A STUDY ON THERMAL CONDUCTIVITY AND VISCOSITY OF Al_2O_3-TRANSFORMER OIL BASED NANOFLUID

A Thesis Submitted in partial fulfillment of requirement for the award of the degree

of

Master of Engineering

IN

THERMAL

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JULY 2013

DECLARATION

I hereby declare that thesis entitled **“A study on Thermal conductivity and Viscosity of Al_2O_3 -Transformer oil based Nanofluid”** is an authentic record of my study carried out as requirements for award of degree of **M.E (Thermal Engineering)** at **Thapar University, Patiala,** under the guidance of **Mr. Kundan Lal,** Assistant Professor Department of Mechanical Engineering, Thapar University, Patiala during **August 2012 to July 2013**. The matter embodied in this thesis has not been submitted in part or full to any other university or institute for the award of any degree.

(MANDEEP SINGH)

This is to certify that above declaration made by the student concerned is correct to best of my knowledge and belief.

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ABSTRACT

A nanofluid is the suspension of nanoparticles in a base fluid. Recent experimental investigations about nanofluids promise their better heat transfer performance which is due to their improved thermo physical properties like, thermal conductivity and viscosity. In our experimental investigations nanofluids are prepared by using Al_2O_3 as nanoparticles of different shape (spherical & elongated) and size (20 nm & 40 nm) in the base fluid which is a transformer oil (transol's). The test samples are prepared by dispersing Al_2O_3 in to a transformer oil at three different concentrations 0.1%, 0.3% and 0.5%. All the experimental investigations are carried out in temperature range from 20^0C- 50^0C. A stable suspension of nanoparticles in transformer oil is prepared by sonicating the sample for 3 hours in Ultra Sonicator. Two important thermo physical properties namely thermal conductivity & viscosity are investigated experimentally for the prepared nanofluid samples. Thermal conductivity of nanotransformer oil is measured by KD2 pro, a thermal property analyzer and viscosity of nanotransformer oil is measured by Brookfield viscometer (LV DV-IIICP). Effect of various parameters like temperature, concentration of nanoparticles, size and shape of nanoparticles in nanofluids have been investigated. The results show that thermal conductivity and viscosity increases with increase in % vol. concentration of nanoparticles. With temperature, thermal conductivity increases and viscosity decreases almost linearly. With increase in size of nanoparticles, it is found that thermal conductivity and viscosity decreases, which is expected due to decrease in nanolayer thickness and interfacial effects. It is also observed that elongated nanoparticles have more thermal conductivity enhancements due to their higher aspect ratio and contact surface area over the spherical nanoparticles. Viscosity also rises with elongated nanoparticles as compared to spherical nanoparticles.

ACKNOWLEDGEMENT

I would like to express my deep sense of gratitude to Mr. Kundan Lal, Assistant Professor Department of Mechanical Engineering, Thapar University Patiala for this invaluable suggestions, excellent supervision , constant encouragement, thought provoking discussions and unabashed inspiration in nurturing the work and during the preparation of manuscript throughout the research work.

My sincere thanks to Dr. Ajay Batish professor & head department of Mechanical engineering thapar university Patiala and Dr. S.K Mohapatra Dean of Academic Affairs, Thapar University, Patiala for providing me with the opportunity to conduct this work and bring it out in the present form.

I Would also like to thank my friends (Mr. Adityabir Singh, Mr.Harpreet Singh, Mr.Kamaldeep Singh, Mr.Gurpinder Singh) for their kind support and encouragement.

The greatest thanks goes to my family members S. Gurmail Singh (Father), Rajinder kaur (Mother) and Bamandeep Kaur (Wife) for their infinite support at each and every part of my life. Above all I express my indebtedness to the “GOD” for all his blessings and kindness.

Mandeep Singh

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NOMENCLATURE

C_p	Specific heat capacity, J/kgK
K	Thermal conductivity, W/mK
r	Radius, m
t	Nanolayer thickness, m
T	Temperature, K
ODP	Ozone depletion potential
GWP	Glowal warming potential
cP	Centi poise

Greek letters

α	Thermal diffusivity, m^2/s
μ	Dynamic viscosity, Pa.s
ρ	Density, kg/m^3
ϕ	Particle volume fraction
ψ	Sphericity

Subscripts

cl	Cluster
f	Base fluid
l	Liquid Nanolayer
nf	Nanofluid
p	Nanoparticle

CHAPTER-1

NANOFLUIDS

1 INTRODUCTION

Heat-transfer fluids play important roles in many industrial applications, like transportation, chemical processes, energy supply of cooling and heating, production, and microelectronics. As far as the performance of the thermal system is concerned thermal conductivity of heat-transfer fluids plays a vital role in the development of energy-efficient heat-transfer equipments. However, conventional heat-transfer fluids, such as water, oil and ethylene glycol which are commonly used in cooling application suffer from a low heat transfer efficiency. So there is a need to develop advance heat transfer fluids with significantly high thermal conductivities and improved heat transfer performances.

Improvements are made in the existing heat transfer systems such as enhancing the performance of the heat transfer fluid, lesser surface area of 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. In this pursuit, numerous researchers have been investigating Better techniques to enhance the thermal performance of heat transfer fluids. The method used is to add nano-sized particles of comparatively high thermally conductive materials like carbon, metal, metal oxides into the heat transfer fluid to improve the overall thermal conductivity of the fluid. The dispersion or suspension thus obtained is called as a “Nanofluid”.

The concept of nanofluid was proposed by Choi S.U.S (1995) as a fluid containing naofluids are expected to have superior thermal properties. The small dimension and relatively large specific surface area of nanoparticles not only increase the stability of the suspension, but also improve the heat transfer capabilities significantly. In the past decade, many researches have been conducted regarding the preparation and thermal conductivity of nanofluids.

1.1.1 Need of nanofluids:

- Need for efficient working.

- Miniaturization.
- Proper working.
- Low conductivity of conventional fluid.
- Due to limitation of solid-liquid suspensions.

Fluids containing suspended crystalline solid particles are expected to display significantly enhanced thermal conductivities as crystalline solids have thermal conductivities of typical 1-3 orders of magnitude larger than those of traditional heat transfer fluids. Numerous theoretical and experimental studies have been conducted on the effective thermal conductivity of suspensions containing millimeter- or micrometer- sized solid particles. However, due to the large size and high density of the particles, there is no easy way to prevent the coarse particles from precipitating out of the suspension state. The lack of stability of such particle suspensions induces additional flow resistance and possible erosion. Hence, the application of dispersing coarse particles in the traditional heat transfer fluids to enhance the thermal conductivity of fluids was very limited.

1.1.2 Conventional methods of heat transfer:-

Disperse micrometer or millimeter sized particles in heat transfer fluids. These fluid faces problems like :

- Setting down
- Cause wearing
- Large mass
- Wear loss
- Erosion

1.2 MATERIALS

1.2.1 Various types of Nano particles (<100 nm) used to prepare nanofluid are such as :-

- Metallic nano particles.
- Non-metallic nano particles.
- Metallic and non metallic oxides.
- Carbon nano tubes
- Ceramics and composites.

1.2.2 Most commonly used base fluids are as:

- Water
- Ethylene glycol.

Table shows the different types of nanofluids whch are being investigated:

Table No:-1.1

Metal Nanofluids	Oxide Nanofluids	Carbon nanofluids(CNT)
For examples • Cu/water • Cu/oil • Cu/EG • Au/water • Au/toluene • Fe/EG	For examples :- • Al_2O_3/water • Al_2O_3/EG • CuO/water • TiO2/ water • Fe3O4/water • CuO/EG	For examples:- • CNTs/water • CNTs/EG • MWCNTs/oil • graphite/water • CNTs/DE • CNTs/EO

1.3 Applications

Nanofluids are suspensions of nanoparticles in base fluids that show significant enhancement of their properties at modest nanoparticle concentrations. Most of the publications on nanofluids are about understanding their behavior so that they can be utilized where straight heat transfer enhancement is paramount as in many industrial applications, like in nuclear reactors, heat transportation, electronics as well as biomedicine area and food. Nanofluid as a type of smart fluid, where heat transfer can be reduced or enhanced at will, has also been reported. This study focuses on presenting the broad range of current and future applications that involve nanofluids, emphasizing their improved heat transfer properties that are controllable and the specific characteristics that these nanofluids possess that make them suitable for such applications.

- Heat Transfer Applications
- Automotive Applications
- Electronic Applications
- Biomedical Applications

1.3.1 Heat transportation

The mixture of ethylene glycol and water is used universally as a vehicle coolant due to its lowered freezing point and its elevated boiling point. The thermal conductivity of ethylene glycol is relatively low as compared to that in case of water, where as the engine oils are much worse conditions of heat transfer fluids than ethylene glycol in thermal transport & its performance. The addition of nanoparticles and nanotubes to these coolants and lubricants to form nanofluids can shows increase their thermal conductivity, and give the potential to improve the heat exchange rates. The above improvements can be used to reduce the size of the cooling systems or remove the heat from the vehicle engine exhaust in the same cooling system.

Oils are widely used in industrial cooling and nuclear reactor cooling. These oils are also used in cooling of heavy equipment in industries, offices and domestic and commercial buildings. Huge amount of energy is used by these equipments. Nano oils have potential to enhance heat transfer rate in a transformer cooling process. Mixing nanoparticles in a transformer oil can be used as coolant in transformer used in power generation process. Thus, making the transformer more compact in size. This consequently will reduce energy consumption in these sectors along with reduction in emissions, global warming potential and greenhouse-gas effects.

1.3.2 Electronics cooling

The power dissipation of IC (Integrated Circuits) and microelectronic components has dramatically increased due to reduction of their size. Better thermal properties management and cooling fluids with improved thermal transport properties are needed for safe operation. Nanofluids have been considered as good option as working fluids in heat pipes for electronic cooling application.

1.3.3 Military applications

Military hardware both mechanical and electrical devices dissipates a large amount of heat and consequently requires high heat flux cooling fluids. Nanofluids have the capability to provide the required cooling capacity in such applications, similarly in other military applications, which including submarines & high power laser.

1.3.4 Medical applications

Nanofluids are now being developed for medical applications, including cancer therapy. Iron based nanoparticles can be used as delivery vehicle for drugs or radiation without damaging the neighboring healthy tissues by guiding the particles up the blood stream to the tumor locations with the magnets. Nanofluids can be used to produce higher temperatures around tumors region, to kill cancerous main cells without affecting the nearby healthy cells. Nanofluids could also be used for safer surgery by cooling around the surgical area region, there by enhancing the patient's health level and reducing the risk of organ damage.

Nanofluids are currently more costly, due to the difficulty in manufacturing them. The development of new synthesis methods is necessary to make nanofluids more affordable before they will see wide-spread applications.

CHAPTER 2

LITERATURE SURVEY

2.1. Thermal Conductivity

In the past a large amount of experimental and theoretical research has been done to investigate the thermo physical behavior of nanofluids. In these investigations higher thermal conductivity enhancement is obtained with addition of small concentration of nanoarticles in the base fluid. Due to suspension formation of these nanoparticles in base fluid which leads to higher thermal conductivity enhancement. The result obtained from most of the experimental work showed that the thermal conductivity enhancement obtained by using nanoparticle suspensions is comparatively higher than that obtained by using suspensions of the articles which are micro or millimeter in size. The results obtained with nanoparticles are more effective than with particles that are millimeter-or micrometer-sized. Many researchers have proposed theoretical models and some classical models also to explain such type of behavior of thermal conductivity of nanofluid. The results obtained by comparing data with different models are differing in some proportions. But still research is going on to predict the actual behavior of thermal conductivity.

2.1.1 Nano- transformer oil with high thermal conductivity property for transformers.

Water, ethylene glycol (EG) and mineral oil (MO) play a vital role as heat-transfer agents in automotive and heavy-duty engines, energy production and supply, nuclear systems cooling and also in many other fields, including space, defense, biomedical and magnetic sealing. High thermal conductivity and low viscosity are the important characteristics of these heat-transfer fluids. To cool an electrical transformer during its operation is main objective of the transformer oil. This oil is customarily a highly refined MO and employed in transformers as a coolant because of its high stability at elevated temperatures and excellent electrical insulating properties. Insulation is essential as the winding inside has to be separated to prevent voltage from leaking or shorting. As the thermal conductivity of MO is low, it is not uncommon to experience thermally driven failures from instantaneous overload. Therefore, to achieve significant extension in transformer lifetime and increment in load/ cooling capacity, it is pertinent to increase the thermal conductivity of the transformer oil. Obviously in the right choice of the materials, one essentially will

Search for suitable dispersants in oils that take heat away, yet remain electrically neutral without increasing the viscosity of the oil.

Ideal transformer oil to possess low viscosity for facilitating continuous flow of oil, high thermal conductivity and excellent electrical insulating properties.

2.1.2. Effects of various parameters on thermal conductivity of nanofluids

Experimental studies show that thermal conductivity of nanofluids depends on many factors such as particle volume fraction, particle material, particle size, particle shape, base fluid material and temperature. Amount and types of additives for the acidity of the nanofluid were also shown to be effective in the thermal conductivity enhancement.

In the following sections, experimental studies about the thermal conductivity of nanofluids are summarized. In each section, various parameters which effect thermal conductivity have been discussed in detail.

2.1.2.1. Particle volume fraction

There are many studies in the literature about the effect of particle concentration or a volume fraction, which is the volumetric concentration of the nanoparticles in the nanofluid on the thermal conductivity of nanofluids.

Some researches show a linear behavior of thermal conductivity with particle volume fraction where as few show a non linear behavior. Here the effect of volume concentration on the thermal conductivity of nanofluid has been investigated. The parameter investigated in almost all of the experimental studies and the results are usually in agreement qualitatively. Researchers have found an increase in thermal conductivity of nanofluid with increase in particle volume fraction behavior is linear (Sungtaek et.al (2008). However, there are also some studies which indicate nonlinear behavior (Hong and Yang (2005).

Eastman et al. (1997) investigated the thermal conductivity of Al_2O_3 , CuO with HE-200 oil and water as base fluid in nanofluid. Al_2O_3/CuO/Cu nanoparticles of diameter 33/36/18 nm were dispersed into HE- 200 oil and in water (up to 5 % vol. concentration) at normal temperature. Thermal conductivity enhancement of CuO - HE-200 oil was found to be 5 %.

Lee. et al. (1999) investigated thermal conductivity of Al_2O_3 , CuO with ethylene glycol and water as a base fluid. Al_2O_3/CuO nanoparticles of diameter 24/18 nm were dispersed into ethylene glycol and water at different volume concentration up to 6% at normal temperature (25^0C). Thermal conductivity enhancement of Al_2O_3/CuO –EG /water was found to be 20 % for 4% vol. concentration of Al_2O_3 and 27 % for CuO at 5% vol. concentration.

Li and Peterson (2006) investigated the thermal conductivity of Al_2O_3 / CuO - water nanofluid. Al_2O_3 / CuO nanoparticles of diameter 36/29 nm were dispersed into water at different volume concentration from 0.02-0.20 % at temperature ranges from 15 – 40^0 C. Thermal conductivity enhancement of Al_2O_3 - water nanofluid was 7.8 % for 0.10 vol %.Similarly thermal conductivity enhancement of CuO - water nanofluid was found to be 11.2 % for 0.08 % vol. concentration.

Hwang et al. (2007) investigated the thermal conductivity of Al_2O_3 - distilled water as a nanofluid. Al_2O_3 nanoparticles of diameter 48 nm were dispersed into distilled water at different volume concentration from 0.3-1% at temperature ranges from 10 - 40^0 C. Thermal conductivity enhancement of Al_2O_3 -distilled water was found to be 4 % for 1%vol. concentration.

Mintsa et al. (2009) investigated the thermal conductivity of Al_2O_3 /- water nanofluid. Al_2O_3 nanoparticles of diameter 48 nm were dispersed into water at different volume concentration from 0.03-0.09% at temperature ranges from 20 - 40^0 C. Thermal conductivity enhancement of Al_2O_3 - water nanofluid was found to be 16 % for 0.06 % vol. concentration.

2.1.2.2. Particle material

Particle material is also an important factor for studying the thermal conductivity behavior of nanofluid. Difference in the thermal conductivity of particle materials is one of the main factor for different type of characteristics shown by various nanofluids with different types of nanoparticle. However, studies show that particle type may affect the thermal conductivity of nanofluids in other ways.

Lee et al. (1999) investigated the thermal conductivity of nanofluids with Al_2O_3 and CuO nanoparticles and they found that nanofluids with CuO nanoparticles have better enhancement was compared to the nanofluids prepared using Al_2O_3 nanoparticles. It should be noted that Al_2O_3, as a material, has higher thermal conductivity than CuO. Therefore, thermal conductivity of particle material may not be the dominant parameter that determines the thermal conductivity of the nanofluid. According to these authors, the key factor is the fact that Al_2O_3 nanoparticles formed relatively larger clusters when compared to CuO nanoparticles. That might be the explanation if the main mechanism of thermal conductivity enhancement is accepted to be the Brownian motion of nanoparticles, since the effect of Brownian motion diminishes with increasing particle size.

Chen et al. (2007) studied the thermal conductivity enhancement of oil based nanofluids containing MWCNT with a mean diameter of around 25 nm and length around 50 nm. The base fluid used was synthetic poly (α olefin) oil. Measurements were taken at room temperature. 160% enhancement (a thermal conductivity ratio of 2.6) was observed for 1 vol.% MWCNT/oil nanofluid. The authors noted that such an anomalous enhancement might be due to the liquid nanolayers forming around the nanotubes. On the other hand, the fact that heat is transported ballistically inside the nanotubes improves the conduction of heat in the tubes, but the effect of this factor is not dominant according to the authors. It should also be noted that the shape of nanotubes might also be effective in the anomalous enhancement values. The length of the nanotubes is of the order of micrometers, and this enables rapid heat conduction across relatively large distances, which is not possible for spherical nanoparticles as long as there is no clustering.

2.1.2.3 Base fluid

According to the conventional thermal conductivity models such as the Maxwell model, as the base fluid thermal conductivity of a mixture decreases, the thermal conductivity ratio (thermal conductivity of nanofluid (k_{nf}) divided by the thermal conductivity of base fluid (k_f) increases. When it comes to nanofluids, the situation is more complicated due to the fact that the viscosity of the base fluid affects the Brownian motion of nanoparticles and that in turn affects the thermal conductivity of the nanofluid (**Timofeeva et al, 2011**). Moreover, (**Gobin et al, 2007)** examined the effect of electric double layer forming around nanoparticles on the thermal conductivity of nanofluids and showed that the thermal conductivity and thickness of the layer depends on the base fluid. It is difficult to determine the quantitative effects of these factors completely. Therefore, systematic experiments are required that will show the effect of base fluid on the thermal conductivity of nanofluids.

Chopkar et al. (2008) also analyzed the effect of base fluid by comparing water and ethylene glycol. Al_2Cu and Ag_2Al nanoparticles was used in the study and it was found that water-based nanofluids showed a higher thermal conductivity ratio. It should be noted that more than 100% enhancement was obtained for the 2.0% vol. concentration of Ag_2Al(30 nm)/water nanofluid. Base fluid effect was also investigated with MWCNT nanofluids.

Liu et al. (2005) Ethylene glycol and synthetic engine oil were used as base fluids in the experiments conducted Thermal conductivity of nanofluids were measured by a transient hot-wire method. 1 vol.% MWCNT/ethylene glycol nanofluid showed 12.4% thermal conductivity enhancement, whereas for 2 vol.% MWCNT/synthetic engine oil nanofluid, enhancement was 30%. It was observed that higher enhancements were achieved with synthetic engine oil as the base fluid, in general.

2.1.2.4 Temperature

In general, the thermal conductivity of nanofluids is more temperature sensitive than that of the base fluid. Consequently, the thermal conductivity enhancement of nanofluids is also rather temperature-sensitive. In conventional suspensions of solid particles (with sizes on the order of millimeters or micrometers) in liquids, thermal conductivity of the mixture depends on temperature only due to the dependence of thermal conductivity of base liquid.

Patel, Sundararajan & Das (2010) experimentally investigated the thermal conductivity of oxide and metal oxide nanoparticle by using transformer oil as base fluid.Al_2O_3, Al, CuO and Cu nanoparticle of 45, 80, 31 and 80 nm respectively were dispersed in to transformer oil at different volume concentration from 0.5 – 3 % volume fraction respectively. The temperature ranges from 20- 50^0C . Thermal conductivity enhancement of Al_2O_3-Transformer oil nanofluids were 3-17% . Similarly conductivity enhancement for Al, CuO, and Cu are 3.5-24, 5-26, 5-38 % respectively.

Xuan and Li (2000) investigated the thermal conductivity of Cu–Transformer oil nanofluid. Cu nanoparticles of diameter 100 nm were dispersed into transformer oil at different volume concentration i.e upto 7.5 % at temperature ranges from 20-60^{0}C. Thermal conductivity enhancement of Cu-Transformer oil nanofluids were 45% maximum.

Xie et al. (2002) investigated the thermal conductivity of Al_2O_3–pump oil nanofluid. Al_2O_3 nanoparticles of diameter 60 nm were dispersed into pump oil at different volume concentration i.e upto 5% at temperature ranges from 25-70^{0}C. Maximum thermal conductivity enhancement of Al_2O_3 -Transformer oil nanofluids were 40%.

Wang et al. (1999) investigated the thermal conductivity of Al_2O_3– engine oil / pump oil nanofluid. Al_2O_3 nanoparticles of diameter 28 nm were dispersed into engine oil and pump oil at different volume concentration i.e upto 7.5 % and 7 % respectively. Thermal conductivity enhancement of Al_2O_3 - engine oil and Al_2O_3 - pump oil were 30 % and 20 % respectively.

Kole and Dey (2011) investigated the thermal conductivity of CuO - gear oil nanofluid. CuO nanoparticles of diameter 40 nm were dispersed into gear oil at different volume concentration from 0.005-0.025 % at temperature ranges from 5 – 80^0 C. Oleic acid used as dispersant to stabilize the system. thermal conductivity enhancement of CuO - gear oil were 10.4 % at 30^0 C.

Liu et al. (2005) measured the thermal conductivities of nanofluids containing CNTs dispersed in ethylene glycol and a synthetic engine oil. The increase in thermal conductivity is up to 12.4% for CNT-ethylene glycol suspensions at 1.0 vol% and 30% for CNT-synthetic engine oil suspensions at 2 % vol. concentration.

Taha-Tijerina et al. (2012) who suggest the 2D hexagonal boron nitride nanosheets (h-BN)/MO fluids as the most likely next-generation thermal nano-oils. These authors obtained nanosheets of h- BN by the exfoliation of micrometresized layered h-BN crystals in isopropyl alcohol (IPA) by sonication (Figure1) as 2D fillers. Temperature dependent variation in thermal conductivity, indicating the role of Brownian motion on thermal conductivity.The observed enhancement in thermal conductivity is 76% for the nanofluids containing 0.1 wt% h-BN/MO.The electrical resistivity of the nanofluids decreases in the expected order h-BN/MO > MO > graphene. Temperature-dependent effective thermal conductivity (TC) enhancement of various nanofluids (percentage of filler amount is mentioned). Pure MO shows no variation of TC with temperature. All nanofluids show an enhancement in thermal conductivity with temperature, indicating the contribution of Brownian motion in thermal conductivity enhancement.

2.1.2.5. Particle size

Particle size is another important parameter which effect the thermal conductivity of nanofluids. It is possible to produce nanoparticles of various sizes, generally ranging between 5 and100 nm.

Chopkar et al. (2008) investigated the effect of particle size on the thermal conductivity of water- and ethylene glycol-based nanofluids with Al_2Cu and Ag_2Al nanoparticles. Nanoparticles with sizes varying between 30 and 120 nm were used in the study. For all four types of nanofluids, so it was observed that thermal conductivity enhancement increases with decreasing particle size.

Eastman et al. (2001) studied Cu nanoparticles, with ethylene glycol as the base fluid. By using a one-step production method, suspensions with Cu nanoparticles smaller than 10 nm were obtained. Thioglycolic acid less than 1 vol.% was added to some of the samples for stabilizing purposes and those samples showed much better enhancement when compared to samples without thioglycolic acid. A 40% increase in thermal conductivity was observed at a particle volume fraction of 0.3% (with thioglycolic acid). To make a comparison, it should be noted that the researchers obtained 20% enhancement with 4 vol.% CuO (23.6 nm)/ethylene glycol nanofluid. As a result of the anomalous enhancements obtained. It is concluded that the size of the nanoparticles is an important factor that effect the thermal conductivity enhancement, which is contrary to the predictions of conventional models such as Hamilton and Crosser model, which does not take in to account the effect of particle size on thermal conductivity.

Thermal conductivity of nanofluids increase with decreasing article size. This type of behavior is mainly influenced by following factors:-

- Liquid layer formation around nanoparticles.
- Brownian motion of nanoarticles.

As particle size increases Brownian motion of nanoparticles decreases due to which heat transfer rate b/w base fluid and nanoparticle decreases due to which thermal conductivity of nanofluid decrease

2.1.2.6 Particle Shape

In the previous studies of the shape effect of nanoparticles on thermal conductivity of nanofluid following two type of shapes are studied :

Spherical particles and cylindrical particles. Aspect ratio of cylindrical particles usually more than spherical particles so more area of contact b/w nanoparticles and base fluid.

Thermal conductivity enhancement in nanofluids was compared with respect to the geometric shape of the particles.. The cylinders show an increase in thermal conductivity enhancement over the spheres, and this result is thought to be due to a mesh formed by the elongated particles that conducts heat through the fluid.

Xie et al. (2002) investigated the thermal conductivity of SiC/distilled water and SiC/ethylene glycol nanofluids two types of nanoparticles were used for the preparation of nanofluids; spherical particles with 26 nm average diameter and cylindrical particles with 600 nm average diameter. It was found that 4.2 vol.% water-based nanofluid with spherical particles had a thermal conductivity enhancement of 15.8%, where as 4 vol.% nanofluid with cylindrical particles had a thermal conductivity enhancement of 22.9%. The authors compared the results with the Hamilton and Crosser model. It was noted that Hamilton and Crosser model was successful in predicting the enhancement in cylindrical particles, whereas it underestimated the values associated with nanofluids with spherical particles.

Generally spherical nanoparticles shows greater thermal conductivity enhancement in nanofluids. But cylindrical particles have more surface area contact with base fluid but these particles has certain disadvantages associated with them like usually have much larger viscosities than those with spherical nanoparticles. As a result, the associated increase in pumping power is large and this reduces the feasibility of usage of nanofluids with cylindrical particles.

2.1.3 Theoretical models of thermal Conductivity

2.1.3.1 Classical models

More than a century ago, Maxwell derived an equation for calculating the effective thermal conductivity of solid-liquid mixtures consisting of spherical particles **(Das et al, 2007)**

$$\mathrm{k}_{\mathrm{n}_\mathrm{f}} = \frac{\mathrm{k}_\mathrm{p} + 2\mathrm{k}_\mathrm{f} + 2\left(\mathrm{k}_\mathrm{p} - \mathrm{k}_\mathrm{f}\right)\phi}{\mathrm{k}_\mathrm{p} + 2\mathrm{k}_\mathrm{f} - (\mathrm{k}_\mathrm{P} - \mathrm{k}_\mathrm{f})\phi}\, \mathrm{k}_\mathrm{f}, \tag{1}$$

Where $\mathrm{k}_{\mathrm{n}_\mathrm{f}}$, k_p, and k_f are the thermal conductivity of the nanofluid, nanoparticles and base fluid, respectively. ϕ is the volume fraction of particles in the mixture. As seen from the expression, the effect of the size and shape of the particles was not included in the analysis. It should be noted that the interaction between the particles was also neglected in the derivation.

Hamilton and Crosser (Yu et al. 2007) Extended the Maxwell model in order to take the effect of the shape of the solid particles into account, in addition to the thermal conductivities of solid and liquid phases and particle volume fraction.

The model is as follows:

$$\mathrm{k}_{\mathrm{n}_\mathrm{f}} = \frac{\mathrm{k}_\mathrm{p} + (\mathrm{n}-1)\mathrm{k}_\mathrm{f} + (\mathrm{n}-1)\left(\mathrm{k}_\mathrm{p} - \mathrm{k}_\mathrm{f}\right)\phi}{\mathrm{k}_\mathrm{p} + (\mathrm{n}-1)\mathrm{k}_\mathrm{f} - (\mathrm{k}_\mathrm{P} - \mathrm{k}_\mathrm{f})\phi}\, \mathrm{k}_\mathrm{f}, \tag{2}$$

where n is the empirical shape factor and it is defined as:

$$\mathrm{n} = \frac{3}{\Psi} \tag{3}$$

where Ψ is the sphericity. Sphericity is the ratio of the surface area of a sphere with a volume equal to that of the particle to the surface area of the particle. Therefore, n = 3 for a sphere and in that case the Hamilton and Crosser model becomes identical to the Maxwell model.

Both Maxwell and Hamilton and Crosser models were originally derived for relatively larger solid particles that have diameters on the order of millimeters or micrometers. Therefore, it is questionable whether these models are able to predict the effective thermal conductivity of nanofluids. Nevertheless, these models are utilized frequently due to their simplicity in the study of nanofluids to have a comparison between theoretical and experimental findings.

Recently, many theoretical studies were made and several mechanisms were proposed in order to explain the anomalous thermal conductivity enhancement obtained with nanofluids. In the following sections, for the proposed mechanisms of thermal conductivity enhancement in nanofluids are discussed and thermal conductivity models based on those mechanisms are summarized.

2.1.3.2. Model based on Brownian motion

Brownian motion is the random motion of particles suspended in a fluid. When nanofluids are considered, this random motion transports energy directly by nanoparticles. In addition, a micro-convection effect, which is due to the fluid mixing around nanoparticles, is also proposed to be important. There are many studies in the literature regarding the effect of Brownian motion on the thermal conductivity of nanofluids.

Koo and Kleinstreuer (Koo.J 2004) considered the thermal conductivity of nanofluids to be composed of two parts:

$$k_{n_f} = k_{static} + k_{Brownian} \tag{4}$$

where k_{static} represents the thermal conductivity enhancement due to the higher thermal conductivity of the nanoparticles and $k_{Brownian}$ takes the effect of Brownian motion into account. For the static part, the classical Maxwell model was proposed.

For $k_{Brownian}$, Brownian motion of particles was considered together with the effect of fluid particles moving with nanoparticles around them. As a result, the following expression was proposed:

$$k_{Brownian} \equiv 5 \times 10^4 \beta \phi \rho_f C_{P,f} \sqrt{\frac{k_B T}{\rho_p d_p} f}, \tag{5}$$

where ρ_p and ρ_f are the density of nanoparticles and base fluid, respectively, and T the temperature in K. $C_{P,f}$ is specific heat capacity of base fluid. In the analysis, the interactions between nanoparticles and fluid volumes moving around them were not considered and an additional term, β, was introduced in order to take that effect into account. Koo and Kleinstreuer indicated that this term becomes more effective with increasing volume fraction. Another parameter, f, was introduced to the model in order to increase the temperature dependency of the model. Both f and β were determined by utilizing available experimental data:

$$f = (-134.63 + 1722.3\phi) + (0.4705 - 6.04\phi)T, \tag{6}$$

which is obtained by using the results of the study of (Das et al. 2007) for CuO nanofluids. For other nanofluids, f can be taken as 1 due to lack of experimental data. Associated values are listed in Table 2. It is difficult to determine theoretical expressions for f and due to the complexities involved and this can be considered as a drawback of the model.

Table 2. β values for different nanoparticles to be used in Eq.(5)

Types of particles	$\boldsymbol{\beta}$	**Remarks**
Au-citrate, Ag-citrateand CuO	0.0137(100 ϕ)-0.8229	$\phi < 1\%$
Cuo	0.0011(100 ϕ)$^{-0.7272}$	$\phi > 1\%$
Al_2O_3	0.0017(100 ϕ)$^{-0.0841}$	$\phi > 1\%$

2.1.3.3. Models based on clustering

Xuan et al (2003) studied the thermal conductivity of nanofluids by considering Brownian motion and clustering of nanoparticles. An equation was proposed to predict the thermal conductivity of nanofluids:

$$k_{n_f} = \frac{k_p + 2k_f + 2(k_p - k_f)\phi}{k_p + 2k_f - (k_P - k_f)\phi}\, k_f + k_f \phi \rho_p C_{p,p} \sqrt{\frac{k_B T}{3\pi r_{cl} \mu_f}} \qquad (6)$$

Here, $r_{cl}$is the apparent radius of the nanoparticle clusters, which should be determined by experiment. T is temperature in K. μ_f is the dynamic viscosity of the base fluid. The first term on the right-hand side of Eq. (6) is the Maxwell model for thermal conductivity of suspensions of solid particles in fluids. The second term on the right-hand side of Eq. (6) adds the effect of the random motion of the nanoparticles into account.

2.1.3.4 Models based on liquid layering

Yu and Choi (2003) presented a model for the determination of the effective thermal conductivity of nanofluids by modifying the Maxwell model. In the modification, the effect of the liquid nanolayers formed around nanoparticles was taken into account. The nanoparticle and the layer around it were considered as a single particle and the thermal conductivity of this particle was determined by using effective medium theory . The result was substituted into the Maxwell model and the following expression was obtained.

$$\mathrm{k_{n_f}} = \frac{\mathrm{k_{pe}} + 2\mathrm{k_f} + 2(\mathrm{k_{pe}} - \mathrm{k_f})(1+\beta)^3\phi}{\mathrm{k_p} + 2\mathrm{k_f} - (\mathrm{k_{Pe}} - \mathrm{k_f})(1+\beta)^3\phi}\, \mathrm{k_f} \qquad (7)$$

Where k_{pe} is the thermal conductivity of the equivalent nanoparticle;

$$\mathrm{k_{pe}} = \frac{[2(1-\gamma)+(1+\beta)^3(1+2\gamma)]\gamma}{(1+\beta)^3(1+2\gamma)-(1-\gamma)}\ \mathrm{k_{p,}} \qquad (8)$$

$$\gamma = \frac{\mathrm{k_l}}{\mathrm{k_p}}\ , \qquad (9)$$

where, $\mathrm{k_l}$ is thermal conductivity of the nanolayer. β is defined as:

$$\beta = \frac{\mathrm{t}}{\mathrm{r_p}}\ , \qquad (10)$$

Where t is nanolayer thickness and $\mathrm{r_p}$ the nanoparticle radius.

2.2 Viscosity

2.2.1. Viscosity of Nano-oil

Viscosity describes the internal resistance of a fluid to flow and it is an important property for all thermal applications involving fluids . The pumping power is related with the viscosity of a fluid. In laminar flow, the pressure drop is directly proportional to the viscosity. Furthermore, convective heat transfer coefficient is influenced by viscosity. Hence, viscosity is as important as thermal conductivity in engineering systems involving fluid flow There has been a lot of research carried out about nanofluids, recently but most of them are related with the heat transfer properties which are having different contents including heat transfer enhancement, thermal conductivity measurement thermal conductivity enhancement, effective thermal conductivity ,thermal conductivity of suspensions. Recently some new issues have been introduced in literatures like thermal diffusion coefficient of nanofluid, slip mechanisms in nanofluids, electrical conductivity of nanofluids ,nanofluids for cooling of electronic devices, but few researches have been performed on the viscosity of nanofluids. Although viscosity seems to be a significant property of nanofluid and viscosity should be taken into consideration for heat transfer performance of a nanofluid.

Studies on the influence of temperature on shear viscosity measurements indicate that in general the viscosity of MO, graphene/MO and h-BN/MO (at different concentrations of h-BN) decreases with temperature. This is a desirable quality of the nano-oil for the smooth circulation of fluid in the transformers at high temperature. However, at 298 K and 0.35 wt% of 2D h-BN, the viscosity increases.

2.2.2 Factors effecting viscosity: -

- Temperature
- Volume fraction
- Shear rate
- Dispersion method, stabilizers and clustering
- Shape and size

2.2.2.1 Effect of temperature

Nguyen et al. (2008) investigated the dynamic viscosity for the Al_2O_3- water–nanofluid. Al_2O_3 nanoparticles of diameter 36 and 47 nm were dispersed into water at different volume concentrations from 1- 9.4% and temperature in the range 22 to 75^0 C. It has been found that in general, the nanofluid viscosity strongly depends on both temperature and concentration. Viscosity decreases with increase in temperature of nanofluid.

Kole and Dey (2011) investigated the viscosity for the Al_2O_3- car engine coolant nanofluid. Al_2O_3 nanoparticles of diameter 50 nm were dispersed into coolant at different volume concentrations from 0.1 -1.5 % and temperature in the range from 10 to 50^0 C. The viscosity of the nanofluids is measured both as a function of alumina volume fraction and temperature. While the pure base fluid display Newtonian behavior over the measured temperature, it transforms to a non-Newtonian fluid with addition of a small amount of alumina nanoparticles .It has been found that, the nanofluid viscosity decreases with temperature.

Lee et al. (2011) investigated the viscosity for the SiC - distilled water nanofluid. Al_2O_3 nanoparticles of diameter 45 nm were dispersed into coolant at different volume concentrations from 0.5- 2 % and in the temperature range 28 to 72^0 C. The viscosity of the nanofluids is measured both as a function of alumina volume fraction and temperature. It has been found that, the nanofluid viscosity decreases sharply with rise in temperature.

Namburu et al. (2007) investigated the viscosity for the SiO_2 - ethylene glycol nanofluid. SiO_2 nanoparticles of diameter 60 nm were dispersed into ethylene glycol at different volume concentrations from 0.1- 1.5 % and in the temperature range from 35 to 50^0 C. They also found that at low temperature nanofluids containing SiO2 nanoparticles with ethylene glycol and water as base fluids demonstrate a newtonian behavior at low temperature and at high temperature it behaves as a non- newtonian fluid. The viscosity of the nanofluids is measured as a function of SiO_2 volume fraction and temperature. .It has been found that, the nanofluid viscosity decreases exponentially with temperature.

2.2.2.2. Volume fraction

Anoop et al. (2009) investigated the viscosity for the Al_2O_3 /CuO - ethylene glycol nanofluid. Al_2O_3 /CuO nanoparticles of diameters 50 nm were dispersed into coolant at different volume concentrations (0.5, 1, 2, 4 and 6 vol. %) in the temperature range from 20 to 50^0 C. The viscosity of the nanofluids is measured as a function of Al_2O_3 /CuO volume fraction. Augmentation factor is nearly linear at higher volume fractions and not quite linear at lower volume concentrations. It has observed that viscosity becomes higher when the particle concentrations rise.

Nguyen et al. (2008) investigated the viscosity for the Al_2O_3 - water nanofluid. Al_2O_3 /CuO nanoparticles of diameters 36/47 nm were dispersed into coolant at different volume concentrations (1, 4, 9, and 12 vol. %) in the temperature range 10 to 45^0 C. The viscosity of the nanofluids is measured as a function of Al_2O_3 /CuO volume fraction. Augmentation factor is nearly linear at higher volume fractions and not quite linear at lower volume concentrations. It has observed that viscosity becomes higher when the particle concentrations rise.

Putra et al. (2003) investigated the viscosity for the Al_2O_3 - water nanofluid. Al_2O_3 nanoparticles of diameters 40 nm were dispersed into water at different volume concentrations (1, 4 vol. %) in temperature range 20 to 50^0 C. The viscosity of the nanofluids is measured as a function of Al_2O_3 volume fraction. It has been observed that at lower concentration nanofluid shows newtonian behavior.

Chandrasekar et al. (2010) investigated the viscosity for the Al_2O_3 - water nanofluid. Al_2O_3 nanoparticles of diameters 60 nm were dispersed into water at different volume concentrations 0.33 - 0.5 vol.% respectively and temperature ranging from 10 to 45^0 C. The viscosity of the nanofluids is measured as a function of Al_2O_3 volume fraction. Viscosity rises with the increase of volume fraction and also that the viscosity increases linearly up to 2% volume concentrations. After that exponential rise in viscosity with increase in nanoparticle concentration.

2.2.2.3 Shear rate

Shear rate is another parameter which can affect the viscosity in non Newtonian nanofluids. (Ding et al., 2007) worked by CNTs found shear thinning phenomenon in nanofluids. It means nanofluids can sometimes show more appropriate fluid flow performance because of shear thinning which happens at higher shear rates. Shear viscosity of nanofluids, which can be especially altered in non-Newtonian nanofluids, (Chen et al., 2008). They showed Newtonian behavior and proved that shear viscosity depends on both temperature and particle's concentration.

Prasher et al. (2006) reported that the viscosity of alumina-based nanofluid is independent of shear rate providing that the nanofluid shows a Newtonian behavior. They measured water-based Al_2O_3 and CuO in different shear rates. They observed Newtonian behavior for these nanofluids in volume concentration range of 1% to 4%.

2.2.2.4 Effect of nanoparticle size

Anoop et al. (2009) shown experimentally by taking two particle sizes of Al2O3 – 45 nm and 150 nm for a particle concentration of 1, 2, 4 and 6 % vol. with water they observed that viscosity increases with the reduction of particle size.

Chevalier et al. (2007) measured the viscosity of SiO_2 with ethanol for three different sizes of particle diameter as 35, 94, 190 nm and discovered that viscosity increases with the decrease of particle size.

Pastoriza-Gallego et al. (2011) also investigated the viscosity of CuO in water for different particle sizes and volume concentrations. They used two different samples of CuO of 23–37 nm and other 11 ± 3 nm diameter and measured the viscosity of both samples for 0–10 wt% with temperature in the range of 283.15–323.15 K and realized that the sample containing smaller size exhibits larger viscosity.

2.2.2.5 Effect of nanoparticle shape

There are very few results available in literature about particle shape effect on viscosity of nanofluids.

Timofeeva et al. (2009) studied that viscosity has a strong dependence with nanoparticle shape. Such that elongate particles like platelets and cylinders result in higher viscosity at the same volume fraction. And for lower viscosities spherical particles or lower aspect ratio spheroids should be used.

2.2.2.6 Dispersion method, stabilizers

Wang et al. (1999) made a dispersion method and its contribution to viscosity. They analyzed three different methods of dispersion and measured dianoized water-based Al_2O_3 with 5 vol. % and particle size of 28 nm. They reported a 86 % increment in viscosity for this nanofluid- The dispersion method that they used was a mechanical blending technique (method 1). Besides, coating particles with polymers (method 2) and ltration (method 3) were applied for dispersion of nanoparticles. 40 % increment is showed for ethylene glycol based Al_2O_3 at a volumetric loading of 3.5 vol. % by them. In general their results demonstrate a dependency of viscosity on dispersion method and first method contributes to viscosity increment compared to two other ones. Moreover, other parameters such as pH and sonication time can affect the viscosity of nanofluids.

2.2.3 Viscosity Models for nanofluids

There are number of fundamental models used to predict the viscous behaviour if nanofluid. Few of them are listed here.

Einstein (1906) was the first who determines the effective viscosity of the suspension of the spherical particles as a function of volume fraction.This model is valid for 0.5% volume fraction of nanoparticles. The equation was developed by using phenomenological hydrodynamic equations. This equation was expressed by:

$$\mu_{eff} = \mu_f (1 + 2.5\phi)$$

Used with infinitely dilute suspension of spheres. Assumptions for the models are that there is no interaction between the spheres and model is valid for relatively low particle volume fractions only.

Brinkman (1952) invented a viscosity correlation that extended Einstein's equation to concentrated suspensions derived by considering the effect of addition of one solute molecule to an existing solution:

μ_{eff} = (1+2.5 ϕ + 4.365 ϕ^2………..) μ_f

This model is valid for high moderate particle volume fraction. Mostly used with spherical nanoparticles.

Batchelor (1977) The effect of Brownian motion on the effective viscosity in a suspension of rigid spherical particles was studied by For isotropic structure of suspension, the effective viscosity was given by:
μ_{eff} = (1+2.5 ϕ + 6.2 ϕ^2………..) μ_f

This model is used for rigid and spherical nanoparticles.it also takes in to account the effect od brownian motion on the viscosity of nanoluids.

CHAPTER 3

Preparation and Characterization

3.1 Preparation of Nanofluids

There are mainly two methods of nanofluid preparation namely, one step and two-step technique. In the two-step technique, the first step is the preparation of nanoparticles and the second step is the dispersion of the nanoparticles in base fluid. It is advantageous to use two-step technique when mass preparation of nanofluids is required, because in these days, nanoparticles can be produced in large quantities by utilizing the technique of inert gas condensation. The main disadvantage of the two-step technique is that the nanoparticles form clusters during the preparation of the nanofluid which prevents the proper dispersion of nanoparticles inside the base fluid.Two step technique mostly used for oxide nanoparticles (Al_2O_3, CuO, ceramics etc.)

One-step technique combines the preparation of nanoparticles and dispersion of nanoparticles in the base fluid into a single step. There are some alternative methods of this technique. In one of the method, named direct evaporation i.e one-step method, the nanofluid is produced by the solidification of nanoparticles in liquid form, which are initially gas phase, inside the base fluid. The dispersion characteristics of nanofluids produced with one-step techniques are better than those produced with two-step technique. The main drawback of one-step techniques is that they are not proper for mass preparation, which limits their commercialization.one step technique mostly used with metallic nanoparticles (Ag, Cu, Al etc.)

3.1.1 One-Step Method

Four steps to be followed in the process of the direct evaporation - condensation method:

- The cylinder contains a heat transfer fluid, such as ethylene glycol or water is rotated so that a thin film of the fluid is constantly transported over the top of the chamber.
- A piece of the metallic material as the source of the nanoparticle is evaporated by heating on a crucible.
- Evaporating particles are within the fluid overhead and condense as a nanofluid.
- The fluid is cooled at the base of the chamber to prevent any of its unwanted evaporation.

There are four guidelines for the synthesis of nanofluids.

- Dispersability of nanoparticles
- Stability of nanoparticles
- Nanoparticles should be chemically compatible.
- Thermal stability of nanofluids

3.1.2 Two-Step Method

The preparation of nanofluids begins by direct mixing of the base fluid with the nanomaterials. In the first step, nanomaterials are synthesized and obtained as powders, which are then introduced to the base fluid in second step. The nanoparticles can be produced from various processes which can be categorized into one of five general synthetic methods. These five methods are:

- Transition metal salt reduction
- By thermally decomposition and photochemical methods
- Legend reduction and displacement from organometallics
- Metal vapor synthesis
- Electrochemical synthesis

Transition-metal nanoclusters are only kinetically stable because the formation of the bulk metal is its thermodynamic minimum. Therefore, nanoclusters that are freely dissolved in solution must be stabilized in a way that prevents the nanoclusters from coalescing, because such agglomeration would eventually lead to the formation of the thermodynamically favoured bulk metal.

The two-step process is commonly used for the synthesis of carbon nanotube-based nanofluids. Single-wall carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) which are basically cylindrical allotropes consist of carbon. SWCNTs consist of a single cylinder of graphene, while MWCNTs contain multiple graphene cylinders nesting within each other.

3.2 Characterization techniques of nanoparticles and nanofluids:

3.2.1 X-ray Diffraction Analysis (XRD): X-ray powder diffraction (XRD) is a rapid analytical technique primarily used for phase identification of a crystalline material and can provide information on unit cell of dimensions. Material to be analyzed is finely ground, homogenate, and bulk of average composition is determined.

Principal of X-ray diffraction: X-ray diffraction is a technique used for the study of structures made of crystals. X-ray diffraction is generally depends on constructive interference of monochromatic X-rays and a crystalline material sample. Generally these X-rays are originated from a cathode ray tube, filtered to produce monochromatic radiation are , collimated focused to concentrate, and directed on the sample. The interaction of the falling incident rays with the sample produces constructive interference (and a diffracted ray).

When conditions satisfy Bragg's Law $(n\lambda = 2d \sin\theta)$. This law directed the wavelength of electromagnetic radiation to the diffraction angle and the lattice spacing in a crystalline sample. These diffraction produced X-rays are then detected, processed and counted. By scanning of the given sample through a range of 2θ angles, so all possible diffraction directions of the lattice obtained should be attained due to the random orientation of the powdered material. Conversion of the diffraction produced peaks to d-spacing allows the identification of the mineral because each type of mineral has a set of unique d-spacing. This is achieved by comparison of d-spacing with standard reference patterns. Fig 3.1 shows the principal of XRD:

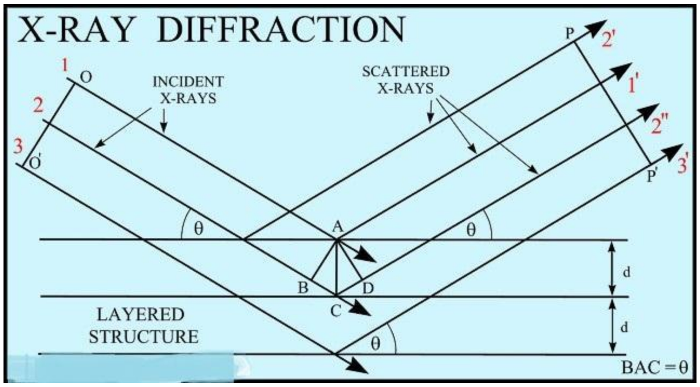


Figure 3.1 Principal of X-Ray Diffraction

3.2.2 Scanning Electron Microscope:

SEM is standardized method for imaging and the measuring the dimensions of nanometer and micrometer size particles because of high imaging speed and high resolution of SEM. Scanning Electron Microscope uses electrons to form an image. The scanning electron microscope has more advantages over other microscopes. The SEM has a large depth of field occurs, which allows the more of specimen to be in focus at one time. The SEM also have much higher value of resolution, so the closely spaced specimens can be more magnified at much higher levels as required. Because the SEM uses an electromagnets rather than lenses used, the researcher has much more control in the degree of magnification. All of these advantages, as well as the actual strikingly of the clear images, make the scanning electron microscope is one of the most useful than other instruments in research today.

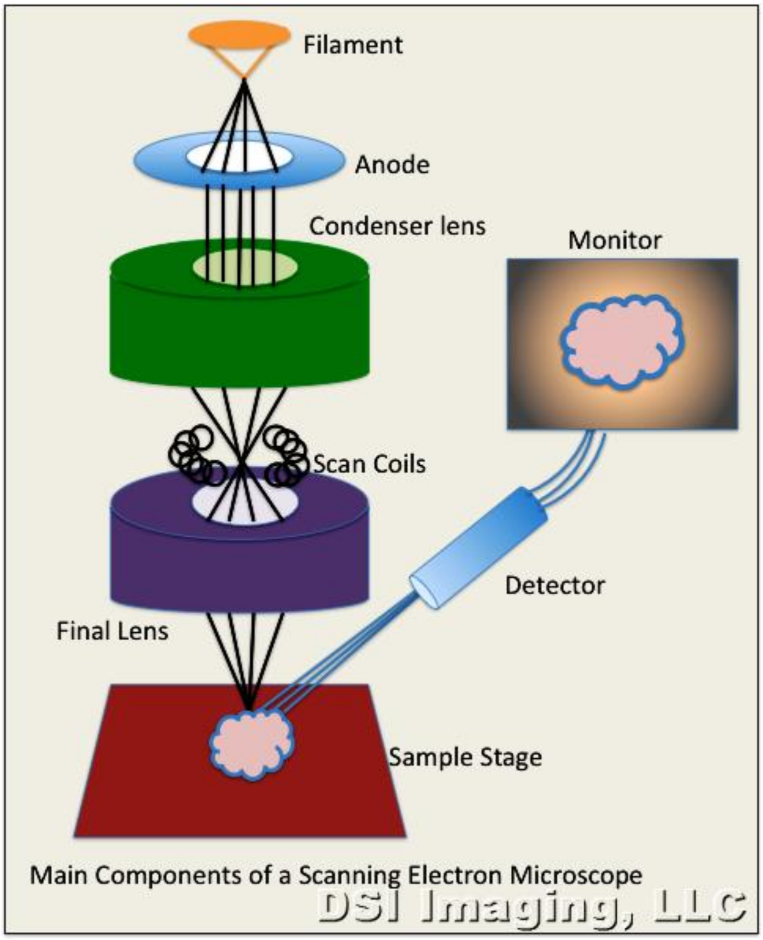


Figure 3.2 Scanning Electron Microscopy

As shown in fig. 3.2 the SEM is an instrument that produces a largely magnified image by using electrons instead of light to form on image. A focused beam of electrons is produced at the top of the microscope by an electronic gun. The electron beam follows a vertical path for through the microscope, which is held in a vacuum. The beam travels through electromagnetic fields and lenses, which focus the beam down toward the fitted sample. Once the beam hits the sample, electrons and caused to X-rays are ejected from the fitted sample as shown in fig. 3.2 Detectors collect these X-rays on screen, backscattered electrons, and secondary electrons and convert all of them into a signal that is sent screen similar kind of the television screen. This rsults the final image.

3.2.3 Transmission electron microscopy (TEM):

Transmission electron microscopy (TEM) is also a standardized method for imaging and measurements of dimension of nano and micro size structures due to their high imaging speed and high resolution (Buhr et al., 2009). The advantage of TEM over SEM is that the specimen's cellular structures can be viewed at extremely high magnifications (Stadtlander, 2007). The transmission electron microscope is used to characterize the microstructure of materials with very dense spatial resolution. Information about the morphology of sample , crystal structure and defects, on the crystal phases and composition.

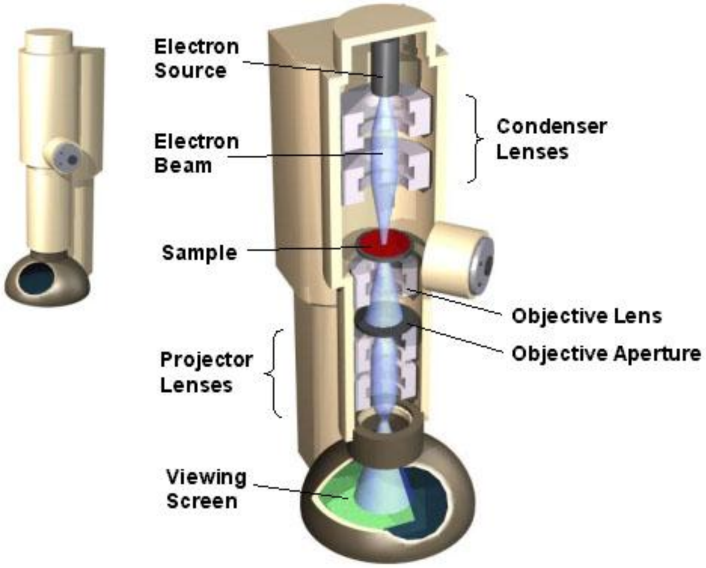


Figure 3.3 The schematic outline of a TEM.

Note: TEM and SEM images from: barrett-group.mcgill.ca

A TEM contains four parts: electron source, condenser lens system, sample holder, and viewing screen .

1. Electron source:

The electron source consists of a cathode and anode. The cathode is a type of tungsten filament which emits electrons upon heating. The beam is then directed towards the specimen by the positive anode. Electrons at the rim of main beam will fall on the anode while the others at the center will pass through the small hole at the anode. The electron source works like a cathode emitted ray tube.

2. Condenser lens system:

After leaving the electron source, the electron beam is tightly focused on by using Condenser type lens and metal type apertures. The system only allows the electrons within a small energy range of for passing through it.

3. Sample holder:

The sample holder is a type of platform equipped with a mechanical arm for holding the specimen and controlling its position.

4. Viewing Screen:

The imaging system consists of another projector lens system and a viewing screen. The projector lens system has two lens systems, one for use of refocusing the electrons after they pass through the placed specimen, and the other for the enlarging the image and projecting it onto the screen. The viewing screen has a phosphorescent plate which glows when being hit by electrons. Image in the forms similar to photography.

CHAPTER 4

EXPERIMENTAL WORK

4.1 KD2 pro Thermal Property analyzer:

KD2 pro is a hand held device used to measure thermal properties it consist of a hand held controller and sensor that can be inserted in to medium. The single needle sensor can measure thermal conductivity and resistivity while the dual needle sensor also measure volumetric specific heat capacity and diffusivity.KD2 pro sensor needle contains heating element and thermistor.The controller module contains a battery , a16 bit microcontroller/AD convertor, and power control circuit.

4.1.1 Working principal of KD2 Pro:- Each measurement cycle consist of 90 s, during the first 30s the KD2 pro will equilibrate which is followed by heating and cooling of needle of sensor for 30 s each. At the end of reading controller computes the thermal conductivity using the change in temperature (ΔT)- time data form as :

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

Where q is constant rate of heat applied to infinitely long and small line source ΔT_1 and ΔT_2 are the changes in temperature at the time t_1 and t_2 respectively. Thermal conductivity measurement assumes several things. Although these assumptions are not true in strict sense, they are adequate for accurate thermal property measurements.

- The long heat source can be treated as infinitely long heat source.
- The medium is homogeneous and isotropic.
- Uniform initial temperature of the sample.

Experiments results from pervious researcher's shows that sensor needle KS-1 of KD2 Pro takes accurate measurements up to and about 50^0 C. Above this range viscosity of fluid becomes low and free convection begins to effect the measurements.

KD2 pro is used for measurements because it has certain advantages over the guarded plate method used for thermal conductivity measurements. It has more accurate and higher range of thermal conductivity measurement as compared to guarded plate method in which convection mostly effect the measurements.

Specification:

Operating environment:

Controller: 0 to 50^0 C

Sensor: -50 to 150^0C

Power: 4aa cells

Display: 3cm x 6cm, 128 x 64 pixels graphics LCD.

Data storage: 4095 readings in flash memory.

Read mode: manual and automatic

Figure 4.1 KD2 pro Thermal property analyzer

Sensors:

4.1.2 Ks-1 single needle:

The small (60 mm long , 1.3 mm diameter) single KS-1 sensor measure thermal conductivity and thermal resistivity. It is designed primarily for liquid samples insulating materials (thermal conductivity < 0.1 W/m.k) . The KS-1 sensor applies very small amount of heat to needle which helps to prevent free convection in liquid samples.

Figure 4.2 Ks-1 single needle

Specification of KS-1 Needle:

Size: 1.3 mm diameter x 60 mm long

Range: 0.02 to 2.00 W/m.k (thermal conductivity)

500 to 50000C cm/W (thermal resistivity)

Cable length : 0.8m

Accuracy Conductivity: 5% from 0.2 - 2 (W/m.k)

0.01% from 0.02-0.2 (W/m.k)

Note : All the above data and Fig is taken from KD2 pro thermal properties analyzer, Operator's Manual (Version 10), supplied by Decagon Devices, Inc., WA 99163 USA .

4.2 Ultrasonic processor/sonicator:

Sonication is the act of applying sound (usually ultrasound) energy to agitate particles in a sample, for various purposes. In the laboratory, it is usually applied using a probe known as a sonicator. Sonication is commonly used in nanotechnology to disperse nanoparticles in liquids. Sonication can be used to speed dissolution, by breaking intermolecular interactions. It is especially useful when it is not possible to stir the sample. During the experiment, Oscar sonicator was used as shown in fig 4.1 below.

Figure 4.3 Ultra Sonicator

Table 4.1 Specifications:

Model	Processor SONOPROS PR-250MP
Ultrasonic Power	250 W
Processing capacity	250 ml
Frequency	20± 3KHZ
Convertor	PZT sandwich type OUC 116
Generator	Solid state LOT type.
Power input	230 V, 50HZ , 3 Amp
Application	Particle Dispersion

The probe is immersed in the sample which is to be sonicated. The probe bottom surface just touches the surface layer of the sample.

4.3 Brookfield DV-III Viscometer:

The Brookfield DV-III Ultra Programmable Rheometer measures fluid parameters of Shear Stress and Viscosity at given Shear Rates. Viscosity is a measure of a fluid’s resistance to flow. The principle of operation of the DV-III Ultra is to drive a spindle (which is immersed in the test fluid) through a calibrated spring. The viscous drag of the fluid against the spindle is measured by the spring deflection. Spring deflection is measured with a rotary transducer.

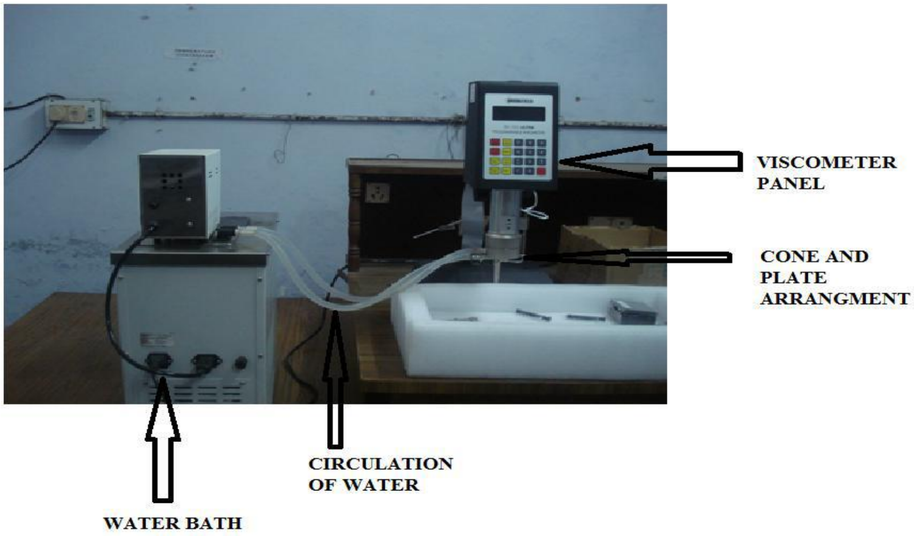


Figure 4.4 Brookfield DV-III Viscometer

Table 4.2 Specifications:

Model	DV-III Ultra
Speed Range	0.01 - 250 RPM
Temperature sensing range	-100^{0} C to 300^{0} C
Temperature Accuracy	$\pm$ 1.0^{0}C from -100^{0}C to 150^{0}C $\pm$ 2.0^{0}C from 150^{0}C to 300^{0}C
Analog Torque output	0-1 Volt DC (0-100 % torque)
Computer Interface	RS232
Torque accuracy	$\pm$ 1.0 % of full scale range
Torque repeatability	$\pm$ 2.0 %

4.4 Magnetic stirrer

A **magnetic stirrer** or **magnetic mixer** is a laboratory device that employs a rotating magnetic field to cause a stir bar immersed in a liquid to spin very quickly, thus stirring it. The rotating field may be created either by a rotating magnet or a set of stationary electromagnets, placed beneath the vessel with the liquid. Since glass does not affect a magnetic field appreciably (it is transparent to magnetism), and most chemical reactions take place in glass vessels, magnetic stir bars work well in glass vessels. On the other hand, the limited size of the bar means that magnetic stirrers can only be used for relatively small experiments.

Figure 4.5 Magnetic stirrer

CHAPTER-5

RESEARCH METHODOLGY

5.1 Introduction

The main aim of thesis work is to prepare nanofluids with Al_2O_3 nanoparticles and transformer oil as a base fluid which can be used for improving the heat transfer characteristics of the transformer oil. In this work the thermal conductivity and viscosity of transfer oil is studied by using Al_2O_3 nanoparticles. These analyses are performed by measuring thermal conductivity and viscosity of samples at different temperatures for the different volume concentrations and also by using different size of nanoparticles.

5.2 Materials used for preparing Nanofluids

5.2.1 Various types of nanoparticles used-

- Al_2O_3 (Average size- 20 nm (spherical)
- Al_2O_3 (Average size- 40 nm (spherical)
- Al_2O_3 (Average size- 40 nm (elongated)

5.2.2 Transformer oil and its properties:

(Transol - EHV grade-II):- Manufactured by Savita oil engines technology ltd.

This oil is mostly used in transformers due to its low viscosity and density. It has also low dielectric dissipation factor which reduces temperature rises during service because of lower electrical losses. It has high initial interfacial tension which helps in smoother functioning of oil. Following are the various properties of transol transformer oil.

Table no. 5.1 Properties of Transformer oil

Viscosity	< 16.5 cSt at 40^0C
Thermal conductivity	0.118 W/mk at 20^0C
Pour point	-30^0C
Flash point	$\geq 140^0$C
Electric strength	≥30 Kv rms (also called breakdown voltage)
Water content	≤50 ppm

Specific resistance	>1500 X 10^{12} at 27^0C

Note : www.savita.com/products_**transol**.htm :- Properties of transformer oil.

5.3 Selection of Temperature range for measurement:

The operating limits of transformer oil are bounded by the following factors:-

- Ambient temperature.
- Average winding temperature.
- The maximum winding hottest-spot temperature.

According to the IEEE C57.12.00-2000 standard, power transformer is rated on a maximum ambient temperature of 40° C. This standard also states that an average winding rise of 65° C shall not be exceeded when the transformer is operated at its rated load (KVA), voltage (V), and frequency (Hz). The average temperature of the winding cannot exceed 65° C above ambient, when operated at rated conditions. Maximum hottest-spot winding temperature cannot exceed a value of 80° C above ambient.

So due to above reasons and by taking in to account the measuring equipment accuracy the temperature range in our experiment is 20^0-50^0C.

5.4 Preparation of samples

Alumina (Al_2O_3 -40 nm (spherical & elongated) nanoparticles were purchased from Reinste Nano Ventures lab, Noida.

Alumina (Al_2O_3 -20 nm (spherical) nanoparticles were purchased from Nanoshel - Intelligent materials pvt Ltd. dera bassi, Punjab.

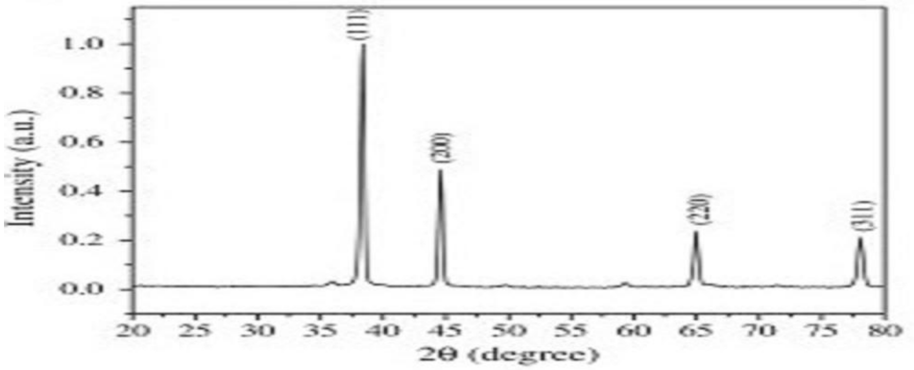


Figure 5.1 XRD result for Al_2O_3 nanoparticle diameter 20 nm

The size of nanoparticles is 20 nm.

Similarly SEM (scanning electron microscopy) results as provided by the supplier are sown in figure 5.2.

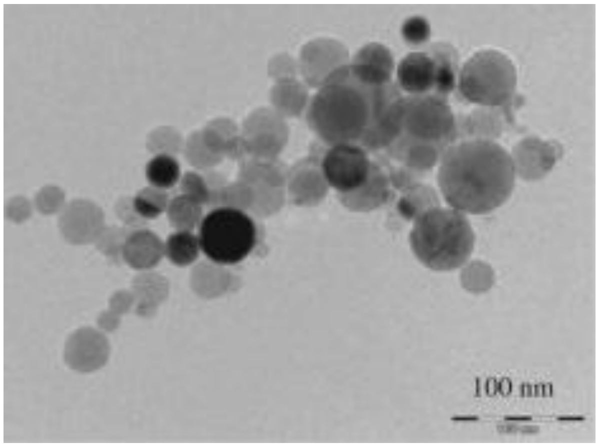


Figure 5.2 SEM result for Al_2O_3 nanoparticle diameter 20 nm

Similarly for verification of 40 nm (gamma) and 40 nm (alpha) nanoparticles XRD and TEM (Transmission electron microscopy) is done at NIPER (National institute of Pharmaceutical and Educational research) Mohali-Punjab.

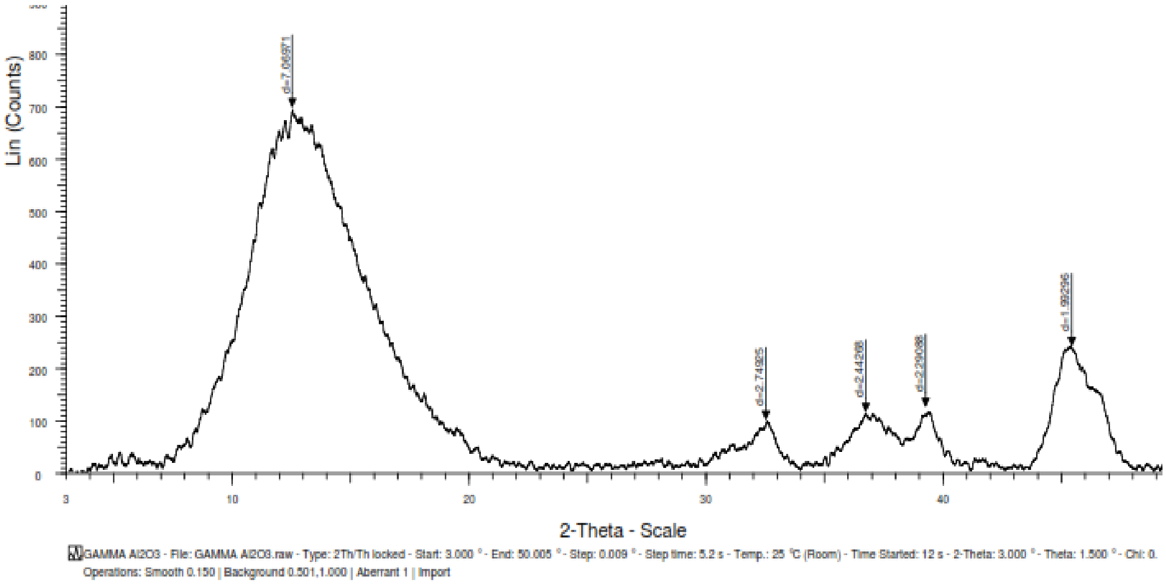


Fig 5.3 XRD result for Al_2O_3 nanoparticle diameter 40 nm (gamma)

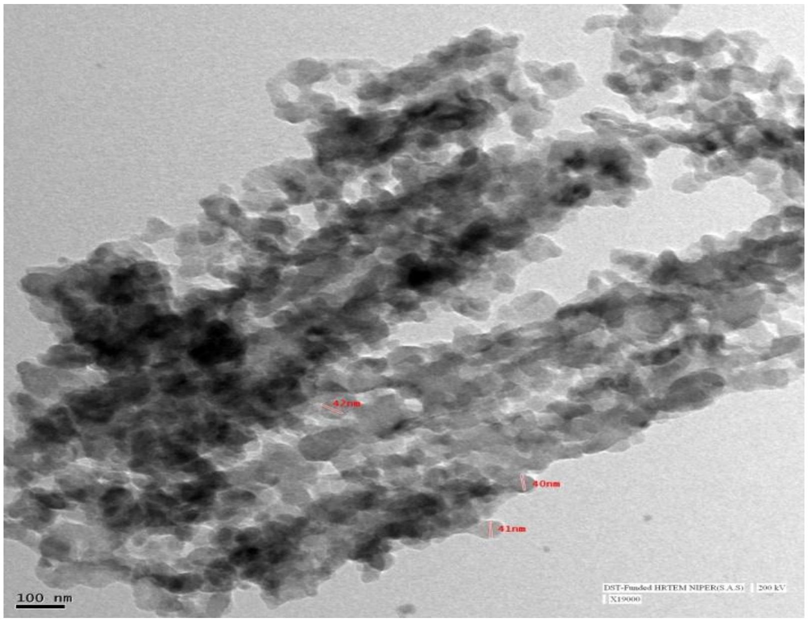


Fig 5.4 TEM result for Al_2O_3 nanoparticle diameter 40 nm (gamma)

For 40 nm alpha nanoparticles which are elongated in shape the XRD and TEM results obtained from NIPER as shown in the following figures:

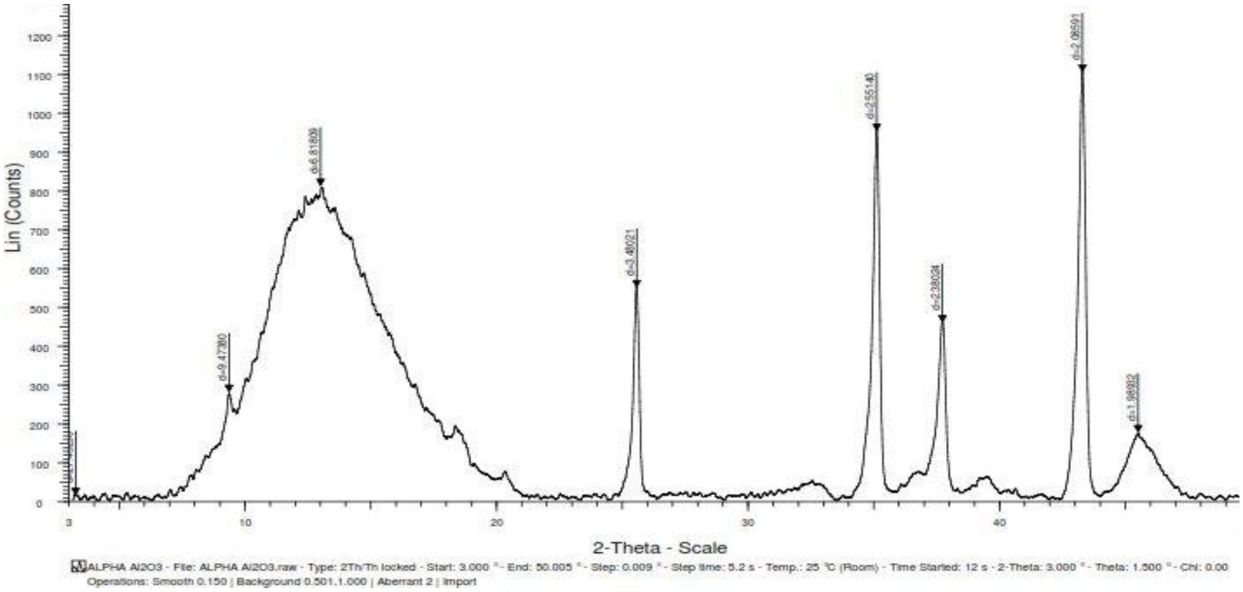


Fig 5.5 XRD result for Al_2O_3 nanoparticle diameter 40 nm (alpha)

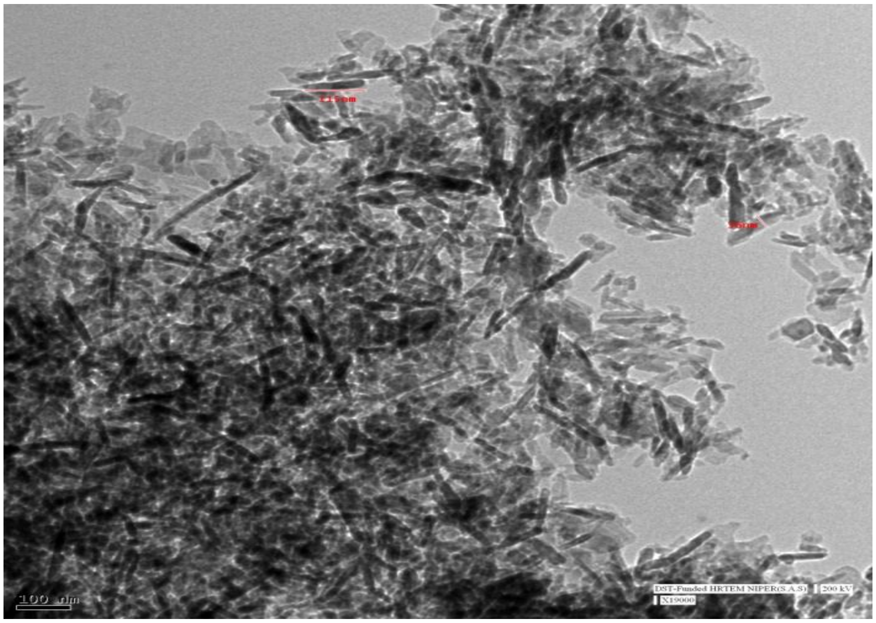


Fig 5.6 TEM result for Al_2O_3 nanoparticle diameter 40 nm (alpha)

Nanofluids are prepared by two step process. The nanoparticles are dispersed into the base fluid i.e. transformer oil. Different samples are prepared with volume concentration of 0.1 %, 0.3 %, and 0.5 % by mixing 3.2 gm, 6.4 gm, and 32 gm of nanoparticles in 50 ml of transformer oil. To make the nanoparticles more stable and remain more dispersed in water, ultra sonicator is used.

Sonication is done for 3 hours before testing thermal conductivity & viscosity of the nanotransformer oil. Sonication ensure more uniform dispersion of nanoparticles in base fluid. Figure 5.2 shows the prepared samples of nanotransformer oil which were taken for testing.

Fig 5.7 Prepared sample at different % vol. concentrations

Table No. 5.2 Concentrations and weights of prepared sample:

Sample / quantity	Sample 1	Sample 2	Sample 3
% vol. fraction	0.1	0.3	0.5
Weight (grams)	0.190	0.570	0.954
Nanoparticle density (gm /cm^3)	3.89	3.89	3.89

5.4.1 Sonication with Ultra Sonicator

Sonication is the act of applying sound (usually ultrasound) energy to agitate particles in a sample. In the laboratory, it is usually applied using an ultrasonic bath known as a sonicator.

Sonication can be used to speed dissolution, by breaking intermolecular interactions. It is especially useful when it is not possible to stir the sample. it is commonly used in nanotechnology for evenly dispersing nanoparticles in base fluids.

Sonication is the process of converting an electrical signal into a physical vibration that can be directed toward a substance. In our thesis work we have used probe type sonicator. It also transmits the vibration to the solution being sonicated. This probe is a carefully constructed tip that moves in time with the vibration, transmitting it into the solution. The probe moves up and down at a very high rate of speed, although the amplitude can be controlled by the operator and is chosen based on the qualities of the solution being sonicated.

Figure 5.8 Sonication of sample in Ultra Sonicator

5.5 Thermal Conductivity measurement

Thermal conductivity of nanotransformer oil is measured by using KD2 Pro instrument. The KD2 Pro uses the transient heated needle to measure thermal properties of solid and fluid media. With this technique, a heat pulse is applied to a needle, and the temperature response with time is monitored either at the heated needle or at an adjacent needle both during and after the heat pulse. The nature of the temperature response is a result of the thermal properties of the material. In low viscosity fluids, heat transfer by convection can be much greater than heat transfer by conduction.

Hence, accurate measurement of thermal properties of fluids requires that convective heat exchange should be negligible.

Fig 5.9 Measurement of thermal conductivity

During the measurement KS-1 sensor needle inserted in the sample taken in tube. The sensor needle dipped in sample for 90 s for each cycle of measurement. For first 30 s instrument will bring equilibrium. This is followed by heating and cooling of sensor needle for 30 s each. At the end of the cycle controller computes the thermal conductivity using transient hot wire method (THU) i.e. is change in temperature of nanotransfer oil w.r.t time.The needle used to measure thermal conductivity having following specification which suits our requirement:

Table No. 5.3 KD2 Pro needle specifications:

60 mm (small) single-needle (KS-1)	
Size	1.1 mm diameter x 60 mm long
Range of thermal conductivity	0.02 to 2.00 W/(m· K)
Range of thermal resistivity	50 to 5000 °C·cm/W
Accuracy (Conductivity)	± 5% from 0.2 - 2 W/(m· K) ±0.01 W/(m· K) from 0.02 - 0.2 W/(m· K)

Key points for KS-1 sensor needle:

- it adds very small amount of heat to the sample to minimize the problems with free convection
- Sensor needle should be orient vertically during the measurement and also not touches the walls of test tube to obtain more accurate results.

5.6. Measurement of viscosity

For the measurement of viscosity of nanofluids, Brookfield Viscometer (LV-DIII CP) is used as discussed in previous chapter. This is a new type of viscometer in which the amount of sample used is very less generally of 1 ml. It consists up a cone, which is attached to the spindle of the viscometer and a plate which is usually the inner part of sample chamber in the instrument. For the temperature variation, a water bath is attached with the viscometer where temperature can be varied from -10^{0}C to 100^{0}C. Auto zeroing of the viscometer is essential before starting the operation.

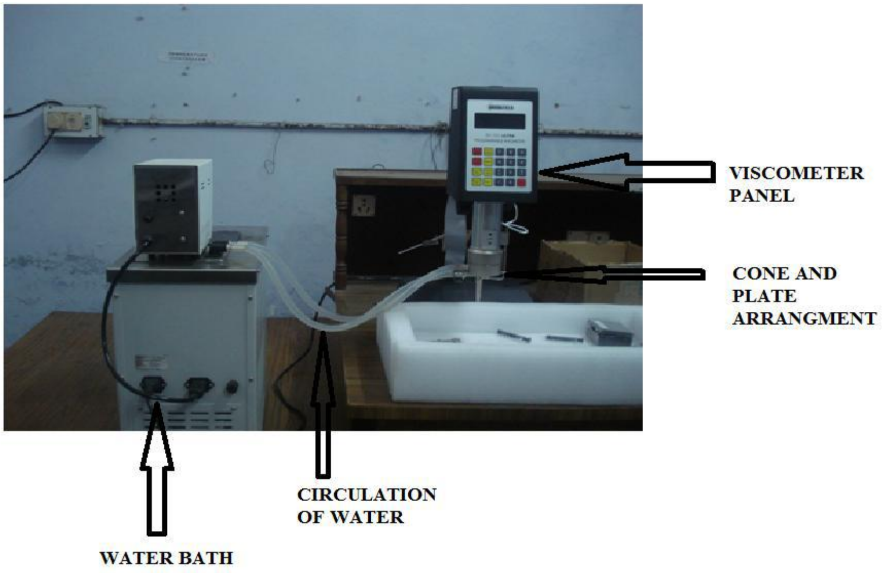


Figure. 5.10 Viscosity measurement using Brookfield Cone/Plate viscometer

As the cone rotates sample layer at the bottom offers viscous drag to the rotation of cone this viscous drag results change in tension in the spring and the results are computed on the digitizer screen. The arrangement is like in way that, water circulates from the outer portion of sample chamber and in this way the temperature of the sample chamber can be increased or decreased according to the requirement as shown in figure 5.10

Before starting the viscometer, the main point is the gap setting. The gap in between the sample holder (plate) and the cone is 0.005 in. So this gap should be maintained properly and then maintain the temperature of sample chamber. After maintaining the gap and temperature, we can use the viscometer. Fig. 5.11 shows the gap indicator which indicates the gap in between the cone and sample chamber.

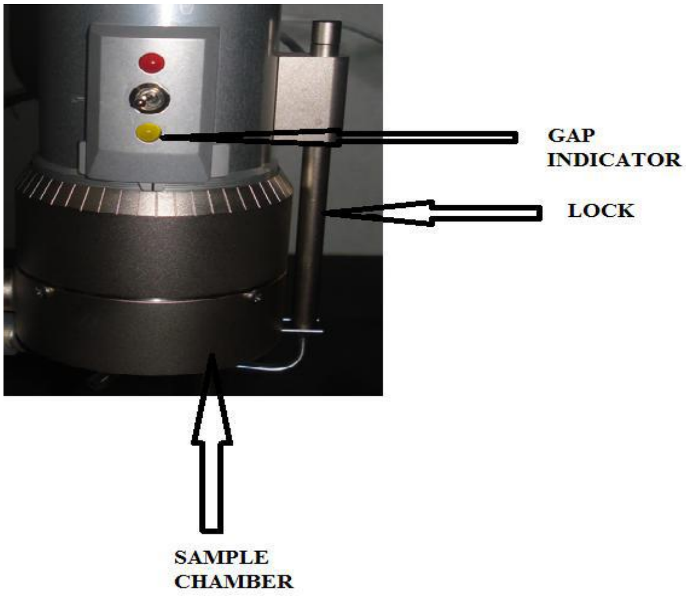


Figure 5.11 Gap setting in the viscometer

For taking the readings set the temperature to be maintained from the back side switch of its refrigerating unit. As the required temperature is obtained readings are taken by varying the R.P.M of spindle in the range 10-70.Viscometer not provides more accurate results above this range. Fig. 5.12 shows the cone which rotates inside the sample chamber.

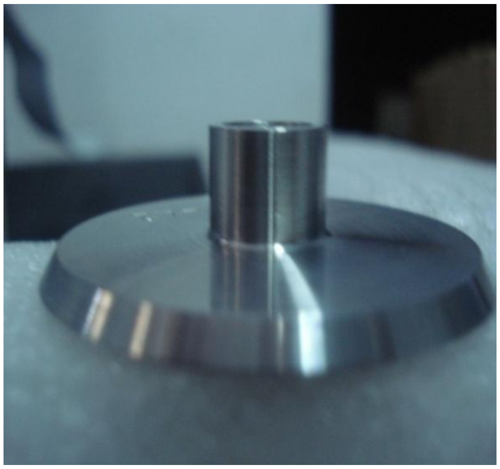


Fig. 5.12 cone plate used in viscometer

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Thermal Conductivity & Viscous behavior of nanotransformer oil

Experiments are performed to measure the Thermal conductivity & viscosity of Al_2O_3 - transformer oil based nanofluid. A detailed report on the observed results is presented in this chapter.

6.2 Thermal Conductivity behavior of nanotransformer oil

6.2.1 Effect of % Vol. fraction on thermal conductivity of nanotransformer

6.2.1.1 Transformer oil with 20 nm Al_2O_3 nanoparticles:

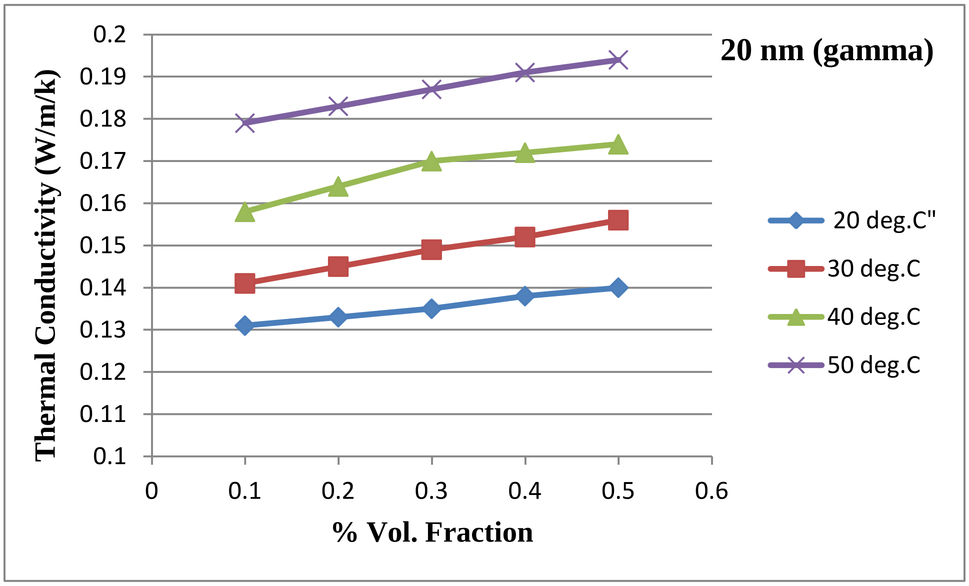


Fig. 6.1 Thermal conductivity v/s % vol. fraction for 20nm nanoparticles

6.2.1.2 Transformer oil with 40 nm (gamma) Al_2O_3 nanoparticles:

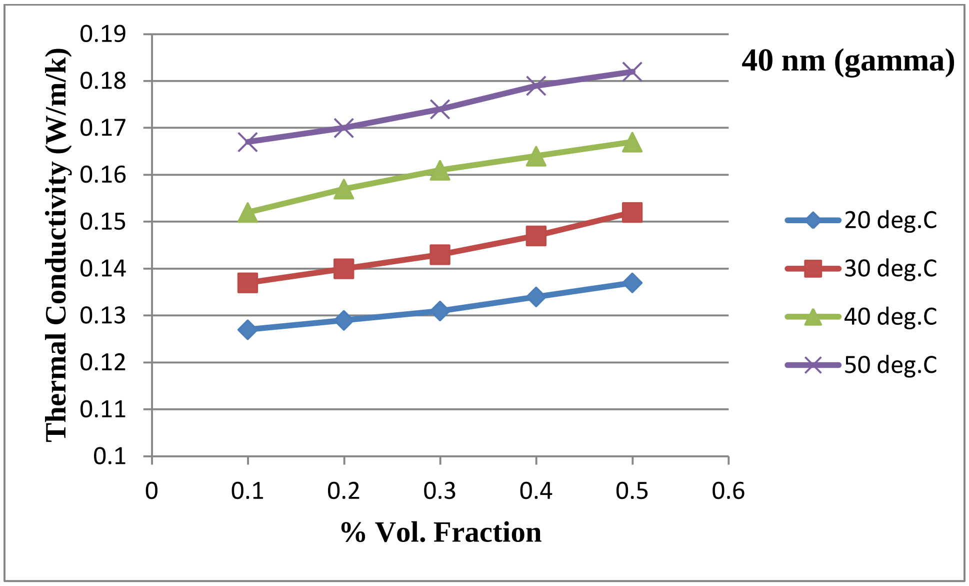


Figure 6.2 Thermal conductivity v/s % vol. fraction for 40nm nanoparticles

6.2.1.3 Transformer oil with 40 nm (alpha) Al_2O_3 nanoparticles:

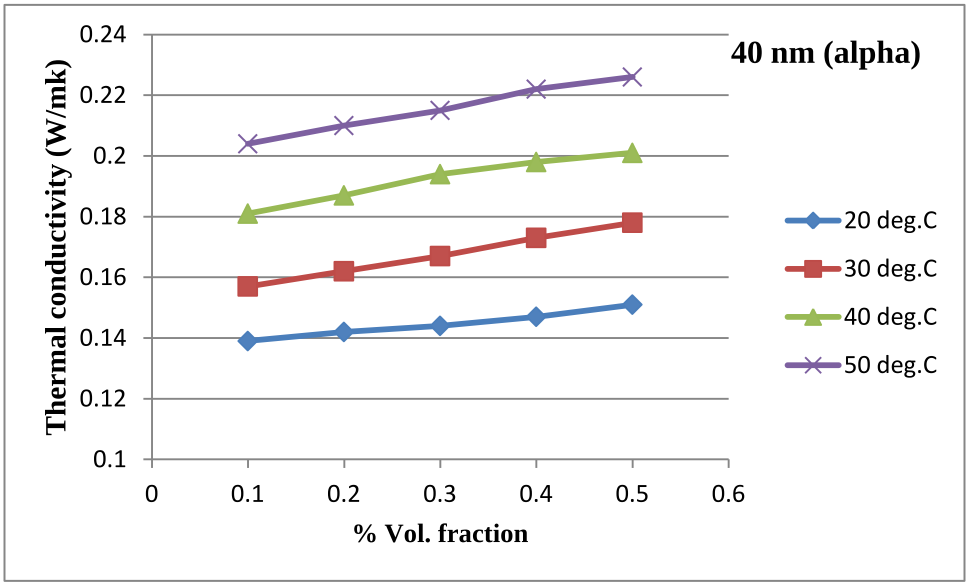


Fig. 6.3 Thermal conductivity v/s % vol. fraction for 40nm (alpha) nanopaerticles

Thermal conductivity of nanotransformer oil increases almost linearly with volume concentration of nanoparticles. As the volume fraction of nanoparticles increases particle to particle interaction increase in the nanotransfomer oil due to which leads to higher heat transfer from one particle to another. This leads to increase in thermal conductivity with increase in particle volume fraction.

For 20 nm size nanoparticles at 0.1 % vol. fraction of nanoparticles the thermal conductivity enhancement is up to 36% .At lower temperature increase in thermal conductivity is less w.r.t volume fraction of nanoparticles. In the temperature range from 20^0 to 30^0 C the volume fraction has lesser effect on thermal conductivity rise but in the temperature range of 40^0-50^0 C thermal conductivity rises sharply, reason being potential energy of nanoparticles increase with increase in temperature of nanotransformer oil. For 0.3 % vol. fraction of nanoparticles the thermal conductivity enhancement up to 38.5%. Similarly for 0.5% vol. fraction of nanoparticles the enhancement in thermal conductivity enhancement is 38%. It has been observed that thermal conductivity enhancement for the volume fraction from 0.3 to 0.5 % as compared to 0.1 to 0.3 %. It is expected that at higher concentration stability concern arises and particle settling problems occurs which effect the Thermal conductivity enhancement of nanotransformer oil.

For 40 nm (gamma) at 0.1 % vol. fraction of nanoparticles the thermal conductivity enhancement is up to 31.4 %. Similarly at 0.3 & at 0.5% vol. fraction thermal conductivity enhancement is 32.8 and 32 % respectively. It is also observed that thermal conductivity is not increasing significantly with increase in volume fraction of nanoparticles in the range from 0.3 to 0.5 %.

For 40 nm (alpha) particles which are elongated in shape shows significant rise in thermal conductivity as compared to spherical nanoparticle of 20 and 40 nm respectively. At 0.1% volume fraction of nanoparticles the thermal conductivity rise is 46.7%.Similarly for 0.3 and 0.5 % volume fraction of nanoparticles thermal conductivity rises is 49.3 % and 49.6 % respectively. Elongated nanoparticles shows 17% more rise in thermal conductivity as compared to spherical nanoparticles at same volume fraction. This occurs due to their more surface contact area with the base fluid to conduct heat more efficiently.

6.2.2 Effect of Temperature on thermal conductivity of nanotransformer oil.

6.2.2.1 Transformer oil with 20 nm Al_2O_3 nanoparticles:

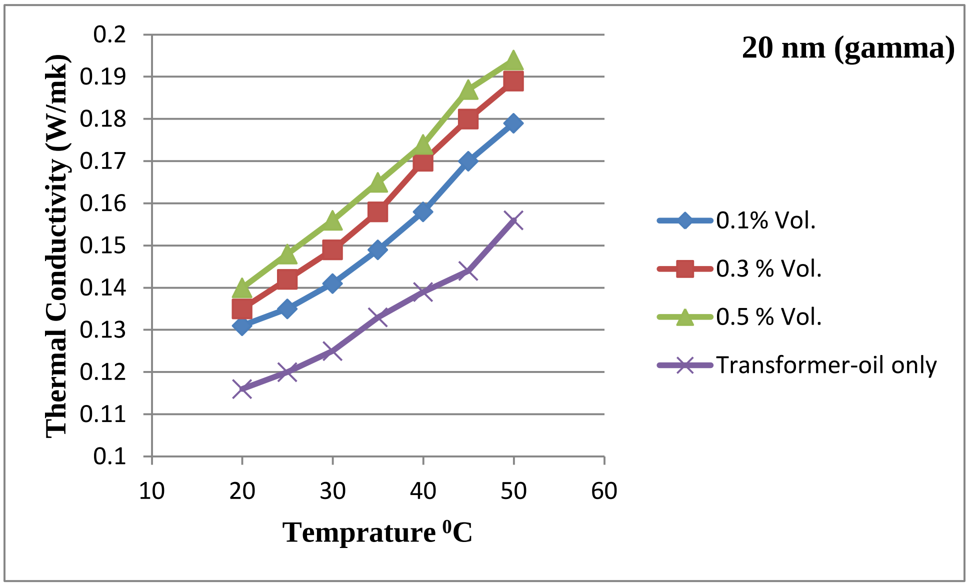


Fig. 6.4 Thermal conductivity v/s Temperature with 20nm nanoparticles

6.2.2.2 Transformer oil with 40 nm (gamma) Al_2O_3 nanoparticles:

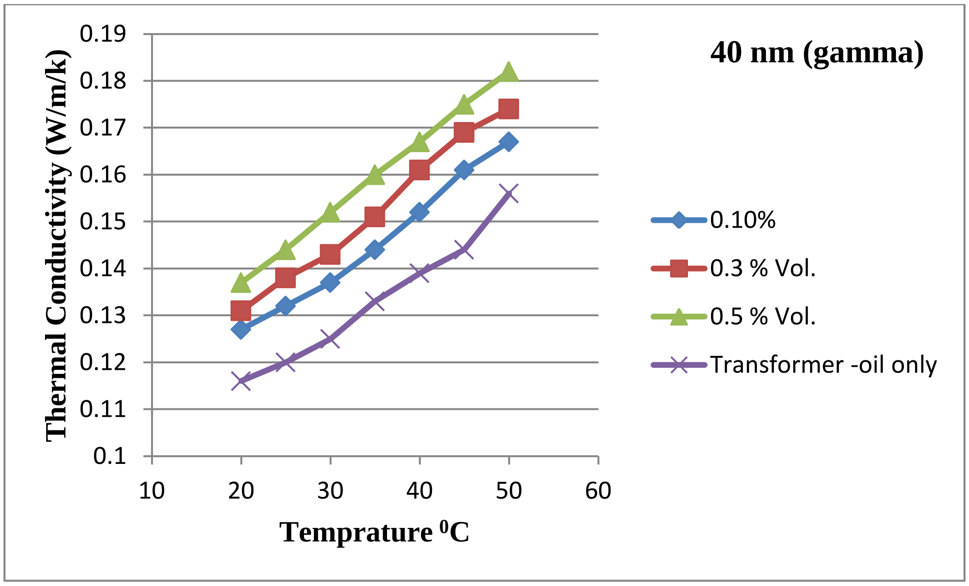


Figure 6.5 Thermal conductivity v/s Temperature with 40nm (gamma)

6.2.2.3 Transformer oil with 40 nm (alpha) Al_2O_3 nanoparticles:

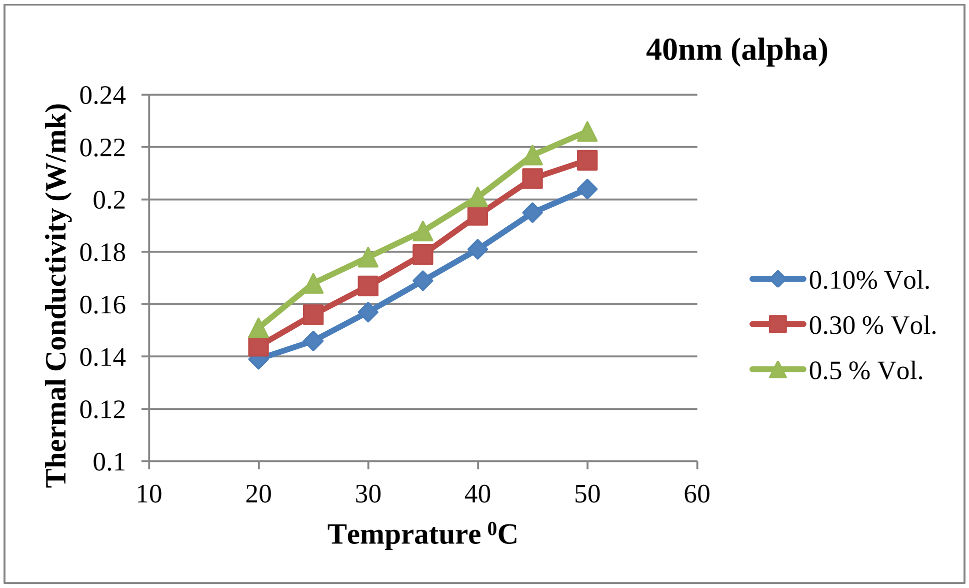


Figure 6.6 Thermal conductivity v/s Temperature with 40nm (alpha)

Temperature has significant effect on thermal conductivity behavior of nanotransformer oil. Thermal conductivity of nanotransformer oil increase with increase in temperature of base fluid. Molecular momentum transfer of nanoparticles increase with increase temperature of base fluid .Brownian motion and Brownian speed of nanoparticles also effect the Thermal conductivity of nanotransformer oil with change in temperature.

For 20 nm nanoparticles at 0.1% vol. fraction the thermal conductivity rises from 7.6 % in the temperature range from 20^0-30^0C. Similarly 12.7 % and 12.6% rise in thermal conductivity is observed in the temperature range from 30-40^0C and 40-50^0C respectively. In the lower temperature range thermal conductivity increase is not sharp, where as for higher temperature range significant increase in thermal conductivity is observed. This occurs because at higher temperature Brownian motion of the nanoparticles which effects the thermal conductivity of nanotransformer oil. Brownian motion of the particles increases with increase in temperature due to this heat transfer rate from particle to particle increases which leads to increase in thermal conductivity. Brownian speed of nanoparticles also increase with increase in temperature of base fluid and momentum transfer of nanopaticles increases.

In the temperature range of 20^0-30^0C thermal conductivity rise is 10.3 and 11.4 % at 0.3 and 0.5 % vol. fraction of nanoparticles respectively. Similarly In the temperature range of 30^0-40^0C thermal conductivity rise is 14.1 and 11.5 % at 0.3 and 0.5 % vol. fraction of nanoparticles respectively. For 40^0-50^0C thermal conductivity rise is 11.1 and 11.5 at 0.3 and 0.5 % vol. fraction of nanoparticles.

For 40 nm (gamma) nanoparticles in the temperature range of 20^0-30^0C thermal conductivity rises are 7.8, 9.1, and 10.9 % at 0.1, 0.3 and 0.5 % vol. fraction respectively. For the temperature range of 30^0-40^0 C thermal conductivity rise is 10.9, 12.6 and 9.8 % at 0.1, 0.3 and 0.5 % vol. fraction respectively. For the higher temperature range of 40^0-50^0C thermal conductivity rise is 9.8, 8.1 and 8.8 % at 0.1, 0.3 and 0.5 % vol. fractions respectively.

For 40 nm (alpha) elongated shape particles shows significantly higher rise in thermal conductivity of nanotransformer oil as compared to 20 nm and 40 nm (gamma) nanoparticles. In the temperature range 20^0- 30^0C thermal conductivity rise is 12.9, 15.8 and 17.8 at 0.1, 0.3 and 0.5 % vol. fraction respectively. Similarly for the temperature range of 30^0- 40^0C Thermal conductivity rises are 15.2, 16.3 and 12.9 % at 0.1, 0.3 and 0.5 % vol. fraction respectively. For the higher temperature range of 40^0- 50^0C Thermal conductivity rise is 12.7, 10.8 and 12.4 % at 0.1, 0.3 and 0.5 % vol. fraction respectively. Elongated particles shows more increase in thermal conductivity due to their higher surface of contact with the base fluid due to which more conductive heat transfer in case of these particles.

From the results it indicates that thermal conductivity increases significantly up to temperature range 30^0- 40^0C and % vol. fraction from 0.1-0.3.

6.2.3 Effect of Nanoparticle size on thermal conductivity of nanotransformer oil.

6.2.3.1 Size effect with 0.1 % vol. fraction

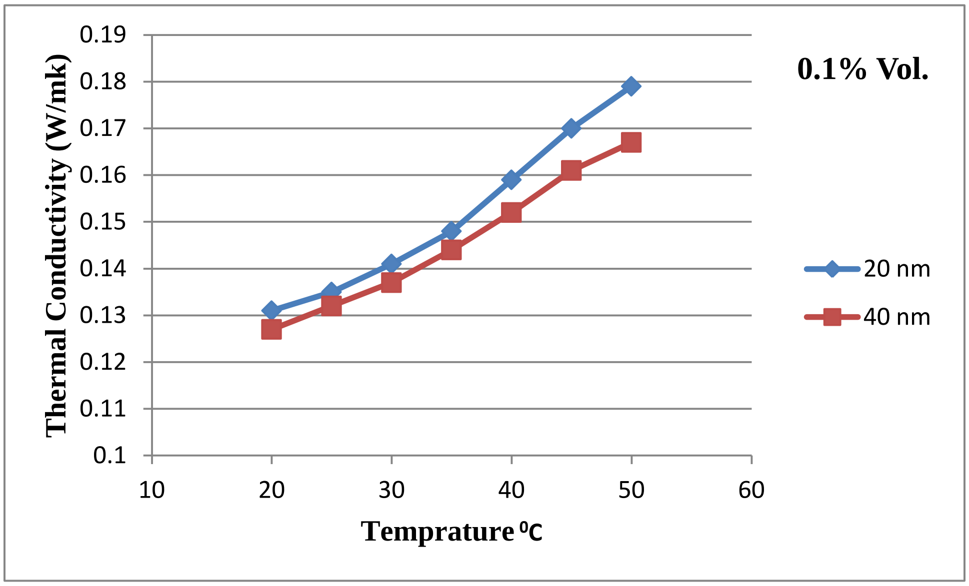


Figure 6.7 Thermal conductivity v/s Temperature at 0.1 % vol fractions

6.2.3.2 Size effect with 0.3 % vol. fraction

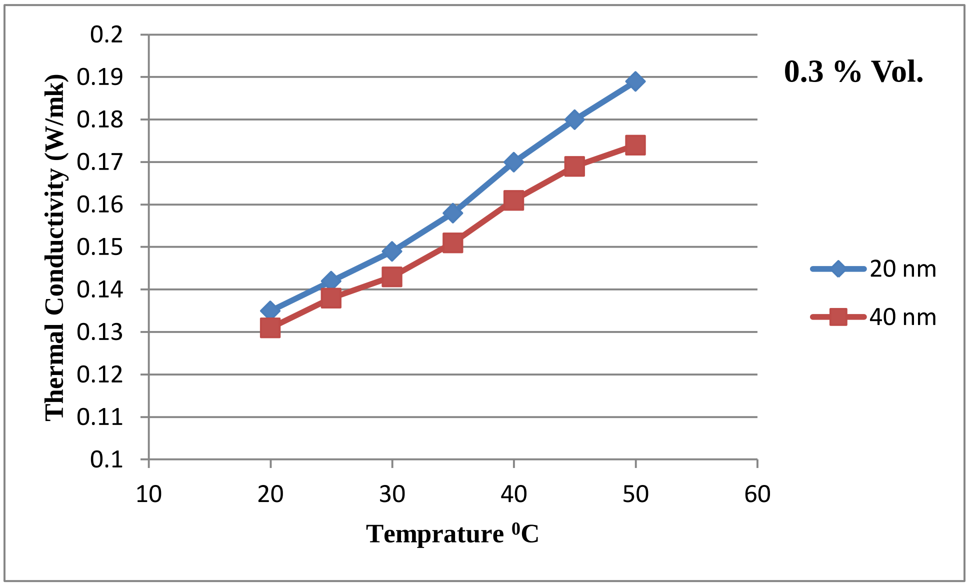


Figure 6.8 Thermal conductivity v/s Temperature at 0.3 % vol fractions

6.2.3.3 Size effect with 0.5 % vol. fraction

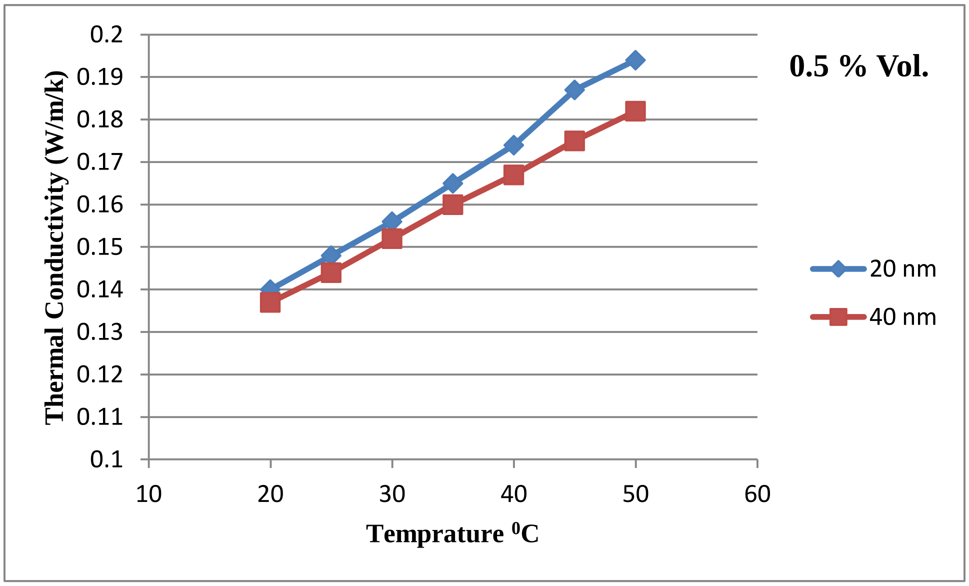


Figure 6.9 Thermal conductivity v/s Temperature at 0.5% vol fractions

Size of the nanoparticles is also one of significant parameter in studying the thermal conductivity behavior of nanotransformer oil. Nanoparticle size effect the distribution of nanoparticles in the base fluid. It also effects the formation of nanolayer i.e. thickness of base fluid around the nanoparticles. Nanoparticle size also produces considerable effect on Brownian motion of the nanoparticles in base fluid. Thermal conductivity decrease with increase in size of nanoparticles.

With increase in size of nanoparticles from 20 nm to 40 nm thermal conductivity decreases to 2.7, 4.4 and 3.1 % at 0.1, 0.3 and 0.5% vol. fraction respectively in the temperature range from 30^0-40^0 C. This decrease in thermal conductivity occurs due to the reason that smaller size nanoparticles have more uniform distribution in base fluid and nanolayer thickness also affects the thermal conductivity. For smaller size nanoparticles nanolayer thickness is more because average spacing between the particles is more so more rise occurs in thermal conductivity. As the particle size increase average spacing between the nanoparticles decreases which decrease thermal conductivity of nanotransformer oil.

Similarly for the temperature range 40^0-50^0 C thermal conductivity decreases to 5.3, 6.1 and 6.4 % at 0.1, 0.3 and 0.5% vol. fraction respectively. Larger particle size Brownian motion also affects their thermal conductivity because Brownian speed of larger nanoparticles reduces as compared to smaller particles which lead to decrease in thermal conductivity. At lower temperature range their is significant decrease in thermal conductivity with increase in size due to lesser Brownian speed because at low temperature momentum transfer of nanoparticle decreases.

6.2.4 Effect of Nanoparticle Shape on Thermal conductivity of Nanotransformer oil.

6.2.4.1 Shape effect of nanoparticles with 0.1% vol. fraction

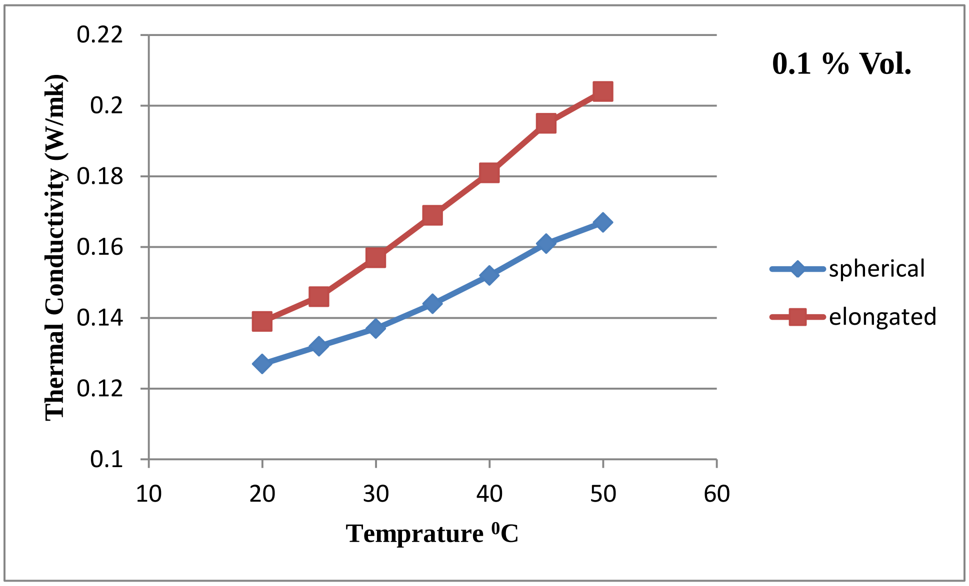


Figure 6.10 Thermal conductivity v/s Temperature at 0.1% vol. fractions

6.2.4.2 Shape effect of nanoparticles with 0.3% vol. fraction

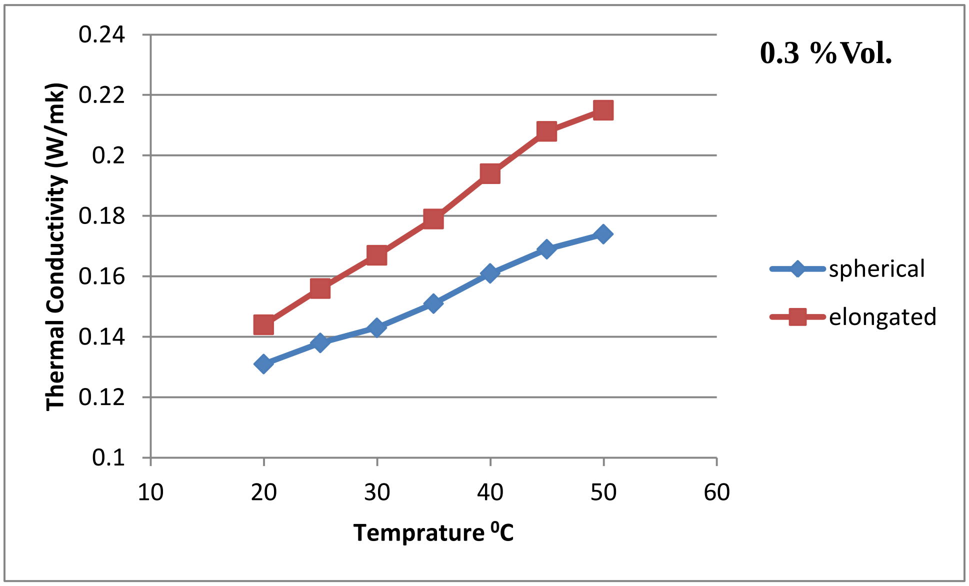


Figure 6.11 Thermal conductivity v/s Temperature at 0.3% vol. fractions

6.2.4.3 Shape effect of nanoparticles with 0.5% vol. fraction

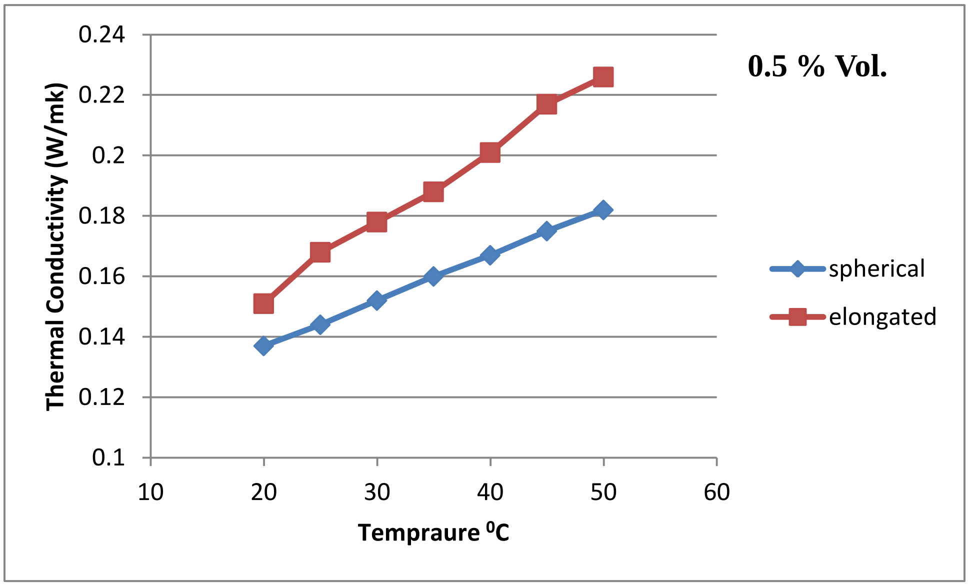


Figure 6.12 Thermal conductivity v/s Temperature at 0.5% vol. fractions

Nanoparticle shape is one of significant parameter in studying the thermal conductive behavior of nanotransformer oil. Elongated nanoparticles shows higher thermal conductivity rise as compared to spherical particles because of their higher aspect raito and more surface area of contact with base fluid. Significant rises obtained in thermal conductivity of nanotransformer oil by changing shape of particles are as follow:

Thermal conductivity enhancements is 17.4, 18.6 and 17.5 at 0.1, 0.3 and 0.5 % vol. fraction respectively in the temperature range from 30^0-40^0. Similarly in the temperature range of 40^0-50^0 C Thermal conductivity enhancements is 21.1, 18.7 and 24 % at 0.1, 0.3 and 0.5% vol. fraction respectively. In the lower temperature range from 20^0-30^0C thermal conductivity enhancements are 10.6, 13.1 and 16.6 % at 0.1, 0.3 and 0.5 % vol. fraction respectively.

Higher thermal conductivity enhancements for elongated particles over the spherical particles due to the mesh formed by elongated particles to conduct heat through the fluid. Elongated particles are more properly aligned in the nanolayer which also affects their thermal conductivity. Due to this the thickness of nanolayer more uniform and increases which leads to increase in thermal conductivity for elongated particles as compared to spherical particles.

6.3 Viscosity behavior of Nanotransformer oil

6.3.1 Effect of % Vol. fraction of on Viscosity of nanotransformer

6.3.1.1 Effect of % Vol. fraction of 20 nm Al_2O_3 on Viscosity

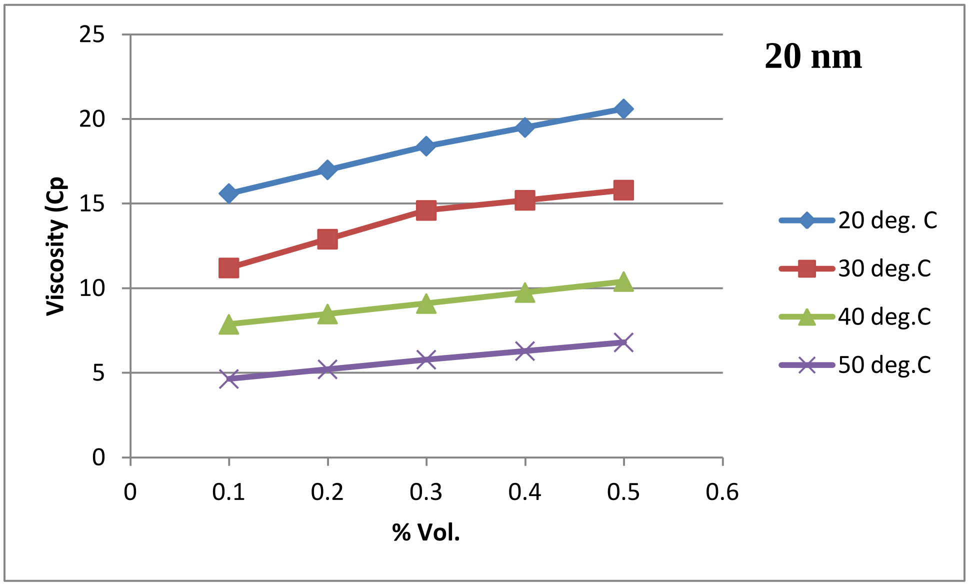
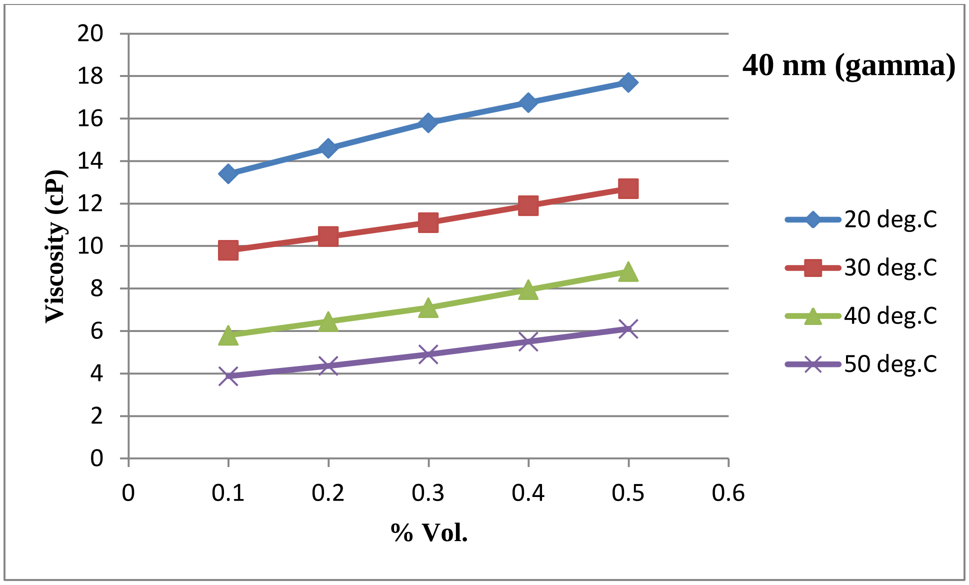


Figure 6.13 Viscosity v/s % Vol. fractions for 20 nm Al_2O_3 particles.

6.3.1.2 Effect of % Vol. fraction of 40 nm (gamma) Al_2O_3 on Viscosity



6.3.1.3 Effect of % Vol. fraction of 40 nm (alpha) Al_2O_3 on Viscosity

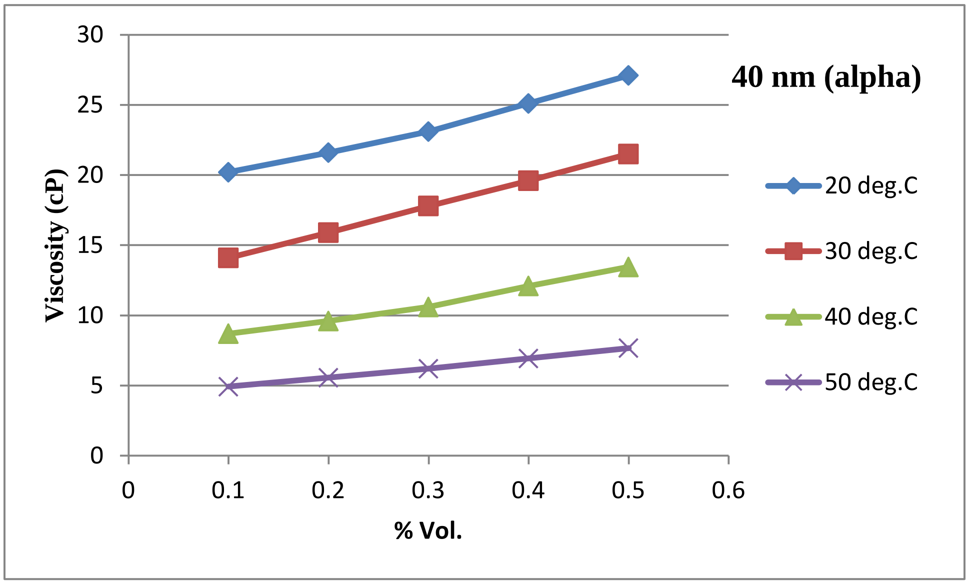


Figure 6.15 Viscosity v/s % Vol. for 40 nm (alpha) Al_2O_3 particles.

Viscosity of nanotransformer oil increases linearly with nanoparticle loading. Due to increase in concentration of nanoparticle shear stress in nanotransformer oil increases which leads to increase in viscosity of nanotansformer oil. It is observed that viscosity increase for 20 nm size nanoparticle is 17.9, 15.6 and 24.5% for volume fraction from 0.1 to 0.3 % in the temperature range from 20- 50^0 C.

Viscosity increases sharply in the lower concentration range because significant increase in shear stress w.r.t shear rate. But at the higher concentration range shear stress increases not at faster rate as compared to lower concentration range. So viscosity enhancement is less in the higher concentration range.

For 40nm (gamma) the viscosity rise is 17.1, 13.2 and 26.6% at volume faction 0.1, 0.3 and 0.5% respectively. At higher volume fraction the rise in viscosity is more as compared to 20 nm nanoparticles. Because for larger size particles viscous shear stress is more as compared to smaller size particles at higher volume fraction of nanoparticles.

For 40nm (alpha) nanoparticles which are elongated in shape the viscosity rise due to volume fraction is more at higher concentration as compared to 40nm gamma and 20nm size nanoparticles. Viscosity rise is 18.3, 26.2 and 28.3% at volume faction 0.1, 0.3 and 0.5% respectively.

6.3.2 Effect of Temperature on Viscosity of nanotransformer oil

6.3.2.1 Effect of Temperature on Viscosity with 20 nm Al_2O_3

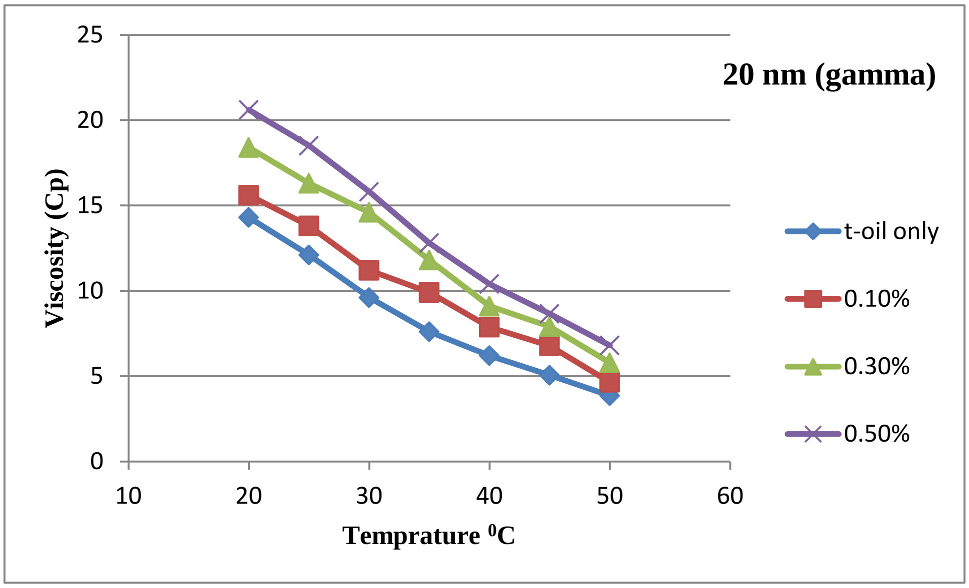


Figure 6.16 Viscosity v/s Temperature for 20 nm (gamma) Al_2O_3 particles.

6.3.2.2 Effect of Temperature on Viscosity with 40 nm (gamma) Al_2O_3

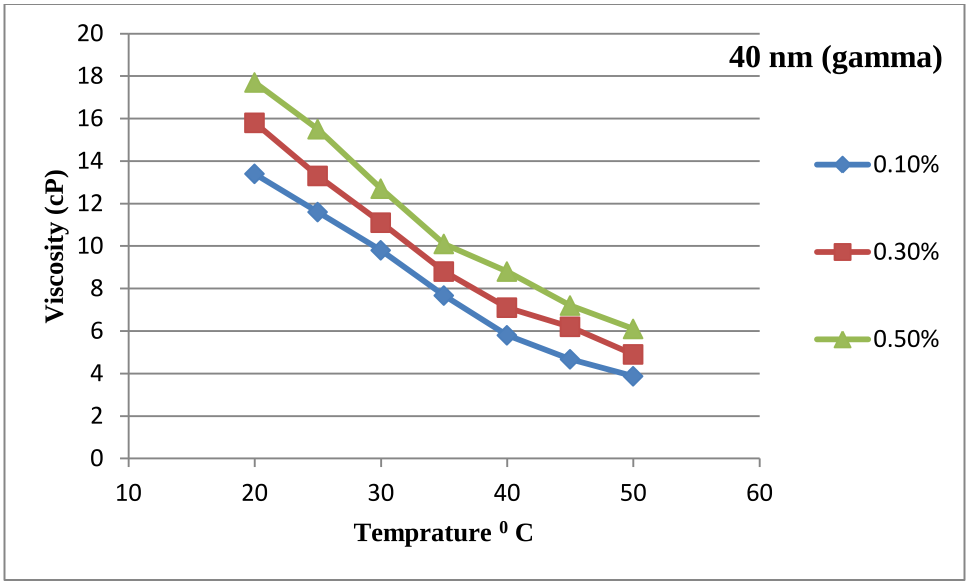


Figure 6.17 Viscosity v/s Temperature for 40 nm (gamma) Al_2O_3 particles.

6.3.2.3 Effect of Temperature on Viscosity with 40 nm (alpha) Al_2O_3

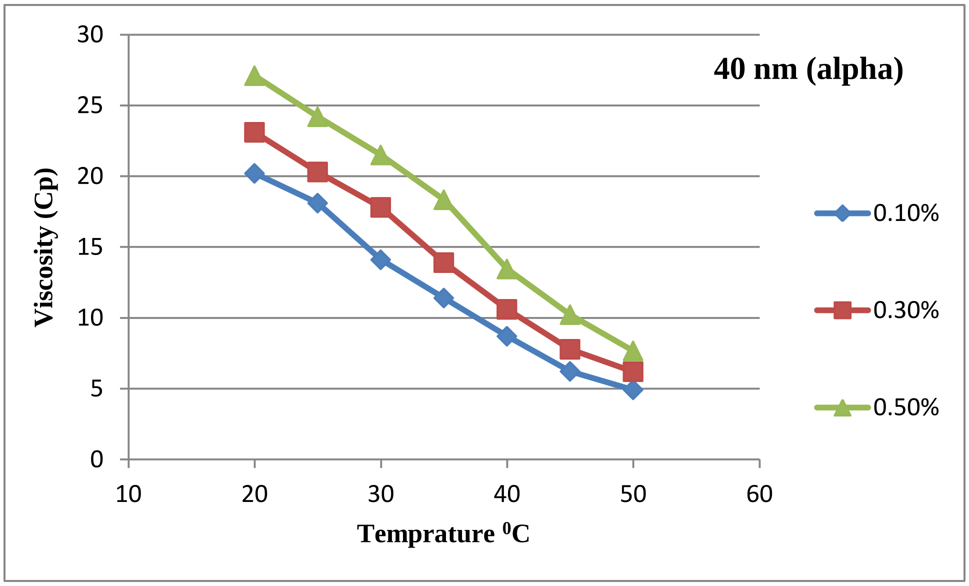


Figure 6.18 Viscosity v/s Temperature for 40 nm (alpha) Al_2O_3 particles.

Viscosity of nanotransformer oil decrease significantly with the increase in temperature. Viscosity is the property possessed by fluid by virtue of its interfacial layer resistance over the other layer. As the nanotransformer oil temperature rises the viscous shear force in particular layer of nanotransformer oil decreases due to which viscosity of nanotransformer oil decreases. For higher temperature range larger decrease in viscosity of nanotransformer oil observed as compared to lower temperature range at same volume fraction of nanoparticles.

For the temperature range from 20^0-30^0C viscosity decreases to 28.2, 20.6 and 23.3 % at the volume concentrations of 0.1, 0.3 and 0.5 % respectively. In the lower concentration range of nanoparticles more decrease in viscosity is observed at the same temperature range. Similarly for the temperature range from 30^0-40^0 C viscosity decreases is 29.7, 37.6 and 34.1 % at the volume concentration of 0.1, 0.3 and 0.5 % respectively. For the higher temperature range decrease in viscosity is more as compared to lower temperature in the given volume concentration range. For the temperature range from 40^0-50^0 C viscosity decreases to 41.1, 20.4 and 23.3 % at the volume concentrations 0.1, 0.3 and 0.5% respectively

6.3.3 Effect of Nanoparticle size on Viscosity of nanotransformer oil.

6.3.3.1 Size effect on Viscosity with 0.1 % vol. fraction of nanoparticles.

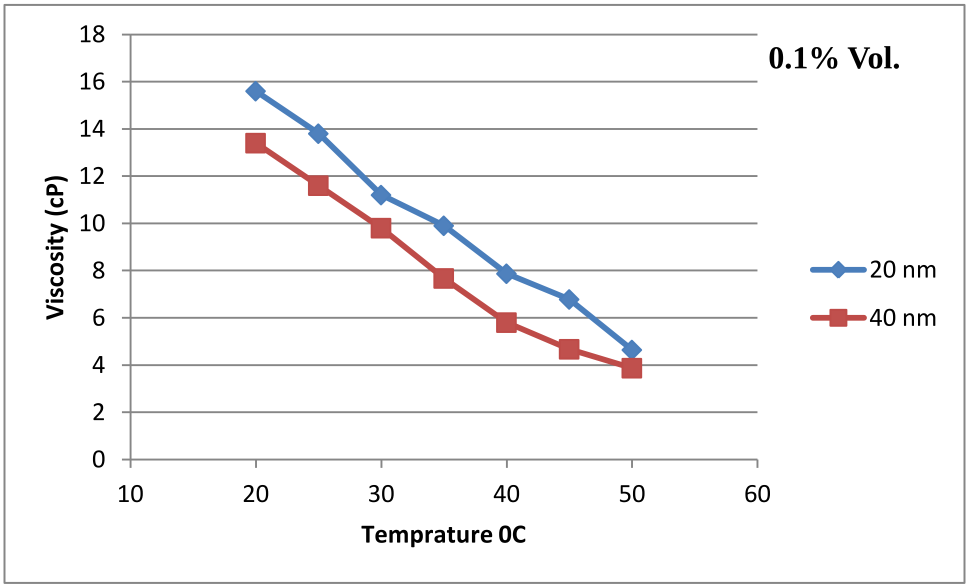


Figure 6.19 Viscosity v/s Temperature at 0.1% vol fractions

6.3.3.2 Size effect on Viscosity with 0.3 % vol. fraction of nanoparticles.

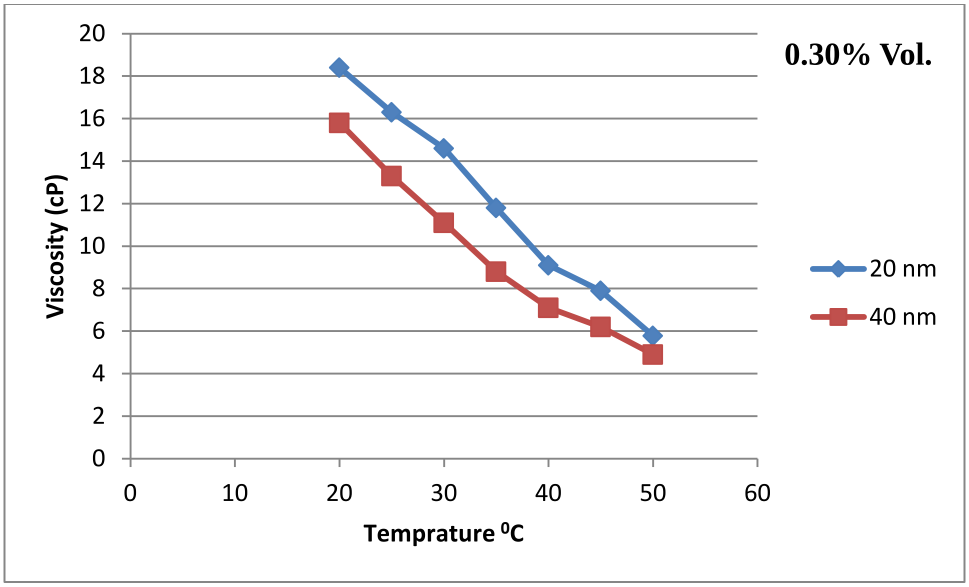


Figure 6.20 Viscosity v/s Temperature at 0.3% vol fractions

6.3.3.2 Size effect on Viscosity with 0.5 % vol. fraction of nanoparticles.

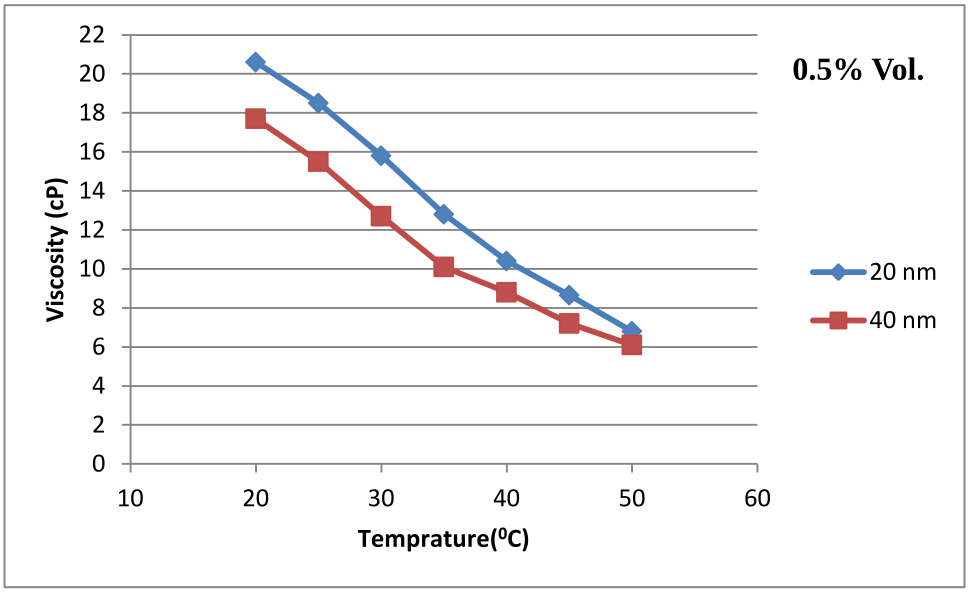


Figure 6.21 Viscosity v/s Temperature at 0.5% vol. fractions

Viscosity of nanotransformer oil decrease with increase in size of nanoparticles. Viscosity of nanotransformer oil proportional to the average spacing b/w the nanoparticles.Avereage spacing b/w the nanoparticles proportional to the diameter of nanoparticles. With increase in diameter of nanoparticles the average spacing b/w the particles decrease which leads to decrease in viscosity of nanotransformer oil. Internal resistance b/w the nanotransformer oil layers decreases and significant decrease in viscosity is observed.

For increase in diameter from 20 nm to 40 mn viscosity decreases is 16.4, 26.3 and 16.6% at 20^0, 40^0 and 50^0C respectively at 0.1% volume fraction. Similarly at 0.3% volume fractions the viscosity decreases is 14.1, 21.9 and 15.2% at the same temperature ranges.

At higher volume fraction viscosity drop in the value is almost same up to 40^0 C but at higher temperature it drops significantly. At 0.5% volume fractions the viscosity decreases is 14.2, 15.4 and 10.3 % at the same temperature ranges. Also at higher temperature viscous shear stress decreases sharply.

6.3.4 Effect of Nanoparticle Shape on Viscosity of nanotransformer oil.

6.3.4.1 Shape effect of alumina nanoparticles with 0.1% vol. fraction

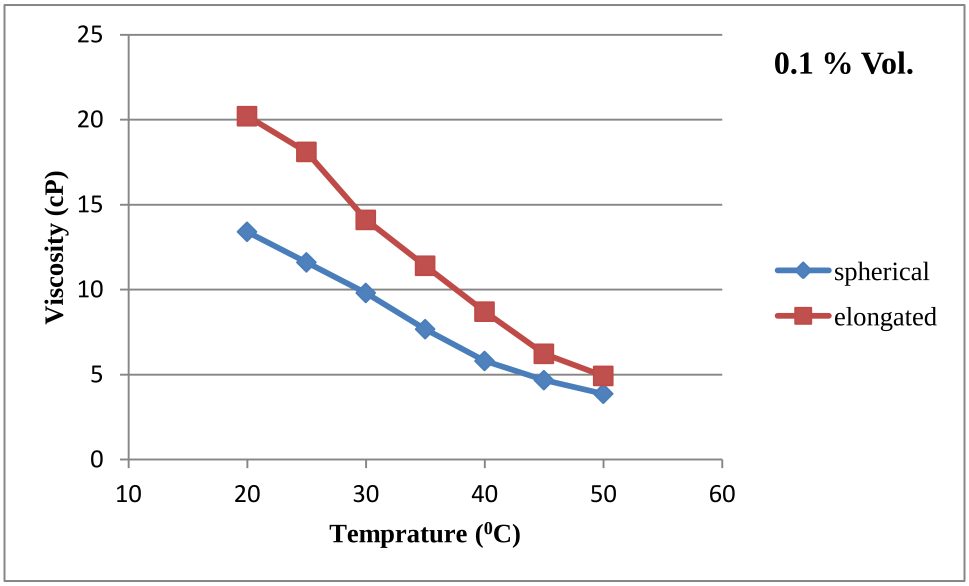


Figure 6.22 Viscosity v/s Temperature at 0.1% vol fractions

6.3.4.2 Shape effect of alumina nanoparticles with 0.3% vol. fraction

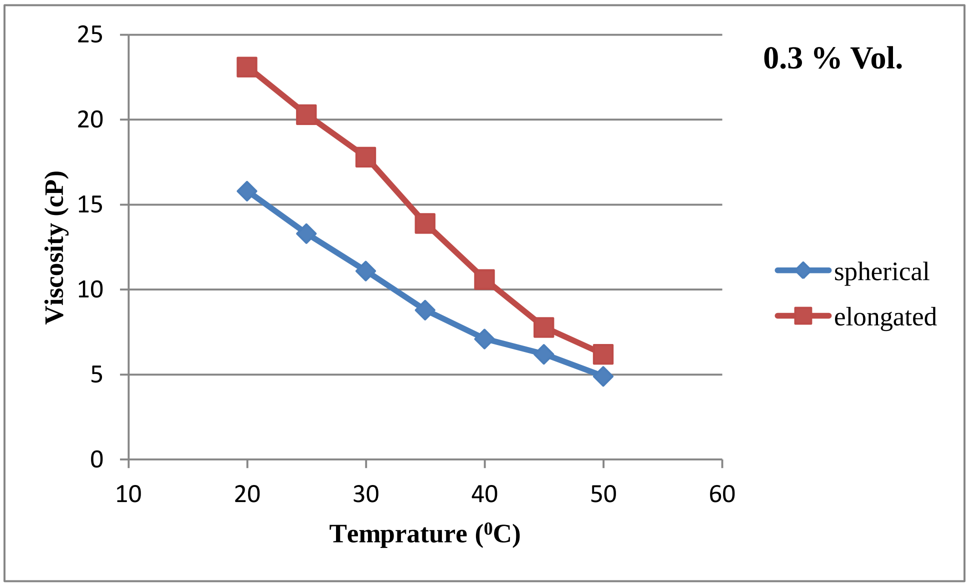


Figure 6.23 Viscosity v/s Temperature at 0.3% vol. fractions

6.3.4.3 Shape effect of alumina nanoparticles with 0.5% vol. fraction

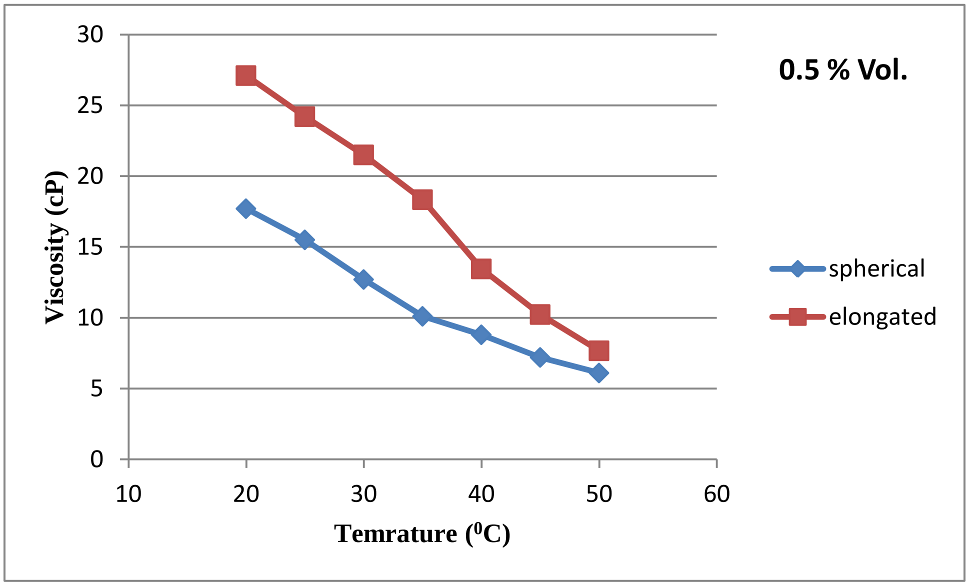


Figure 6.24 Viscosity v/s Temperature at 0.5% vol. fractions

Elongated particles results higher viscosity rise at same volume fraction due to structural limitation of rotational and transitional Brownian motion. Due to increase in size of nanoparticles average spacing between the particles decreases. When average spacing between particles is much larger and the rotational and transitional motion are not restricted it leads to more shear and thinning behavior of nanotransformer oil. Due to this viscosity of nanotransformer oil is more with elongated nanoparticles as compared to spherical nanoparticles.

With change in shape of the nanoparticles from spherical to elongated the viscosity rise is 50.7, 46.2 and 54.1% at 0.1, 0.3 and 0.5 % volume fractions respectively. Elongated nanoparticles shows higher viscosity rise as compared to spherical nanoparticles at the same volume fraction and in the same temperature range.

CHAPTER 7

CONCLUSION & FUTURE SCOPE

7.1 Thermal conductivity of nanotransformer oil:

- Thermal conductivity of nanotransformer oil increase linearly with increase in volume fraction of nanoparticles.
- Maximum enhancement in thermal conductivity w.r.t volume fraction is 38.5 % at 0.5% vol. fraction of nanoparticles. More significant rise in thermal conductivity is observed in the range 0.1- 0.3 % vol. fraction as compared to 0.3- 0.5 % vol. fraction of nanoparticles.
- Thermal conductivity of nanotransfer oil increases almost linearly with increase in temperature.
- Maximum Thermal conductivity enhancement is 14.7% at 0.3% vol. fraction of nanoparticles in the temperature range 30^0- 40^0 C. At higher temperature range Brownian

motion and Brownian speed of nanoparticles leads to significant rise in thermal conductivity of nanotranformer oil.

- Thermal conductivity of nanotransformer oil decrease with increase in size of nanoparticles.
- For smaller size nanoparticles there is more uniform distribution and nanolayer thickness in transformer oil shows significant increase in thermal conductivity as compared to larger size nanoparticles.
- Maximum decrease in thermal conductivity of nanotransformer oil with increase in size from 20 nm to 40 nm is 6.4 % at 0.5 % vol. fraction of nanoparticles in temperature range 40^0- 50^0 C.
- Elongated nanoparticle shows more increase in thermal conductivity as compared to spherical nanopaerticles due to their higher aspect ratio and more surface area of contact. Higher value of thermal conductivity is due to the mesh formed by elongated particles to conduct heat through the fluid.
- Maximum thermal conductivity enhancements with elongated particles are 24% at 0.5% vol. fraction of nanoparticles in the temperature range 40^0-50^0C.

7.2 Viscosity of nanotransformer oil:

- Viscosity of nanotransformer oil increases almost linearly with volume fraction of nanoparticles. Viscous shear stress increase with particle volume fraction which leads to increase in viscosity.
- Viscosity increases sharply in lower concentration range but at higher concentration range shear stress change is not at faster rate as compared to lower concentration range.
- Maximum rise in viscosity is 28.3% for alpha nanoparticles at 0.5% vol. fraction of nanoparticles.
- Viscosity of nanotransformer oil decrease significantly with temperature. Due to increase in temperature the interfacial layer resistance and intermolecular forces in the nanotransformer oil decreases.

- Maximum decrease in viscosity is 41.1% at 0.1% volume fraction of nanoparticles. In the higher temperature range 40^0- 50^0 C more decrease in viscosity is observed as compared to lower concentration range.
- With increase in size of nanoparticle viscosity of nanotransformer oil decreases. Viscosity of nanotransformer oil depends upon the average spacing between the nanoparticle, as particle diameter increases average spacing b/w the particles decrease .
- Due to decrease in spacing nanolayer thickness also decreases which leads to decrease in viscosity of nanotransformer oil.
- Maximum viscosity decrease is 26.3% at 0.1% vol. fraction in the temperature range 30^0-40^0C.
- Elongated nanoparticle shows more increase in viscosity as compared to spherical nanoparticles in transformer oil. It occurs due to the structural limitation of rotational and transitional Brownian motion of elongated nanoparticles in transformer oil. Results in more increase in viscosity.
- Maximum increase in viscosity with elongated nanoparticle as compared to spherical nanoparticle is 54.1% at 0.5% vol. fraction of nanoparticles.

Two main properties required in transformer oil for their efficient working in transformer are high thermal conductivity and low viscosity. High thermal conductivity is helpful in avoiding excessive heating of the coil winding in overload conditions.

Significant increase in thermal conductivity with nanoparticles is observed. Viscosity is another critical parameter in transformer oil due to its circulation from primary winding to secondary winding in transformer. Lower concentration 0.1-0.3% vol. fraction shows significant rise in thermal conductivity and viscosity in this range also looking suitable for its use in transformer oil. Elongated nanoparticle shows higher thermal conductivity but problem associated with high viscosity rise above 0.1% vol. fraction of nanoparticles.

So nanoparticles are suitable for use in transformer oil with in lower concentration 0.1-0.3% in the temperature range from $40\text{-}50^0$ C.

7.3 Future Scope

In our experimental investigations, a report has been represented about the nanotransformer oil. But still apart from these investigations, there are other parameters like, surfactants, pH value, sonication time, hybrid transformer oil etc which also effect the performance of nanotransformer oil, need to be investigated. As these parameters also effects the thermal conductivity of nanofluid and further research is required regarding the effects of these parameters. The theoretical study of thermal conductivity of oils based nanofluids is very limited and further investigation is required to predict more accurate behavior with transformer oil, engine oil etc. Development of new mechanisms and comparison of these models predictions with experimental data will provide theoretical explanation of thermal conductivity enhancement with nanotransformer oil.

Numerical studies in the literature about viscosity of nanofluids are generally with water and ethylene glycol as base fluid. So there is a need to develop theoretical correlations for oil based nanofluids also. There is a limited experimental data available about viscosity of nanotransformer oil and this prevents the actual prediction of experimental results with previous database. Similar to thermal conductivity, viscosity of nanotransformer oil is also dependent on many parameters such as nanoparticle material, sonication time, and transformer oil type (like by using oils of other different grades also). Detailed experimental investigation of the effects of most of these parameters on thermal conductivity and viscosity has not been performed yet.

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PUBLICATIONS

Journal :

Singh, Mandeep & Kundan, L ‘Experimental study on thermal conductivity and viscosity of Al_2O_3-nanotransformer oil, *International Journal on Theoretical and Applied Research in Mechanical Engineering (IJTARME)*, ISSN (Print): 2319-3182. (Accepted).

Conference :

Singh, Mandeep & Kundan, L, ‘Experimental study on thermal conductivity and viscosity of Al_2O_3-nanotransformer oil, at the International conference on ICMIE-2013 held at Chandigarh on 24th March 2013.

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