Experimental Investigation of Thermal Conductivity through Nanofluids

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ABSTRACT

The method used in this experimental work is the Temperature Oscillation Technique (TOT). Thermal conductivity measurement through Temperature Oscillation Technique is to fill the cylinder with the nanofluids, and apply the temperature oscillations at both ends of the cylinder. It measures the phase and amplitude of the temperature oscillation in the center and at both ends of the cylinder. Thermal diffusivity is calculated from the phase and amplitude values. Furthermore, thermal conductivity is calculated from thermal diffusivity values. Nanofluid used in this study is Al_2O_3. First of all this technique is validated by calculating the thermal conductivity of pure water. After getting the acceptable results, Al_2O_3 nanoparticles mixed in water (80% water, 20% Al_2O_3) with the particle size of 20 nm has been used and its thermal conductivity has been calculated. Thermal conductivity data has been compared with other researchers work. The results are very much in acceptable range which is a proof that our experimental setup is well designed and can be used to measure the thermal conductivity and thermal diffusivity very accurately.

Keywords: Cylinder, Nanofluids, Aluminum Oxide, Thermal Conductivity, Temperature Oscillation, Thermal Diffusivity.

ÖZ

Bu deneyde kullanılar yöntem sıcaklık salınım tekniği yöntemidir. Sıcaklık Salınım Tekniği ile termal iletkenlik katsayısının ölçümünün yapılması, silindir şeklindeki bir kaba akışkan bir sıvının doldurulması ve bu kabın her iki ucuna sıcaklık salınımlı sınır noktası koşulu uygulanması ile gerçekleştirilir. Termal yayılım, faz ve fazın şiddeti değerlerinden hesaplanabilir. Ayrica termal yayılım değerinden termal iletkenlik değeri de bulunabilir. Bu çalışmada kullanılan nanoakışkan Al_2O_3. Bu tekniğin sağlaması saf suyun termal iletkenlik katsayısının bulunması ile yapılmıştır. Kabul edilebilir bir katsayının bulunmasından sonra, boyutu 20 nm olan nanoparçacık saf su ile belli oranda (80 % saf su, 20% Al_2O_3) karıştırılmıştır ve karışımın termal iletkenlik katsayısı hesaplanmıştır. Bulunan termal iletkenlik katsayısı diğer araştırmacıların çalışmalarında bulunan değerlerle karşılaştırılmıştır. Sonuçlar oldukça kabul edilebilir değerlerde çıkmıştır. Bundan dolayı diyebiliriz ki kurulan deney düzeneğimiz doğru dizayn edilmiştir ve bu deney düzeneği kullanılarak farklı malzemelerin termal yayılım ve termal iletkenlik katsayıları bulunabilir.

Anahtar kelimeler: Boşluk, Nanoakışkanlar, Aluminium Oxide, Termal iletkenlik, Sıcaklık salınım, Termal yayılım.

To My Family

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NOMENCLATURE

C_p	specific heat capacity (J/kg.°C)
G	period of oscillation (rad)
T	temperature (°C)
T_m	mean temperature of oscillation (°C)
t	time (s)
t_p	time period of oscillation (s)
u	amplitude of oscillation (°C)
x	distance (m)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β*	ratio of complex amplitudes
τ	non-dimensional time
ν	kinematic viscosity (m^2 s^{-1})
ω	angular velocity of oscillation (rad s^{-1})
ξ	non-dimensional distance

Subscripts

0	value at x = 0
L	value at x = L

Chapter 1

INTRODUCTION

Conventional heat transfer fluids like water, oil and ethylene glycol have low thermal conductivities as compared to solids. Advancements were really necessary to improve heat transfer characteristics of these fluids. Researchers have been trying for decades to find the best suitable method to improve heat transfer rate and to increase the thermal conductivity of the fluids. The recent discovery of nano-fluids (which is a suspension of colloidal particles of metals and metal oxides dispersed in a base fluid) that they increase the heat transfer rate of fluids in multiples just by the addition of small amount of particles, has been experimentally proved. The properties such as conduction heat transfer coefficient, density, and viscosity of the nanofluid depends on the number of parameters. These include the properties of the base fluid and the dispersed phases, particle concentration, particle size, as well as dispersants and surfactants.

S.U. Choi was the pioneer researcher who used these colloidal particles in the base fluid and named them as nano-fluids. He showed that the addition of small amount of nano-particles into the base fluids increases the thermal conductivity of fluids up to approximately two times [1]. Several other researchers experimentally and theoretically investigated the flow and thermal characteristics of nano-fluids. Eastman et al showed that the increase in thermal conductivity of approximately 60% can be obtained with 5 vol% of CuO nano-particles in the base fluid of water [2]. Masuda et al, Lee et al. and

Xuan and Li [3] stated that at low nano-particles concentrations (1-5 vol %) the thermal conductivity of suspensions can increase more than 20%. However, some contradictory results have been found, that the addition of nano-particles into the base fluid decreases the heat transfer rate instead of increasing it. Putra et al [4] performed an experimental study for natural convection heat transfer of fluids. They used Al_2O_3 and CuO particles in the base fluid of water with the volume fraction of (1-4) %. Their results revealed that heat transfer rate could become significantly deteriorated and a decrease of 150% to 300% in the Nusselt number was observed. Same effect was recorded by Wen and Ding [5]; they reported that natural convection heat transfer rate decreased sharply with the increase of particle diameter.

The aim of this research work will be to find the thermal conductivity (k) of nano-particles dispersed in deionized water. Aluminum Oxide (Al_2O_3) nanoparticles are used in the present study. The flow characteristics of dilute and concentrated suspensions of nanoparticles will be studied. Nanofluids with different volume percentages are put into the cylindrical chamber and the thermal diffusivity (α) and conduction heat transfer coefficient, i.e., thermal conductivity (k) will be obtained. Our experimental findings would lead us to decide whether the dispersion of nano-particles into the base fluid increases or decreases the thermal conductivity (k) of the base fluid. This work will be compared with other researchers' work to find how close the obtained results are and how it can be applied in real world problems.

Chapter 2

LITERATURE REVIEW OF NANOFLUIDS

2.1 Background

Heat transfer plays an important role in many fields such as power generation, air conditioning, transportation, and microelectronics due to the heating and cooling processes involved. It is desirable to increase the efficiency of heat transfer devices used in these fields, since in case of such an improvement, it becomes possible to reduce the size of the devices and decrease the operating costs of the associated processes. Therefore, various attempts have been made in order to enhance heat transfer in these devices.

One of the major parameters in heat transfer is the thermal conductivity of the working fluid. Commonly used fluids in heat transfer applications; such as water, ethylene glycol, and engine oil have low thermal conductivities, when compared to thermal conductivities of solids, especially metals. As a consequence, researchers have tried to find a way of improving thermal conductivity of these commonly used fluids. One of the methods to achieve this objective is to create mixtures by adding solid particles into the fluid. Since solid materials have thermal conductivities much higher than fluids, such an attempt obviously results in a thermal conductivity enhancement. Unfortunately, when the particle sizes are on the order of millimeters or micrometers, there exist severe problems in the usage of these mixtures in practice [9]. Some of the problems are that the mixtures are unstable, therefore, sedimentation occurs and solid particles may erode the channel walls. In addition to these, presence of solid particles increases the pressure drop significantly, which increases the required pumping power and associated operating cost. Due to these significant drawbacks, usage of solid particles has not become practically feasible.

Recent improvements in nanotechnology made it possible to produce solid particles with diameters smaller than 100 nm. As a result, an innovative idea of preparing liquid suspensions by dispersing these nanoparticles instead of millimeter- or micrometer-sized particles in a base fluid and utilizing them for heat transfer enhancement was proposed [10,11]. These liquid suspensions are called nanofluids. An important feature of nanofluids is that since nanoparticles are very small, they behave like fluid molecules and this solves the problem of clogging of small passages in case of the usage of larger particles. It is even possible to use nanofluids in microchannels [12]. It was also shown that by the use of proper activators and dispersants, it is possible to obtain stable suspensions.

In the last decade, a significant amount of experimental and theoretical research was made to investigate the thermo physical behavior of nanofluids. In these studies, it was observed that a high thermal conductivity enhancement could be obtained with nanofluids, even in the case of very small particle volume fractions. Furthermore, most of the experimental work showed that the thermal conductivity enhancement obtained by using nanoparticle suspensions was much higher than that obtained by using conventional suspensions with particles that are millimeter- or micrometer- sized. Many researchers proposed theoretical models to explain and predict those anomalous thermal conductivity ratios, defined as effective thermal conductivity of the nanofluid (k_{eff}) divided by the thermal conductivity of the base fluid (k_f).

2.2 Literature Survey

S.U. Choi was the pioneer researcher who used these colloidal particles in the base fluid and named them as nano-fluids. He showed that the addition of small amount of nano-particles into the base fluids increased the thermal conductivity of the fluid up to approximately two times. Several other researchers experimentally and theoretically investigated the flow and thermal characteristics of nano-fluids.

The first results on the enhanced effective thermal conductivity of nanofluids were reported by Eastman et al. [13]. By dispersing Al2O3 and CuO nanoparticles in water, the reported increase in thermal conductivity were 29% and 60%, respectively for a nanoparticles volumetric loading of 5%. Surprisingly, in the case of Cu/oil-based nanofluids, the thermal conductivity was increased by about 44% by dispersing only 0.052 vol% of Cu nanoparticles in HE-200 oil. The same group [14] later showed a moderate enhancement of thermal conductivity for the same ceramic nanoparticles (Al2O3 and CuO) dispersed in water and ethylene glycol. For instance, a 20% enhancement in the thermal conductivity of ethylene glycol was observed for 4.0 vol% of CuO nanoparticles. Wang et al. [15] reported a significant 17% increase in the thermal conductivity for a loading of 0.4 vol% of 50 nm sized same nanoparticles (CuO) in water. Recently, Li and Peterson [16] measured the thermal conductivity of the same ceramic nanofluids i.e. CuO (29 nm)/water and Al2O3 (36 nm)/water by using a steady-state method named as ‘‘cut-bar apparatus”. Their results were more astounding as both the CuO and Al2O3 nanoparticles increased the thermal conductivity of water by 52% and 22%, respectively at a volume fraction of just 6% at 34 °C.

Choi et al. [17] measured the thermal conductivity of oil suspensions containing multi-walled carbon nanotubes (MWCNT). At 1% volumetric loading, the thermal conductivity was increased by 160%. Interestingly, the conductivity increase as a function of nanotubes loading is nonlinear even at very low volume fractions. The possible reason was thought to be strong interactions of thermal fields associated with different fibers.

Thermal conductivities of several types of nanofluids were experimentally studied by Wang et al. [18]. In their study, nanofluids were prepared by suspending CuO (33 nm), Al_2O_3 (29 nm) and TiO_2 (40 nm) in ethylene glycol and their thermal conductivities were measured by the steady-state parallel plate method. The Al2O3/EG-based nanofluids showed 18% increase in the thermal conductivity at particle vol% of 4. In contrast, Xie et al. [19] observed about 30% increase in the thermal conductivity for 5 vol% of Al2O3 (60.4 nm) nanoparticles in the same base fluid. Although the particle size used by Xie et al. was double that of the particles of Wang et al., their results showed a much higher thermal conductivity than that of Wang et al. for this nanofluid. This discrepancy could be due to different measurement methods and adjustment of pH values of the nanofluids used by Xie et al. However, Xie et al.'s [19] study showed that the effective thermal conductivity of nanofluids depends on the particle size and the pH values of the suspension.

Patel et al. [20] used gold and silver nanoparticles to prepare water and toluene-based nanofluids. Their results showed that at room temperature, the conductivity of Au/toluene nanofluid was enhanced by 4–7% for very low volumetric loading of 0.005–

0.011%, whereas the enhancement for Au/water nanofluid was about 3.2–5% for a vanishingly small concentration of 0.0013–0.0026%. The reason for such anomalously high thermal conductivities was the small size of nanoparticles and high thermal conductivity of particle materials. Later, a larger enhancement in thermal conductivity of Au (4 nm)/water-based nanofluids was reported by the same group [21]. At extremely low volumetric loading of 1.3 vol% of ultra-fine Au nanoparticles, the thermal conductivity was found to increase by 20% at 30 °C.

Murshed et al. [22] measured the thermal conductivity of TiO2 of 15 nm and 10 - 40 nm sized spherical and cylindrical shape nanoparticles in deionized water. For the low volume fraction (<1%), their results showed a nonlinear increase in thermal conductivity. They, however, found significant increase i.e. 32% (for 5 vol %) in thermal conductivity with volume fraction. Furthermore, their results showed that cylindrical shape nanoparticles exhibit slightly higher thermal conductivity compared to spherical shape nanoparticles. Subsequently, Murshed et al. [23, 24] and Leong et al. [25] presented more results for several types of nanofluids i.e. Al2O3/DI water, TiO2/EG, and Al/EG to validate their thermal conductivity models. For a particle volumetric loading of 5%, the maximum enhancement of thermal conductivities of TiO2 (15 nm)/EG- and Al (80 nm)/EG-based nanofluids are 18% and 45%, respectively. Nanofluids having higher thermally conductive nanoparticles (Al) exhibit much higher thermal conductivity compared to the nanofluids having lower thermally conductive nanoparticles (TiO_2).

For Fe (10 nm)/EG-based nanofluids, a large increase in thermal conductivity was reported by Hong et al. [26]. They obtained an enhancement of 18% with just 0.55 vol% of Fe nanoparticles. They also noticed that sonication has a significant effect on the thermal conductivity of nanofluids. Nonetheless, their observed enhancement for this nanofluid was even much higher than that of the Cu/EG-based nanofluids obtained by Eastman et al. [27]. This indicates that the suspension of high conductivity materials is not always effective to improve thermal conductivity of nanofluids.

By using the co-precipitation method, Zhu et al. [28] prepared Fe_3O_4 (10 nm)/water-based nanofluids and measured the thermal conductivity by the THW method. They found a 38% increase in the thermal conductivity for the nanoparticles volume fraction of 0.04. Zhu et al. ascribed such anomalously high thermal conductivity to the nanoparticles alignment in clusters.

Putnam et al. [29] performed experiments to measure the thermal conductivity of Au (4 nm) ethanol-based nanofluids by the optical beam deflection technique. For the first time, their results showed no anomalous enhancement of thermal conductivity of nanofluids with very low particle volume fraction. Their observed maximum enhancement in thermal conductivity was 1.3% ± 0.8% for 0.018% volumetric loading of 4 nm Au particles in ethanol. This result is directly in conflict with the anomalous result of Patel et al. [30] for the same nanofluid.

From a comparison of the reported studies, the increments of thermal conductivities are different for different types of nanofluids. The thermal conductivity of nanofluids varies with the size, material of nanoparticles as well as base fluids. For instance, nanofluids with metallic nanoparticles were found to have a higher thermal conductivity than nanofluids with nonmetallic (oxide) nanoparticles. The smaller the particle size, the larger the thermal conductivities of nanofluids. Furthermore, several studies reported that high conductivity nanoparticles are not always effective in enhancing the thermal conductivity of nanofluids [31, 32].

Table 1. Summary of the experimental work for thermal conductivity enhancement [37]

Year	Nanofluid	Property	Reference
1999	CuO and Al2O3 nanoparticles dispersed in water and ethylene glycol	20 % enhancement in thermal conductivity of ethylene glycol by dispersing 4 vol % CuO nanoparticles	Lee et al.
1999	CuO and Al2O3 nanoparticles dispersed in water and ethylene glycol and vacuum pump oil	20 % enhancement in thermal conductivity of water by dispersing 3 vol % Al2O3 nanoparticles	Wang et al.
1999	Cu nanoparticles dispersed in water	Thermal conductivity ratio varies from 1.24 to 1.78 if volume fraction of Cu nanoparticles increases from 2.5 to7.5%	Xuan et al.
2001	Cu nanoparticles dispersed in ethylene glycol	Effective thermal conductivity of ethylene glycol improved up to 40 % through the dispersion on 0.3% Cu nanoparticles	Eastman et al.
2003	Ag and Au nanoparticles dispersed in water and toluene	0.011vol. % of Au nanoparticles dispersed toluene nanofluid shows enhancement in thermal conductivity 7% at 30 C and 14% at 60 C	Patel et al.
2003	CuO and Al2O3 nanoparticles dispersed in water (effect of temperature)	4 volume % Al2O3 dispersed water nanofluids thermal conductivity raise 9.4% to 24.3% with increase in temperature from 21 to 51 ˚C	Das et al.
2001	Carbon nanotube dispersed in oil	Thermal conductivity ration exceeded 2.5 at I volume % nanotube	Choi et al.
2003	Carbon nanotube dispersed in water distilled and ethylene glycol	At 1 volume %, the thermal conductivity enhancements are 12.7% and 7.0% for TCNT in ethylene glycol and distilled water.	Xie et al.
2012	Al2O3 nanoparticles dispersed in water	At 20 vol% %, the thermal conductivity enhancement is 5.58 to 14.16 % in pure water with increase in temperature from 11 to 47 ˚C	H.S. Aybar, M.Abid

The particle size is important because shrinking it down to nanoscale not only increases the surface area relative to volume but also generates some nanoscale mechanisms in the suspensions [33–36]. Theoretical evidence [34, 35, 37] indicates that the effective thermal conductivity of nanofluids increases with decreasing particle size. Chon and Kihm [38] experimentally measured the thermal conductivity of nanofluids with nanoparticles of different sizes. They showed that the 47 nm Al2O3 nanoparticles in water gave a larger increase in thermal conductivity compared to the 150 nm nanoparticles.

It has since been shown that the nano-fluids can have higher thermal conductivities than that of base fluids, thus posing as a promising alternative for future thermal applications. Although nano-fluid has become an innovative idea because of its intriguing nature, but still there are many questions to be unanswered and need researching. Theoretical and Experimental research both on micro scale and macro scale are needed in order to clarify the causes of enhancement in heat transfer.

2.3 Thermal conductivity measurement techniques for nanofluids

Over the years different techniques have been adopted for measuring the thermal conductivity of liquids. A number of such techniques have also been used for nanofluids. Fig. 3 provides a summary of the available measurement techniques. Out of all the techniques, the transient hot-wire method has been used most extensively. Based on the literature survey a relative popularity and frequency of use of each of the methods for the characterization of nanofluids has been presented in Fig. 2. Illustrations of the techniques given in Fig. 1 are given in the following sections.

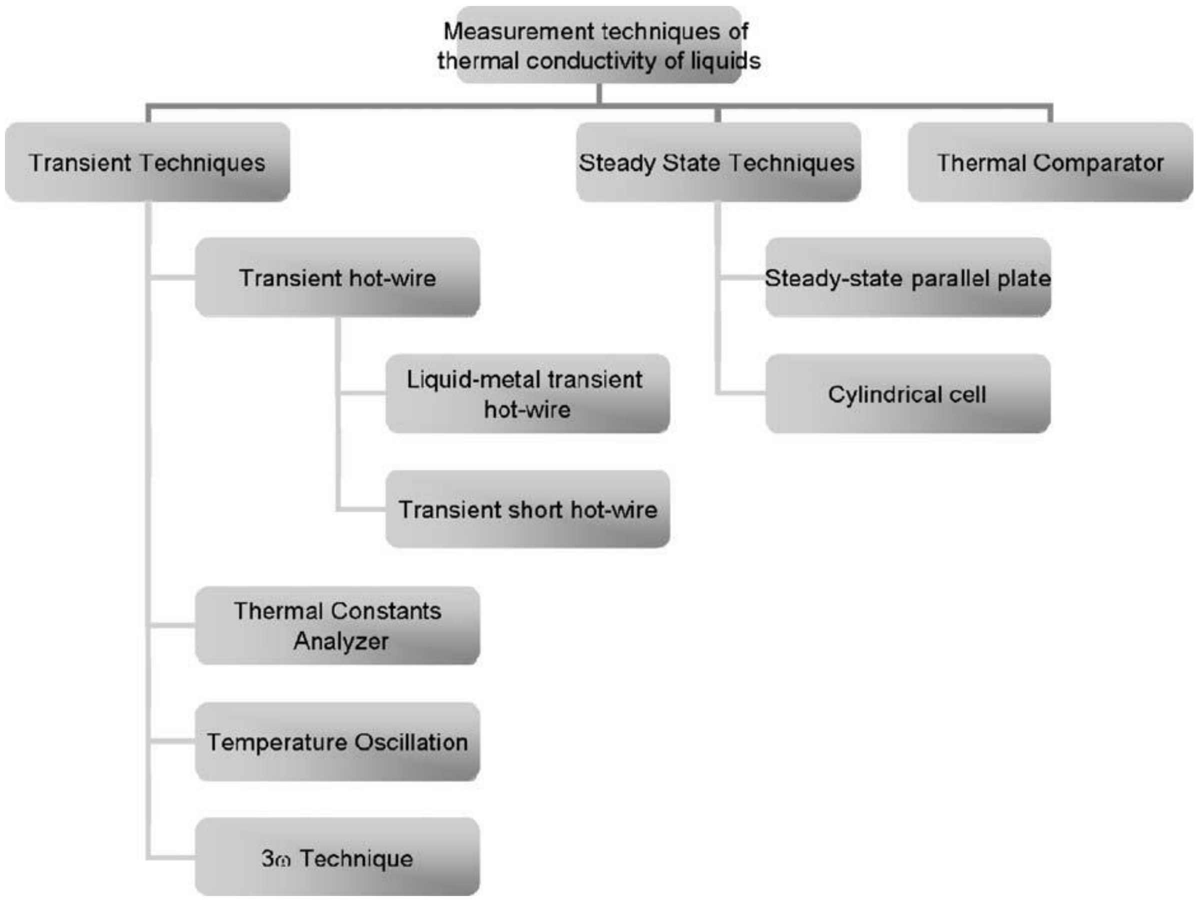

Figure 1. Different thermal conductivity measurement techniques for nanofluids [44]

2.3.1 Transient Hot Wire Method

The transient hot-wire (THW) method was first suggested by Stalhane and Pyk Horrocks and McLaughlin in 1931 to measure the absolute thermal conductivity of powders. Many researchers have modified the method to make it more accurate. There are several advantages for the THW method. The most attractive advantage of this method for application to fluids is its capacity for experimentally eliminating the error due to natural convection. In addition, this method is very fast compared to other techniques. The conceptual design of the hot-wire apparatus is also simple compared to the arrangements needed for other techniques.

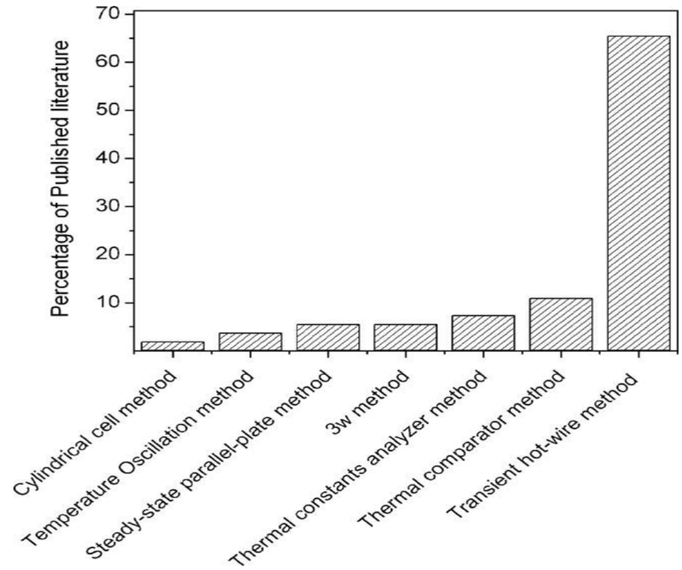

Figure 2. Comparison of the thermal conductivity measurement techniques for nanofluids [44]

In this method, a platinum wire is used for the measurement. The wire is used both as a heater and as a thermometer. This method is based on the principle of measurement of temperature and time response of the wire subjected to an abrupt electrical pulse. Carslaw and Jaeger, 1959 [39] modeled the temperature surrounding an infinite line heat source with constant heat output and zero mass, in an infinite medium.

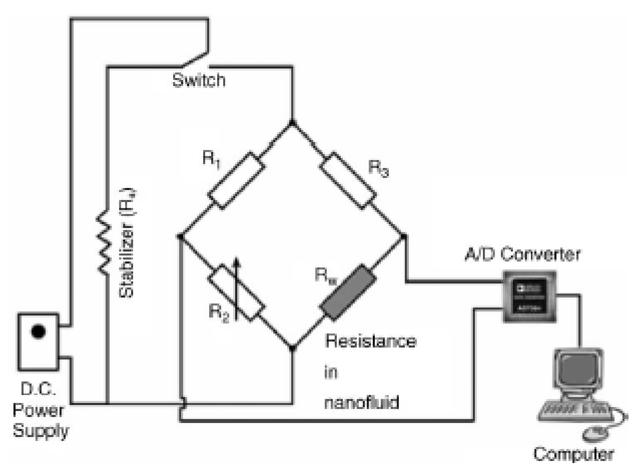

Figure 3. Schematic of transient hot-wire experimental setup [10].

2.3.2 Thermal constants analyzer technique

The thermal constants analyzer utilizes the transient plane source (TPS) theory to calculate the thermal conductivity of nanofluid. In this method, the TPS element behaves both as the temperature sensor and the heat source. The TPS method uses the Fourier law of heat conduction as its fundamental principle for measuring the thermal conductivity, just like the THW method. Advantages of using this method are (a) the measurements are fast, (b) samples having wide range of thermal conductivities (from 0.02 to 200 W/m K) can be measured, (c) no sample preparation is required, and (d) sample size can be flexible.

The experimental setup comprises of thermal constants analyzer, a vessel, a constant temperature bath, and a thermometer. The probe of the thermal constants analyzer is immersed vertically in the vessel containing the nanofluid. The vessel is placed in the constant temperature bath and the thermometer is immersed in the vessel to measure the temperature of the nanofluid. The thermal conductivity of the nanofluid is determined by measuring the resistance of the probe. The probe consists of an electrically conducting thin foil of a typical pattern which is sandwiched inside an insulating layer.

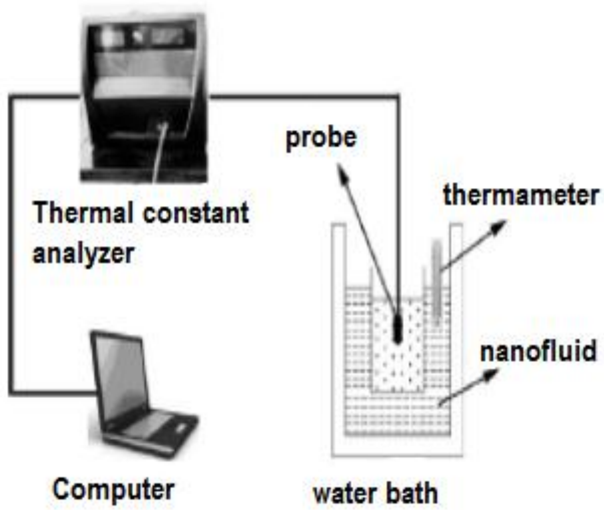

Figure 4: Schematic diagram of the experimental setup for transient plate source method [44].

2.3.3 Steady-state parallel-plate method

Based on steady-state heat conduction various design of test cells can be constructed for the measurement of thermal conductivity of liquids. To facilitate the heat transfer predominantly in one direction either parallel-plate type or concentric cylindrical cell type test facilities are preferred. The apparatus for the steady-state parallel-plate method can be constructed on the basis of the design by Challoner and Powell. A schematic diagram of the experimental set up is shown in Figure, where a small volume of the fluid sample is placed between two parallel round pure copper plates. A detailed description of the setup has been given by Wang et al. They have used this method for measuring the thermal conductivity of alumina and copper oxide based nanofluids. In this method, two important parameters are to be carefully controlled. One needs to accurately measure the temperature increase in each thermocouple. The difference in temperature readings need to be minimized when the thermocouples are at the same temperature. As the total heat supplied by the main heater flows through the liquid between the upper and lower copper plates, the overall thermal conductivity across the two copper plates, including the effect of the glass spacers, can be calculated from the one-dimensional heat conduction equation relating the power $q^{\cdot}$ of the main heater, the temperature difference ΔT between the two copper plates, and the geometry of the liquid cell as

$$k = \frac{\dot{q}L_g}{S\Delta T} \tag{1}$$

Where,

L_g is the thickness of the glass spacer between the two copper plates and S is the cross-sectional area of the top copper plate. The thermal conductivity of the liquid can be calculated as

$$k_e = \frac{kS - kgSg}{S - Sg} \tag{2}$$

Where,

kg, S, and S_g are the thermal conductivity, cross-sectional area of the top copper plate, and the total cross-sectional area of the glass spacers, respectively. In this method, it has to be ensured that there is no heat loss from the fluid to the surrounding. To take care of this, guard heaters are used to maintain a constant temperature of the fluid. The guard heaters are heated to a temperature same as that of the fluid. If the fluid and the guard heater temperature are equal, then there will be no heat radiated to the surroundings from the fluid.

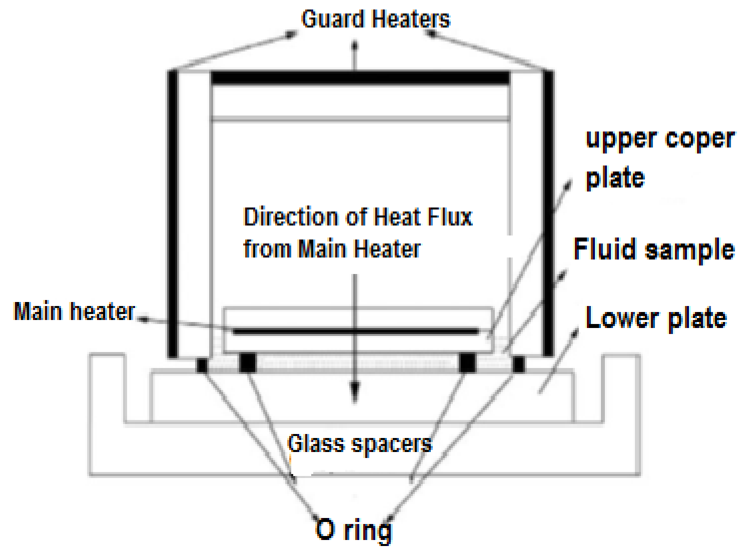

Figure 5. Experimental set up for steady-state parallel-plate method [44].

2.3.4 Cylindrical cell method

Cylindrical cell method is one of the most common steady-state methods used for the measurement of thermal conductivity of fluids. In this method the nanofluid whose thermal conductivity is to be measured fills the annular space between two concentric cylinders. Kart and Kayfeci has given a detailed description of the equipment. A brief description is as follows. The equipment (shown in Fig. 6) consists of a coaxial inner cylinder (made of copper) and outer cylinder (made of galvanize). An electrical heater is placed inside the inner cylinder and the front and back sides of the equipment are insulated to nullify the heat loss during the measurement. During the experiment, heat flows in the radial direction outwards through the test liquid, filled in the annular gap, to the cooling water. Two calibrated Fe–Constantan thermocouples are used to measure the outer surface temperature of the glass tube (Ti) and the inner cylinder (T_o). The thermocouples are positioned in the middle of test section and connected to a multi-channel digital read out with an accuracy of 0.1 8C. The required measurements for the calculation of the thermal conductivity are the T_i and T_o temperatures, adjusted voltage and current of the heater.

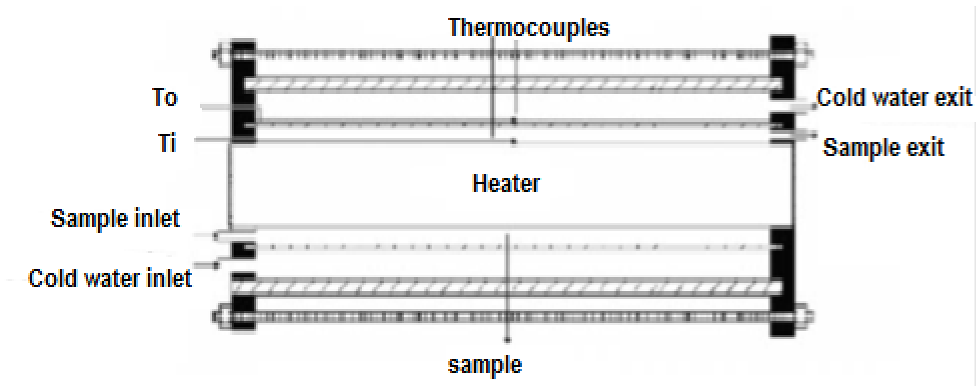

Figure 6. Cross-section of the cylindrical cell equipment [44].

2.3.5 Temperature oscillation technique

This method measures the temperature response of the nanofluid when a temperature oscillation or heat flux is imposed. The measured temperature response of the nanofluid is the result of averaged or localized thermal conductivity in the direction of nanofluid chamber height. The experimental method used here is based on the oscillation method proposed by Roetzel et al. and further developed by Czarnetski and Roetzel. The principle of thermal conductivity measurement has been described by Das et al. who have used this technique to measure the thermal conductivity of nanofluids comprising of Al2O3 and CuO nanoparticles dispersed in water. The experimental setup (shown in Fig. 8) requires a specially fabricated test cell (1) which is cooled by cooling water (2) on both the ends, coming from a thermostatic bath (3). Electrical connection provides power to the Peltier element (4). The temperatures are measured in the test section through a number of thermocouples and these responses are amplified with amplifier (5) followed by a filter which is finally fed to the data acquisition system (6) comprising of a card for logging the measured data. The data logger is in turn connected to a computer with proper software (7) for online display which is required to assess the steady oscillation and for recording data.

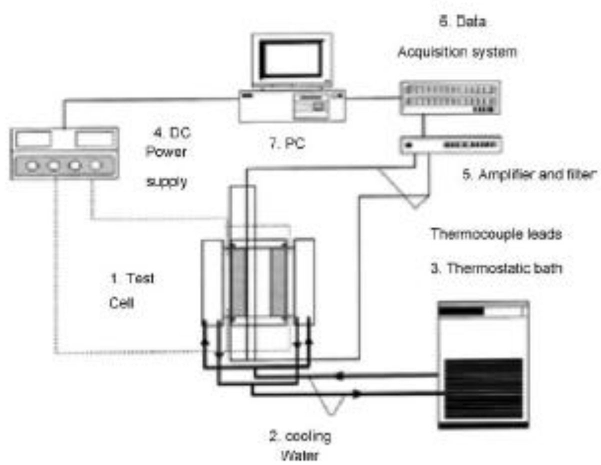

Figure 7. Schematic of experimental set up for temperature oscillation technique [44]

2.3.6 3-ω method

Similar to hot-wire technique, the 3ω method uses a radial flow of heat from a single element which acts both as the heater and the thermometer. The use of the temperature oscillation instead of the time dependent response is the major difference. A sinusoidal current at frequency ω passes through the metal wire and generates a heat wave at frequency 2ω, which is deduced by the voltage component at frequency 3ω. According to Cahill, the exact solution at a distance r = (x2 + y2)1/2 from an infinitely narrow line-source of heat on the surface of an infinite half-volume

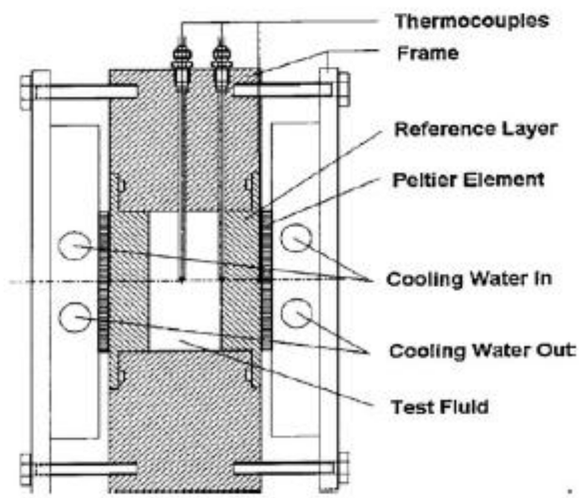

Figure 8. Test cell construction for 3ω method [44]

2.4 Potential benefits of Nanofluids

The impact of nanofluid technology is expected to be great considering that heat transfer performance of heat exchangers or cooling devices is vital in numerous industries. For example, the transport industry has a need to reduce the size and weight of vehicle thermal management systems and nanofluids can increase thermal transport of coolants and lubricants. When the nanoparticles are properly dispersed, nanofluids can offer numerous benefits [48, 50] besides the anomalously high effective thermal conductivity.

These benefits include:

(1) *Improved heat transfer and stability:* Because heat transfer takes place at the surface of the particles, it is desirable to use particles with larger surface area. The relatively larger surface areas of nanoparticles compared to microparticles, provide significantly improved heat transfer capabilities. In addition, particles finer than 20 nm carry 20% of their atoms on their surface, making them instantaneously available for thermal interaction [48]. With such ultra-fine particles, nanofluids can flow smoothly in the

tiniest of channels such as mini- or micro-channels. Because the nanoparticles are small, gravity becomes less important and thus chances of sedimentation are also less, making nanofluids more stable.

(2) *Microchannel cooling without clogging:* Nanofluids will not only be a better medium for heat transfer in general, but they will also be ideal for microchannel applications where high heat loads are encountered. The combination of microchannels and nanofluids will provide both highly conducting fluids and a large heat transfer area. This cannot be attained with macro- or micro-particles because they clog microchannels.

(3) *Miniaturized systems:* Nanofluid technology will support the current industrial trend toward component and system miniaturization by enabling the design of smaller and lighter heat exchanger systems. Miniaturized systems will reduce the inventory of heat transfer fluid and will result in cost savings.

(4) *Reduction in pumping power:* To increase the heat transfer of conventional fluids by a factor of two, the pumping power must usually be increased by a factor of 10. It was shown that by multiplying the thermal conductivity by a factor of three, the heat transfer in the same apparatus was doubled [49]. The required increase in the pumping power will be very moderate unless there is a sharp increase in fluid viscosity. Thus, very large savings in pumping power can be achieved if a large thermal conductivity increase can be achieved with a small volume fraction of nanoparticles.

2.5 Potential applications of Nanofluids

With the aforementioned highly desired thermal properties and potential benefits, nanofluids can be seen to have a wide range of industrial and medical applications, which are elaborated here.

2.5.1 Engineering applications

Nanofluids can be used to improve thermal management systems in many engineering applications including:

(a) *Nanofluids in transportation:* The transportation industry has a strong demand to improve performance of vehicle heat transfer fluids. Enhancement in cooling technologies is also desired. Because engine coolants, engine oils, automatic transmission fluids, and other synthetic high temperature fluids currently possess inherently poor heat transfer capabilities, they could benefit from the high thermal conductivity offered by nanofluids. Nanofluids would allow for smaller, lighter engines, pumps, radiators, and other components. Lighter vehicles could travel further on the same amount of fuel i.e. more mileage per liter. More energy-efficient vehicles would save money. Moreover, burning less fuel would result in lower emissions and thus reduce environment pollution. Therefore, in transportation systems, nanofluids can contribute greatly.

(b) *In micromechanics and instrumentation:* Since 1960s, miniaturization has been a major trend in science and technology. Microelectromechanical systems (MEMS) generate a lot of heat during operation. Conventional coolants do not work well with high power MEMS because they do not have enough cooling capability. Moreover, even if large-sized solid particles were added to these coolants to enhance their thermal conductivity, they still could not be applied in practical cooling systems, because the particles would be too big to flow smoothly in the extremely narrow cooling channels required by MEMS. Since nanofluids can flow in microchannels without clogging, they would be suitable coolants. They could enhance cooling of MEMS under extreme heat flux conditions.

(c) *In heating, ventilating and air-conditioning (HVAC) systems*: Nanofluids can improve heat transfer capabilities of current industrial HVAC and refrigeration systems. Many innovative concepts are being considered; one involves pumping of coolant from one location where the refrigeration unit is housed in another location. Nanofluid technology could make the process more energy efficient and cost effective.

2.5.2 Medical applications

Magnetic nanoparticles in body fluids (bio-fluids) can be used as delivery vehicles for drugs or radiation, providing new cancer treatment techniques. Due to their surface properties, nanoparticles are more adhesive to tumor cells than normal cells. Thus, magnetic nanoparticles excited by an AC magnetic field are promising for cancer therapy. The combined effect of radiation and hyperthermia is due to the heat-induced malfunction of the repair process right after radiation-induced DNA damage. Therefore, in future nanofluids can be used as advanced drug delivery fluids.

Chapter 3

EXPERIMENTAL SETUP

3.1 Experimental Apparatus

3.1.1 Cylinder

A lot of research is been done to decide what cylinder size to be used for the experiment. So the cylinder used for this experiment is made of carbon steel. It is forty millimeter in diameter and five millimeter in height. The selection of the dimensions for this cylinder will be discussed in next chapter.

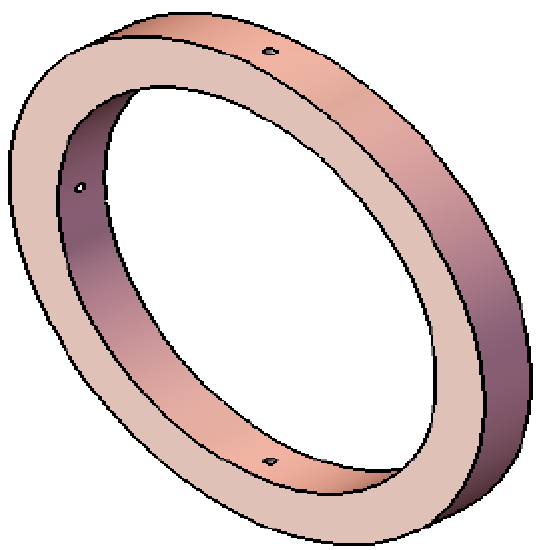

Figure 9. Schematic of the cavity used for the experiment

3.1.2 Peltier Elements

It is a device uses the Peltier effect to create a heat flux between the junctions of two different types of materials. A Peltier cooler or a heater is a solid-state active heat pump which transfers heat from one side of the device to the other side against the temperature gradient (from cold to hot), with consumption of electrical energy [41]. So the devices selected for this experimental work is of$(40x40x3.5)\ mm$, its functionality is clearly visible in the figure given below.

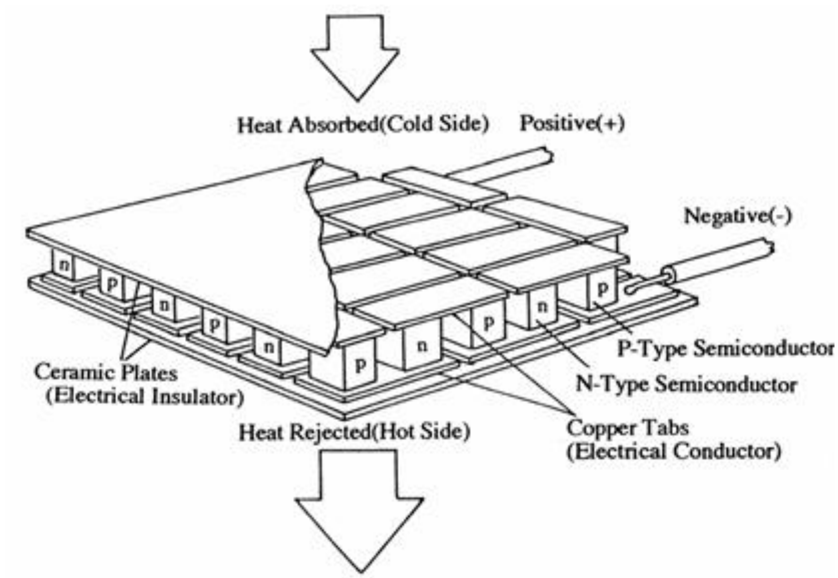

Figure 10. Schematic of the Peltier device with hot and cold sides [41].

3.1.3 Reference Plates

There are two reference plates which are used as heat spreaders. These are made of copper material because of high thermal conductivity. They have the dimensions of 5cm x 5cm with a thickness of 6mm, and are placed at the ends of the test chamber to increase the rate of heat transfer.

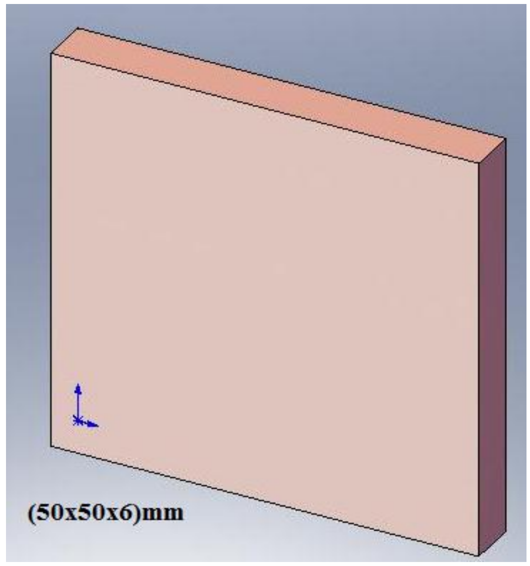

Figure 11. Schematic of the reference (copper) material used for heat distribution

3.1.4 Heat Exchangers

Two heat exchangers are used in this system to remove the heat from it. They are made of brass. Each heat exchanger consists of two brass plates. One of them is smooth which is used as the uniform temperature and the other one has grooves in it for the water to pass through it. Cold water is supplied to the heat exchanger through a separate constant temperature bath. Water from the bath flows through the heat exchanger grooves and take the heat (extracted from the test chamber) back to the bath by completing the closed loop.

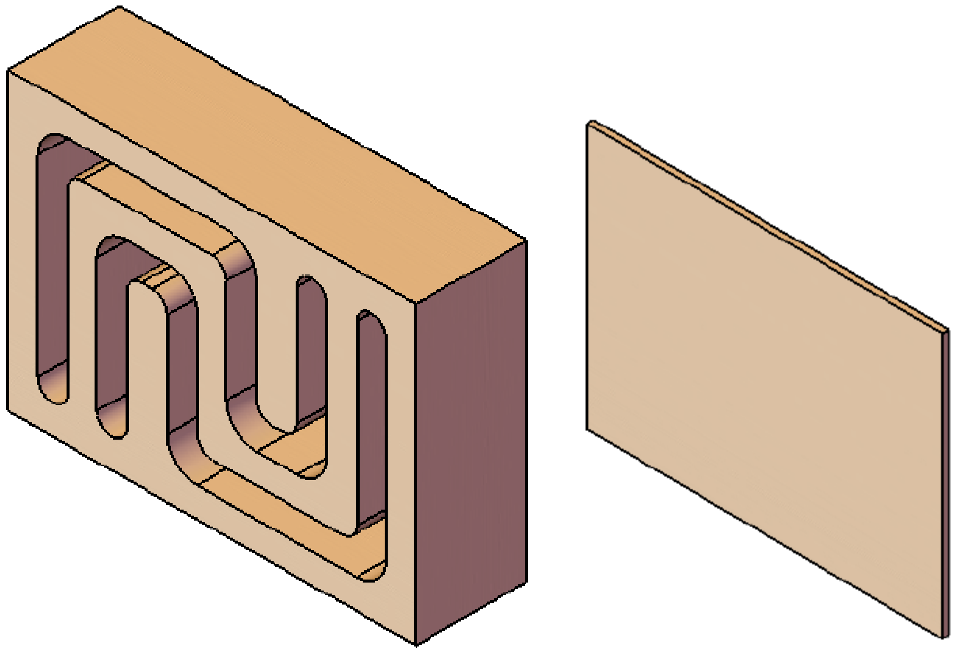

Figure 12. Heat exchanger with its cover to remove heat from the system

3.1.5 Circulating Water Bath

A circulating water bath is connected with the cavity. Cold water from the bath circulates through heat exchanger tubes, Extract the heat produced by the system and takes it back to the bath by completing the loop. The circulation process is repeated again and again to keep the environment cool by removing heat.

Figure 13. Constant temperature bath used for the experiment

3.1.6 Temperature Controller

The device which is been used to control the temperature of the system is ETC 4420 PID TEMPERATURE CONTROLLER. It takes the temperature data from one of the Peltier devices and communicates that information to a Daqview program and based on that, receives the command about how many current needs to be supplied to the Peltier devices, and in which direction the current should flow. The use of this controller can assure that the required temperature is achieved at that particular Peltier device surface.

Figure 14. Schematic diagram of the temperature controller used for the experiment [42].

3.1.7 Data Acqausiton System

The device used for logging the data is (OMB-DAQ-3005). It has the properties like, 16-bit, 1-MHz USB data acquisition module with 16 analog inputs, 24 digital I/O, four counters, and two timers; includes DaqView software, support for Visual Studio and Visual Studio .NET, with examples for Visual C++, Visual C#, Visual Basic and Visual Basic .NET; drivers for DASYLab and LabVIEW; DaqCal software application. This device can be used to collect temperature and voltage values simaltaneousley at 32 places. It can also be operated at two different modes (single ended and diferential mode).

Figure 15. Data acqusition used for the experiment [43]

3.2 Nanofluids used in the experiment

The selection of nanofluids was an important aspect of the experiment. After a thorough literature review it's been decided to use double distilled pure water (H_2O) and Aluminum oxide (Al2O3). They have been decided because of their high thermal properties and the research available in the literature. The purchased nanofluid is a dispersion of Al2O3 nanospheres in pure water. The mixture contains 20%Wt of nanoparticles with 80% of pure water. Two bottles of nanofluid dispersion having the volume of 120 ml each were purchased.

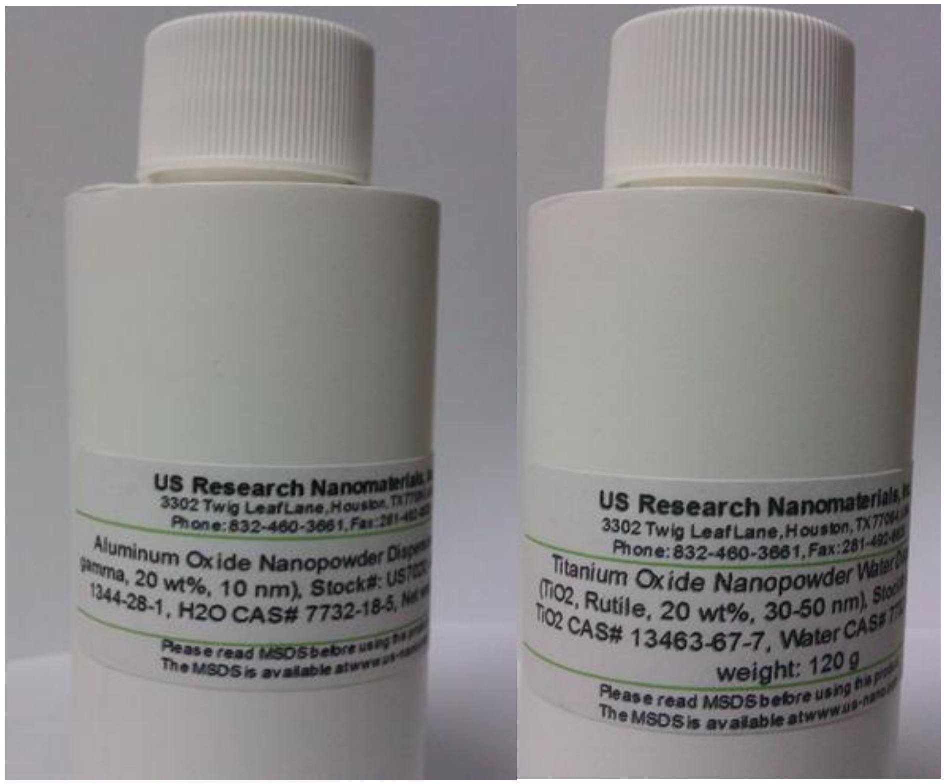

Figure 16. Nanomaterial used for the experiment

3.3 Experimental Procedure

A typical experiment involves cleaning of the test chamber by distilled water many times before starting the experiments. It needs to be very clean to get the required results. So the experimental setup which is used for present study is shown in figure below. Fluid is placed inside the cylindrical test chamber, the two ends of which are closed with the help of the reference plates which act as heat spreaders. We use two Peltier devices at the two ends of the test chamber on the outer surface of the reference material as the heating/cooling devices. These are used to supply the input temperature oscillations. The two Peltier devices are electrically connected in series so that they carry the same current and consequently have the same temperature at the load side. The entire system is held together by the two endplates. The endplates also act as heat spreaders on the heat sink sides of the Peltier devices. Two copper heat exchangers are used as heat sinks, and water at constant temperature is used as the heat transfer fluid in the heat sink system [40].

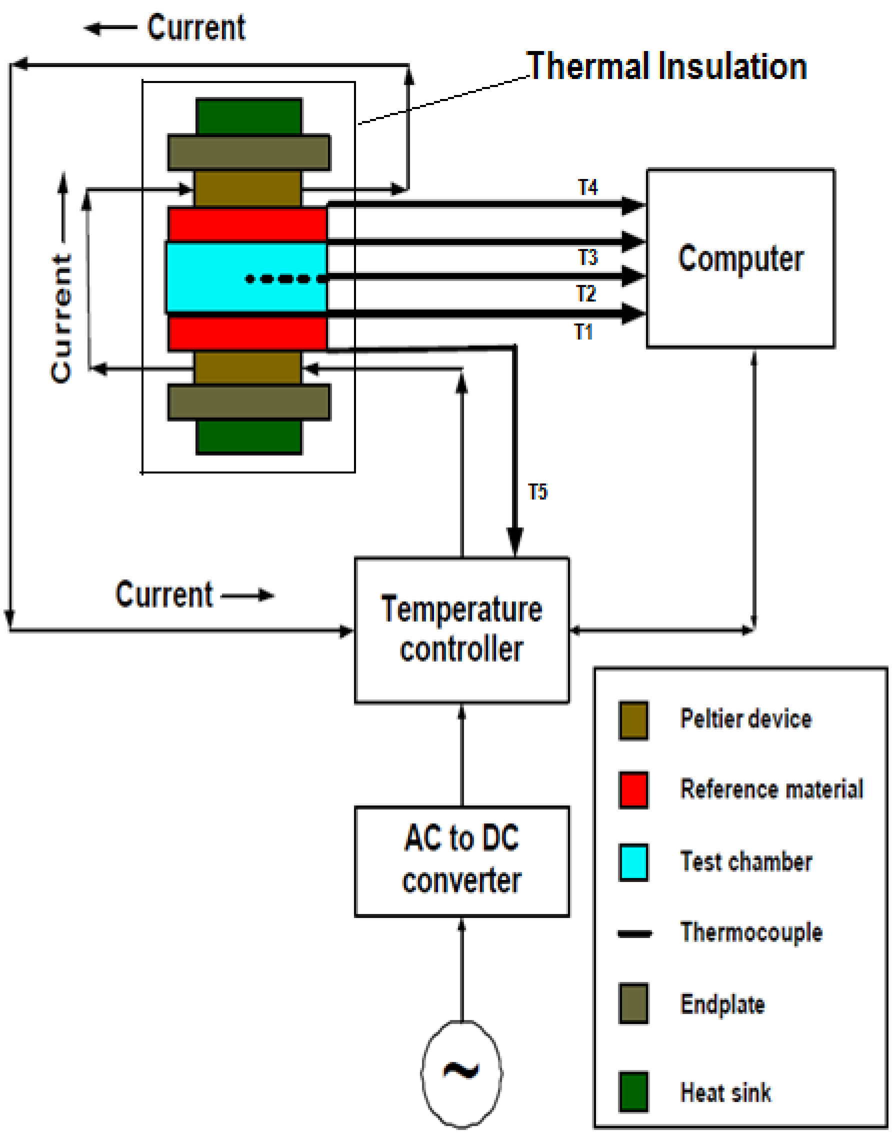

Figure 17. Schematic diagram of the experimental setup used in the experiment [40].

There are five thermocouples connected at five different points as shown in figure. One of them reads the temperature of the load side of one of the Peltier devices, and sends the data to the temperature controller. The temperature controller, in turn, communicates that information to a daqview program and based on that, receives commands about how much current need to be supplied to the Peltier devices, and in which direction the current should flow. The Peltier devices used for this work has the dimensions$(4x4)\ cm$. These Peltier devices can attain maximum current of 7 amperes at a voltage of 12 Volts of direct current. The required current provided to the Peltier devices through AC to DC convertor power supply.

For the temperature range of 11 °C to 47 °C the current required is about 2.5 amperes at a voltage of 12 VDC which was attained easily with the help of AC to DC convertor power supply. The PID temperature controller used to control and keep the temperature of the Peltier devices to the required temperature value. Because of the series connection, the same temperature is also attained at the load surface of the other Peltier device. The other four thermocouples are directly connected to the data acquisition device. One of them measures the temperature at the center of the fluid volume (T2), two of them measure the temperatures at the center of the end surfaces of the fluid volume (T1 at x = 0 and T3 at x = L), and the fourth one measures the temperature at the load side of the second Peltier device (T4) [40].

Chapter 4

DATA ANALYSIS AND RESULTS

4.1 Temperature oscillation theory

Thermal diffusivity and thermal conductivity measurement depends on the solution of transient heat conduction equation [40].

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{3}$$

Where t is the time, T is the temperature and is α is the thermal diffusivity. The cylindrical cavity which is used for the experiment is shown in the figure given below.

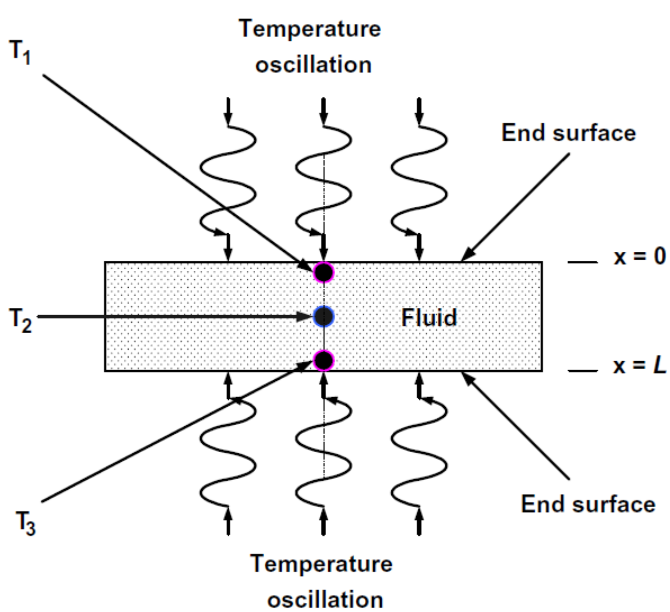

Figure 18.Cylindrical cavity with the temperature oscillations applied from two ends and T1, T2 and T3 are three thermocouples [40].

Periodic temperature oscillations have been generated from both the ends of the cylinder with an angular frequency, ω given as

$$\omega = \frac{2\pi}{t_p} \tag{4}$$

Where, t_p is the time period of the oscillation. It is assumed here that there is no radial heat transfer, which means that the heat transfer takes place only in the vertical direction. So one dimensional heat conduction equation (3) is used for analysis. To solve the equations easily we defined non-dimensional space, ξ and time, τ, coordinates.

$$\xi = x.\sqrt{\frac{\omega}{\alpha}} \tag{5}$$

$$\tau = \omega.\mathrm{t} \tag{6}$$

Equation (1) is been non-dimensionalized by using equations (5) and (6).

$$\frac{\partial^2 T}{\partial \xi^2} = \frac{\partial T}{\partial \tau} \tag{7}$$

The boundary conditions for the general case of temperature oscillations with amplitude and phases at $x = 0$ and $x = L$ are given below

$$T(\xi = 0, \tau) = T_m + u_0 \cos(\tau + G_0) \tag{8}$$

$$T\left(\xi = L\sqrt{\frac{\omega}{\alpha}}, \tau\right) = T_m + u_L cos(\tau + G_L) \tag{9}$$

Where, u_0 the amplitude of oscillation at$x = 0$, U_L the amplitude of oscillation at$x = L$, G_0 the phase of the oscillation at$x = 0$, T_m is the mean of the imposed temperature oscillations and G_L the phase of the oscillation at $x = L$.Under steady periodic conditions, the solution of Eq. (7) with boundary conditions given by Equations

(8) and (9) can be obtained by using the method of Laplace transforms [4]. The solution can be written in complex form as [4]:

$$T(\xi,\tau) = T_{\mathrm{m}} + \frac{u_L e^{iG_L} \sinh(\xi\sqrt{i}) - u_0 e^{iG_0} \sinh[(\xi - \xi_L)\sqrt{i}]}{\sinh(\xi_L\sqrt{i})} . e^{\mathrm{it}} \tag{10}$$

The ratio of the complex amplitude at $x = 0$ to that at any point along the length, B^*_0, is given by:

$$\mathrm{B}_0^* = \frac{u_0 \mathrm{e}^{\mathrm{i}G_0} \sinh(\xi_L\sqrt{i})}{\mathrm{u_L e^{iG_L}} \sinh(\xi\sqrt{\mathrm{i}}) - \mathrm{u_0 e^{iG_L}} \sinh[(\xi - \xi_L)\sqrt{\mathrm{i}}]} \tag{11}$$

The ratio of the complex amplitude at $x = L$ to that at any point along the length, B^*_L, is given by:

$$\mathrm{B}_L^* = \frac{u_L \mathrm{e}^{\mathrm{i}G_L} \sinh(\xi_L\sqrt{i})}{\mathrm{u_L e^{iG_L}} \sinh(\xi\sqrt{\mathrm{i}}) - \mathrm{u_0 e^{iG_0}} \sinh[(\xi - \xi_L)\sqrt{\mathrm{i}}]} \tag{12}$$

The real measurable phase shift, ΔG, and the amplitude ratio, r_u, can be expressed as,

$$\Delta \mathrm{G} = \left(\mathrm{G_j} - \mathrm{G(x)}\right) = arctan\left[\frac{Im(B_j^*)}{Re(B_j^*)}\right] \tag{13}$$

$$\mathrm{r_u} = \frac{u_j}{\mathrm{u(x)}} = \sqrt{\left[\mathrm{Re}(\mathrm{B_j^*})\right]^2 + \left[\mathrm{Im}(\mathrm{B_j^*}\right]^2} \tag{14}$$

Where $j = 0$ or L. By measuring ΔG and r_u, α of the fluid can be obtained by solving either Eq. (13) or (14). Once we know α, by knowing the density and the heat capacity of the fluid, we can calculate the fluid thermal conductivity (*k*).

4.2 Size of the test chamber

Cylinder dimensions are a very important aspect of the experiment. The theory requires that the heat conduction should be one dimensional along the length of the cylindrical test chamber. It can be achieved in two different ways. First, the diameter-to-length ratio of the chamber should be greater than one Second, the reference plates, which act as heat spreaders at the two ends of the cylinder, should have high thermal conductivity, and they should be sufficiently thick to enable adequate heat distribution from the Peltier devices. In our case, the length and the diameter of our cylindrical test chamber are 5 mm and 40 mm, respectively, and our reference plates are made of 6-mm-thick aluminum plate [44].

The theory also requires that the only mechanism for heat transfer within the fluid to be conduction, which means in practice that natural convection, must be avoided. The onset of natural convection depends on the type of fluid, the dimensions of the test chamber, and the amplitude and the frequency of the temperature oscillation. The rest of this section will address this issue. The critical Rayleigh number, $Ra_{x,cr}$, where x is the characteristic length, decides the onset of natural convection. For vertical heat transfer between two plates its value is 1700, while for horizontal heat transfer between two plates its value is 1000 [44]. Natural convection becomes significant when Ra_x is higher than these critical values. That is one reason why we chose to use a vertical cylinder rather than a horizontal cylinder. Therefore, for all our subsequent calculations we will use $Ra_{cr} = 1700$. For the system in consideration, where the same temperature oscillation is applied at the two ends of a vertical cylindrical fluid volume, the characteristic length would be half of its length. The Rayleigh number for this system can thus be expressed as,

$$Ra_{L/2} = \frac{g.\beta.\Delta T.\left(\frac{L}{2}\right)^3}{\alpha v} \tag{15}$$

Where, g is the acceleration due to gravity, β the volumetric thermal expansion coefficient of the fluid, ΔT the temperature difference driving the natural convection, and ν the kinematic viscosity of the fluid.

By having the properties known for pure water at 85C we found the $Ra_{L/2}$ =1661.814 which is less than the 1700. So it can be concluded that there is no natural convection present in the test chamber.

4.2.1 Temperature data acquisition

Temperature readings have been taken by using five different thermocouples. Values at different temperatures like, 20°C, 30°C and 40°C have been taken and their graphs are drawn respectively, where T1, T2, T3 and T4 are temperature values at different places in the system.

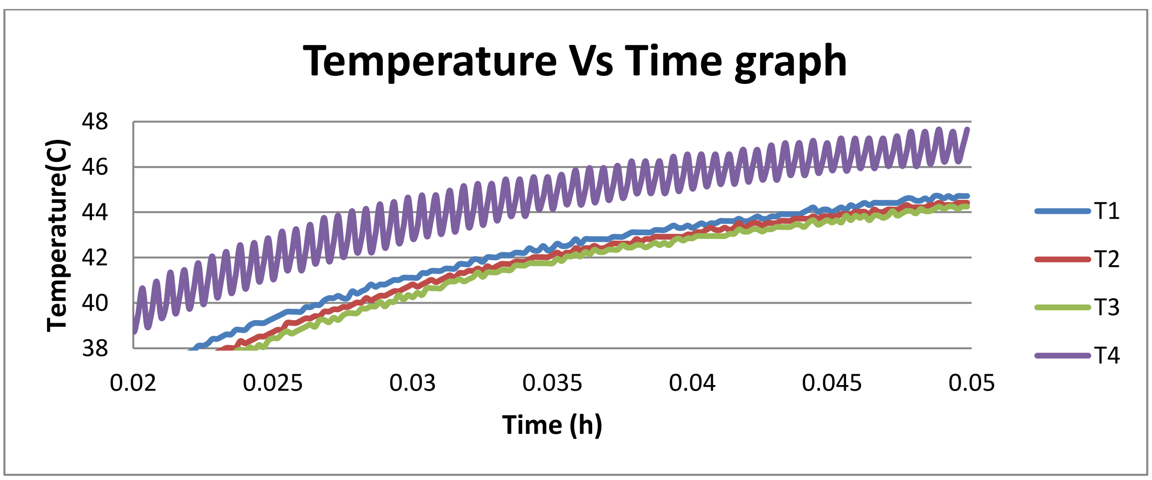

Figure 19.Increment in temperature with respect to time with four thermocouples, see figure 17 for details.

Figures 19 and 20 shows the temperature readings of different thermocouples. In figure 20 the values are taken in hours while in figure 21 the values are taken in seconds against the temperature.

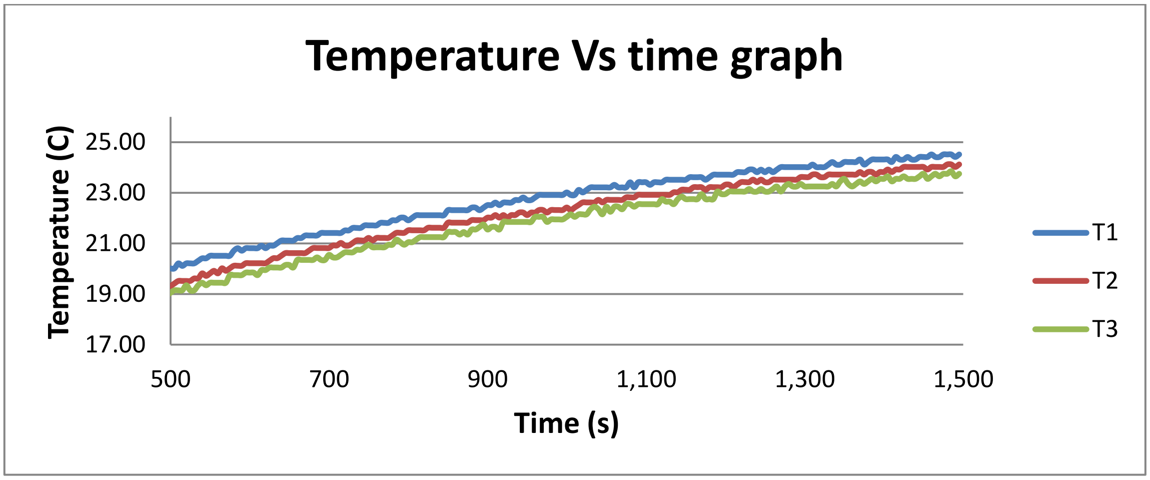

Figure 20.Increment in temperature with respect to time with three thermocouples.

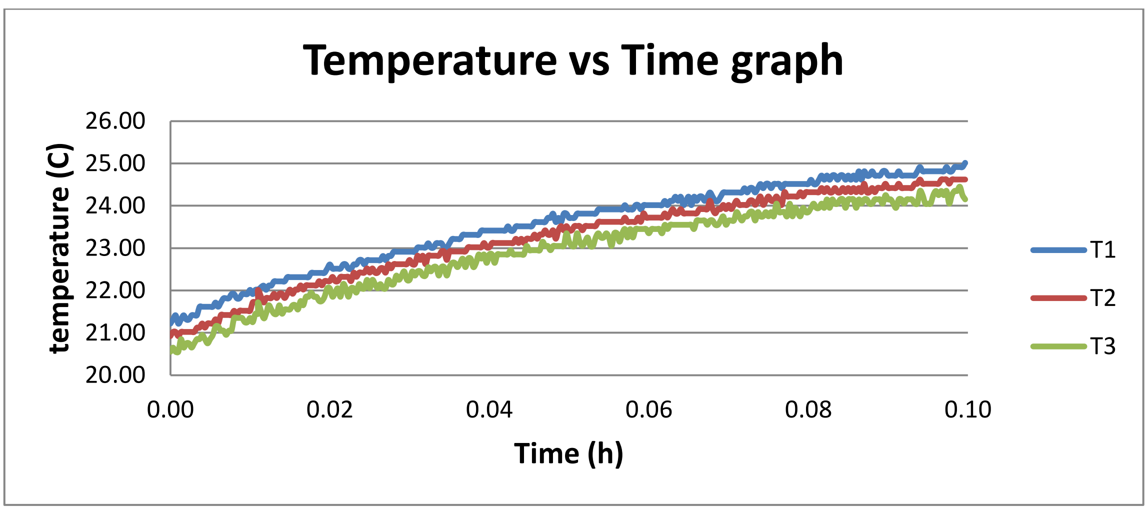

Figure 21.Increment in temperature with respect to time with different temperature range.

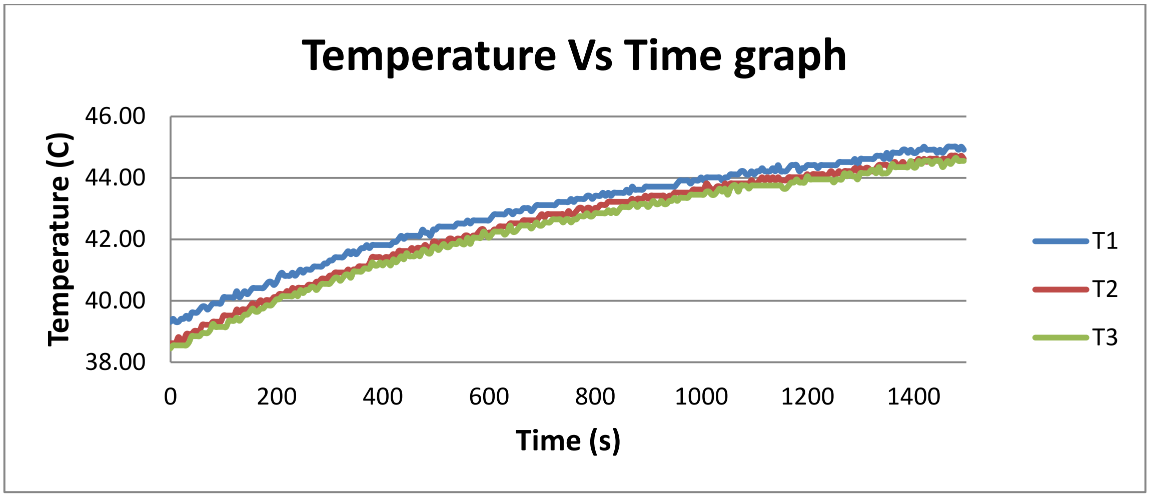

Figure 22.Increment in temperature with respect to time with different temperature range.

Figures 22 and 23 show that there is oscillation in temperature. The results would be more accurate if the data would be taken on a steady state temperature.

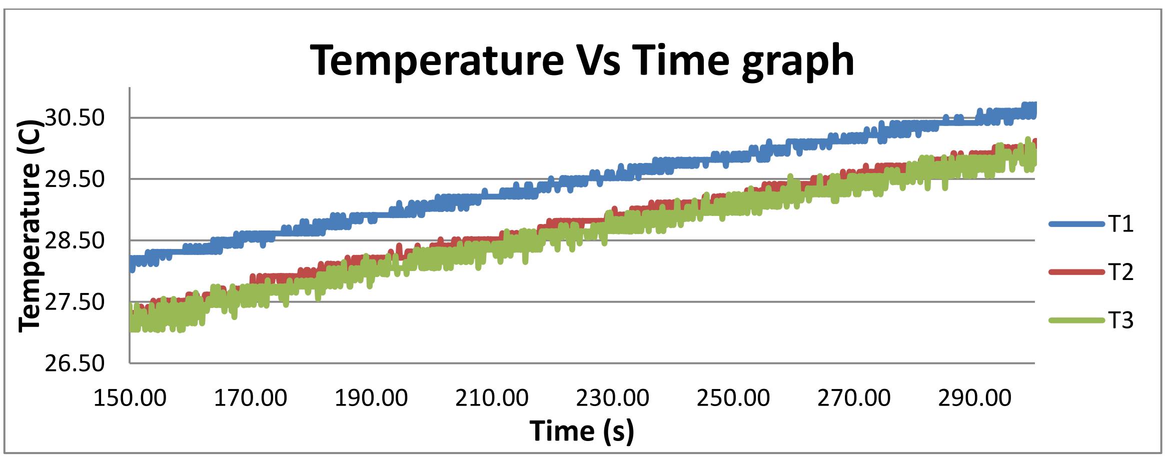

Figure 23. Increment in temperature with respect to time with different temperature range, figure 17 for details.

The figure given below shows the temperature oscillation with a time period of hundred seconds (100s) which means the frequency of 0.01Hz. The data has been taken for more than four hours for this figure and the oscillation is very dominant. The research is continuing on this topic to get the better results. If you compare this figure with the figures above it is very clear that we need to make the process steady to get the acceptable data.

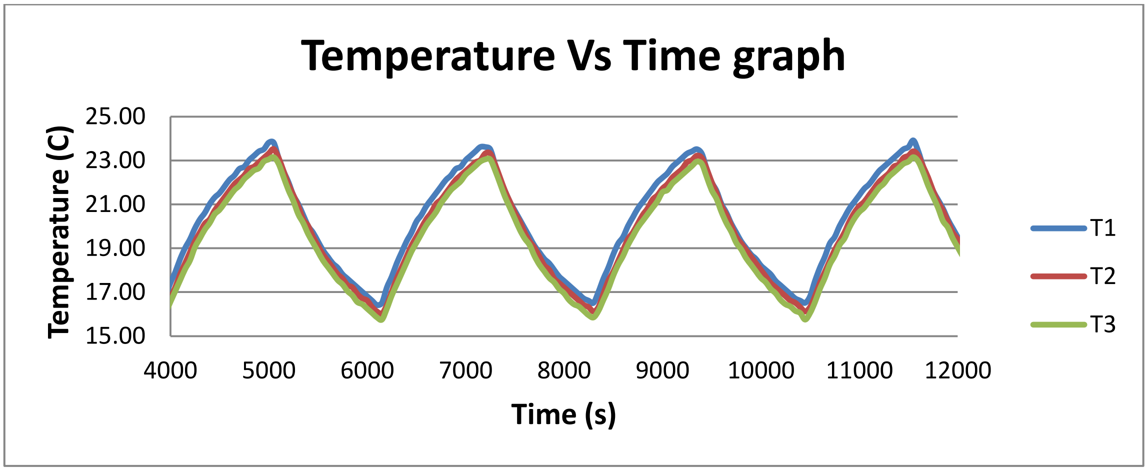

Figure 24. Temperature oscillation with respect to time, see figure 17 for details.

4.2.2 Fast Fourier Transform (FFT Analysis)

Fast Fourier Transform is the best way to solve the complex mathematical problems and bring them into simple linear form. We used this method to solve our complex data values and to bring them in real values. FFT analysis can be performed in any of the software's like, MS Excel, mat lab or FORTRAN; we did the analysis by using Excel. And the details of each step are given below [47].

As explained above the Fourier analysis has been done to find the ω and U of the temperature data obtained from the experiment at different temperatures. Thermal diffusivity and then thermal conductivity has been found from the amplitude and frequency data. The graph shown below describes the amplitude and frequency obtained by FFT analysis and the temperature is between (29-34) °C. The thermal conductivity (k) value found in this range is 0.66038W/m.°C which is little above the real value.

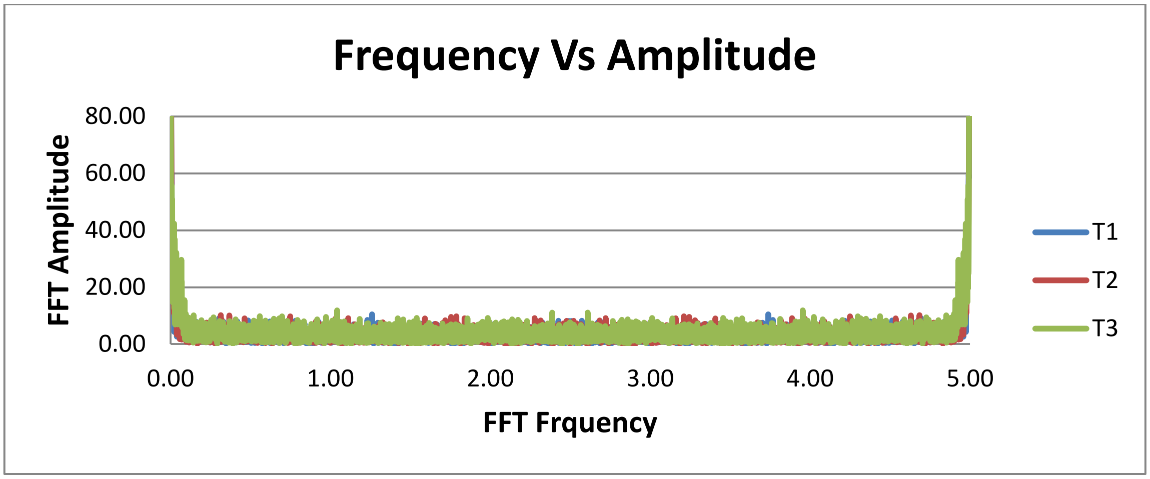

Figure 25. Fast Fourier analysis of the temperature within the range of (29-31) ˚C.

The experiment is repeated for several times and different thermal conductivity values have been found which are very close to the real value of thermal conductivity of pure water.

The figure given below shows the frequency and amplitude graph obtained by using FFT analysis. The temperature range is between (20-21) ˚C. The thermal conductivity value found from this graph is 0.5136W/m.˚C which is close to the *k* of pure water. Temperature table are provided for the reader in the appendix.

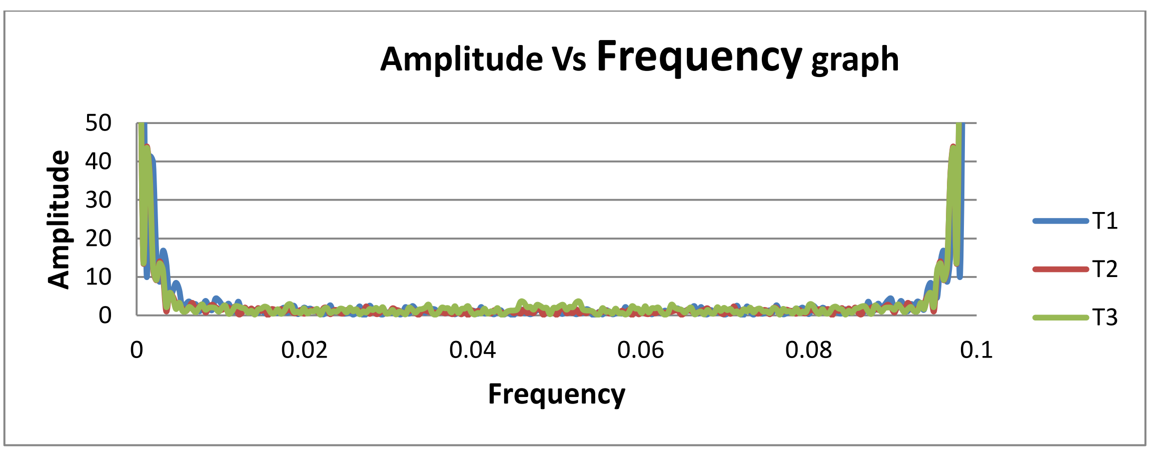

Figure 26. Fast Fourier analysis of the temperature within the range of (38-44) ˚C

The figure given below shows the frequency and amplitude graph obtained by using FFT analysis. The temperature range is between (22-23) ˚C. The thermal conductivity value found from this graph is 0.69087W/m.˚C which is very near to the *k* of pure water. The temperature table is provided for the reader in the appendix.

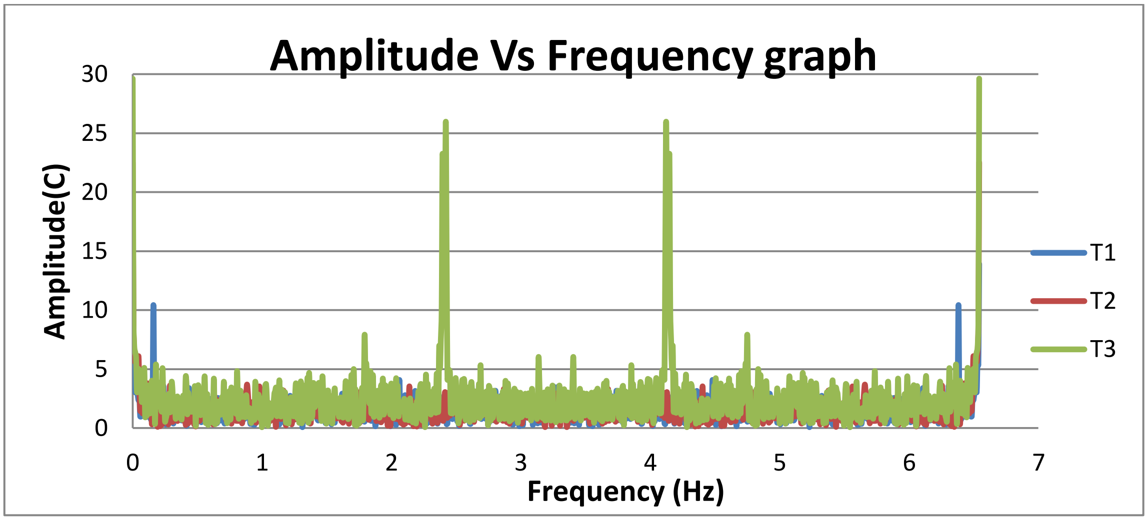

Figure 27. Fast Fourier analysis of the temperature within the range of (26-27) ˚C see figure 17 for details.

The figure given below shows the temperature oscillation with a time period of hundred seconds (100s) which means the frequency of 0.01Hz. The data has been taken for more than four hours for this figure and the oscillation is very dominant. The FFT analysis has been done for different *U* and the ω values. The temperature is between (16-24) ˚C. The data tables are given in the appendix at the end of the thesis.

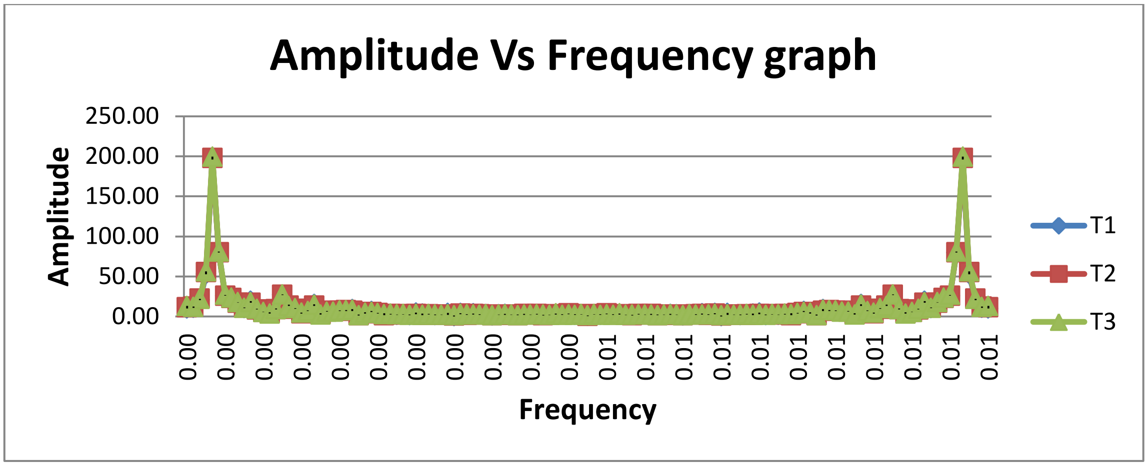

Figure 28. Fast Fourier analysis of the temperature within the range of (16-24) ˚C.

Tables 2 and 3 show the values of thermal conductivity within the temperature range of 21 to 23 ˚C. As you can see the difference between temperatures is not very much but the thermal conductivity values are much different as compared to the temperature. The enhancement in thermal conductivity is not linear.

Table 2. Measurement of thermal conductivity (*k*) at 21˚C

No.	Temperature	Amplitude	Phase	Frequency	Density (ρ)	Th. Diffusivity	Th. Conductivity
TC1	21.214	5965.78	0.262077	0.1	998.3	1.23x10^-7	**0.5136**
TC2	20.94	5888.27	0.1734849	0.1			
TC3	20.55	5807.9	0.09687	0.1			
Amp. Ratio		0.98629					

Table 3. Measurement of thermal conductivity (*k*) at 23˚C

No.	Temperature	Amplitude	Phase	Frequency	Density (ρ)	Th. Diffusivity	Th. Conductivity
TC1	22.71	1236.041	2.44676	0.15	997.6	1.656x10^-7	**0.69087**
TC2	22.22	1301.21	2.74127	0.15			
TC3	22.25	1310.221	2.757297	0.15			
Amp. Ratio		1.006925					

Tables 4 and 5 also show the values of thermal conductivity within the temperature range of 26 to 34 ˚C. As you can see the difference between temperatures is much but the thermal conductivity values are very much different as compared to the temperature. Again we can say that the enhancement in thermal conductivity in not linear.

Table 4. Measurement of thermal conductivity (k) at 26°C

No.	Temperature	Amplitude	Phase	Frequency	Density (ρ)	Th. Diffusivity	Th. Conductivity
TC1	26.34	1236.041	-1.4248	6.554799	997.1	1.53x10^-7	**0.637889**
TC2	26	1301.21	-0.90524	6.554799			
TC3	26	1310.221	-1.315	6.554799			
Amp. Ratio		0.9930794					

Table 5. Measurement of thermal conductivity (k) at 34°C

No.	Temperature	Amplitude	Phase	Frequency	Density (ρ)	Th. Diffusivity	Th. Conductivity
TC1	34.51	17865.67	1.430725	0.15	994.1	1.59x10^-7	**0.66038**
TC2	34.4	17746.44	1.448786	0.15			
TC3	34.5	17803.9	1.385821	0.15			
Amp. Ratio		1.003237					

Table 6 shows the thermal conductivity values at different temperatures.

Thermal diffusivity values are found within the temperature range of 21-34 °C. The graph of the thermal conductivity versus temperature is given below and it clearly shows the enhancement in thermal conductivity values.

Table 6. Thermal diffusivity and thermal conductivity value against different temperature.

No.	Temperature	Th. Diffusivity	Th. Conductivity
1	21	1.23x10^-7	0.5136
2	23	1.656x10^-7	0.6908
3	26	1.53x10^-7	0.63788
4	34	1.59x10^-7	0.66038

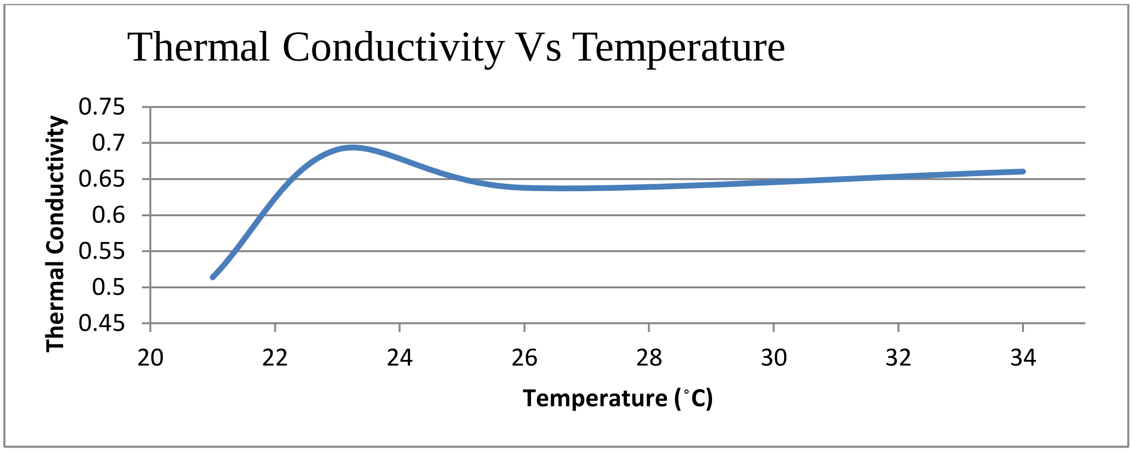

Figure 29. Thermal conductivity value against different temperature.

The thermal conductivity values in the graph above clearly shows an increase in the *k* values with increasing temperature. It can be concluded that our experimental setup is properly designed and the required parameters are selected wisely. The data taken from different thermocouples is in complete harmony with each other.

4.2.3 Temperature data for Aluminum Oxide (Al_2O_3)

The next three graphs shown below are of the same temperature value ranges in (23-27) ˚C. The first of the three graphs show the phase difference between Thermocouples (TC1 or TC3) and TC2.

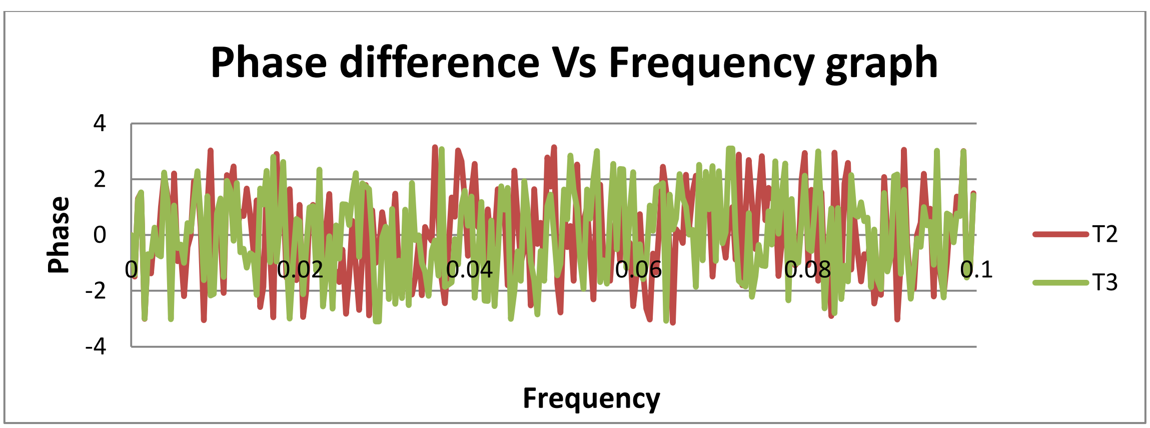

Figure 30. Graph of phase versus frequency within the temperature range of (23-27) ˚C

The graph given below is of the amplitude versus frequency of the same temperature range and it clearly shows that the amplitude values are in complete harmony with each other.

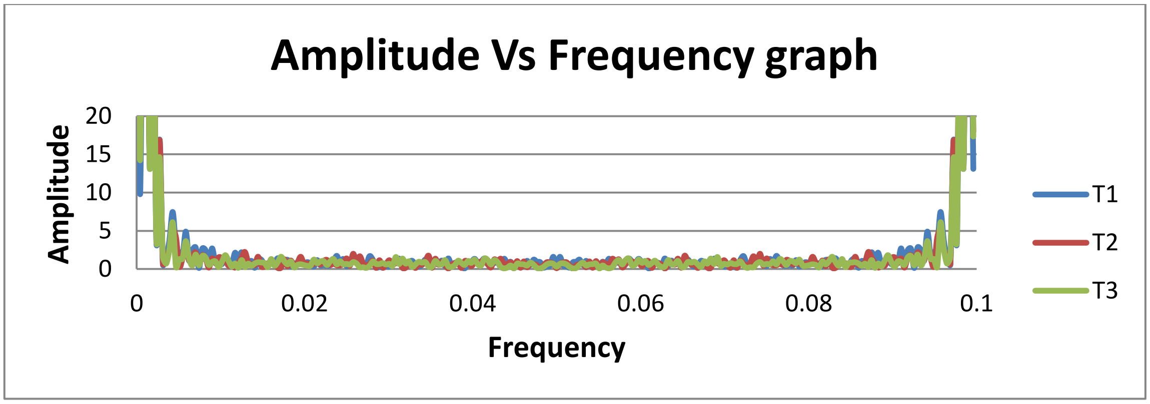

Figure 31. Graph of amplitude versus frequency within temperature range of (23-27) ˚C see figure 17 for details.

The graph given below is for the temperature range of (23-27) ˚C. The graph is of Aluminum oxide (Al_2O_3) nanoparticles mixed in pure water (80% water and 20% Aluminum oxide). The thermal conductivity found against this temperature range is 0.642 W/m.˚C which is 6.045% higher than the thermal conductivity value of pure water (0.60 W/m.˚C). Further research is continue on this topic to verify these values by comparing with other researcher's work

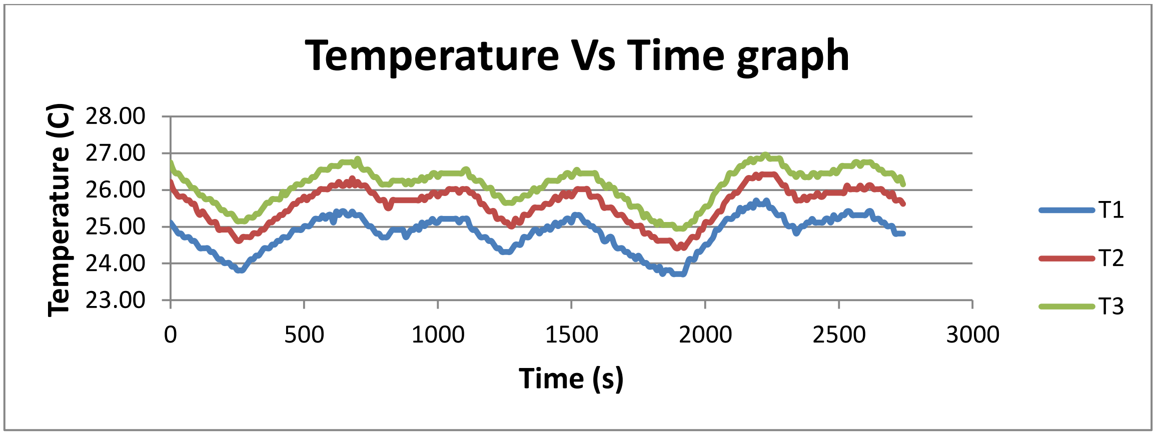

Figure 32. Graph of temperature versus time within the temperature range of (23-27) ˚C

Table 7 given below shows the enhancement in thermal conductivity values of pure water (80% by volume) against Aluminum oxide (20% by volume) nanofluid. The temperature range is between 11 to 47 ˚C and there is clear improvement in the thermal conductivity values by increasing the temperature.

Table 7. Thermal conductivity values of pure water and Aluminum oxide nanofluid against different temperatures.

No.	Temperature (˚C)	Th. Cond. (k), Water	Th. Cond (k), Mixture	% increase
	11	0.5872	0.63693	5.58
1	25	0.6054	0.642	6.045
2	30	0.618	0.66033	6.85
3	40	0.632	0.7032	13.78
4	47	0.637	0.727199	14.16

Chapter 5

CONCLUSION

Measurement of thermal conductivity by using temperature oscillation technique is simple as compared to other techniques, but it’s very sensitive if the parameters are not chosen properly. In the present study, thermal conductivity of pure water and Al_2O_3 nanoparticles in water have been obtained experimentally. Pure water is used to calibrate the system and to validate the acquired data. It’s been proved from the thermal conductivity data of pure water that our experimental setup and parameters are selected wisely. By using temperature oscillation technique and our selected parameters one can get the better results by using different types and percentages of nanofluids. We observed the enhancement in thermal conductivity of Al_2O_3 nanoparticles from 5.58% to 14.16% by increasing the temperature from 11 $^\circ$C to 47 $^\circ$C. It clearly shows that thermal conductivity increases by increasing the temperature of the nanofluid. The other parameters those influences the enhancement of thermal conductivity is the particle size and shape.

The results given above are compared with the results of Das et al. [46] and they are very much in acceptable range. These results would be more precise and reasonable if we could get the nanomaterial in different particle sizes and volume percentages. Another important aspect of getting the acceptable results is the better understanding of the nanofluids behavior.

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APPENDIX

Table 1. Amplitude and frequency obtained by FFT analysis.

TIME	TC 1	FFT FRQ	FFT CPLX	FFT MAG		S	N	No. DATA	S/2)/(N/2)		TC 2	FFT CPLX	FFT MAG			TC 3	FFT CPLX	FFT MAG	
0.00	26.41	0.00	27020.736	27,020.74	0.00	6.55	1,024.00	0.00	0.01		26.02	26681.28	26,681.28	0.00		25.95	26498.5	26,498.50	0.00
0.15	26.41	0.01	6721-13.76	13.91	-1.42	6.55	1,024.00	1.00	0.01		26.12	6999-17.70	22.51	-0.91		26.05	9458-28.66	29.62	-1.32
0.31	26.41	0.01	05203-5.196	5.36	-1.82	6.55	1,024.00	2.00	0.01		26.12	5213-7.723	8.54	-1.13		25.85	24607-8.670	8.70	-1.49
0.46	26.51	0.02	30356-5.680	5.74	-1.43	6.55	1,024.00	3.00	0.01		26.12	27685-6.33	6.40	-1.71		26.05	17973-6.767	6.77	-1.54
0.61	26.41	0.03	08534-2.557	3.06	-2.15	6.55	1,024.00	4.00	0.01		26.12	4242-5.369	5.59	-1.85		26.05	0343-6.262	6.44	-1.80
0.76	26.41	0.03	47126-4.25	4.30	-1.71	6.55	1,024.00	5.00	0.01		26.12	32489-5.913	6.00	-1.74		25.75	01709-5.638	6.00	-1.92
0.92	26.61	0.04	6915-4.618	4.90	-1.23	6.55	1,024.00	6.00	0.01		26.22	06215-4.403	4.41	-1.50		26.05	36826-3.017	3.12	-1.32
1.07	26.41	0.04	28641-2.685	2.89	-1.19	6.55	1,024.00	7.00	0.01		26.12	4793-3.888	3.96	-1.38		25.95	0225-3.646	3.80	-1.28
1.22	26.41	0.05	01688-2.311	2.37	-1.35	6.55	1,024.00	8.00	0.01		26.22	38538-6.03	6.10	-1.72		25.85	51788-4.499	5.03	-2.03
1.37	26.41	0.06	136964-2.48	2.62	-1.89	6.55	1,024.00	9.00	0.01		26.22	94156-2.896	3.34	-2.09		26.05	00839-2.758	3.42	-2.20
1.53	26.41	0.06	4091-0.300	0.99	-0.31	6.55	1,024.00	10.00	0.01		26.22	09867-1.137	1.47	-0.88		25.95	9754-3.233	3.44	-1.22
1.68	26.61	0.07	5437+0.639	0.99	0.71	6.55	1,024.00	11.00	0.01		26.22	50676-1.623	1.82	-1.10		26.05	4858-3.326	3.82	-1.06
1.83	26.41	0.08	5878-1.487	2.15	-2.38	6.55	1,024.00	12.00	0.01		26.22	81756-1.58	1.76	-2.03		26.05	26342-1.075	2.21	-2.63
1.98	26.41	0.08	26126-1.235	1.33	-1.18	6.55	1,024.00	13.00	0.01		26.12	36709-1.11	1.29	-2.10		25.85	119592-2.99	3.47	-2.10
2.14	26.41	0.09	00774-3.260	3.27	-1.50	6.55	1,024.00	14.00	0.01		26.12	53E-002-4.0	4.08	-1.56		26.05	60049-3.13	3.18	-1.73
2.29	26.41	0.10	90474-2.60	2.66	-1.78	6.55	1,024.00	15.00	0.01		26.12	7997-3.037	3.20	-1.89		25.95	26142-4.817	5.06	-1.88
2.44	26.41	0.10	5447-0.7200	1.25	-0.61	6.55	1,024.00	16.00	0.01		26.12	4327-0.9634	1.55	-0.67		25.75	54674-0.913	0.94	-1.31
2.59	26.41	0.11	178E-002-1	1.42	-1.64	6.55	1,024.00	17.00	0.01		26.22	09E-002-2.	2.28	-1.59		26.15	35913-0.963	1.29	-2.29
2.75	26.41	0.12	9454-0.373	0.99	-0.39	6.55	1,024.00	18.00	0.01		26.12	5378-0.381	2.25	-0.17		25.95	29764+1.01	1.08	1.23
2.90	26.41	0.12	78259-2.809	2.96	-1.25	6.55	1,024.00	19.00	0.01		26.22	478-3.2948	3.80	-1.05		25.95	2418-3.236	3.60	-1.12
3.05	26.41	0.13	0774-1.954	2.50	-0.90	6.55	1,024.00	20.00	0.01		26.12	89E-002-1.	1.66	-1.63		26.05	0611-3.132	3.52	-1.10
3.20	26.41	0.13	4E-002-0.9	0.94	-1.54	6.55	1,024.00	21.00	0.01		26.22	04861-1.075	1.91	-2.55		25.85	4148-1.374	1.74	-0.91
3.36	26.51	0.14	8987-1.443	1.70	-1.01	6.55	1,024.00	22.00	0.01		26.22	73345-1.71	1.78	-1.84		26.05	7159-0.9749	1.25	-0.90
3.51	26.41	0.15	16-6.40627	0.73	-0.09	6.55	1,024.00	23.00	0.01		26.22	72854-1.705	2.49	-2.39		25.95	60409-1.954	1.96	-1.49
3.66	26.41	0.15	14-6.10484	2.31	-0.03	6.55	1,024.00	24.00	0.01		26.12	1783+0.182	0.36	0.53		25.85	269-0.7214	4.02	-0.18
3.81	26.41	0.16	0287-1.706	2.73	-0.68	6.55	1,024.00	25.00	0.01		26.22	00096-0.652	0.66	-1.74		26.05	97402-1.85	2.05	-2.01
3.97	26.41	0.17	5977+9.308	10.43	1.10	6.55	1,024.00	26.00	0.01		26.12	06135+1.27	1.37	1.96		25.95	0406+1.920	2.35	0.96
4.12	26.51	0.17	38786-2.201	2.94	-2.29	6.55	1,024.00	27.00	0.01		26.12	43469-1.13	1.14	-1.69		25.85	7296-2.062	3.42	-0.65
4.27	26.41	0.18	24E-002-0.9	0.91	-1.66	6.55	1,024.00	28.00	0.01		26.12	19467-2.591	2.80	-1.96		26.05	277-4.95813	0.36	-3.00
4.42	26.41	0.19	37179-1.448	1.84	-2.24	6.55	1,024.00	29.00	0.01		26.02	49739-3.357	3.63	-1.96		25.75	28355-4.986	5.40	-1.97
4.58	26.41	0.19	16613-1.241	1.40	-1.09	6.55	1,024.00	30.00	0.01		26.22	44E-002-2.	2.22	-1.61		25.95	4207-1.1715	1.88	-0.67
4.73	26.41	0.20	6359+0.474	0.51	1.17	6.55	1,024.00	31.00	0.01		26.12	203-4.64477	0.12	-2.75		26.05	0592+1.247	2.64	0.49
4.88	26.41	0.20	1571-0.627	0.83	-0.86	6.55	1,024.00	32.00	0.01		26.12	58E-002-1.3	1.37	-1.56		25.95	34849-2.038	2.25	-1.14
5.03	26.41	0.21	51981-1.291	2.15	-2.50	6.55	1,024.00	33.00	0.01		26.12	2464-0.258	3.16	-3.06		25.95	37546-3.426	3.84	-2.04
5.19	26.41	0.22	9789-0.864	1.26	-0.75	6.55	1,024.00	34.00	0.01		26.22	061+2.9225	0.20	2.99		25.95	2641+0.670	2.05	2.81
5.34	26.41	0.22	45844-1.57	1.79	-2.07	6.55	1,024.00	35.00	0.01		26.12	38972-1.058	1.44	-0.82		26.05	6187-2.756	3.03	-1.14
5.49	26.41	0.23	534-0.8196	1.45	-0.60	6.55	1,024.00	36.00	0.01		26.12	381+6.0005	0.31	3.12		26.05	5756-0.7907	1.44	-0.58

Table 2. Temperature values with the time period of 100 seconds

Type	T	T	T	T	CJC	CJC	CJC	CJC	CJC
Polarity	**Bipolar**	**Bipolar**	**Bipolar**	**Bipolar**	**Bipolar**	**Bipolar**	**Bipolar**	**Bipolar**	**Bipolar**
Units	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**	**°C**
Time, s	**Temp 1**	**Temp 2**	**Temp 3**	**CH03**	**CJC00-00**	**CJC01-02**	**CJC03-03**	**CJC04-04**	**CJC05-06**
0.00	24.01	23.62	23.35	24.95	23.90	22.90	22.70	23.20	22.40
100.00	24.21	23.82	23.65	24.95	23.90	23.00	22.70	23.20	22.40
200.00	23.41	23.52	23.15	21.75	23.90	23.00	22.70	23.20	22.40
300.00	22.01	22.12	21.75	20.55	23.80	22.90	22.70	23.10	22.40
400.00	21.01	21.12	20.75	19.55	23.80	22.90	22.60	23.10	22.30
500.00	20.11	20.02	19.75	18.65	23.70	22.80	22.60	23.00	22.30
600.00	19.41	19.32	19.05	17.95	23.60	22.80	22.50	22.90	22.20
700.00	18.61	18.52	18.25	17.25	23.60	22.70	22.50	22.90	22.20
800.00	18.01	17.82	17.55	16.65	23.60	22.70	22.40	22.80	22.10
900.00	17.61	17.32	17.05	16.15	23.50	22.70	22.40	22.80	22.10
1,000.00	17.11	16.82	16.55	15.65	23.40	22.60	22.30	22.80	22.00
1,100.00	16.81	16.52	16.25	15.35	23.40	22.50	22.30	22.70	22.00
1,200.00	16.31	16.12	15.75	15.05	23.40	22.50	22.20	22.70	22.00
1,300.00	17.01	16.22	16.05	17.55	23.40	22.50	22.20	22.70	22.00
1,400.00	18.21	17.42	17.15	19.55	23.40	22.40	22.20	22.60	22.00
1,500.00	19.31	18.52	18.35	19.55	23.40	22.40	22.10	22.60	21.90
1,600.00	20.01	19.42	19.25	20.65	23.30	22.40	22.10	22.60	21.90
1,700.00	20.81	20.22	19.85	22.05	23.30	22.40	22.10	22.50	21.90
1,800.00	21.41	20.82	20.55	21.75	23.30	22.40	22.10	22.50	21.90
1,900.00	22.01	21.52	21.15	22.75	23.30	22.30	22.00	22.50	21.80

2,000.00	22.61	22.02	21.85	23.75	23.20	22.30	22.00	22.50	21.80
2,100.00	23.01	22.52	22.25	23.35	23.20	22.30	22.00	22.40	21.80
2,200.00	23.31	22.92	22.65	23.95	23.20	22.20	21.90	22.40	21.80
2,300.00	23.81	23.42	23.15	25.05	23.10	22.20	21.90	22.40	21.70
2,400.00	24.01	23.62	23.45	24.45	23.10	22.20	21.90	22.40	21.70
2,500.00	24.31	23.92	23.65	25.05	23.10	22.20	21.90	22.30	21.70
2,600.00	23.31	23.42	23.25	21.95	23.10	22.10	21.80	22.30	21.70
2,700.00	22.01	22.02	21.85	20.55	23.00	22.10	21.80	22.30	21.60
2,800.00	20.91	20.92	20.55	19.45	23.00	22.10	21.80	22.30	21.60
2,900.00	20.01	20.02	19.75	18.65	23.00	22.10	21.80	22.30	21.60
3,000.00	19.21	19.12	18.95	17.85	23.00	22.10	21.80	22.20	21.60
3,100.00	18.61	18.42	18.05	17.15	23.00	22.00	21.70	22.20	21.60
3,200.00	17.91	17.72	17.35	16.55	23.00	22.00	21.70	22.20	21.60
3,300.00	17.41	17.22	16.95	16.05	22.90	22.00	21.70	22.20	21.60
3,400.00	16.91	16.72	16.45	15.55	22.90	22.00	21.70	22.20	21.50
3,500.00	16.61	16.42	16.05	15.25	22.90	22.00	21.70	22.20	21.50
3,600.00	16.21	16.02	15.75	14.95	22.90	22.00	21.70	22.20	21.50
3,700.00	17.21	16.42	16.15	17.95	22.80	21.90	21.70	22.20	21.50
3,800.00	18.41	17.52	17.25	18.55	22.80	21.90	21.70	22.10	21.50
3,900.00	19.41	18.72	18.35	20.25	22.80	21.90	21.60	22.10	21.50
4,000.00	20.11	19.42	19.15	20.85	22.80	21.90	21.60	22.10	21.50
4,100.00	20.91	20.32	19.95	21.15	22.70	21.90	21.60	22.10	21.40
4,200.00	21.51	20.82	20.65	22.55	22.70	21.80	21.60	22.10	21.40
4,300.00	22.11	21.52	21.25	23.05	22.70	21.80	21.60	22.10	21.40
4,400.00	22.61	22.12	21.85	22.85	22.70	21.80	21.60	22.00	21.40
4,500.00	23.01	22.52	22.35	24.05	22.70	21.80	21.60	22.00	21.40
4,600.00	23.31	22.92	22.65	24.15	22.60	21.80	21.50	22.00	21.40

4,700.00	23.71	23.32	22.95	23.95	22.60	21.80	21.50	22.00	21.40
4,800.00	24.01	23.62	23.35	25.15	22.60	21.70	21.50	22.00	21.30
4,900.00	24.21	23.72	23.55	25.15	22.60	21.70	21.50	22.00	21.30
5,000.00	23.11	23.32	22.95	21.75	22.60	21.70	21.50	22.00	21.30
5,100.00	21.91	22.02	21.65	20.25	22.60	21.70	21.50	22.00	21.30
5,200.00	20.91	20.82	20.45	19.35	22.50	21.70	21.50	22.00	21.30
5,300.00	19.91	19.92	19.45	18.45	22.50	21.70	21.50	22.00	21.30
5,400.00	19.11	19.12	18.75	17.75	22.50	21.70	21.40	21.90	21.30
5,500.00	18.51	18.42	18.05	17.05	22.50	21.70	21.40	21.90	21.30
5,600.00	17.91	17.72	17.45	16.45	22.50	21.70	21.40	21.90	21.30
5,700.00	17.31	17.22	16.85	15.95	22.50	21.70	21.40	21.90	21.20
5,800.00	16.91	16.62	16.35	15.45	22.50	21.70	21.40	21.90	21.20
5,900.00	16.61	16.32	15.95	15.05	22.50	21.60	21.40	21.90	21.20
6,000.00	16.21	15.92	15.55	14.95	22.50	21.60	21.40	21.90	21.20
6,100.00	17.41	16.72	16.45	18.15	22.50	21.60	21.40	21.80	21.20
6,200.00	18.61	17.82	17.55	19.75	22.40	21.60	21.40	21.80	21.20
6,300.00	19.51	18.82	18.65	19.85	22.40	21.60	21.40	21.80	21.20
6,400.00	20.31	19.72	19.35	20.95	22.40	21.60	21.40	21.80	21.20
6,500.00	21.01	20.42	20.15	22.25	22.40	21.50	21.30	21.80	21.10
6,600.00	21.51	21.02	20.75	21.95	22.40	21.50	21.30	21.80	21.10
6,700.00	22.11	21.72	21.45	22.85	22.40	21.50	21.30	21.80	21.10
6,800.00	22.61	22.12	21.85	23.85	22.40	21.50	21.30	21.80	21.10
6,900.00	23.01	22.62	22.35	23.35	22.40	21.50	21.30	21.70	21.10
7,000.00	23.41	22.92	22.65	24.05	22.40	21.50	21.30	21.70	21.10
7,100.00	23.61	23.22	22.95	24.95	22.40	21.50	21.20	21.70	21.10
7,200.00	23.91	23.52	23.35	24.35	22.40	21.50	21.20	21.70	21.00
7,300.00	24.31	23.92	23.65	24.65	22.30	21.50	21.20	21.70	21.00

7,400.00	22.81	23.02	22.75	21.45	22.30	21.40	21.20	21.70	21.00
7,500.00	21.61	21.72	21.35	20.05	22.30	21.40	21.20	21.70	21.00
7,600.00	20.61	20.62	20.25	19.15	22.30	21.40	21.10	21.70	21.00
7,700.00	19.71	19.62	19.35	18.15	22.30	21.40	21.20	21.70	21.00
7,800.00	18.91	18.92	18.45	17.45	22.30	21.40	21.20	21.70	21.10
7,900.00	18.21	18.22	17.75	16.85	22.30	21.40	21.20	21.70	21.10
8,000.00	17.71	17.62	17.35	16.25	22.30	21.40	21.10	21.70	21.00
8,100.00	17.11	16.92	16.65	15.75	22.30	21.30	21.10	21.60	21.00
8,200.00	16.71	16.52	16.15	15.35	22.30	21.30	21.10	21.60	21.00
8,300.00	16.21	16.02	15.65	14.95	22.30	21.40	21.10	21.60	21.00
8,400.00	16.31	15.92	15.45	16.35	22.30	21.30	21.10	21.60	21.00
8,500.00	17.61	16.82	16.55	18.35	22.30	21.30	21.10	21.60	20.90
8,600.00	18.71	18.02	17.75	19.95	22.30	21.30	21.10	21.60	20.90
8,700.00	19.51	18.82	18.65	19.95	22.30	21.30	21.10	21.60	20.90
8,800.00	20.21	19.72	19.45	21.05	22.30	21.30	21.00	21.50	20.90
8,900.00	20.91	20.32	20.15	22.25	22.30	21.30	21.00	21.50	20.90
9,000.00	21.61	21.02	20.65	21.95	22.30	21.30	21.00	21.50	20.90
9,100.00	22.01	21.62	21.45	22.85	22.30	21.30	21.00	21.50	20.90
9,200.00	22.51	22.02	21.75	23.75	22.30	21.30	21.00	21.50	20.90
9,300.00	22.81	22.52	22.25	23.25	22.20	21.30	21.00	21.50	20.90
9,400.00	23.31	22.82	22.65	24.05	22.20	21.30	21.00	21.50	20.90
9,500.00	23.51	23.12	22.85	24.85	22.20	21.30	21.00	21.50	20.90
9,600.00	23.71	23.42	23.15	24.25	22.20	21.30	21.00	21.50	20.90
9,700.00	23.91	23.62	23.45	24.75	22.20	21.30	21.00	21.50	20.90
9,800.00	24.21	23.92	23.85	25.55	22.20	21.30	21.00	21.50	20.90
9,900.00	23.31	23.42	23.15	21.95	22.20	21.30	21.00	21.50	20.90
10,000.00	22.01	22.12	21.95	20.55	22.20	21.20	21.00	21.50	20.90

10,100.00	20.91	20.92	20.65	19.45	22.20	21.20	21.00	21.50	20.90
10,200.00	19.81	19.82	19.55	18.45	22.20	21.20	21.00	21.50	20.90
10,300.00	19.11	19.12	18.75	17.75	22.20	21.20	21.00	21.50	20.90
10,400.00	18.41	18.32	18.05	17.05	22.20	21.20	21.00	21.50	20.90
10,500.00	17.91	17.72	17.35	16.35	22.10	21.20	21.00	21.50	20.90
10,600.00	17.31	17.02	16.75	15.85	22.10	21.20	21.00	21.50	20.90
10,700.00	16.91	16.72	16.25	15.45	22.10	21.20	21.00	21.50	20.90
10,800.00	16.41	16.12	15.85	15.05	22.20	21.20	21.00	21.50	20.90
10,900.00	16.11	15.82	15.55	14.75	22.20	21.20	21.00	21.50	20.90
11,000.00	16.31	15.72	15.45	17.35	22.20	21.20	21.00	21.50	20.90
11,100.00	17.61	16.82	16.55	18.05	22.20	21.30	21.00	21.50	20.90
11,200.00	18.61	18.02	17.75	19.35	22.20	21.30	21.00	21.50	20.90
11,300.00	19.51	19.02	18.75	20.95	22.20	21.30	21.00	21.50	20.90
11,400.00	20.21	19.72	19.45	20.75	22.20	21.30	21.00	21.50	20.90
11,500.00	20.81	20.32	20.15	21.65	22.20	21.30	21.00	21.50	20.90
11,600.00	21.51	20.92	20.85	22.75	22.20	21.30	21.00	21.50	20.90
11,700.00	22.01	21.52	21.35	22.45	22.20	21.30	21.00	21.50	20.90
11,800.00	22.41	22.02	21.75	23.15	22.20	21.30	21.00	21.50	20.80
11,900.00	22.91	22.42	22.25	24.25	22.20	21.30	21.00	21.50	20.80
12,000.00	23.21	22.82	22.65	23.65	22.20	21.30	21.00	21.50	20.80
12,100.00	23.51	23.12	22.95	24.35	22.20	21.30	21.00	21.50	20.80
12,200.00	23.81	23.42	23.25	25.15	22.10	21.30	21.00	21.50	20.80
12,300.00	24.01	23.72	23.45	24.25	22.10	21.20	21.00	21.50	20.80
12,400.00	22.91	23.02	22.75	21.45	22.10	21.20	21.00	21.50	20.80
12,500.00	21.61	21.72	21.35	20.05	22.10	21.20	21.00	21.50	20.80
12,600.00	20.51	20.52	20.25	19.05	22.10	21.20	21.00	21.40	20.80
12,700.00	19.61	19.62	19.25	18.25	22.10	21.20	21.00	21.40	20.80

12,800.00	18.91	18.82	18.45	17.55	22.10	21.20	20.90	21.40	20.80
12,900.00	18.21	18.12	17.85	16.85	22.20	21.20	21.00	21.40	20.80
13,000.00	17.61	17.52	17.15	16.25	22.10	21.20	21.00	21.40	20.80
13,100.00	17.11	16.92	16.55	15.75	22.10	21.20	21.00	21.40	20.80
13,200.00	16.61	16.42	16.05	15.15	22.10	21.20	20.90	21.40	20.80
13,300.00	16.21	16.02	15.65	14.85	22.10	21.20	20.90	21.40	20.80
13,400.00	16.51	15.92	15.65	17.55	22.10	21.20	20.90	21.40	20.80
13,500.00	17.81	17.02	16.75	18.35	22.20	21.20	20.90	21.40	20.70
13,600.00	18.71	18.12	17.95	19.55	22.20	21.20	20.90	21.40	20.70
13,700.00	19.51	18.92	18.75	20.95	22.20	21.20	20.90	21.40	20.70
13,800.00	20.21	19.72	19.55	20.75	22.20	21.20	20.80	21.30	20.70
13,900.00	20.81	20.32	20.25	21.65	22.20	21.20	20.90	21.40	20.70

Table 3. Temperature values with respect to time with four different thermocouples.

Time (s)	Temp 1	Temp 2	Temp 3	Temp 4		Time (s)	Temp 1	Temp 2	Temp 3	Temp 4		Time (s)	Temp 1	Temp 2	Temp 3	Temp 4
0.00	21.21	20.92	20.55	22.45	36	0.01	22.01	21.72	21.35	22.45	71	0.02	22.61	22.42	22.05	22.85
0.00	21.31	21.02	20.65	22.55	37	0.01	22.11	21.72	21.35	22.95	72	0.02	22.61	22.32	21.95	23.15
0.00	21.41	21.02	20.55	22.05	38	0.01	22.01	21.82	21.45	23.25	73	0.02	22.71	22.42	22.15	23.55
0.00	21.21	20.92	20.55	21.65	39	0.01	22.11	21.82	21.65	23.15	74	0.02	22.71	22.42	22.05	23.95
0.00	21.31	21.02	20.85	21.95	40	0.01	22.11	21.82	21.55	22.75	75	0.02	22.61	22.42	22.05	23.85
0.00	21.41	21.02	20.65	22.35	41	0.01	22.21	21.92	21.45	22.45	76	0.02	22.71	22.52	22.25	23.35
0.00	21.31	21.02	20.75	22.65	42	0.01	22.21	21.82	21.45	22.65	77	0.03	22.71	22.42	22.05	22.95
0.00	21.31	21.02	20.75	22.65	43	0.01	22.21	21.92	21.65	23.05	78	0.03	22.71	22.52	22.25	23.25
0.00	21.41	21.02	20.65	22.15	44	0.01	22.21	21.92	21.45	23.35	79	0.03	22.71	22.42	22.15	23.65
0.00	21.41	21.02	20.75	21.85	45	0.01	22.21	21.82	21.55	23.25	80	0.03	22.71	22.42	22.05	23.95
0.00	21.41	21.12	20.85	22.05	46	0.01	22.31	21.92	21.55	22.85	81	0.03	22.71	22.52	22.15	23.85
0.00	21.61	21.12	20.85	22.45	47	0.02	22.31	22.02	21.55	22.45	82	0.03	22.81	22.52	22.05	23.45
0.00	21.61	21.22	20.95	22.85	48	0.02	22.31	21.92	21.65	22.75	83	0.03	22.71	22.42	22.05	22.95
0.00	21.61	21.12	20.85	22.75	49	0.02	22.31	22.02	21.65	23.25	84	0.03	22.81	22.62	22.25	23.35
0.00	21.61	21.22	20.75	22.25	50	0.02	22.31	22.02	21.55	23.45	85	0.03	22.81	22.52	22.15	23.75
0.01	21.61	21.22	20.85	21.95	51	0.02	22.31	22.12	21.75	23.55	86	0.03	22.91	22.62	22.15	24.05
0.01	21.61	21.22	20.95	22.15	52	0.02	22.31	22.02	21.65	22.85	87	0.03	22.91	22.62	22.35	24.05
0.01	21.71	21.32	21.15	22.55	53	0.02	22.31	22.12	21.85	22.65	88	0.03	22.91	22.62	22.25	23.55
0.01	21.61	21.22	21.15	22.85	54	0.02	22.31	22.12	21.85	22.95	89	0.03	22.91	22.62	22.35	23.15
0.01	21.71	21.42	21.05	22.95	55	0.02	22.41	22.12	21.95	23.35	90	0.03	22.91	22.62	22.45	23.45
0.01	21.81	21.42	21.05	22.35	56	0.02	22.41	22.12	21.85	23.65	91	0.03	22.91	22.62	22.25	23.85
0.01	21.81	21.42	20.95	22.05	57	0.02	22.41	22.12	21.85	23.55	92	0.03	22.91	22.72	22.25	24.15
0.01	21.81	21.42	21.05	22.35	58	0.02	22.41	22.22	21.75	23.05	93	0.03	22.91	22.62	22.45	24.05
0.01	21.91	21.42	21.05	22.75	59	0.02	22.41	22.12	21.75	22.65	94	0.03	22.91	22.62	22.35	23.55
0.01	21.91	21.52	21.35	23.05	60	0.02	22.41	22.22	21.85	22.95	95	0.03	23.01	22.82	22.45	23.35
0.01	21.81	21.42	21.35	22.95	61	0.02	22.51	22.22	22.05	23.35	96	0.03	23.01	22.72	22.45	23.45
0.01	21.81	21.52	21.35	22.45	62	0.02	22.61	22.22	22.05	23.75	97	0.03	23.01	22.82	22.35	23.95
0.01	21.91	21.52	21.35	22.15	63	0.02	22.51	22.32	21.85	23.65	98	0.03	23.01	22.62	22.35	24.15
0.01	21.91	21.52	21.25	22.45	64	0.02	22.51	22.22	21.95	23.15	99	0.03	23.11	22.82	22.55	24.25
0.01	21.91	21.52	21.25	22.85	65	0.02	22.51	22.22	22.05	22.85	100	0.03	23.01	22.82	22.45	23.65
0.01	22.01	21.52	21.35	23.15	66	0.02	22.51	22.32	21.85	23.05	101	0.03	23.01	22.82	22.55	23.35
0.01	21.91	21.72	21.25	23.15	67	0.02	22.61	22.32	22.15	23.55	102	0.03	23.11	22.82	22.55	23.55
0.01	22.01	21.72	21.45	22.65	68	0.02	22.61	22.32	22.05	23.85	103	0.03	23.11	22.82	22.35	23.95
0.01	22.01	21.72	21.45	22.35	69	0.02	22.51	22.32	21.85	23.75	104	0.03	23.11	22.92	22.55	24.25
36	0.01	22.01	21.72	21.35	22.45	0.02	22.51	22.22	22.05	23.15	105	0.03	23.01	22.92	22.55	24.25

Table 4. Thermocouple values with cold junction compensation (CJC) values

Time, s	CH00	CH01	CH02	CH03	CJC00-00	CJC01-02	CJC03-03	CJC04-04	CJC05-06		Time, s	CH00	CH01	CH02	CH03	CJC00-00	CJC01-02	CJC03-03	CJC04-04	CJC05-06
0	22.01	21.82	21.45	23.55	21.60	20.60	20.40	20.80	20.10		175	22.31	22.12	21.95	23.55	21.80	20.90	20.70	21.10	20.40
5	22.01	21.82	21.55	22.75	21.60	20.60	20.40	20.90	20.10		180	22.31	22.12	21.95	23.75	21.80	20.90	20.70	21.10	20.40
10	22.01	21.92	21.55	22.35	21.60	20.60	20.40	20.90	20.10		185	22.31	22.12	21.75	23.15	21.80	20.90	20.70	21.10	20.40
15	22.01	21.92	21.65	22.45	21.60	20.60	20.40	20.90	20.10		190	22.31	22.12	21.85	22.45	21.80	20.90	20.70	21.10	20.40
20	22.01	21.92	21.65	22.95	21.60	20.60	20.40	20.90	20.10		195	22.31	22.22	21.95	22.65	21.90	20.90	20.70	21.10	20.40
25	22.01	21.92	21.65	23.35	21.60	20.60	20.40	20.90	20.10		200	22.31	22.12	22.05	23.05	21.90	20.90	20.70	21.20	20.40
30	22.01	21.92	21.75	23.65	21.60	20.60	20.50	20.90	20.10		205	22.41	22.22	21.85	23.65	21.90	20.90	20.70	21.20	20.40
35	22.01	21.82	21.55	22.85	21.60	20.60	20.50	20.90	20.20		210	22.21	22.12	21.75	23.75	21.90	20.90	20.70	21.20	20.40
40	22.11	21.82	21.65	22.25	21.60	20.60	20.50	20.90	20.20		215	22.21	22.02	21.85	23.05	21.90	20.90	20.70	21.20	20.40
45	22.11	21.92	21.65	22.45	21.60	20.70	20.50	20.90	20.20		220	22.31	22.22	21.95	22.45	21.90	20.90	20.70	21.20	20.40
50	22.21	21.92	21.65	22.95	21.70	20.70	20.50	20.90	20.20		225	22.31	22.12	21.95	22.75	21.90	20.90	20.70	21.20	20.40
55	22.11	21.92	21.75	23.35	21.70	20.70	20.50	20.90	20.20		230	22.31	22.12	21.95	23.15	21.90	20.90	20.80	21.20	20.40
60	22.11	21.92	21.65	23.65	21.70	20.70	20.50	20.90	20.20		235	22.31	22.12	21.95	23.55	21.90	20.90	20.80	21.20	20.40
65	22.11	22.02	21.55	23.05	21.70	20.70	20.50	20.90	20.20		240	22.31	22.12	21.95	23.85	21.90	20.90	20.80	21.20	20.40
70	22.01	22.02	21.75	22.35	21.70	20.70	20.50	21.00	20.20		245	22.41	22.22	21.95	23.25	21.90	21.00	20.80	21.20	20.40
75	22.11	21.82	21.65	22.35	21.70	20.70	20.50	21.00	20.20		250	22.41	22.22	21.95	22.55	21.90	21.00	20.80	21.20	20.50
80	22.11	21.82	21.65	22.85	21.70	20.70	20.50	21.00	20.20		255	22.41	22.22	21.95	22.65	21.90	21.00	20.80	21.20	20.50
85	22.11	22.02	21.75	23.45	21.70	20.70	20.50	21.00	20.20		260	22.41	22.22	21.95	23.25	21.90	21.00	20.80	21.20	20.50
90	22.31	22.12	21.85	23.85	21.70	20.70	20.60	21.00	20.20		265	22.41	22.22	21.85	23.65	21.90	21.00	20.80	21.20	20.50
95	22.21	22.02	21.65	22.95	21.70	20.70	20.60	21.00	20.20		270	22.41	22.22	21.85	23.95	22.00	21.00	20.80	21.20	20.50
100	22.21	21.92	21.75	22.35	21.70	20.70	20.60	21.00	20.20		275	22.41	22.22	22.05	23.25	22.00	21.00	20.80	21.20	20.50
105	22.21	21.92	21.75	22.55	21.70	20.80	20.60	21.00	20.30		280	22.51	22.22	21.95	22.55	22.00	21.00	20.80	21.30	20.50
110	22.21	22.02	21.65	23.05	21.70	20.80	20.60	21.00	20.30		285	22.41	22.22	21.95	22.75	22.00	21.00	20.80	21.30	20.50
115	22.21	22.02	21.85	23.45	21.70	20.80	20.60	21.00	20.30		290	22.41	22.22	21.95	23.15	22.00	21.00	20.80	21.30	20.50
120	22.21	22.02	21.85	23.75	21.80	20.80	20.60	21.00	20.30		295	22.51	22.22	22.15	23.75	22.00	21.00	20.80	21.30	20.50
125	22.11	22.12	21.75	23.05	21.80	20.80	20.60	21.00	20.30		300	22.41	22.22	21.95	23.95	22.00	21.00	20.80	21.30	20.50
130	22.21	22.12	21.75	22.45	21.80	20.80	20.60	21.00	20.30		305	22.41	22.22	21.95	23.25	22.00	21.00	20.90	21.30	20.50
135	22.21	22.12	21.85	22.55	21.80	20.80	20.60	21.10	20.30		310	22.41	22.32	22.05	22.65	22.00	21.00	20.90	21.30	20.50
140	22.31	22.12	21.75	23.05	21.80	20.80	20.60	21.10	20.30		315	22.41	22.22	21.95	22.75	22.00	21.00	20.90	21.30	20.50
145	22.21	22.12	21.75	23.55	21.80	20.80	20.60	21.10	20.30		320	22.51	22.22	22.05	23.25	22.00	21.00	20.90	21.30	20.50
150	22.21	22.02	21.85	23.75	21.80	20.80	20.60	21.10	20.30		325	22.51	22.22	22.05	23.65	22.00	21.10	20.90	21.30	20.50
155	22.31	22.12	21.75	23.05	21.80	20.80	20.60	21.10	20.30		330	22.51	22.32	22.05	24.05	22.00	21.10	20.90	21.30	20.60
160	22.21	22.12	21.75	22.45	21.80	20.80	20.70	21.10	20.30		335	22.51	22.32	21.95	23.35	22.00	21.10	20.90	21.30	20.60
165	22.21	22.12	21.85	22.65	21.80	20.80	20.70	21.10	20.30		340	22.41	22.32	22.05	22.75	22.00	21.10	20.90	21.30	20.60
170	22.31	22.02	21.95	23.05	21.80	20.90	20.70	21.10	20.40		345	22.51	22.32	22.05	22.75	22.00	21.10	20.90	21.30	20.60