sebagai penipisan ricih dan cacair bukan Newtonian. Kelikatan meningkat kepada maksimum untuk sampel yang mengalami sonikasi selama 50minit dan kemudiannya berkurangan dengan pertambahan masa sonikasi. Oleh yang demikian kelikatan yang terendah dan konduktiviti termal yang tertinggi dicapai dengan memanjangkan tempoh sonikasi dimana ianya amat berguna untuk aplikasi pemindahan haba.

ABSTRACT

In the verge of acute energy demand the heat transfer fluids were required to modify and develop a high performance liquid as nanofluid. The properties of the fluids are not yet fully obtained. The carbon nanotubes (CNT`s) are able to enhance the thermal performance of the conventional heat transfer liquids, nonetheless the majority of past works have been focused on the impacts of concentrations of carbon nanotubes on the thermo-physical properties of the nanofluids. No considerable researches have been performed to straightly indicate the influence of preparation methods on stability, thermal conductivity and viscosity of carbon nanotubes suspensions. The thermo-physical properties of CNT` nanofluids differ under different preparation techniques and the precise measurements were performed in this current experiment to figure out the impacts of these methods. The effect of variation of ultrasonication time and different surfactants on the thermal properties of Multi-walled carbon nanotubes(MWCNT`s) were studied. The thermo-physical properties measured were thermal conductivity and viscosity under different temperatures. Gum Arabic (GA), Sodium dodecylbenzenesulfonate (SDBS) and Sodium dodecyl sulfate (SDS) were used as surfactants. Addition of GA showed superior thermal conductivity of nanofluids than that of SDBS and SDS dispersants in it. Samples of 0.5 wt% MWCNT, 0.25% GA and distilled water as the base liquid were prepared at different ultrasonication times in this study. Imaging was carried out by TEM technique to view the dispersing characteristics of samples and observed both the reduction of CNT agglomerations and length. The reduction in agglomerations was found to be more important than that of CNT length. The results exhibited that the ultrasonication affects thermal conductivity, viscosity and dispersion. The maximum thermal conductivity enhancement was found to be 22.31% (the ratio of 1.22) at 45 ^{o}C temperature of the sample sonication bath for 200 minutes. The thermal conductivity enhanced with the increase of both temperature and sonication time.

In the consideration of viscosity, the nanofluids treated as shear thinning and non-Newtonian fluids. The viscosity was raised to the maximum for the sample sonication of 50 minutes and the subsequently decreased with the further increase of sonication time. Thus the lowest viscosity and the highest thermal conductivity ratios were achieved by utilizing prolonged sonication time, which could be useful in heat transfer applications.

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LIST OF ABBREVIATIONS

ANL	Argon National Lab
ASHRAE	American Society of Heating, Refrigerating and Air- Conditioning
BET	Brunauer Emmett Teller
CNT	Carbon Nano-tube
Co.	Company
Conc.	Concentration
CTAB	Cetyltrimethylammoniumbromide
DI	Deionised
GA	Gum Arabic
EG	Ethylene Glycol
JCPDS	Joint Committee onPowder Diffraction Standard
H-C	Hamilton-Crosser
HVAC	Heating, Ventilation and Air conditioning
MWCNT	Multi-walled Carbon Nano-tube
PG	Propylene Glycol
SWCNT	Single-walled carbon nanotube
SDS	Sodium dodecyl sulfate
SDBS	Sodium dodecyl benzene sulfonate
TEM	Transmission electron microscopy
THW	Transient Hot Wire
UDD	Ultra Dispersed Diaamond
VOL.	Volume
XRD	X-ray Diffraction
ZP	Zeta Potentioal

CHAPTER ONE: INTRODUCTION

1.1 Background

Due to rapid growth in power consumption,also rapid development in all sectors, such as Industrial, Infrastructure, Transportation, Defense, Space,etc, call for saving energy is a daily campaign; in addition,managing high thermal loads has become critical. For these reasons, energy efficiency should be enhanced in heating and cooling systems for all of the sectors mentioned above,at which the conventional technique of heat transfer employed by means of a flow system, including fluids,such as: water,ethylene glycol and mineral oils,are used as the heat transfer fluid. A fluid used to cool or heat a system,or to transfer heat from one part to another call heat transfer fluid.

In spite of the low heat transfer properties of such fluids which obstruct the performance of the heat transfer equipments they had always been desired and would always remain in demand, because of their simple characteristics.

The systems working by Conventional heat transfer fluids, used in applications same aspower generation,refining andpetrochemical,are very large and include considerable amount of heat transfer fluids,however in specific usages like electronics, cooling in laptops and microprocessors, cooling in space applications and many other areas, the small heat transfer systems are needed, these applications have a critical relationship between the mechanical system size,and the cost related tooperation and manufacturing. If developments may be done in the existing systems of heat transfersuch as increasing the heat transfer fluid performance, smaller heat exchanger and hence, a lesser space would be required to handle a specified amount of cooling load, the situation would lead to smaller heat transfer systems with lower capital costs and higher energy efficiencies [3] .Micro-channel heat exchanger could be developed in HVAC and automotive industries with the space saving and lighter weight features. These advantages could also come out as an attractive approach to companies in saving more material.

Low heat transfer performance reduced the efficiency of lower thermal conductivity of the base liquids (i.e. water, ethylene glycol and oil). In this pursuit numerous researchers have been investigating better methods to increase the thermal conductivity of heat transfer liquids. For the first time, long ago the basic concept of dispersing solid particles in fluid (millimeter or micrometer sized) to enhance the thermal conductivity was introduced by James clerk Maxwell (W Yu & Choi, 2003)

In over the years the incorporation into base liquid high thermal conductive particulate solid such as metals and metal oxide had been used for enhancement (Ahuja, 1975a, 1975b; Hetsroni & Rozenblit, 1994; Lee, Choi, Li, & Eastman, 1999; Sohn & Chen, 1981; Xuan & Li, 2000)

Because solid particles have a higher thermal conductivity compared to conventional heat transfer based liquid for example at room temperature, copper has 700 and 3000 times greater thermal conductivity than that of water and engine oil respectively as shown in Figure 1.1(S. Choi, Zhang, & Keblinski, 2004; Komarneni, Parker, & Wollenberger, 1997)

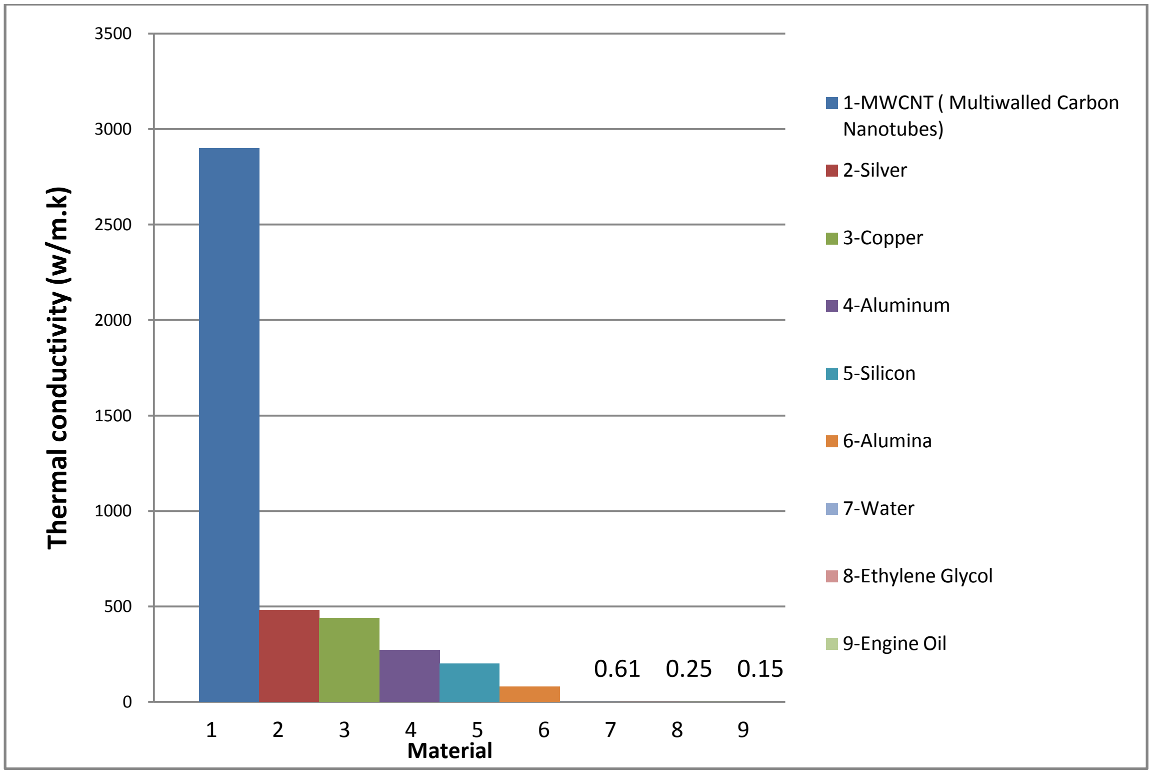

Figure 1.1 Thermal conductivity of some materails(solids and liquids) at 300 K

Metallic solid particles have higher thermal conductivity than non-metallic particles except some substance like Carbon Nanotubes(CNT) and diamond(Marquis & Chibante, 2005).

Despite the improved thermal conductivity by dispersing solid particles (mm or µm sized) in based fluids, it couldn`t be used in practical application because of problems such as sedimentation, erosion, fouling and increased pressure drop of the flow channel and also channel clogging which caused by poor suspension stability particularly in the case of mini and micro channels(Ding, Alias, Wen, & Williams, 2006; Trisaksri & Wongwises, 2007; Wang & Wei, 2009)

Over the last several decades, scientists and engineershave attempted to develop fluids, which offer better coolingor heating performance for a variety of thermal systemscompared to conventional heat transfer fluids.

Until for the first time choiat the Argonne National Laboratory employed the particles of nanometer dimension (nanoparticle) suspended in solution as nanofluid and showed considerable increase in the nanofluid thermal conductivity(S. U. Choi & Eastman, 1995).

This new class of heattransfer fluids (nanofluids) is engineered by dispersing nanometer sized (one billionth of a meter) solid particles,rods or tubes (nanotube) in traditional heat transfer fluids. From theinvestigations in the past decade, nanofluids were foundto exhibit significantly higher thermal properties, in particular,thermal conductivity and convective heat transfer than those of base fluids ,Liu et al.(M. S. Liu, Lin, Huang, & Wang, 2006), Eastman et al.(Eastman, Choi, Li, Thompson, & Lee, 1997), Yu et al.(Wei Yu, Xie, Chen, & Li, 2009),and Mintsa et al.(Mintsa, Roy, Nguyen, & Doucet, 2009), Hwang et al.(Hwang, Park, Lee, & Jung, 2006), Eastman et al.(Eastman, Choi, Li, Yu, & Thompson, 2001), Xuan, Y. and Q. Li (Xuan & Li, 2000), putranandi(Putra, Thiesen, & Roetzel, 2003), P. Garg et al.(Garg et al., 2009),murshed(Murshed, Leong, & Yang, 2005), hong et al.(Hong, Yang, & Choi, 2005) and,li and Peterson (C. H. Li & Peterson, 2006),observed great enhancement of nanofluids' thermal conductivity.Enhancement of convective heat transfer was reported by ZeinaliHeris et al.(Zeinali Heris, Nasr Esfahany, & Etemad, 2007), Kim et al.(D. Kim et al., 2009), Jung et al.(Jung, Oh, & Kwak, 2009)and Sharma et al.(Sharma, Sundar, & Sarma, 2009)

Thus, nanofluids have attracted great interest from theresearch community due to their potential benefits andapplications in numerous important fields such as microelectronics,transportation, manufacturing, medical, andHVAC

The better stability of nanofluids will prevent rapid settlingand reduce clogging in the walls of heat transfer devices.The high thermal conductivity of nanofluids translates intohigher energy efficiency, better performance, and lower operatingcosts. They can reduce energy consumption for pumpingheat transfer fluids. Miniaturized systems require smallerinventories of fluids where nanofluids can be used. Thermalsystems can be smaller and lighter. In vehicles, smaller componentsresult in better gasoline mileage, fuel savings, loweremissions, and a cleaner environment.

Dispersion of Nano-particles like metal (copper), metal oxide (alumina) and carbon component (Carbon Nanotubes) augment heat transfer of the fluid by transferring more energy, resulting to fuel, energy and money saving. for example dispersion of copper Nanoparticles and alternatively carbon Nanotubes provided the most promising result so far with observed thermal conductivity enhancement of 40% and 160% respectively in relation to the base fluid(Assael, Chen, Metaxa, & Wakeham, 2004; S. Choi, Zhang, Yu, Lockwood, & Grulke, 2001; Eastman et al., 2001)

Actually it is the goal of Nanofluids to achieve the highest thermal properties with lower concentration and good stability.

Thermal conductivity enhancement of nanofluids offers plenty of benefits and applications like higher heat transfer, decreased pumping power needs, smaller and lighter cooling systems, reduced inventory of heat transfer fluids, reduced friction coefficients and improved wear resistance, those kind of benefits prepared nanofluids for various application such as coolants, lubricants, hydraulic fluids and metal cutting fluids(Saidur, Leong, & Mohammad, 2011)

Comparedwith millimeter or micrometer sized particle suspensions, Nanofluids have higher stability due to the ultra small particle size, and can have dramatically higher thermal conductivities(Ding et al., 2006; M.-S. Liu, Ching-Cheng Lin, Huang, & Wang, 2005; Saidur et al., 2011)

Nanofluids does not carry too big a momentum as in case of micro fluids, which reduced erosion and wear in tube and channel, figure 1.2 compares the effect of micro particles and nanoparticles with the same volume concentration in a cooling system.

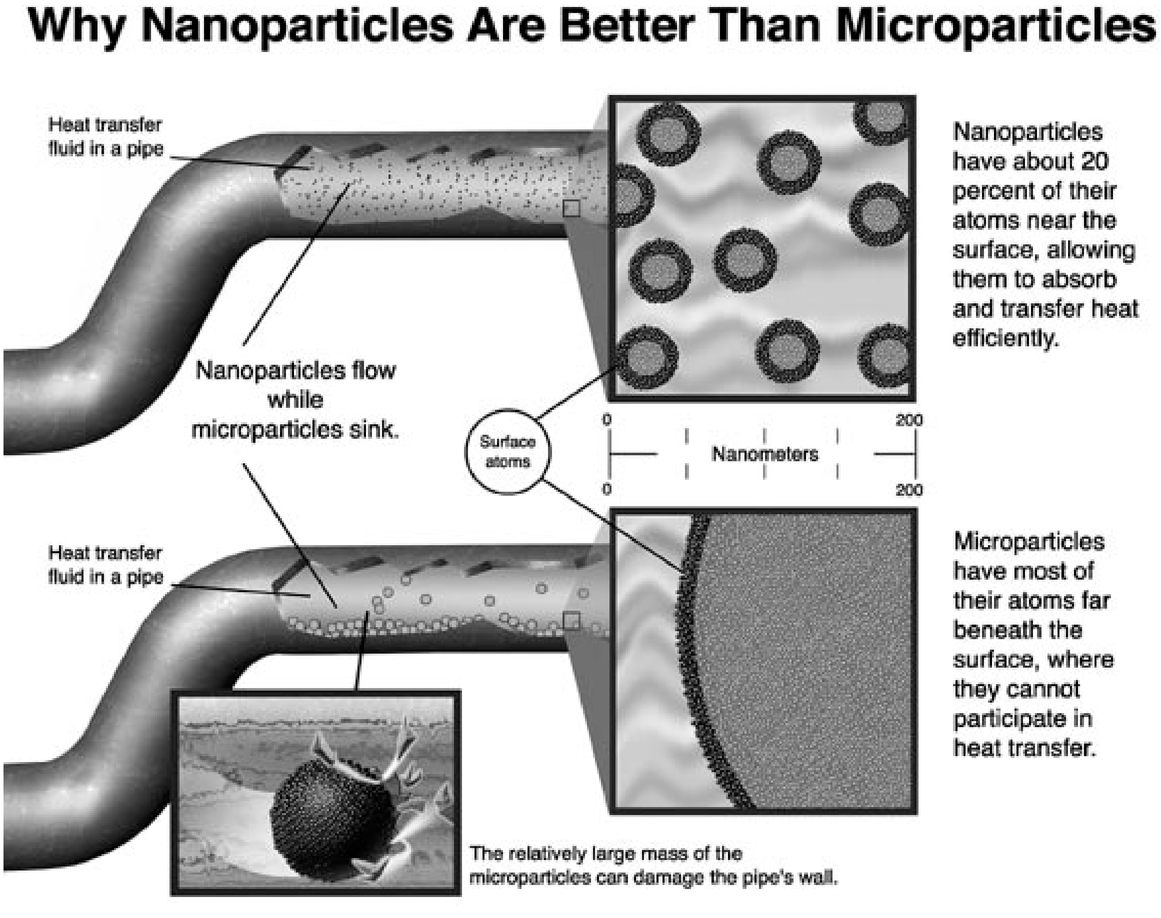

Figure 1-2 effects of micro particles and nanoparticles in a cooling system [34]

These liquid suspensions containing particles significantly smaller than 100 nm in at least one dimension (Ding et al., 2006)

Serrano et al.(Serrano, Rus, & Garcia-Martinez, 2009) provided an excellent example of nanometer in comparison with millimeter and micrometer to understand clearly as can be seen in Figure1-3nano–sized particles could be either spherical or cylindrical. The metal and metal oxidenanoparticles are generally synthesized in spherical form, however, carbon nanoparticlescould be synthesized both in spherical and cylindrical form. Of the two forms of carbonnanoparticles, the cylindrical form is more common and is called as (CNT) carbon nanotubes. A kind of these nanotubes is called multi-walled carbon nanotubes (MWCNT)which are more popular in heat transfer based applications.

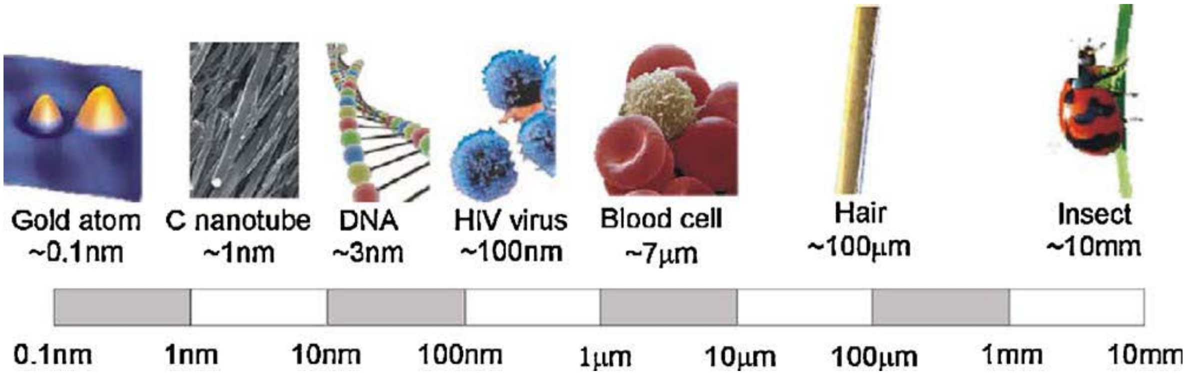

Figure1-3 Length scale and some examples related

The main focus of this work is concerned with the preparation of Nanofluids by dispersingMWCNTs in Distilled water (DW) and its use in heat transfer fluids. It has been proven, when CNT`s are dispersed in common heat transfer liquids, increase in thermal conductivity is observed (Assael et al., 2004; Assael, Metaxa, Arvanitidis, Christofilos, & Lioutas, 2005; S. Choi et al., 2001; Ding et al., 2006; Nasiri, Shariaty-Niasar, Rashidi, Amrollahi, & Khodafarin, 2011) The enhancement can be significant even when CNTs are added in small concentrations, the motivations in present work are as follows.

No considerable researches have been performed to straightly indicate the influence of preparation methods on stability, thermal conductivity and viscosity of carbon nanotubes suspensions since The thermo-physical properties of CNT` nanofluids differ under different preparation techniques, In this study in order to prevent aspect ratio (L/D) reduction a combination of a mechanical method through ultrasonication and a chemical method through surfactants were used for dispersing.

The thesis comprises of five chapters. The current chapter gives the introduction and the importance of the research. The chapter 2 is the literature review done in relevance to the past work done in nanofluid research and how it is connected to this work. Experimental set-ups experimental procedures and measurements technique are provided in chapter 3. Chapter 4 presented the outcome of experiments, discussion about results and comparison with other studies. Finally, conclusion and suggestions for future works are provided in chapter 5.

1.2 Objectives

The overall goal of this study was to investigate the impact of sonication time onviscosity and thermal conductivity of aqueous suspensions of multi-walled carbon nanotubes. To satisfy the overall objective of this research, the following tasks are were undertaken:

1. Prepared multi-walled carbon nanotubes aqueous suspensions with concentration of 0.5wt%, by using threedifferent kinds of surfactants of SDS, SDBS and GA
2. Measured the thermal conductivity for all MWCNT samples employing KD 2 Pro Thermal Properties Analyzer, under temperature range of 20 to 45°C

3. The microscopic pictures of the sampleswere taken by utilizing Transmission Electron Microscopy (TEM) imaging technique. And compared the pictures together.
4. Measured the viscosity under different shear rates and temperatures of 30 and 15 ^{o}C for each of the samples using a rotating DG spindleBrookfield Rheometer.

CHAPTER TWO: LITERITURE REVIEW

2.1 History of nanofluids

Historical evidence has shown that nanoparticles and nanofluids were and initially exploited by the artisans for color and shine effect, apparently no one was aware of their particles size and abnormal properties. Medieval artisans used the gold nanoparticles suspension for coloring the windows glass of cathedral. Also in 15th century, Italian`s potters applied metal nanoparticle in liquid host to make shiny pottery(S. U. Choi, 2009).

Study to develop advanced energy transmission fluids began in 1985 at Argon National Laboratory (ANL). Masuda et al.(Masuda, Ebata, Teramae, & Hishinuma, 1993)firstly, studied thermal conductivity and viscosity influence of ultra fine alumina, titanium dioxide and silicon dioxide in Japan. Following Masuda, Choi(S. U. Choi & Eastman, 1995) came up with the result of enhanced thermal conductivity of colloidal dispersion with nanoparticles which coined them nanofluids. Indeed ANL`s research was the first coherent research in nanofluids and thermal conductivity enhancement; although some parts were in common with Masuda`s work but there were several distinctions between them. Dramatic enhancement of thermal conductivity of nanofluids, reported by previous researchers, attracted the present scientists and commercial investigators to launch an expansion effort on exploration of properties and utilization of nanofluids. The importance and attraction of this area is apparent from compilation report on publication about nanofluids, figure 2-1.

Many scientists and engineer studied nanoparticle production and preparation of nanofluids for experimental and application. Also they investigated effective function on thermal conductivity and viscosity of nanofluids like particle size and volume concentration, temperature, etc. however, researches on viscosity behavior are much less compare to thermal conductivity.

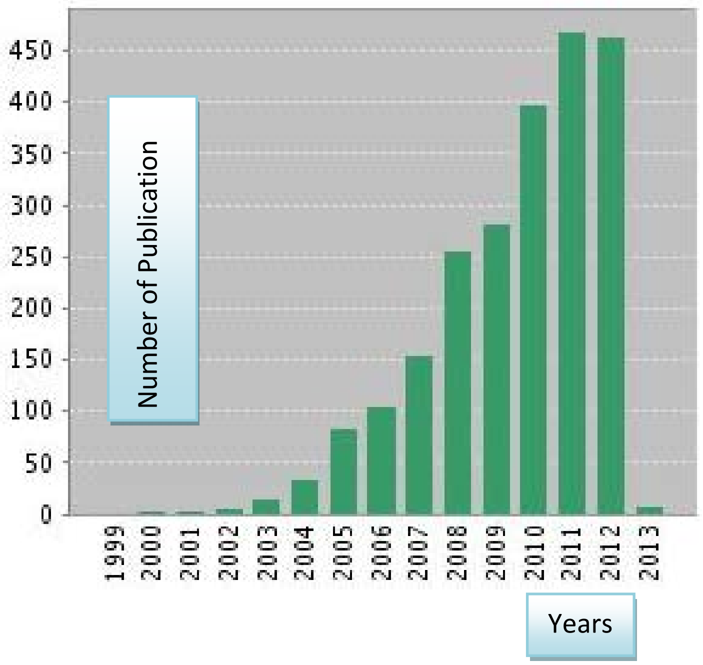

Figure 2-1 Publications in nanofluids (Web of science on Dec 2012)

In this chapter, review and discussion on experimental and basic theoretical activity in synthesis and thermal conductivity are presented.

2.2 Carbon Nanotubes (CNTs)

Carbon nanotubes are allotropes of carbon, structured as long, thin hollow cylinders of carbon. A typical nanotube has the diameter of the order of a nanometer and the length of the order of a few micrometers. They can be thought of as a sheet of graphite (a hexagonal lattice of carbon) rolled into a cylinder. They were discovered in 1991 by S.Iijima(Iijima, 1991). He reported the first observation of multi-walled carbon nanotubes (MWCNT) in carbon-soot made by arc-discharge. About two years later, he made the observation of single-walled nanotubes (SWCNT)(Iijima & Ichihashi, 1993). The basic structural difference between MWCNT and SWCNT is that the former has concentrically nested multiple layers of graphene structures whereas the later has only a single layer of grapheme structure. These intriguing structures have given a very broad range of electronic, thermal, and mechanical properties which have sparked excitement amongst the researchers in recent years. SWCNTs exhibit certain important electric properties whichare not shared by the MWCNTs and thus are more likely candidates for miniaturizingelectronics. One useful application of SWCNTs is in the development of the firstintramolecular field effect transistors (FETs)(Martel et al., 2001). On the other hand, MWCNTs havecertain distinguished mechanical and thermal transport properties which make themsuitable for applications related to structural composites, energy storage and heattransfer. Basic research over the past decade has shown that CNTs could have a thermalconductivity an order of magnitude higher than copper, ~3000 W/m-K for MWCNTs(P. Kim, Shi, Majumdar, & McEuen, 2001) and ~6000W/m-K for SWCNTs(Berber, Kwon, & Tomanek, 2000). This suggests that CNTs have the potential toimprove thermal conductivity of base fluids like water, ethylene glycol, mineral oils,etc., even when added in small quantities. Though based on the figures, SWCNTs have more potential to improve thermal conductivity; however, due to cost advantage and comparatively easy deagglomeration of MWCNTs, they have been studied more in heattransfer applications. The peculiar property of MWCNTs has made researchersinterested all together in an area directed towards heat transfer-based nanotechnologyapplications.

2.3. Preparation of nanofluids

A dominant influence on behavior of nanofluids is governed by the preparation procedure of them. Proper dispersion of nanoparticles in base liquid, stability of suspension, stability of thermal conductivity of nanofluids and durability of nanofluidsare crucial roles for production of nanofluids. Nanoparticles can be produced in two ways, the physical processes that include mechanical grinding method and the inert-gas-condensation technique, and chemical processes that include chemical precipitation, micro-emulsions, chemical vapour deposition, spray pyrolysis, and thermal spraying. Sonochemical synthesis is also able to make suspensions of iron nanoparticles with oleic acid as a dispersant(Q. Yu, Kim, & Ma, 2008).

Generally nanofluids are the suspension of nanoparticles such as metals (Cu, Ag, Au), ceramics (Al2O3, CuO, TiO2, SiC) and also carbon components (Diamond, MWCNT) in proper liquid like water, ethylene glycol and oil, the procedure of mixing nanoparticles with basic liquid are divided in two main techniques: two-step method and one –step method.

2.3.1 Two-step method

Thefirst and classic method of preparing the nanofluids was the two-step method, which was also the most common way for nanofluids synthesis in the last decade. In this method the prepared nanoparticle by physical or chemical methods are dispersed in base liquid. The size of nanoparticles is maintained to prepare different nanofluids with different particle size and having different properties. One of the disadvantages of this method is agglomeration and settlement of nanoparticles in host liquid due to van der Waals bonding effect. Ultrasonication or advanced mechanical mixing devices are used for well dispersion of nanoparticles and reduction of agglomeration effect. Sonication and mixing time should be optimized for obtaining suspension of smaller nanoparticle size, higher stability loading to higher thermal conductivity and also lower viscosity of nanofluids(Tavman & Turgut, 2010) This method has shown a fairly good result for oxide nanoparticles (S. U. Choi, 2009).

2.3.2 One step method

Thismethod is preferable for nanofluids containing metal nanoparticles like copper to prevent nanoparticles from oxidation.With this technique,nanoparticles are formed and dispersed in a fluid ina single process. One step method involving direct evaporationhas been used to prevent nanofluid from agglomeration and produce nanoparticles that remain uniformly dispersed and stably suspendedin base fluids. This technique as shown in figure 2-2 involves condensingnanophase powders from the vapor phase directly into flowinglow-vapor-pressure liquid in a vacuum chamber(Chopkar, Das, & Manna, 2006; Eastman et al., 2001). Thewell-dispersed nanofluids of Cu in ethylene glycol enhance thethermal conductivity of the base fluid by upto 40% at the particlevolume concentration of 0.3 vol. %, significantly larger thanthe prediction of effective medium theory (Wenhua Yu, France, Routbort, & Choi, 2008).

Although the one-step method has producednanofluids in small quantities for research purposes, it is unlikely to become the mainstay of commercial nanofluid production.It would be difficult to scale up for two reasons.Processes that require a vacuum significantly slow the productionof nanoparticles and nanofluids, thus limiting the rate ofproduction. Furthermore, producing nanofluids by onestepphysical processes is expensive.

These two methods are the most regular ways to produce nanofluids but there is still other way for nanofluids production like shape and size control synthesis of Zno that has shown a good potential for controlling nanoparticles (Cao, Cai, & Zeng, 2006).

Recently W.Yu et al. proposed a phase transfer method for kerosene based Fe3O4 nanofluids, which compared to two step technique needs less sonication time. There is no clear relation between particle size and sonication time(W.-Y. Chen & Chen, 2010)

In this work, we would be concentratingon carbon nanotubes dispersed in de-ionized (DI) water based on their optimal thermalproperties as reported by others.

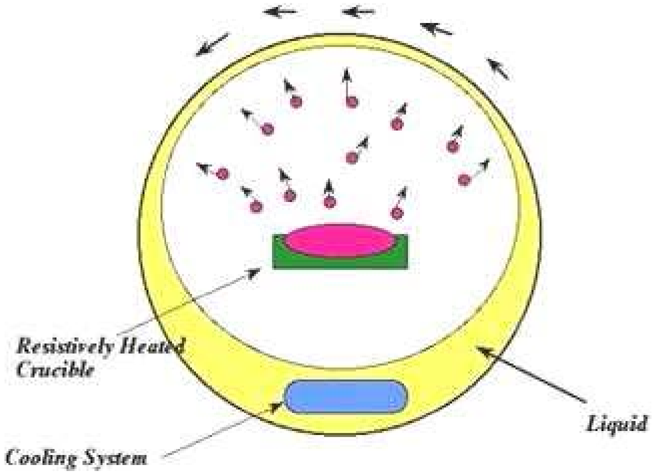

Figure 2-2 Schematic diagram of nanofluid production system designed for direct evaporation of materials into low-vapor-pressure liquids (Eastman et al., 2001)

2.4 preparation of Carbon nanotubes nanofluids(CNTsnanofluids)

Dispersing MWCNT is one of the critical steps in preparing CNTnanofluids inthe base liquids. Due to having aspect ratio and strong Van DerWaal’s forces between carbon surfaces, dispersion of MWCNT`s in base fluids can bechallenging.

The carbon nanotubescannot be dispersed in water under normal conditions, because they are hydrophobic in nature. Even when they are being dispersed, they have a tendency toentangle and form clusters or agglomerates. There are regularly two procedures to disperseCNT`s in base liquids : chemical and mechanical(Hilding, Grulke, George Zhang, & Lockwood, 2003).

Mechanical methodsuch as ultrasonication can separate the nanotubes but if it is not done in a controlledway, it may physically damage the nanotubes by decreasing the corresponding aspectratio. Chemical methods include using surfactants or hydrophilic functional groups(functionalization) to attach onto CNT`s to stabilize them. for this approach, hydrophilic functional groups such as nitric/sulfuric acid mixture, potassium hydroxide group(L. Chen, Xie, Li, & Yu, 2008; Ko et al., 2007). The method changes the wetting or adhesion treatment which helps in decreasingtheir trend to agglomerate. Chemical functionalization generally includes treating theCNTs with acids at high temperature. This results in addition of polar groups like –COOH or – OH at defect sites on nanotube surface, thus making CNTs hydrophilic innature. However, aggressive chemical functionalization, can damage the CNT`s.For the chemical methods to be effective either aggressive chemical functionalization or high concentrations of surfactant need to be used, for example, jiang et al.(Jiang, Gao, & Sun, 2003) reported that the optimum amounts of SDS used to obtain a stable homogeneous suspension of 0.5 wt% CNTs was 2wt%. On the other hand aggressive chemical functionalization can cause defects on CNTs altering their thermal and physical properties. High surfactant concentrations can significantly increase the base fluid viscosity and the interface thermal resistance between the carbon nanotubes, thus, limiting the thermal transport in the nanotubes matrix(L. Chen & Xie, 2010b)

Both chemical andmechanical methods can alter the CNT aspect ratio. It has been reported that thermal conductivity enhancement in CNTnanofluids increases with aspect ratio (Amrollahi, Hamidi, & Rashidi, 2008; Garg et al., 2009;Nasiri et al., 2011), however, proper care still has to be takenduring processing to minimize adverse effects.In this work, a combination of chemicalmethod with surfactants and mechanical method through sonication, is used. Ultrasonication disperses particles by a series of bubblenucleation and collapse events. Ultrasonication can be done either by using an ultrasonicbath or by ultrasonic probe. Ultrasonication of fluids leads to three physical mechanisms:cavitations of the fluid, localized heating, and the formation of free radicals (Hilding et al., 2003). In thecase of CNTs, this phenomenon reduces the nanotube length and reduces their tendencyto entangle, which helps them disperse in a base fluid. However, even the mechanicalmethod is not good enough to form stable suspensions. Through our experimental work,it has been found that nanotubes dispersed by just ultrasonication re-agglomerate andsettle down after few days. This phenomenon results in sedimentation. This is why achemical method involving surfactants is used as it provides milder conditions thanfunctionalization using acids.The surfactant gets adsorbed on the carbon nanotube surface which induces electrostaticrepulsions to counterbalance Van der Waals attractions (Hunter, 1986) between CNTs. Thisprevents the agglomeration of nanotubes under Van der Waal's attractions and thusprovides stable suspensions. Surfactants have been used to disperse carbon nanotubes inseveral cases. Wide range of surfactants such as sodium dodecyl benzene sulfonate (SDBS)(Wen & Ding, 2004), sodium dodecyl sulfate(SDS)(Assael et al., 2004), Nanosperse AQ (Assael et al., 2005), Hexadecyltrimethylammonium bromide (CTAB) (Assael et al., 2005) , Chitosan (Phuoc, Massoudi, & Chen, 2011)and Gum Arabic (GA)(Ding et al., 2006; Garg et al., 2009) have been used.Through past works Cationic surfactants such as hexadecyltrimethylammonium bromide (CTAB), Gemini surfactant (L. Chen & Xie, 2010b), and cationic-onionic mixed surfactant(Madni, Hwang, Park, Choa, & Kim, 2010) have been found to be effective in stabilizing CNTs and various metal particles(G.-y. Li, Jiang, Huang, Ding, & Chen, 2008) with low surfactant concentrations. Because higher concentration of Cationic Gemini give rise to the sediment of MWNTs in the nanofluids, resulting in decrease of thermal conductivity enhancement of MWNTs nanofluids.(L. Chen & Xie, 2010a). another kind of Cationic surfactant called Chitosan, found as an effective stabilizer for dispersing CNTs in water by T.X. Phuoc et al (Phuoc et al., 2011), it is biocompatible and is a natural polymer isolable from crustacean cell.(Hwang et al., 2006) displayed addition of sodium dodecyle sulfate (SDS) can improve the stability of CNT nanoparticles in aqueous suspensions.k. Wusiman et al (Wusiman, Jeong, Tulugan, & Chung, 2012)exhibited that CNT nanofluid with SDBS shows better thermal conductivity than that with SDS dispersant. M. Bystrzejewski et al(Bystrzejewski et al., 2010)studied the suspensions of MWCNT in aqueoussolutions of SDS and SDBS AS two anionic surfactants It was found that bothdispersing agents form stable suspensions of CNTs. The SDBS surfactant has 26–45% higher dispersingpower in comparison to SDS. Also they shown the surfactant structure has also an effect on the diameter distribution of dispersednanotubes. SDBS have increased affinity to the narrower CNTs,whilst nanotubes suspended in SDS solution has the same diameter distribution as pristine CNTs. However Experiments on SDBS at a temperature above 60-70°C showed that the dispersant failed, which led to destabilization of nanofluids(Wen & Ding, 2004).Moreover RajdipBandyopadhyaya et el. used a novel method for achieving the dispersion of nanotubes (Bandyopadhyaya, Nativ-Roth, Regev, & Yerushalmi-Rozen, 2002)The method makes use of physical adsorption of a water soluble polymer called Gum Arabic, which is a natural polysaccharide and produced by Acacia Senegal trees. ithas already been described to be helpful for CNTdispersion (Ding et al., 2006).This method can be used for both SWCNTs and MWCNTs, according to the current and past research, GA was found to be suitable surfactant. However, GA has a tendency to increase viscosity when added in small quantities to a base fluid like DI water. The high viscosity in nanofluids could result in sticking of nanotubes to the walls of the sample bottles and also to the surfaces of measuring instruments. Thus, a highly viscous nanofluid would also result in increase in pumping power for commercial applications. Therefore, it becomes important that the amount added is optimum(Ding et al., 2006).Through previous work and also by repeated experimentsin laboratory, it was found that 0.25 wt % of GA would be suitable,the method of preparation would be discussed in detail in next chapter.

2.5 Thermal conductivityof nanofluids

Heat transfer process can be increased by altering variety of parameters like temperature difference, heat transfer surface area and heat transfer coefficient is flowing fluid. Heat transfer coefficient is mainly represented by function of Nusselt number, and thermal conductivity of fluid. Hence thermal conductivity enhancement of nanofluids became significant in heat transfer development of nanofluids. As previously noted, Argon National Labrotory (ANL) was the pioneer in nanofluids arena.Since then, numerous researches have been launched about thermal conductivity enhancement of metal oxide nanofluidsbut less works have been done on CNTnanofluids. Regarding CNT`s ,reports on thermal conductivity of nanofluids containing CNT`s have not been consistent, this might be due to the differences in the experimental conditions such as carbon nanotube aspect ratios, dispersants used and the approaches used for preparing the experimental nanofluids.

2.5.1Past research on thermal conductivity of carbon nanotubes nanofluids

As the sequence of experiments and exploration of various nanofluids in Argon National Lab (ANL) continued, for the first time a dramatic enhancement of thermal conductivity observed by Choi et al.(S. Choi et al., 2001)for multiwalled carbon nanotubes (MWCNT) dispersed in synthetic poly(α-olefin) oil as a base fluids .they reports nonlinear enhancement of thermal conductivity up to 160% at only 1% volume concentration of Carbon nanotubes in oil. They have also explained the cause of this anomalous enhancement of strangely higher magnitude than theoritical prediction for nanofluids with particle high thermal conductivity (3000 w/mk), size and shape of nanotubes. Subsequently, data was published by Xie et al.(Xie, Lee, Youn, & Choi, 2003)where, enhancements were reported for water, ethylene glycol and decene as base fluids.Assaelet al. (Assael et al., 2004; Assael et al., 2005) data focused on aqueous MWCNT nanofluids with SDS, CTAB andNanosperse AQ as dispersants. However, both these works reported much less enhancements as compared to those reported by Choi et al.(S. Choi et al., 2001). The maximum thermalconductivityenhancement observed by Xie et al. (Xie et al., 2003) was only 20% for 1% nanotubes indecene by volume, andAssael et al.(Assael et al., 2004) observed enhancement of 38%, for 0.6vol% MWCNT`s-water nanofluids,using 0.1 wt% SDS (sodium dodecyl sulfate). In 2004, Wen and Ding (Wen & Ding, 2004) observed 23% and 28% enhancements for 0.84 vol% MWCNT-water nanofluids using SDBS as thedispersant at 20 c ad 40 c respectively. Their results were comparable to Xie et al.(Xie et al., 2003) and Assael et al. (Assael et al., 2004) andproposed differences in the interfacial resistances and thermal conductivities of carbonnanotubes used in these studies as the main reasons for the observed discrepancies withrespect to Choi et al. (S. Choi et al., 2001). Additionally, the base fluid used by Choi et al. was poly-α olefin (a lower thermal conductivity than water), though percentage enhancementreported was high, the absolute enhancement was not as high as expected. As SDBS wasalso found to fail at elevated temperatures(Wen & Ding, 2004), in 2006, another set of data was publishedusing Gum Arabic (GA) as dispersant by Ding et al. (Ding et al., 2006). In this work, thermal conductivity enhancement of 28% and 79%was reported at 25 c and 30 c respectively with 1 wt % MWCNT in water.Thermal conductivitymeasurements revealed that the effective thermal conductivityincreased with increasing temperature and CNTconcentration, with the dependence of the conductivity ontemperature much more significant. The enhancement of thethermal conductivity was slightly higher than that reported byAssael et al.(Assael et al., 2004)Xie et al.,(Xie et al., 2003) and Wen and Ding.(Wen & Ding, 2004)They suggestedthat this discrepancy be associated with the thermal properties ofCNTs used, liquid-CNT interfacial resistance, and the aspect ratioofCNTs used. Furthermore the base liquid used also played a role.

Lately L.Chen and H. Xie(L. Chen & Xie, 2010a)by using Cationic Gemini as a surfactant reported thermal conductivity enhancements of 34.3% and 5.6% at a volume fraction of 0.6% with temperatures of 65 c and 5 c respectively, and shown the temperatures strongly affects on enhancement of thermal conductivity of WMCNT-water nanofluids stabilized by cationic Gemini surfactants ,The enhancement is a bit lower than that published by Ding et al.(Ding et al., 2006). Moreover A. Indhuja et al(Indhuja, KS, Manikandan, & KS, 2013) reported the thermal conductivity enhancements of 8% and 33% at a concentration of 5 wt% with temperatures of 28C and 60C respectively.

To date, most of the published data in MWCNT based nanofluids is focused on thethermal conductivity enhancement with parametric effects of particle volumeconcentration, base fluid, and temperature. Though parametric effects of particle size(Length and diameter)(Amrollahi et al., 2008; Ruan & Jacobi, 2012), dispersant (surfactant)(Assael et al., 2004; Assael et al., 2005; Wen & Ding, 2004)and acidity (Ding et al., 2006) have been considered, only a few papershave been published in this area. As nanotubes are cylindrical in nature and exist asagglomerates, direct particle size characterization using techniques like Dynamic LightScattering (DLS) is difficult for nanotubes.The reason behind thermal conductivity enhancement in carbon nanotube dispersions is still not completely understood. There are many phenomena postulated for the enhancement. Studies have indicated that nanotubes conduct current and heatballistically or in fast diffusive manner (Berber et al., 2000). The ballistic conduction is associated withthe large phonon mean-free path in nanotubes. Hence, nanotubes change the cause ofheat conduction from diffusion in liquids to both fast diffusion and ballistic heatconduction in nanofluids. Furthermore, there is evidence that an organized solid-likestructure of a liquid at the interface is a governing factor in heat conduction from a solidwall to an adjacent liquid(Suzuki, 2000). Therefore, it has been postulated that this organizedsolid/liquid interface structure causes the energy transport across the interface.Additionally, in 2004, Jang and Choi(Jang & Choi, 2004) postulated another theory using Brownianmotion of nanoparticles as a potential factor for increased thermal conductivity ofnanofluids at elevated temperatures. It suggested that as temperature is increased, theviscosity of base fluids is decreased and the Brownian motion of nanoparticles isconsequently increased. It has been postulated that convection like effects are induced byBrownian motion which result in increased conductivities. However, previouslyKeblinski et al.(Keblinski, Phillpot, Choi, & Eastman, 2002) showed that Brownian motion is unlikely to have direct role in theenhancement of thermal conductivity.Several years later Amrollai et al (Amrollahi et al., 2008) explored the effects of ultrasonication time on thermal conductivity and sediment of carbon nanotubes-ethylene glycol nanofluidsand foundstrong dependence of the effective thermal conductivity ontemperature and volume fraction of CNT nanofluids. The Thermal conductivity increased with passed ultrasonication time. Brownianmotion and the inter-particle potential, which influences the particle motion, were proposed to account for the phenomenon. Yang et al. (Yang, Grulke, Zhang, & Wu, 2006) explored the sonication energy/time impact on thermal conductivity of nanotube-oil suspensions and observed a decreased thermal conductivity with an increasing sonication energy/time.In the following Garg et al.(Garg et al., 2009) published the effect of ultrasonicationenergy on the thermal conductivity and viscosity of MWCNT-water nanofluids dispersed using gum arabic. An optimumultrasonication energy (or sonication time) was found to existthat would be sufficient to achieve nanotubes' dispersion, withoutcausing breakage of nanotubes.A thermal conductivity enhancement of 20% was observed for 1 wt% MWCNT-water nanofluids atthe optimum ultrasonication energy of 113 J/g (40 min sonication time)

newly Ruan and Jacobi(Ruan & Jacobi, 2012) proved the thermal conductivity of MWCNT-ethylene glycol nanofluids increases nonlinearly when sonication time/energy increases, and achieved the maximum thermal conductivity enhancement of 23% at a concentration of 0.5 wt% with elapsed 1355 minutes sonication time.In addition they observed that the processes of sonication reduced both the agglomerate sizes and the length of carbon nanotubes. But the agglomerate size reduction is more important than the Length reduction. In spite of these researches and experiments it can be foundthat stabilization by Ultrasonicationis a usual way to break up the agglomerates and promote dispersion of nanoparticles into base fluids. However there are limited research reports about sonication effects on Carbon nanotubes nanofluid properties in the open literature.

Table 3-1 presents a summary of data for thermal conductivity comparison of CNT`s nanofluids. Particle volume concentration, particle size, thermal conductivity results, base liquid difference, and the surfactant used have been presented.

Researcher/year/reference	particle	Base fluid	Average Particle size	concentration (vol% or Wt%)	thermal conductivity enhancement	Note
choi et al. (S. Choi et al., 2001)	MWCNT	Oil	25nm*50μm	1 Vol%	150%	-
Xie et al.(Xie et al., 2003)	MWCNT	Decene/ethylene glycole/water	D=15nm L=30μm	1 Vol%	20%/13%/7%	-
Assael et al.(Assael et al., 2004)	MWCNT	(+SDS)-Water	100nm*70μm	0.6 Vol%	38%	-
Xie et al.(Xie et al., 2003)	MWCNT	Water	15*30000	0.4-1 Vol%	1.03-1.07 (Ratio)	Two-step Method
Xie et al.(Xie et al., 2003)	MWCNT	ethylene glycole	15*30000	0.23-1 Vol%	1.02-1.13 (Ratio)	Nitric acid treatment
Xie et al.(Xie et al., 2003)	MWCNT	(+Oleylamine)-decene	15*30000	0.25-1 vol%	1.04-1.20 (Ratio)	-
Wen and Ding (2004)(Wen & Ding, 2004)	MWCNT	(+ sodium dodecyl benzene)- water (20◦C)	20–60 (diameter)	0.04–0.84 Vol%	1.04–1.24	Two-step method
Wen and Ding (2004)(Wen & Ding, 2004)	MWCNT	(+ sodium dodecyl benzene)-water (45◦C)	20–60 (diameter)	0.04–0.84 Vol%	1.05–1.31	Temperature effect
Assael et al. (2005)(Assael et al., 2005)	MWCNT	(+ Nanosperse AQ)- water (40-60) min	L 10μm OD 100-250	0.6 Vol%	1.28-1.27	Sonication time effect
Assael et al. (2005) (Assael et al., 2005)	MWCNT	(+ hexadecyltrimethyl ammonium bromide(CTAB))- water 10 min	L 10μm OD 100-250	0.6 Vol%	1.34 34%	Sonication time effect

Assael et al.(2005)(Assael et al., 2005)	DWCNT	(+ hexadecyltrimethylammonium bromide(CTAB))-water	5 nm (diameter)	1.00 Vol%	1.08	Dispersant effect
Assael et al. (2005) (Assael et al., 2005)	DWCNT	(+ hexadecyltrimethyl ammonium bromide(CTAB))-water	5 nm (diameter)	0.75 Vol%	1.03	Two-step method
Liu et al. (2005)(M.-S. Liu et al., 2005)	MWCNT	ethylene glycol	20–50 (diameter)	0.20–1.00 (1 vol.%)	1.02–1.12 (12.4%)	Two-step method
Liu et al. (2005)(M.-S. Liu et al., 2005)	MWCNT	(+ N-hydroxysuccinimide)-engine oil	20–50 (diameter)	1.00–2.00 (2 vol.%)	1.09–1.30 (30%)	Two-step Method
Marquis and Chibante(2005)(Marquis & Chibante, 2005)	SWCNT	(+ dispersant)-diesel oil (Shell Rotella 15W-40)	(10–50) × (0.3–10 μm)	0.25–1.00	1.10–1.46	Two-step Method
Ding et al. (2006)(Ding et al., 2006)	MWCNT	(+ gum arabic)-water (20◦C)		0.05–0.49	1.00–1.10	Two-step method
Ding et al. (2006)(Ding et al., 2006)	MWCNT	(+ gum arabic)-water (25◦C)		0.05–0.49	1.07–1.27	Temperature effect
Ding et al. (2006)(Ding et al., 2006)	MWCNT	(+ gum arabic)-water (30◦C)		0.05–0.49	1.18–1.8	Temperature effect
Hwang et al. (2006)(Hwang et al., 2006)	MWCNT	mineral oil		0.5	1.09	-

Yang et al. (2006)(Yang et al., 2006)	MWCNT	(+ polyisobutene succinimide)-polyalphaolefin		0.04–0.34	1.06–3.00	Two-step method
P.Garg et al. (2009)(Garg et al., 2009)	MWCNT	(+ gum arabic)-water 40 min Ultrasonication (35◦C)	OD 10-20 nm L 0.5-40 µm	1 wt%	20%	Ultrasonication effect
L.Chen, H. Xie 2010 (L. Chen & Xie, 2010a)	MWCNT	(+Cationic gemini)-water (5◦C-65◦C)	OD 30-50 nm L ~ 20 µm	0.6 Vol%	5.6%-34%	Temperature effect
T.X.Phuoc et al. (2011)(Phuoc et al., 2011)	MWCNT	(+ Chitosan)-water (35◦C)	OD 20-30nm ID 5-10nm L 10-30 µm	(0.5-3) wt% (0.24-1.43) Vol%	2.3%-13%	Two-step Method
N.Singh et al. (2012)(Singh, Chand, & Kanagaraj, 2012)	MWCNT	ethylene glycol+water	D 60-30 nm L 5-15µm	0.4 wt%	72%	Nitric and sulfuric acid treatment
V.Kumaresan,R.Velraj (2012) (Kumaresan & Velraj, 2012)	MWCNT	(+SDBS)-ethylene glycol+water (40◦C)	D 30-50 nm L 10-20 µm	0.45 Vol%	19.75%	effect of different temprature
W.Rashmi et al. (2010)(Rashmi et al., 2011)	MWCNT	(+ gum arabic)-water (25, 40, 60) ◦C	OD 20 nm L 30µm	0.01-0.1 wt%	1.5-2 1.4-1.75 1.25-1.6	surfectant concentration and temprature effect

A. Indhuja et al.(2013)(Indhuja et al., 2013)	MWCNT	(+ gum arabic)-water	ID 10 nm L 5-15 µm	(0.14-0.24) Vol%	0.61-0.67 (3.2%-10%)	effect of different mwcnt concentration
A. Indhuja et al.(2013)(Indhuja et al., 2013)	MWCNT	(+ gum arabic)- water(28-60 ◦C)	ID 10 nm L 5-15 µm	0.5 wt%	0.66-0.93 (8%-33%)	effect of different temprature
A. Indhuja et al.(2013)(Indhuja et al., 2013)	MWCNT	(+ gum arabic)- water(28-60 ◦C)	ID 10 nm L 5-15 µm	0.3 wt%	0.63-0.88 (5%-26%)	effect of different temprature
A.Amrollahi et al.2008(Amrollahi et al., 2008)	MWCNT	Ethylene Glycol (25-50 ◦C)	OD 1-4 ID 0.8-1.1	2.5 vol%	20 %	Temperature Effect
A.Amrollahi et al.2008(Amrollahi et al., 2008)	MWCNT	Ethylene Glycol 1-24 hrsUltrasonication	OD 1-4 ID 0.8-1.1	0.5vol% 2.5 vol%	1.05-1.2 1.1-1.32	Ultrasonication effect
Ruan and Jacobi.2012(Ruan & Jacobi, 2012)	MWCNT	Ethylene Glycol 1355 mins	OD 10-30 L 10-30 ID 5-10	0.5 wt%	23%	Ultrasonication effect

Table 3-1 summary of data for thermal conductivity comparison of CNT`s nanofluids

2.6 viscosity of carbon nanotubes nanofluids

Viscosity, dynamic property of fluids is used for calculation of pumping power in heat transfer system and plays a significant role in application of fluids. In industry, anoptimization is required between heat transfer capability and the viscosity as it has adirect bearing on the sizing of the flow and heat transfer equipment required. As nanofluids are involved, to enhance the efficiency of system by increasing the thermal conductivity and in fact heat transfer of flowing fluid. Effect of any negative parameter on efficiency must be retarded; therefore, viscosity of nanofluids is taken under investigation to assess the efficiency of nanofluids.Experimental data for the effective viscosity of aqueous nanofluids are much limited than that of thermal conductivity. Also current studies in viscosity of CNT`s Nanofluids(Ding et al., 2006; Garg et al., 2009; Phuoc et al., 2011) are much less than metal oxide nanoparticlesnanofluids.The parameters against which viscosity was studiedwere particle volume concentration, temperature and shear rate. These studies reveal that aqueous CNT Nanofluids behave as non-Newtonian shear-thinning fluids. Additionally understanding flow behavior of carbon nanotube(CNT) nanofluids by developing Mathematical viscosity models is an important area for taking the research into the nextPhase. However, a few empirical and accurate analytical models for prediction of the viscosityof high aspect ratio nanofluids(Ding et al., 2006)are available.The works are mainlyfocused on spherical nanoparticles of metal oxides, and have their basis from Einsteintheory. In case of CNT nanofluids, such models cannot correlate the experimentaldata well because the shape of CNTs does not satisfy previous assumptions. It is difficultto do particle size characterizations for CNTs and subsequently incorporate thosecharacterizations in the Einstein viscosity model (Equation 2-1).

$\mu_e = (1+ 2.5\nu_p)\mu_m$ (2-1)

Where, $\mu_m,\nu_p,\mu_e,$and are viscosity of the base fluid, particle volume fraction inthe dispersion, andeffective viscosity of the dispersion respectively.Aqueous CNT nanofluids have shown to exhibit shear thinning or pseudoplastic type ofnon-Newtonian behavior(Ding et al., 2006). However, there is a few works has been done in correlating thisbehavior to theoretical non-Newtonian viscosity models(Ding et al., 2006). The theoretical models provideequations to correlate shear stress of a flowing fluid to shear rate. This could help inclassifying the flow behavior of a new nanofluid under the already studied behavior offluids, and thus help in directing future rheological studies. The widely used models fornon-Newtonian flow are Power Law (Eq 2.2) and Herschel Bulkley (Equation 2-3).

$\tau = K.\gamma$^ n (2-2)

$\tau =\tau$ '+K.γ^ n (2-3)

Where τ,K,γ&,τ ' and n are shear stress, flow consistency index, shear rate, yield shearstress and flow behavior index, respectively. The value of parameters ‘K’ and ‘n’ signifythe flow behavior in quantitative and qualitative terms respectively. A high value of ‘K’is attributed to high viscous behavior and a low value of ‘n’ is attributed to high degree of non-Newtonian behavior of the fluid. Additionally, a few work has been done in studying the effect of processing orultrasonication time and Tempereture(Garg et al., 2009)on the viscosity of MWCNT aqueous suspensions or nanofluids.Experimental work in this area could provide impetus to theoretical model developmentfor CNT nanofluids. In this work, an effort has been made to study this effect andsubsequently fitting the experimental data in the form of a shear stress- shear ratemathematical equation.

CHAPTER THREE: METHODOLOGY

This section explains the objectives, the description of the experimental set-ups used tomeasure viscosity and thermal conductivity of thesamples, and the steps involved in the preparation of aqueous suspensions of MWCNT.

3.1 Set-up description

This section describes the working principle involved behind each of the experimentalset-ups used for preparing sample and measuring viscosity, thermal conductivity

3.1.1Ultrasonication probe

The ultrasonic processor used for sample preparation was 130 watts, 20 kHz ultrasonication probe from Sonics & Materials, Inc. According to the operator's manual of the instrument, the processor's power supply converts 60 Hz line voltage to a highfrequency electrical energy. The high frequency electrical energy is changed intomechanical vibrations through a piezoelectric transducer. The vibrations when beingtransmitted through the probe are further intensified and create pressure waves in theliquid sample. The induction of pressure waves forms several microscopic bubblesinside the sample, which expand during negative pressure excursion and implodeviolently during the positive excursion. As the bubbles implode, they cause severalshock waves and eddies that radiate outwardly from the site of collapse, and alsogenerate extremes in pressures and temperatures at the implosion sites.

Although thisphenomenon, known as cavitation, lasts few microseconds, and the amount of energyreleased by each individual bubble is minimal, however, the cumulative amount ofenergy generated is extremely high. See Figure 3-1 for the set-up picture.

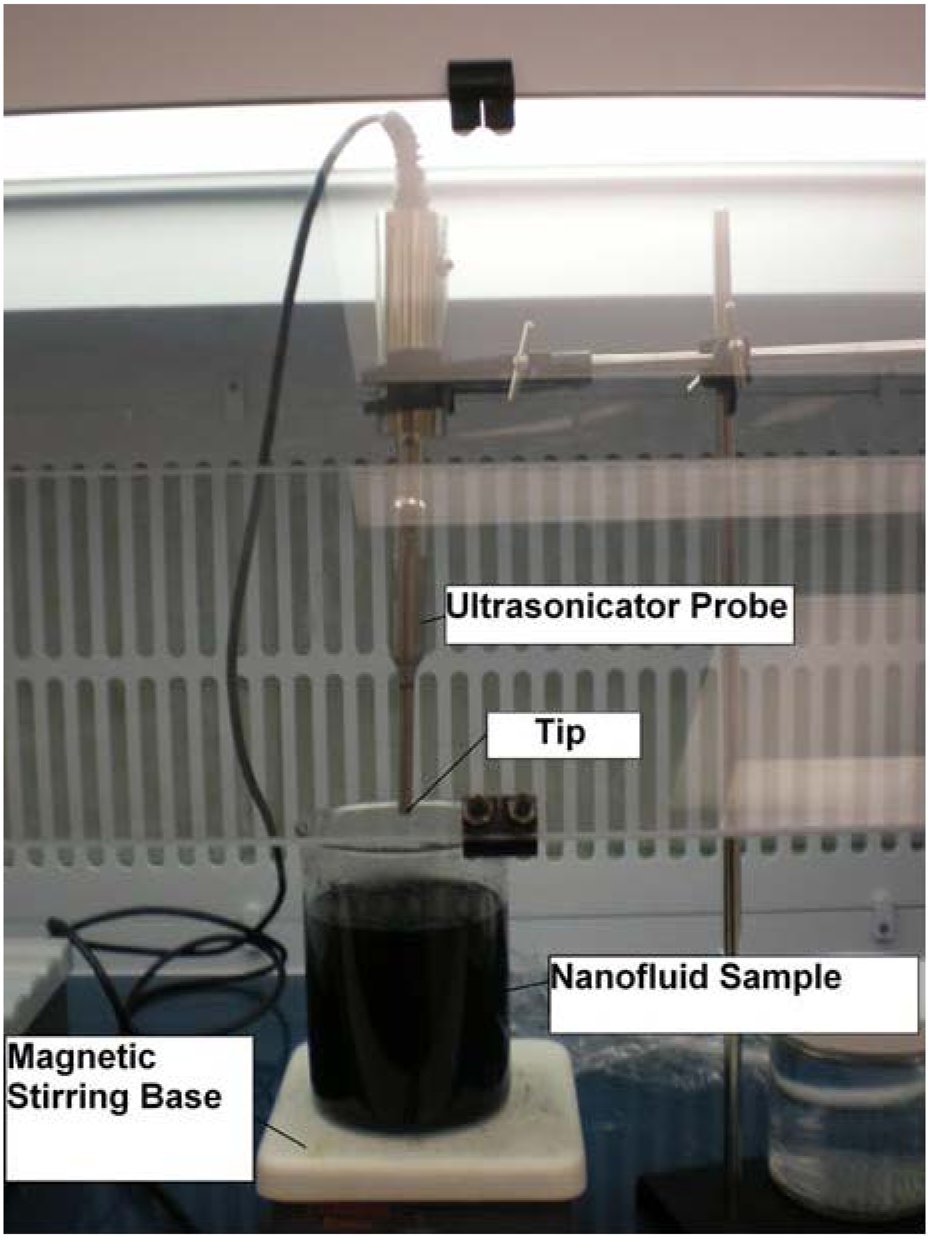

Figure 3-1 Ultrasonication processor

(Powder Lab.)

3.1.2 Viscometer

The viscometer used was from Brookfield Engineering Laboratories, Inc. It was of therotational variety. According to the operator’s manual of the instrument, the instrumentmeasures the torque required to rotate an immersed element (the spindle) in a fluid. Thespindle is driven by a motor through a calibrated spring; deflection of the spring isconverted internally through a set of formulae to display the dynamic viscosity incentipoises (cP). By utilizing a multiple speeds and different spindles, a variety ofviscosity ranges can be measured. For a given viscosity, the viscous drag (indicated bythe degree to which the spring winds up), is proportional to the spindle’s speed ofrotation and is related to the spindle’s size and shape. The drag will increase as thespindle size and/or rotational speed increase. It follows that for a given spindle geometryand speed, an increase in viscosity will be indicated by an increase in deflection of thespring. Measurements made using the same spindle at different speeds are used to detectand evaluate rheological properties of the test samples. The model used in the laboratorywas meant for low viscosity fluids and had a maximum torque rating of 0.06737 milliNewton-m. The instrument had a specified accuracy of ± 1%, which was verified usinga Brookfield’s standard viscosity test fluid. A combination of cylindrical samplecontainer and spindle called as UL Adapter was used for the measurements. The ULAdapter is an attachment provided with the instrument for taking measurements on lowviscosity test samples. See Figure3-2 for the set-up picture.

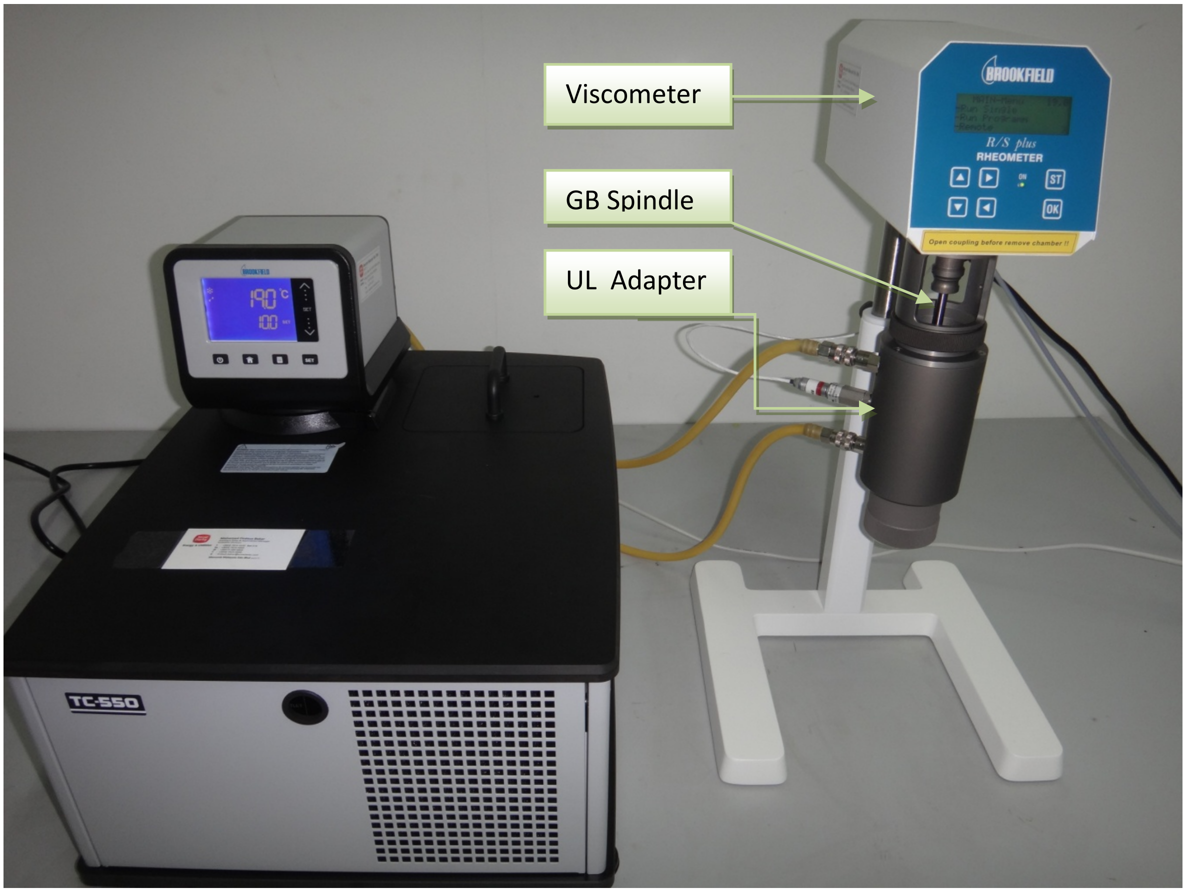

Figure 3-2 viscosity measurements set up

(Heat Transfer Lab.)

3.1.4. Thermal conductivity analyzer

Thermal conductivity is defined as the ability to conduct the heat in materials. Different experimental methods have been developed for the thermal conductivity measurement which may be divided in two main categories: steady state and unsteady state (transient) techniques.

Steady state technique are directly based on integrated form of Fourier`s law that utilize steady conduction in a fluid sample of a specified geometry. The steady state methods have certain merits, which is to ease the equipment design and make use of simple and reliable equations. Unsteady or transient techniques are a time dependent method that performs a measurement during the process of heating up, so the measurement can be conducted relatively quickly, for example transient hot wire method. Transient hot wire (THW) method is well established as the most accurate, reliable and robust technique. In this method a thin metallic wire is used as both a line heat source and a temperature sensor.

It is called transient because heat is supplied suddenly, so that eventually the wire gets heated. It replaces the steady state methods, because of the difficulty to determine the steady state conditions and for fluids the difficulty in preventing the incident of natural convection and consequently the difficulty in eliminating the natural convection effects on the heat flux. The working equation is based on a specific solution of Fourier`s Law for radial transient heat conduction with a line heat source at the axis of the cylindrical domain. Where, q (W/m) is the heat released per unit time per unit length of the line source and k (W/m.K) is the thermal conductivity of sample. If temperatures T_1 and $T_2$of the heat source at time t_1 and t_2, then thermal conductivity of liquid is:

$$K=\frac{q}{4\pi(T_2-T_1)}\ln\frac{t_2}{t_1}$$

In this study thermal conductivity of nanofluids has been measured by KD2 Pro (Decagon, USA), the instrument was basedon the working principle of a transient hot wire method used in past works(Alloush, Gosney, & Wakeham, 1982; Assael et al., 2004; Assael et al., 2005; Ding et al., 2006).KD2 Pro Instrument (figure 3-3) used for thermal conductivity measurement has the instrument accuracy of about 5%. Single needle sensor are also (1.3

mm diameter × 60 mm long) used for thermal conductivity measurement. The needle installed in the package of water jacket connected to the water bath for temperature stability and precise measurement. Thermal conductivity is estimated from temperature responses of thermocouple caused by electrical signals. The total time for measurement of thermal conductivity is about 90 seconds. The first 30 seconds is to ensure the temperature stability. The second and third 30 seconds intervals all are for heating and cooling the probe respectively. In the present study, initial checking of the KD2 Pro is done by measuring the thermal conductivity of base liquids and then checks with reference for comparison and finding the accuracy of the system.It is also necessary to measure thermal conductivity of base liquid for thermal conductivity ratio calculation. After measuring thermal conductivity of base liquid at selected temperature, thermal conductivity of nanofluids up to 0.5wt% was measured.

Temperature effect on thermal conductivity of nanofluids was investigated for all samples, for exploring both higher and lower room temperature effects on nanofluids thermal conductivity. Water bath (made by WiseCircu, Refrigerated circulators) with 0.1 ^{o}C accuracy was used for stabilizing temperature at 20, 25, 30, 35, 40, 45^{o}C for measuring the thermal conductivity of nanofluids in various concentrations. In this case nanofluids are poured into water jacket as a container and temperatures are maintained to obtain stabilized nanofluids, Figure 3-3 presented the set-up including the KD2 Pro and jacketed beaker connected to the Circulating Water Bath water bath with an inlet and an outlet attachments for flowing and circulating water at specific temperature to stabilize the temperature of the nanofluids.

See Figure 3-3 for the set-up picture.

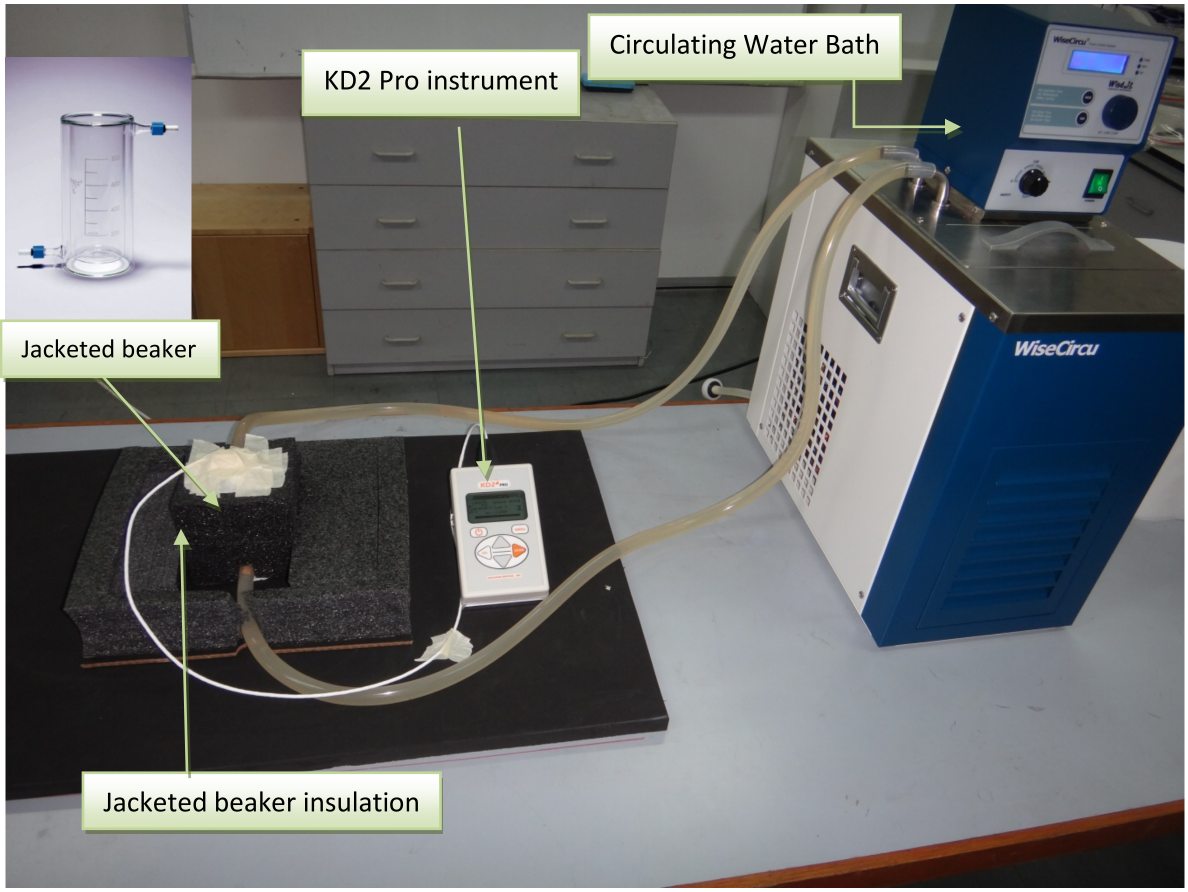

Figure 3-3 Set-up for thermal conductivity measurements set up.

(HeatTaransfer Lab)

3.2 Sample preparation

De-ionized (DI) water, Gum Arabic (GA) and multi-walled carbon nanotubes(MWCNT) were used to produce the aqueous suspensions. The nanotubes were providedfrom

Nanostructured& Amorphous Materials, Inc, USA. Properties of Multi-walled carbon nanotubes employed in this study are showed in Table 3-1.

	Outside Diameter,OD (nm)	Length, L (um)	Density, µ(g/cm3)	Purity(%)	Thermal conductivity, k (w/m2.k) at 300 K	Specific surface area, SSA (m2/g)
sample (MWCNT	20-30	10-30	~2.1	> 95	2800	110-130

Table 3-1 Properties of Multi-walled carbon nanotubes

The nanotubes produced by chemical vapor deposition (CVD) process.Figure 3-4showedTEM images of MWCNT as received. It can be seen that the nanotubes without treatment are not only entangled but also some are in format of agglomerates.

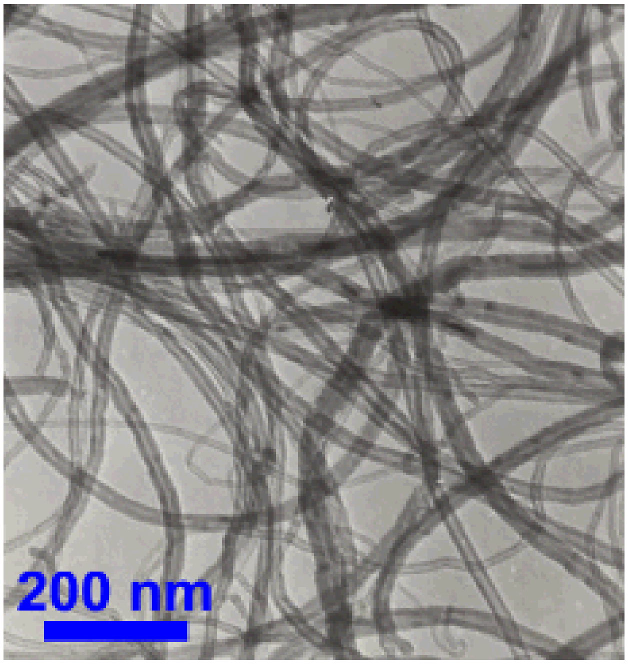

Figure 3-4 TEM Multi-walled Carbon nanotubes (MWCNT) images as received

Gum Arabic was purchased from Sigma-Aldrich Co. Malaysia. The properties of Distilled water have been presented in table 3-2.

Medium	Density (g/ml)	Thermal conductivity (w/m2.k) at 25 oC	Viscosity (mPa.s) at 20 Oc	Boiling point (oC)	Melting Point (Oc)	Specific heat (J/Kg.K)
Water	0.997	0.58	1	100	0	4179

Table 3-2 properties of Distilled-water

Since the surface of the Multi-walled carbon nanotubes is hydrophobic and Water is a polar liquid, Gum Arabic (GA), Sodium dodecylbenzenesulfonate (SDBS) and Sodium dodecyl sulfate (SDS) were used as a dispersants in order to disperse the CNT`s in the Distilled water. The required amount of base fluid was purred in a 100 ml glass beaker,by adding 0.25 and 0.5 wt% SDBS and SDS, and just 0.25 wt% GA respectively into the base fluid (distilled water), dispersed by using magnetic stirring, (Since the GA concentration of 25 wt% used in the literature proven to be optimum amount for preparing stable and high thermal performance water-MWCNT`s nanofluids(Ding et al., 2006), same concentrationis considered in this study) after the surfactants were fully dissolved and a homogenous solutions were achieved, 0.5 wt% MWCNT`s was added to the fluids, using an ultrasonicationprobe, each solutionultrasonicated for five minutes at 100% amplitude, till a homogeneous suspensions was achieved, it was pursued of magnetic stirring by 5 minutes. The magnetic stirring and sonication processes were substituting every 5 minutes until the desired time had been obtained for sonicating samples. Consequently by studying on thermal performance of all nanofluids dispersed by different dispersant, the superior surfactant will be considered for experiments to obtain best results.The sample preparation set-up is shown in Figure 3-5

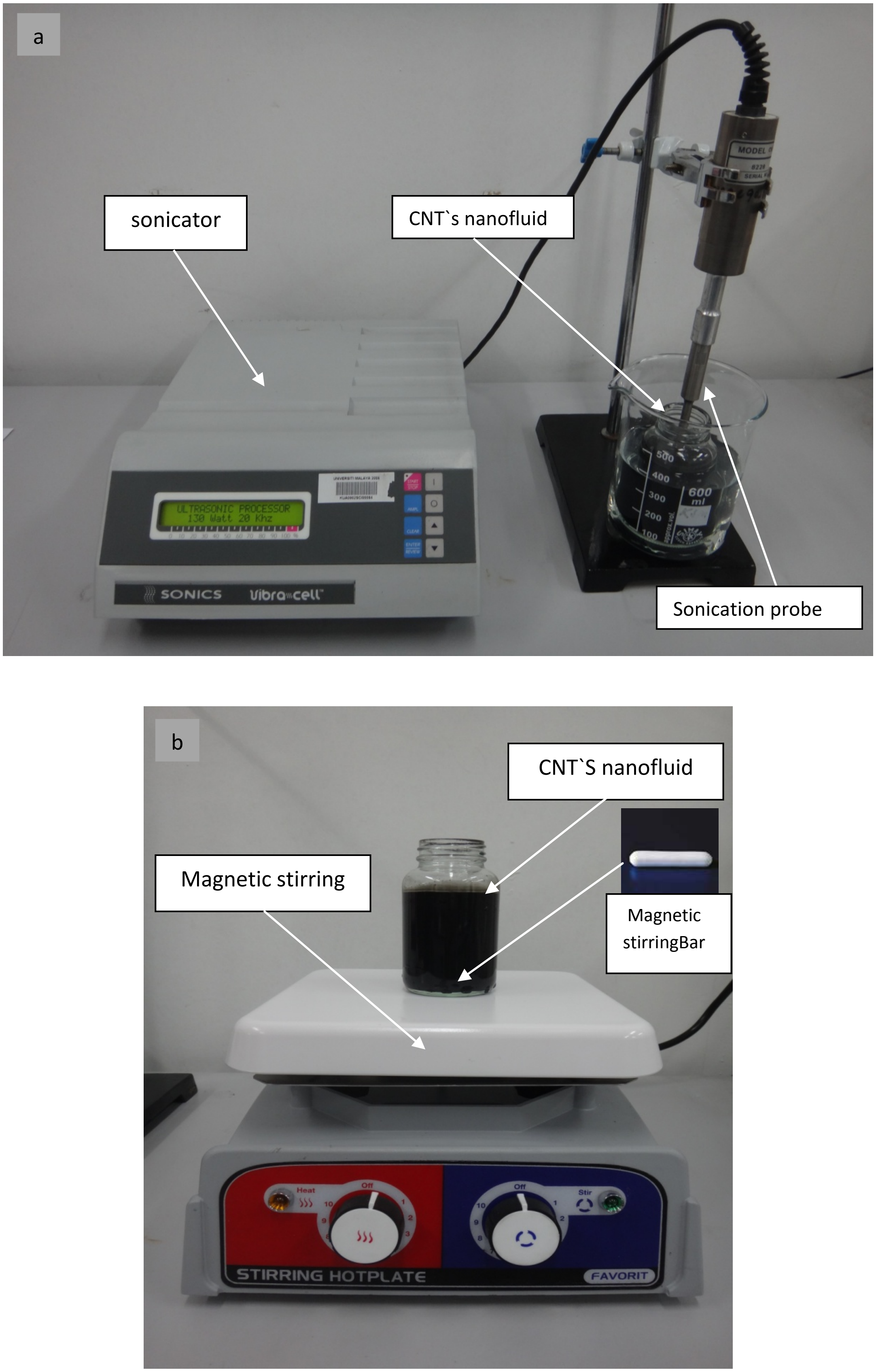

Figure 3-5 nanofluids preparation set-up: (a) Ultrasonication; (b) magnetic stirring

By using this technique the prepared samples were observed to be stable with no settling or sedimentation over 10 days, Figure 3-6 shown a homogeneous dispersion forthe sampleswhich dispersed by GA as a surfactant.

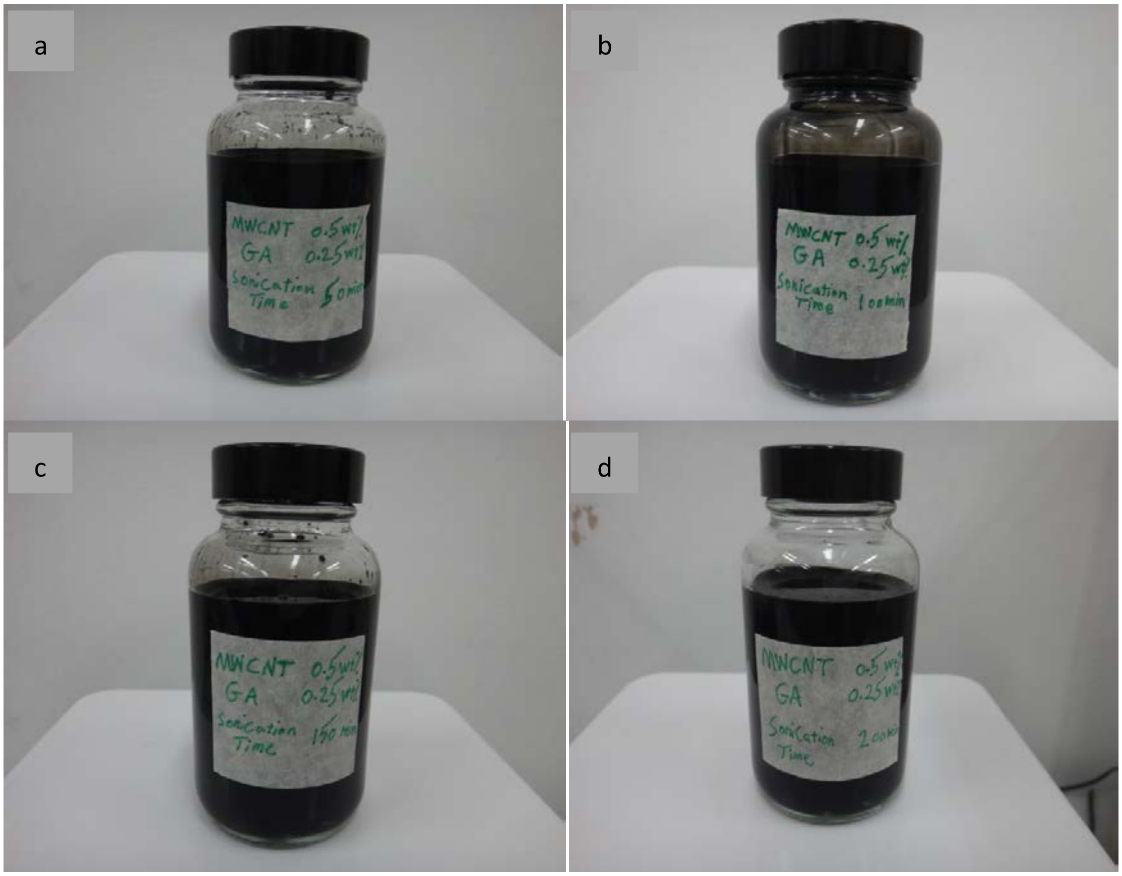

Figure 3.6 Vials including 0.5 wt % of MWCNT`s disspersed in distilled water after 2 weeks and different ultrasonication times: (a) 50 minutes; (b) 100 minutes; (c) 150 minutes; (d) 200 minutes.

3.3 Brief of experiments

Table 3-3 presented the brief of experimental research carried out on the samples

Imaging	**viscosity measurements**	**Thermal Conductivity measurements**
Imaging of samples by using TEM technique	Temperatures of 30 °C and 15 °C at variable shear rates	Temperature range of 20 to 45 °C with step size of 5 °C

Table 3.3 Experiments list

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter presents the data obtained from thermalconductivity and viscosity measurements, and discussesthese results in context of fundamental theory and past research.

4.1. Imaging data

Figures 4-1 to 4-4 show the pictures of Samples 1,2,3, and 4 which ultrasonicatedfor 50,100,150 and 200 minutes respectively as described in chapter 3 at a scale of 500 nm, using TEM technique.

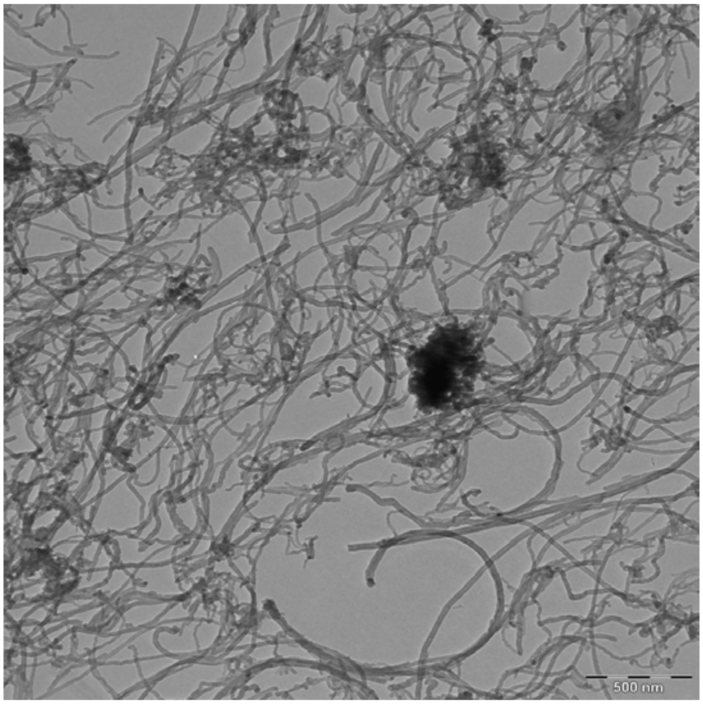

Figure 4-1 TEM image of Sample 1 at 500 nm scale. (50 min sonication, 0.5 wt % MWCNT, 0.25 wt % GA)

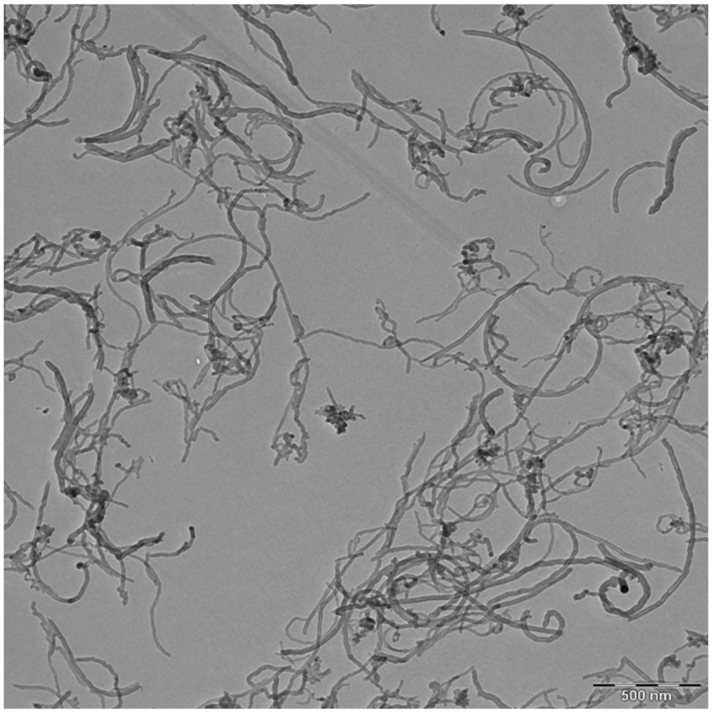

Figure 4.2 TEM image of Sample 2 at 500 nm scale. (100 min sonication, 0.5 wt % MWCNT, 0.25 wt % GA)

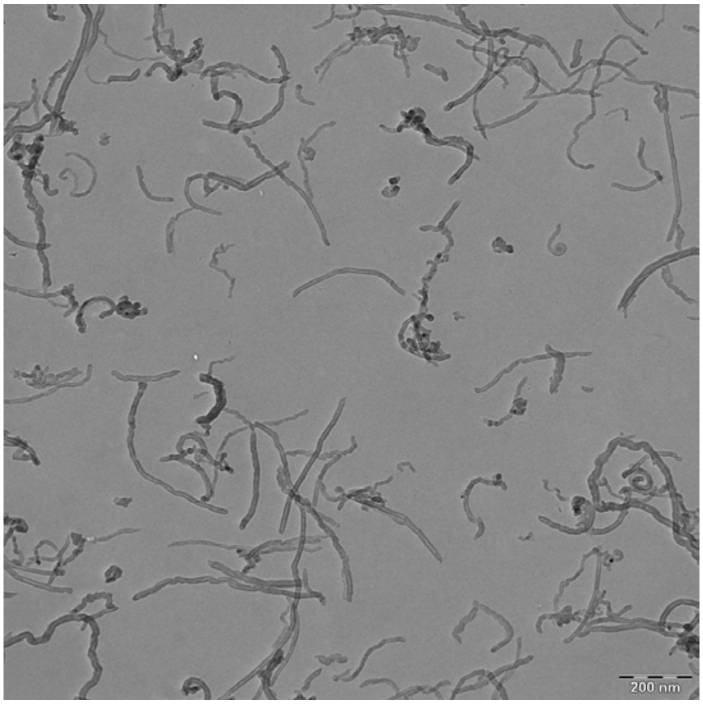

Figure 4.3 TEM image of Sample 3 at 500 nm scale. (150 min sonication, 0.5 wt % MWCNT, 0.25 wt % GA)

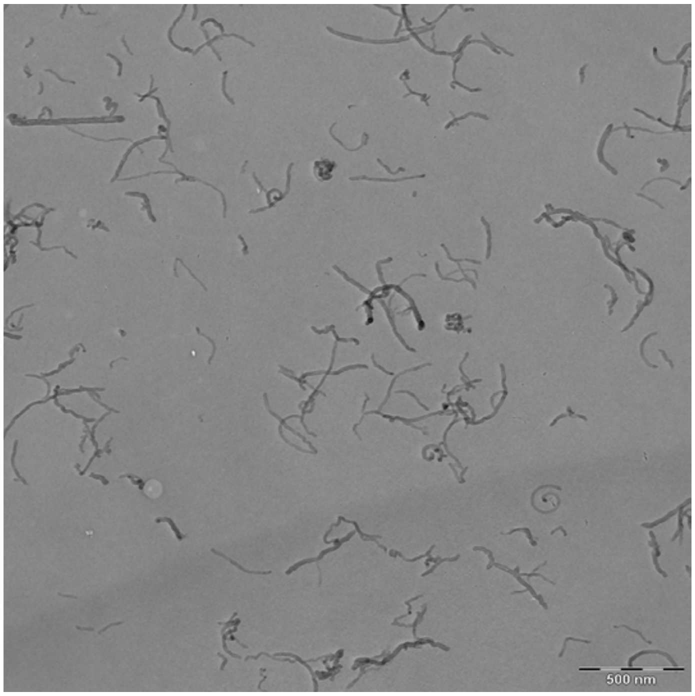

Figure 4.4 TEM image of Sample 4 at 500 nm scale. (200 min sonication, 0.5 wt % MWCNT, 0.25 wt % GA)

From Figure 4-1, it can be seen that Sample 1 exhibits a united cluster of carbon nanotubes. In contrast, from Figures 4-2, 4-3 and 4-4 , the nanotubes are freely placed without a uniform clusters structure which broken into pieces, this observation can be attributed to more ultrasonic processing in case of Samples 2, 3 and 4.

This can be further explained in more detail by comparing Samples 1 to 4. The figures show the formation of aggregates in the nanofluid since the nanofluidprepared, and by increasing the sonication time the aggregates size decreases, so it causes the length of the carbon nanotubes is also reduced. Comparing sample 4 & 1observed also from the figures that the length of the nanotubes has been reduced in Sample 4 as compared to Sample 1, therefore a decline in length lead to reduction in aspect ratio of carbon nanotube.This phenomenon is generally consistent with Pohl et al.(Jang & Choi, 2004), the length of the carbon nanotubes can be expressed as a function of the sonication specific energy E_v(sonication energy per unit volume):

$$L = AE_v^m$$

Where L is the length of the carbon nanotube, and A and m are constant. Yang et al.(Yang et al., 2006) recommended an alternate form of (equation 1), when the specific energy input is stable and the volume of dispersion is constant:

$$L = Bt^n$$

Where B and n are constants and t is sonication time. The value of n was measured -0.2742 by Yang et al.(Yang et al., 2006).

The imaging result would be correlated to the thermo-physical properties of each sample in following parts of this chapter.

4.2 Thermal conductivity Results

4.2.1 Base liquid

In order to establish the reliability and accuracy of our Thermal conductivity measurement set-up, thermal conductivity of base liquid (water)depending on temperature is measured and compared with the ASHRAE data (Wessel, 2001). Figure 4-1 shows the deviation of water thermal conductivity measurements in comparison with ASHRAE data(Wessel, 2001). Experimental results are showing a good agreement with reference data. All the measurements for DW Water were found to be within 1.9 % of the ASHRAE values. The specified accuracy of the Instrument was 5 %.This graph significantly verified the reliability of our subsequent waterbase nanofluid results. Based on Figure 4-1, thermal conductivity increases with rise of temperature in water base liquid.

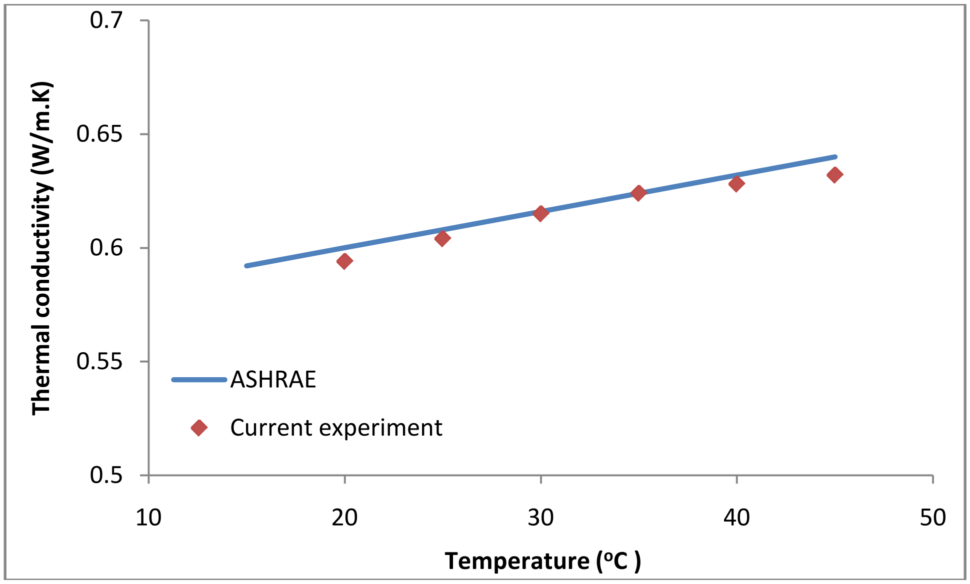

Figure 4.1 Benchmark test for water thermal conductivity

4.2.2Base fluid Data reproducibility

Thermal conductivity measurement has shown a very well data reproducibility, which shows high reliability of KD2 Pro device and environmental stability at working temperature range(20 to 45^{o}C). Figure 4-2 depicts thermal conductivity reproducibility for water. Comparison between first and second measurements shows maximum 1.4% error at 40 and 45^{o}C. It can be obtained that thermal conductivity measurement accuracy reduces with rising temperature. Average value of first and second data has been used for further experiments.

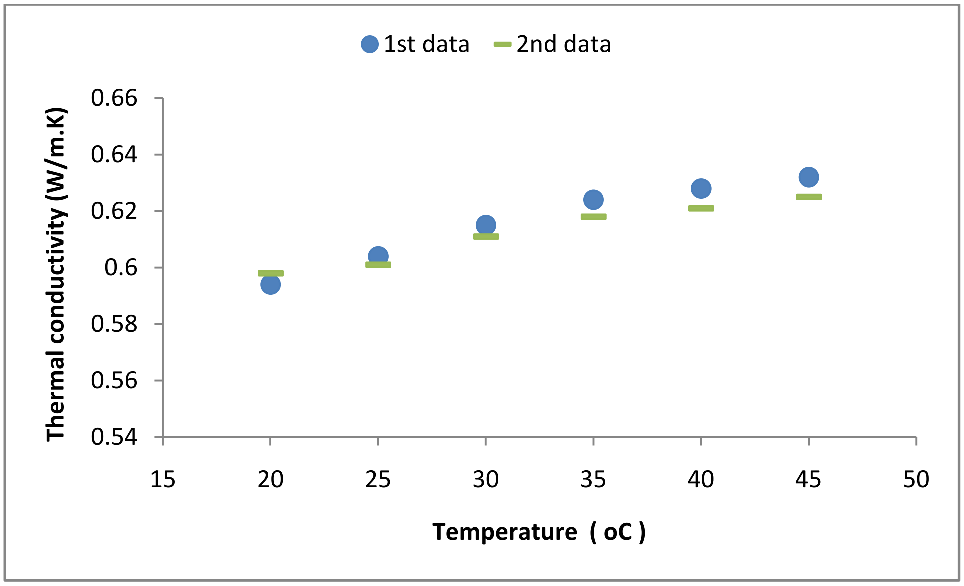

Figure 4.2 Data reproducibility for water as a function of temperature

4.2.3 SDBS, SDS and Gum Arabic dispersed in base fluid

In order to further understand how the surfactants influencenanofluid and distinguish which of the three is superior to the other inaqueous CNT suspensions, it is very necessary to investigate how the surfactantsaffect on thermal conductivity in their base fluid DW. Thus 0.25 wt% of each Gum Arabic, SDBS and SDS in addition 0.5 wt% of SDBS and SDS are dispersed in DWand thermal conductivities of these solutions are measured respectivelyand the values are graphically compared with those of DWas shown inFigure 4-3 Since the 0.25wt% amount of GA is proven to achieve optimum stability and thermal conductivity, it is refused to using 0.5wt% amount of it. The results demonstrate that both surfactants in solutions suppressthe thermal conductivity ofDW. Furthermore, the thermal conductivityof DW decreases with increasing loading of all surfactants.Comparing the three surfactants in DW with the same loading, obviouslyGA is superior to SDS and SDBSbecause GA influences much less than SDS and SDBS onweakening thermal conductivity of base fluid in this figure, as shown in the figure, the thermal conductivity variation is steady over the temperature.Moreover, itseems that the thermal conductivity of DWwith SDS is decreased moreat higher temperature compared with that of SDBS and GA solution.

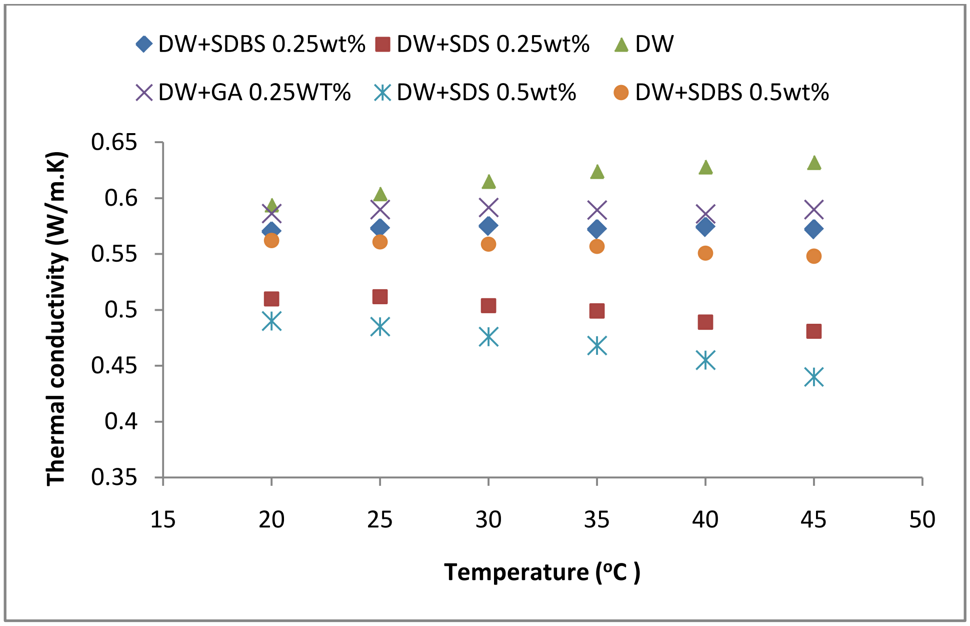

Figure 4.3 Comparison between GA, SDBS and SDS surfactant thermal conductivities

4.2.4. Effects of dispersed GA,SDBS and SDS on thermal conductivity of MWCNT Nanofluids

According to the Figure 4-4 it has been studied the effect of Three kinds of surfactants (GA, SDBS, SDS) with same concentrations (0.25wt%) on thermal conductivity of CNT`s nanofluids, Under this prescription, Fig. 4-4 graphically shows the thermal conductivity variation of CNT nanofluid at 0.5 wt.% as temperature increased. It indicates that the thermal conductivity of CNT nanofluid with SDS tendsto decrease along with the increasing temperature; probably the key reason is that SDS surfactant suppressed thermal conductivity more in base fluid which is illustrated in Figure 4-3,whereas the thermal conductivity ofnanofluids with GA and SDBS disposed to augment with increase in temperature. also it can be observed CNT`s nanofluidcontaining GA show greater thermal conductivity range than that with SDS and SDBS suspensions. According to the Figures 4-3 and 4-4 it can be proven that the GA is superior to both SDS and SDBS in thermal performance of CNT`s suspensions. Consequently GA is a excellent choice as a surfactant for MWCNT`s nanofluids in this experimental study. (All samples include in both Figures 4-3 & 4-4 sonicated for 100 minutes)

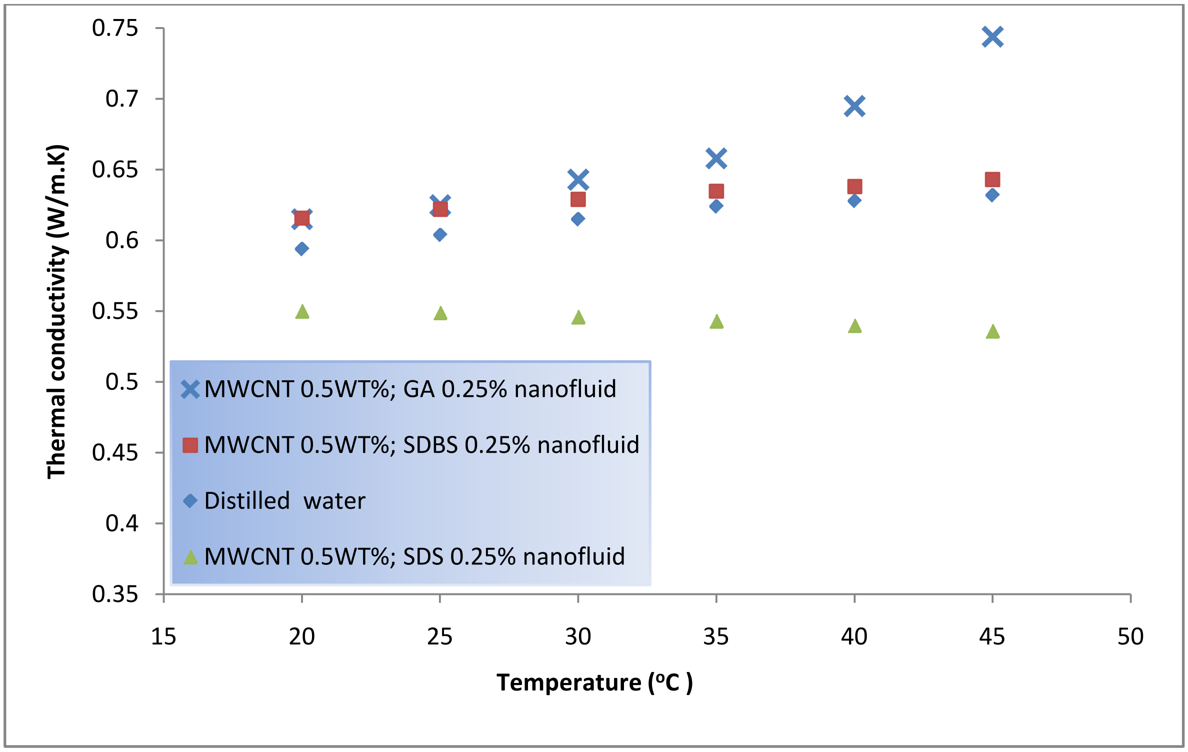

Figure 4.4 Comparison between the thermal conductivities of CNT`s Nanofluids contain GA, SDBS and SDS surfactants

4.2.5 Effects of various ultrasonication time and Temperature on thermal conductivity of MWCNT`sNanofluids

Figures 4-5 presents the absolute thermal conductivity values of MWCNT`s-water nanofluids with 0.5 wt% of MWCNT nanoparticles, temperature range contained in Figure 4-5 is from 20 to 45 ^{o}C.the data obtained using KD 2 Pro thermal properties analyzer. Measurements are taken for different sonication times as a function of Temperature, during sonication at 20 KHz and 100% amplitude, bubbles are created and collapsed, and the resulting shock from this cavitation process breaks up nanotubesaggloromates. However, the process also generates heat and the nanofluid temperature rises, in order to mitigate evaporation of the base fluid during sonication, a cooling system was employed during the sonication, maintaining a sample temperature at about 25 c.each reported measurement is the average of six reading and the specified accuracy of the instruments was 3 %.

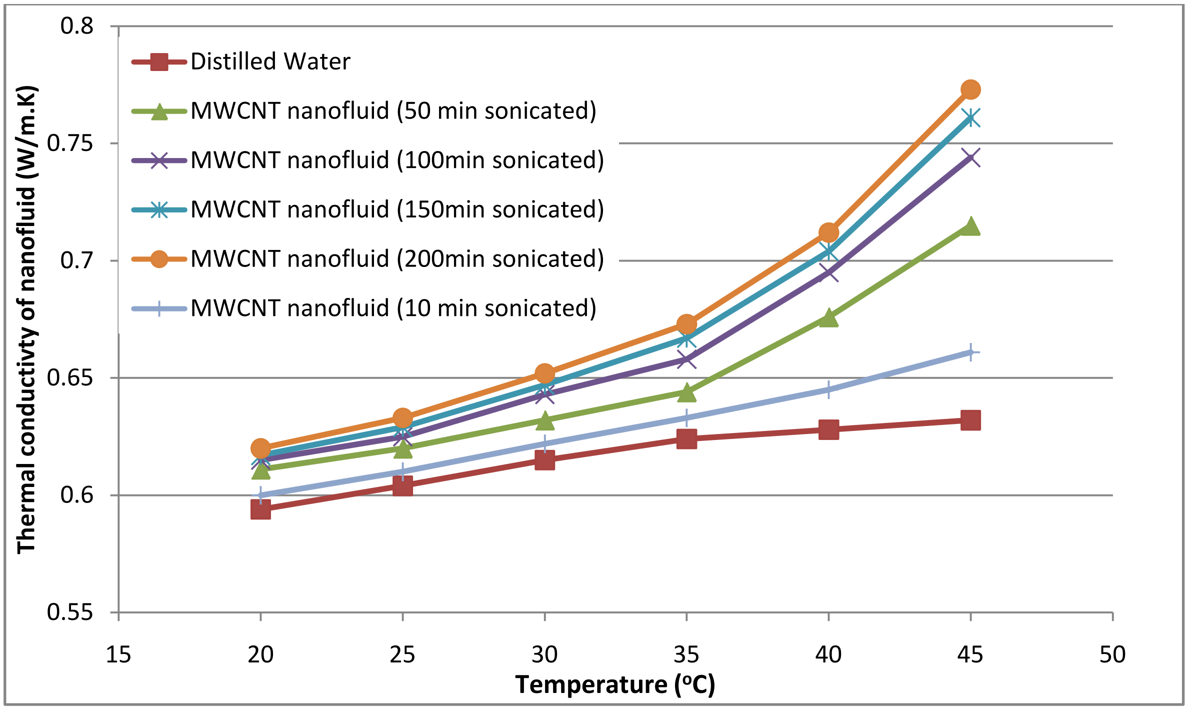

Figure 4.5 Thermal conductivity variations as a function of temperature at different ultrasonication times

As presented in figures 4.5 the temperatureaffects the thermal conductivity of the nanofluids.It has been observed an increase in thermal conductivity of MWCNT-water nanofluids with increase in temperature. The thermal conductivity data for water at this temperature range have also been included for comparison. The thermal conductivity increase of nanofluids with temperature is greater than the thermal conductivityincrease of DI water.

Unlikewater, the thermal conductivity of the nanofluid first increased slightly with temperature and after 30^{o}C it increases nonlinearly with temperature. Figure 4-5 Indicated that the increased thermal conductivity at higher temperatures is not attributed to the corresponding increase in the thermal conductivity of base fluid alone. One of the suggested reasons behind this phenomenon is the increasedBrownian motion effect. A Amrollahi et al.(Amrollahi et al., 2008) suggested that, since random Brownian motion of the suspended nanoparticles shows a strong dependence on temperature, it is expected that the thermal conductivity of a nanofluid will vary remarkably with the suspension temperature. The frequency of the ambient fluidmolecules increases as the nanofluid temperature increases so that the frequency of random motion and the averaged velocity of the nanoparticles increase, therefore the energy transport contributionis enhanced by increasing the temperature. On the other hand Jang and Choi.(Jang & Choi, 2004) suggested that, as the temperature isincreased, the viscosity of the nanofluid decreases, which results in increase in Brownianmotion of nanoparticles, which sets convection-like effects resulting in enhanced thermalconductivity.A strong effect of temperature on thermal conductivity of MWCNT dispersed in water also observed by Ding et al.(Ding et al., 2006).

The ratio and enhancement of nanofluid thermal conductivity to that of base fluid (DI water), are plotted in Figures 4-6 and 4-7 respectively.The influence of temperature on the thermal conductivity ratio of CNT nanofluids is obvious in Figures, the both thermal conductivity enhancement and ratio augmented from 2.02% to 22.31% and 1.2 to 1.22 respectively for all MWCNT suspensions included 0.5 wt% MWCNT and sonicated from 20 to 200 minutes. A highest augment of 22.31% was achieved for sample 4 (0.5 wt% MWCNT, 0.25 wt% GA, sonicated for 200 minutes) at a temperature of 45^{o}C.

Since The MWCNT provided by the supplier contained the average density of 2.1 gm/cm^3, the volume fraction of the nanopowderused in current experiment would be approximately 0.24 vol%.By comparing presented data with the work done by A. Indhuja at al.(Indhuja et al., 2013), it can be shown thethermal conductivity ratiodata in the current study is almost 5% higher than that reported by A. Indhuja at al.(Indhuja et al., 2013)for 0.5 wt%

MWCNT suspensions which was dispersed by GA. the higher thermal conductivity may be caused by the different ultrasonication processor and dispersing method of CNT used in current experiment. The thermal conductivity enhancement reported by T.X Phuoc et al.(Phuoc et al., 2011) were 2.4% and 4.3% with 0.5 and 1 wt% MWCNT (aspect ratio ~ 500-1000) respectively at 25 ^{o}C, and that by L. Chen, H. Xie.(L. Chen & Xie, 2010a) was almost 15% with 0.3 vol %(~0.63 wt %) MWCNT (aspect ratio ~400-670)at 45 ^{o}C.Hence, it can be said that both T.X Phuoc et al.(Phuoc et al., 2011)and L. Chen, H. Xie.(L. Chen & Xie, 2010a)used higher CNTs concentrationthan in this experiment. Nonetheless, thethermal conductivity enhancement values achieved in this study are much higher than both studies.This increase may be dependent on the type of dispersant (GA) used in current experiment.The thermal conductivity ratio shown in Figure 4-6 is much lower than that reported by Ding et al.(Ding et al., 2006)(i.e. 1.1 at 0.5 wt% MWCNT at 20 °C),in spite of the fact that the CNT`s concentration used in both studies is same. The exact reason for this difference is uncertain but it may be associated with thermal and physical properties of the MWNTs used and different dispersion method employed in both works. Moreover Ding et al (Ding et al., 2006) didn`t mention the aspect ratio (L/D) of MWCNT utilized, and it may be different from that (~ 500-1000) in current study.

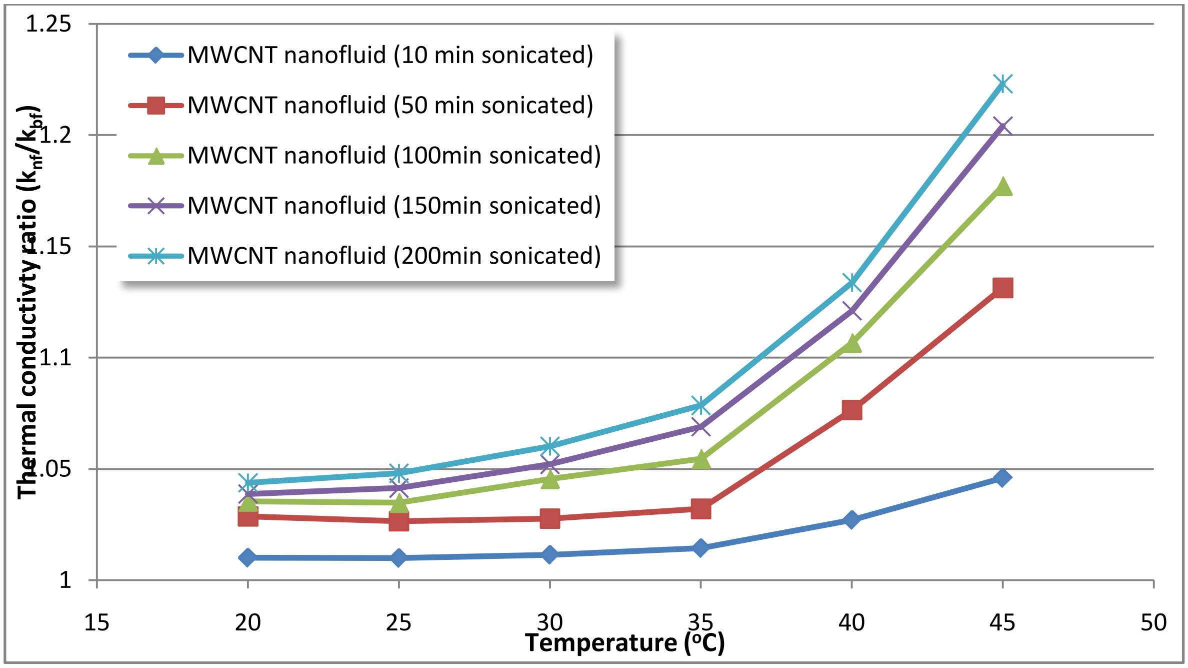

Figure 4-6 variation of Thermal conductivity ratio as a function of temperature at different ultrasonication times

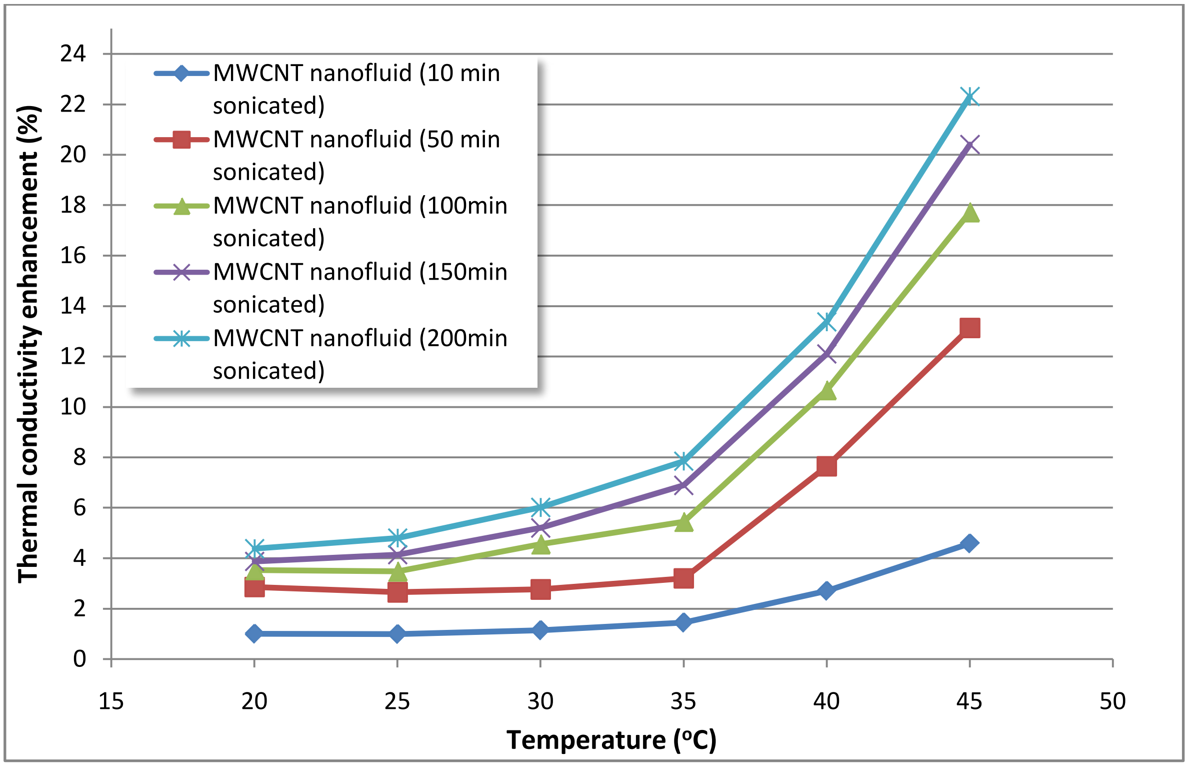

Figure 4-7 variation of Thermal conductivity enhancement as a function of temperature at different ultrasonication times

Figures 4-8 and 4-9 showed the thermal conductivity enhancement and thermal conductivity ratio of MWCNT suspensions, with 0.5 wt% of MWCNT nanoparticles as a function of ultrasonication processing at different temperatures. It is apparent from following figures that the thermal conductivity of the nanofluid initially enhances rapidly when ultrasonication time increases and it gradually reaches a peak at around 200 hours sonication.

The reason for this phenomenon may be associated with the breaking nanoparticles aggregation into smaller dimensions. A Amrollahi et al (Amrollahi et al., 2008) observed thatshorter clusters move faster and include a stronger energy transport inside the nanofluid. It proposed a more steady dispersion of multi-walled CNT nanoparticles which most likely contributes to the enhancementin thermal conductivity with ultrasonication time presented in figures 4-8 and 4-9by observing the figures 4-1 to 4-4 this impact is verified microscopically.

But on the other hand, Assael et al.(Assael et al., 2004) showed that a decline in aspect ratio reduces the enhancement of thermal conductivity. However Ruan and Jacobi (Ruan & Jacobi, 2012) proven that the effect of decline in aspect ratio on thermal conductivity is not very much compared to the enhancement of thermal conductivity resulted in reduction of clusters size.

Additionally A Amrollahi et al (Amrollahi et al., 2008) concluded that when the particles get agglomerated, The effective surface area to volume ratio decreases therefore reducing the effective area of thermal interaction of particles, result in decline in the nanofluid thermal conductivity.

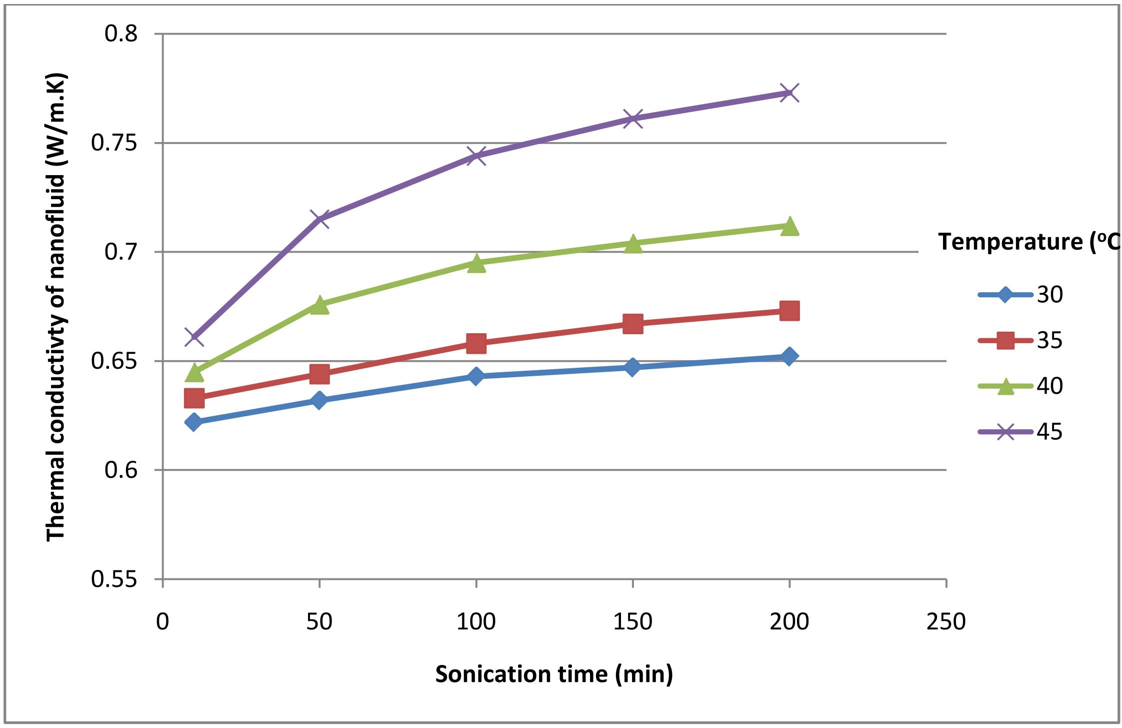

Figure 4-8 Thermal conductivity variations as a function of ultrasonication time at different temperatures

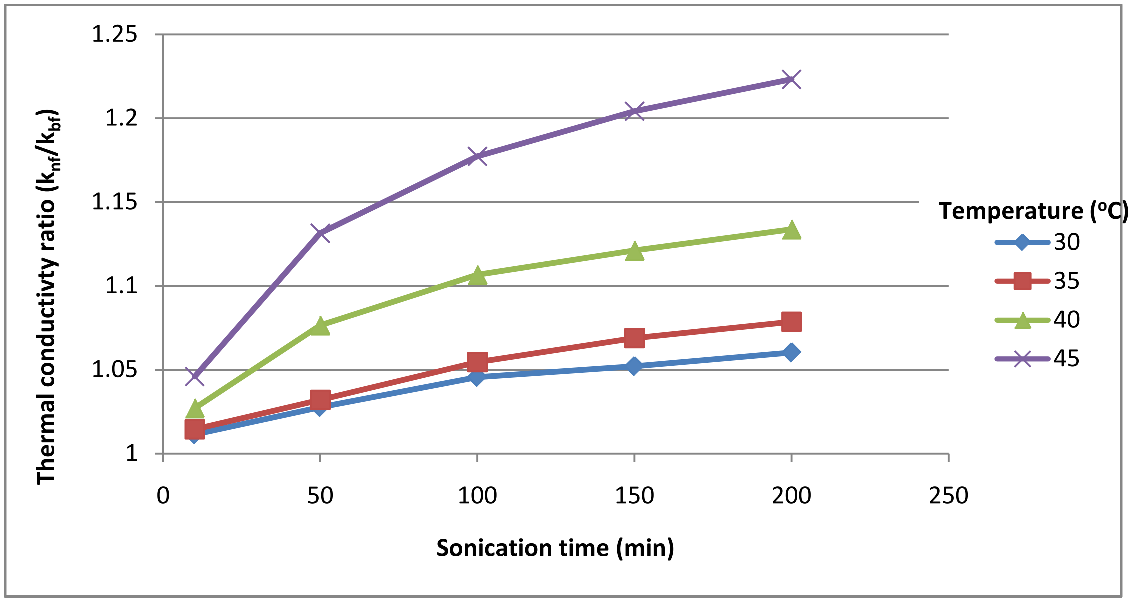

Figure 4-9 the variation of thermal conductivity ratio as a function of ultrasonication time at different temperatures

4.2.6 Study of stability of MWCNT nanofluid by reproducing the Thermal conductivity

One procedure to examine the stability of nanofluids and for any possible sign of visible sedimentation is to experiment the colloidal suspensions properties over a period of time.The stability of the MWCNT-water nanofluidsonicated for 200 minutes is repeated for 10 days. As shown in Figure 4-10, it can be observed that there is very small deviation in the measured thermal conductivity ofnanofluids. Thus the nanofluid stability is verified by monitoring the thermal conductivity of the suspensions at 40 ^{o}C for 10 days periodically.

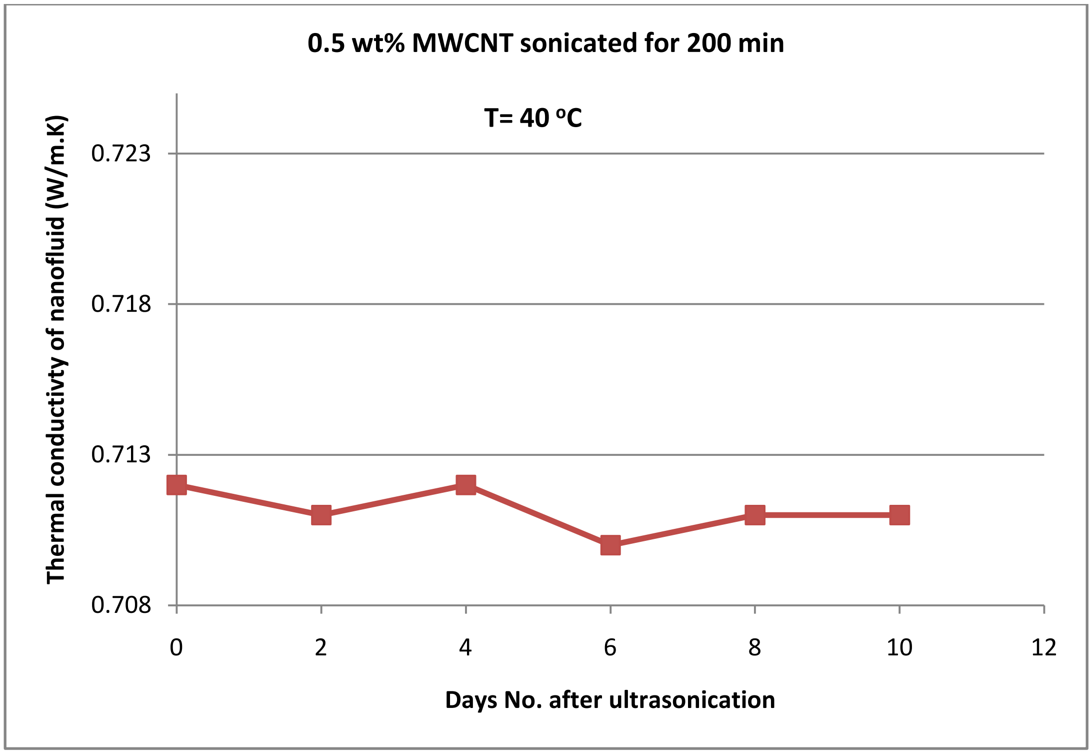

Figure 4.10 Reproducibility of thermal conductivity data within 10 days

4.3 Viscosity result

The viscosity of MWCNT-Water nanofluids stabilized by GA was measured as a function of shear rate under different ultrasonication times. Figures 4-10 and 4-11 are presented these results for 0.5 wt% MWCNT and 0.25 wt% GA at Temperatures 30 and 15^{o}C respectively.The pure distilled water viscosity was measured prior to measure the nanofluid viscosity and compared to the result from literature to confirm the accuracy of system.The data displayed no dynamic viscosity variation with an increase in shear rate for pure distilled water.Unlike water, it can be obviously observed from both figures 4-10 and 4-11 that the MWCNT- water nanofluids behave as a non-Newtonian fluid, it is because the dynamic viscositychanges while the shear rate increases.

A shear thinning behavior was observed, which was also observed by Yang et al(Yang et al., 2006) , (Garg et al., 2009), N. Singhet al(Singh et al., 2012), T.X. Phuoc et al(Phuoc et al., 2011)and Ruan and Jacobi (Ruan & Jacobi, 2012)for CNTnanofluids,causing a decline indynamic viscosity with increase in shear rate. it can been seen that, the viscosity dramatically reduces in lower shear rates and consequently it becomes constant gradually in the higher range of shear rate. The reason could be that since thenanofluid at the parallel plates is in under pressure at high shear force, which leads to break the carbon nanotubes bundled clusters and agglomerationsor realignment in the shearing force direction, resulting in a decrease in viscosity and resistance to flow.also it can be observed that dynamic viscosity of MWCNT which sonicated for 200 minutes indicates more plane viscosity deviation when the shear rate increases in both temperatures 15 and 30 ^{o} C. by comparing figures 4-10 and 4-11, it is obvious that the viscosity of MWCNT suspensions was found to be reduced by elevating the temperature

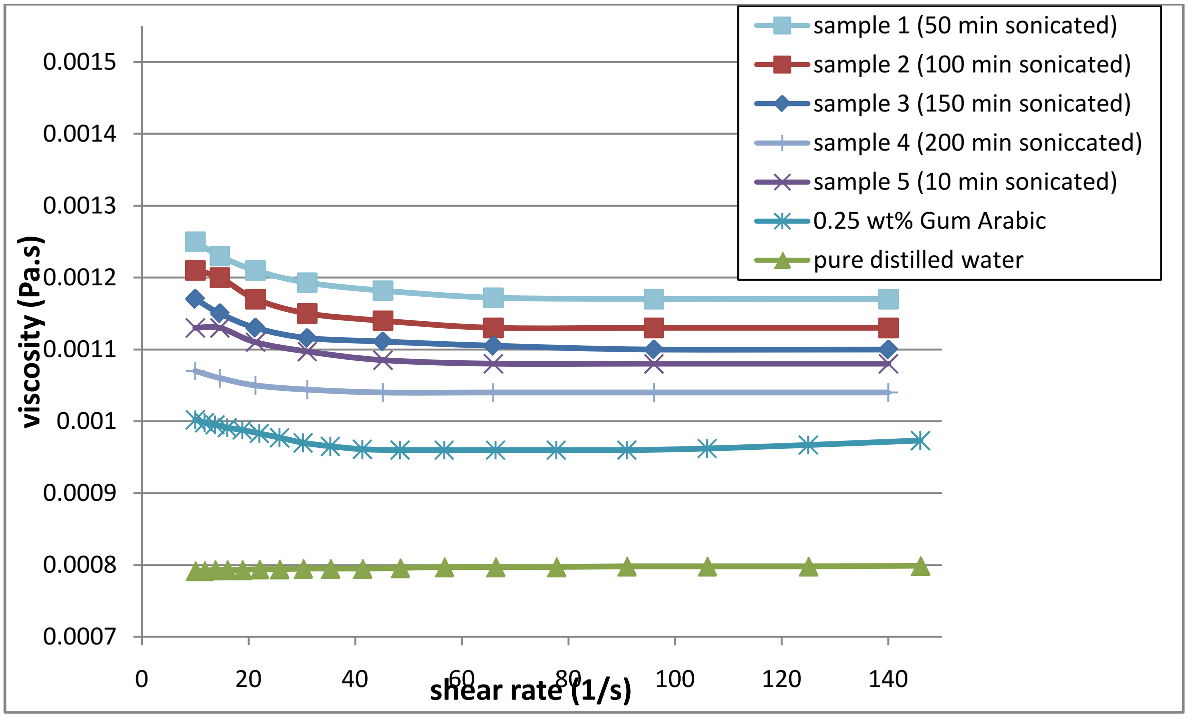

Figure 4-10 The fluctuation of Dynamic viscosity as a function of shear rate at 30 o C

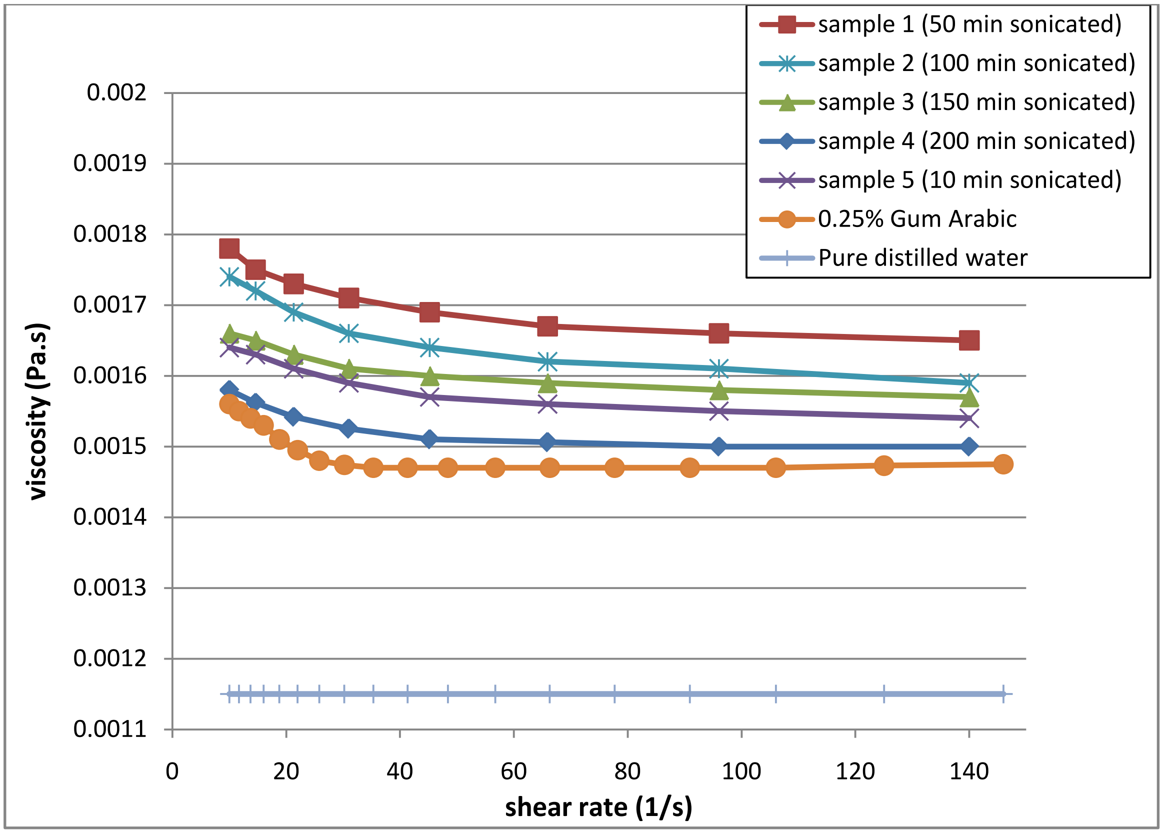

Figure 4-11 The fluctuation of Dynamic viscosity as a function of shear rate at different sonication time (15o C)

Furthermore, figures 4-12 and 4-13 present the dynamic viscosity of MWCNT`s suspensions against ultrasonication time at four different shear rates. It can be observed from both figures that at the same shear rate, the viscosity of MWCNT nanofluids first enhanced from sample 1 (sonicated for 10 min) to sample 2 (sonicated for 50 min), then declined dramatically with an increment in ultrasonication time. In addition, it is obvious that the viscosity of carbon nanotube nanofluid at low shear rates is higher compared to the larger shear rates at a same shear rate. the reason can be described that a agglomerated and non-dispersed nanofluids having lower viscosity than a dispersed nanofluids, because of increased interactions of attractive surface causing a larger surface to volume ratio in dispersed nanotubes suspensions(Starr, Douglas, & Glotzer, 2003)

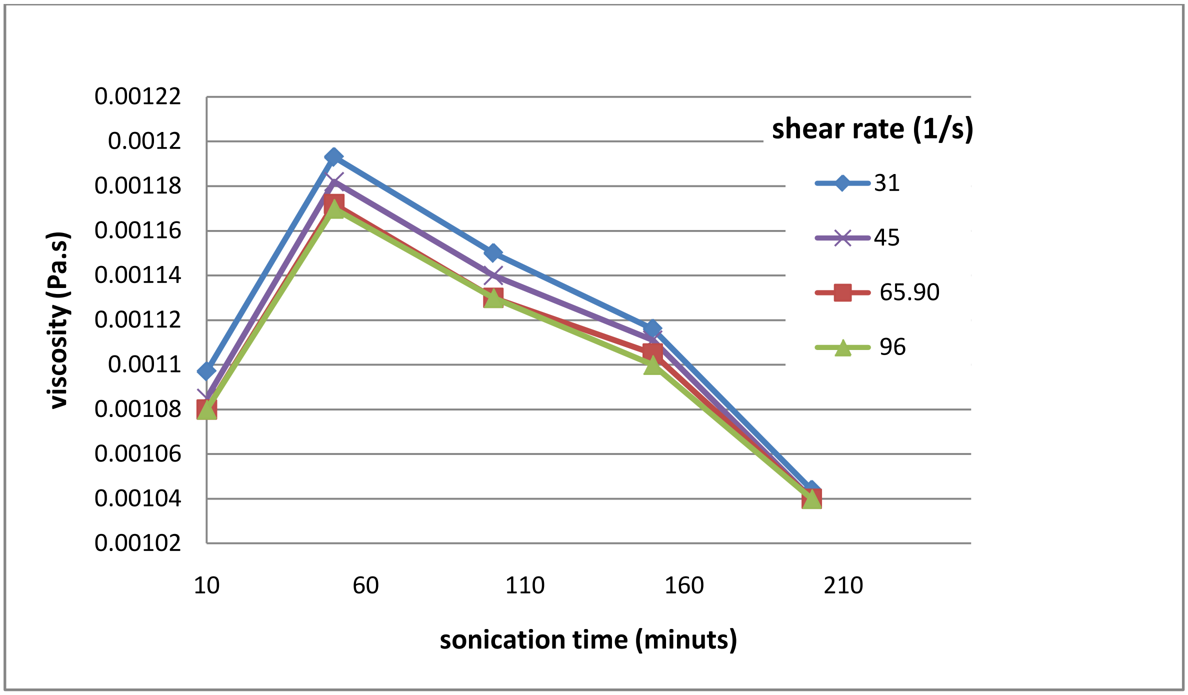

Figure 4.12 The fluctuation of Dynamic viscosity as a function of sonication time at different shear rates (30 oC)

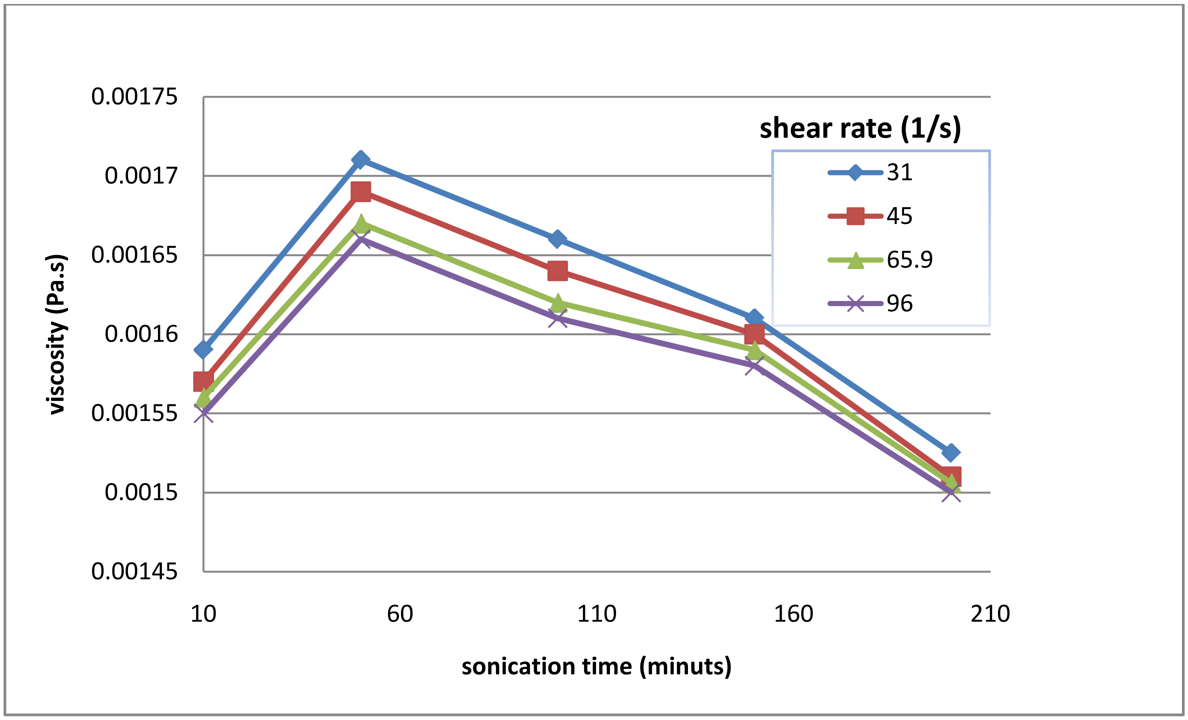

Figure 4-13 The fluctuation of Dynamic viscosity as a function of sonication time at different shear rates (15 oC)

Well-dispersednanofluids display higher dynamic viscosity due to increase in surfaces of enclosed nanoparticles was much higher than that in the agglomerated and clustered nanofluids. In this research, it can be proposed that less sonication in sample 1 (10 min sonication) resulted in high agglomeration, but on the otherhand, sample 2 (50 min sonication) shown a steady dispersion causing higher viscosity than sample 1 (10 min sonication). For further ultrasonication (after 40 min)the dynamic viscosity dramatically declined by increase in sonication time. Breaking the carbon nanotubes bundled clusters and agglomerations may be the exact reason for this phenomena (Amrollahi et al., 2008; Garg et al., 2009;Ruan & Jacobi, 2012). Consequently it could be approved by TEM images in Figures 4-1 to 4-4.

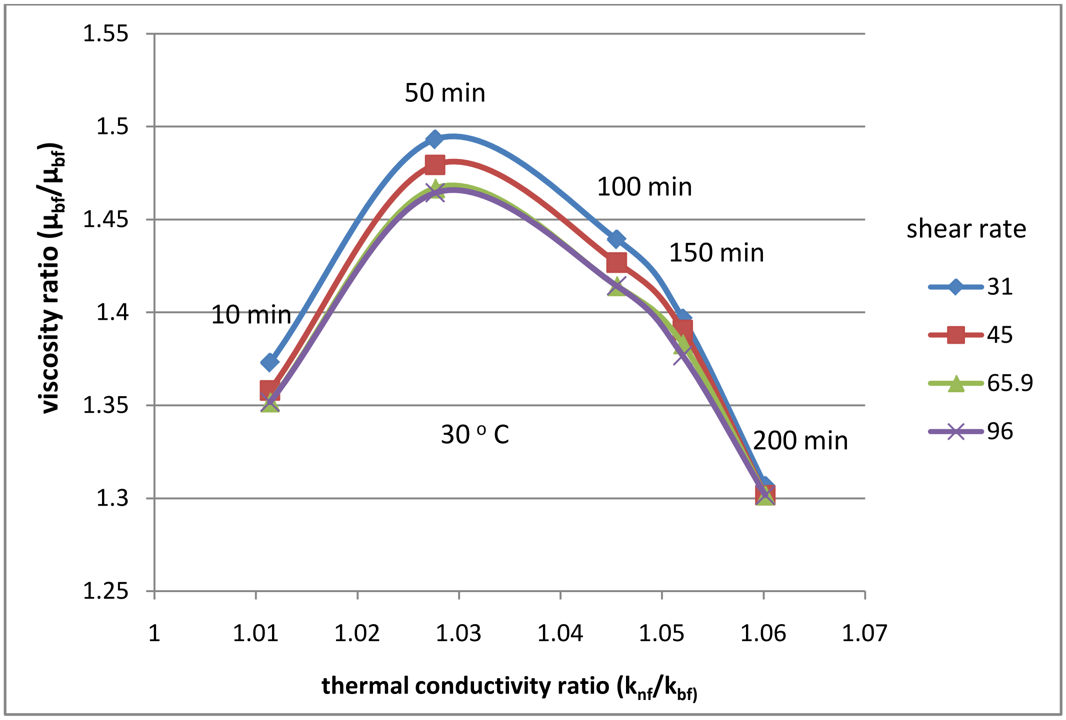

Figure 4-14 The variation of viscosity ratio of MWCNT suspensions against thermal conductivity ratio under different shear rates at 30o C

Figure 4-14 showed the viscosity ratio of MWCNT–water nanofluids as a function of thermal conductivity, under different shear rates at 30^o C.It can be seen that the viscosity ratio increases in lower sonicated samples and consequently decreases dramatically with an increase in thermal conductivity and sonication time. Conclusively, the smallest viscosity and the greatest thermal conductivity could be achieved by a long ultrasonication time for MWCNT- water nanofluids, this detection could be very significant for the nanofluids applications of heat transfer.

CHAPTER FIVE: CONCLUSION

5.1 Imaging conclusion:

- The figures indicate that the aggregates are formed in the nanofluid during preparation but with the increase of sonication time, aggregates size decreases, and it also causes the length reduction of the carbon nanotubes which resulted decrease of the aspect ratio.

5.2 Thermal conductivity conclusion:

- Thermal conductivity measurement of water showed well data reproducibility by KD2 Pro device at the working temperature range of (20 to 45 ^{o}C).

- CNT nanofluids containing GA shows greater thermal conductivity range than those with SDS and SDBS suspensions thus GA is an excellent choice of surfactant for preparation of MWCNT nanofluids.

- Unlike water, the thermal conductivity of the nanofluids first increased slightly with temperature and after 30 ^{o}C, it elevated nonlinearly with temperature due to increased Brownian motion effect. The Greatest enhancement of thermal conductivity 22.31% could be obtained at sonication 200 minutes at a temperature of 45^oC for the sample number 4.

- The thermal conductivity of the nanofluid enhances rapidly at the beginning with the increase of ultrasonication time and it gradually reaches a peak at around 200 hours sonication due to breaking of nanoparticles aggregation into smaller dimensions as the shorter clusters move faster with the stronger energy transport inside the nanofluid.
- The lowest viscosity and the highest thermal conductivity could be achieved by a long ultrasonication time for MWCNT- water nanofluids, this indication could be very significant for the application of nanofluids in heat transfer.

5.3 Viscosity conclusion:

- MWCNT aqueous solution showed a non-Newtonian and shear-thinning behavior due to breaking of the carbon nanotubes bundle clusters and agglomerations with the increment in shear rate.

- The dynamic viscosity of the nanofluid enhances with the increase of ultrasonication time up to the highest value and then declines thereafter. The viscosity of MWCNT susppensions reduces with the rise of temperature.

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