An Experimental Study of Natural Convection of Nanofluid in a Rectangular Cavity

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ABSTRACT

The concept of nanofluids refers to a new kind of heat transport fluids by suspending nano scaled metallic or nonmetallic particles in base fluids. The experimental results showed that the suspended nanoparticles increased convective heat transfer coefficient of the fluid.

The properties and behavior of a nanofluid depend on a number of parameters including the properties of the base liquid and the dispersed phases, particle concentration, particle size and morphology, as well as the presence of dispersants and/or surfactants. From a macroscopic view, the properties of homogenous nanofluids that affect the heat transfer behavior include heat capacity, thermal conductivity, density and viscosity.

Natural convective heat transfer is affected by a number of processes in parallel and/or series, including unsteady state heat conduction through the heating wall, conduction within the boundary layer and its development, as well as convection due to the variation of liquid density and the density difference between the nanoparticles and the liquid.

In this experimental study, natural heat transfer of Nanofluid will be investigated. Nanofluid with different volume percentage will be put between walls of the cavity, and the natural heat transfer will be observed. As a result of the experimental readings, Nusselt number as a function of Rayleigh number (i.e. $Nu= c\ Ra^n$) will be obtained.

Keywords: Nanofluid, Convective heat transfer, Natural convection, Cavity.

ÖZ

Nanofluid konsepti, temel akışkanların içerisinde bulunan nano ölçekteki metal veya ametal parçacıkları etkisiz hale getirerek uygulanan yeni türde ısı geçiş akışkanlarını kapsar. Yapılan deney sonuçlarına göre nano ölçekteki parçacıkların etkisiz hale getirilmesi, akıskanın konveksiyon ısı transferi katsayısını artırmaktadır.

Bir nanofluidin özellikleri ve davranışları çeşitli parametrelere bağlıdır. Bu parametreler temel akışkanın özellikleri ve fazı, molekül yoğunluğu, molekül tipi ve morfolojisi bunlarla birlikte seyreltici varlığı ve yüzeyaktif madde içeriğinin de bulunduğu etkenlerdir. Mikroskopik açıdan bakıldığında bir akışkanın ısı kapasitesi, ısı iletkenliği, yoğunluğu ve viskozitesi yani ısı transfer davranışı homojen nanofluidlerin özellikleri tarafından etkilenir.

Doğal konveksiyon ısı transferi, içerisinde bir duvarın ısıtılmasında kararsız ısı kondüksiyonunun, sınır tabakaları içerisinde kondüksiyon gelişmesinin, sıvı yoğunluğunun farklılığından oluşan konveksiyonun ve nanopartikuller ile sıvı arasındaki yoğunluk farkının bulunduğu çeşitli parallel ya da seri proseslerden etkilenir.

Bu deneysel çalışmada, D Doğal oğal ısı transferi incelenmiştir. Hazne duvarları arasında farklı hacim yüzdelerinde nanofluid yerleştirilmiş ve bu oranlara karşılık Doğal ısı trasferi değerleri ölçülmüştür. Elde edilen deneysel veriler ile Rayleigh Sayısı'nın fonksiyonu olarak Nusselt Sayısı ($Nu=c\ Ra^n$) elde edilmeye çalışılmıştır.

Anahtar kelimeler: Nanofluid, Doğal konveksiyon, konveksiyon ısı transferi,

Hazne.

To My Family

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LIST OF SYMBOLS

A	Aspect ratio
C_p	Specific heat (J/kg. ºC)
G	Gravitational acceleration (m/s^2)
Gr	Grashof number
H	Height of the cavity (m)
K	Thermal conductivity (W/m.ºC)
L	Length of the cavity (m)
m	Mass (kg)
$\dot{m}$	Mass flow rate of hot water (kg/s)
Nu	Nusselt number
Pr	Prandtl number
Q	Heat flux (W/m^2)
Ra	Raleigh number
t	Time (s)
T	Temperature (ºK)
ΔT	Temperature difference between hot and cold walls (ºK)
$(\Delta T)_{bath}$	Temperature difference between hot and cold baths (ºK)
W	Wide of the cavity (m)
X	Dimensionless length
Y	Dimensionless height

Greek Symbols

ϕ	Volume fraction of nanoparticles
α	Thermal diffusivity (m^2/s)
β	Thermal expansion coefficient (1/ ºK)
θ	Dimensionless Temperature
μ	Viscosity (kg/m s)
ν	Kinematic viscosity (m/s^2)
ρ	Density (kg/m^3)

Subscripts

C	Cold
eff	Effective
f	Fluid
H	Hot
L	Low
nf	Nanofluid
s	Nanoparticle

Chapter 1

INTRODUCTION

The heat removal strategies in many engineering applications such as cooling of electronic components rely on natural convection heat transfer due to its simplicity, minimum cost, low noise, smaller size and reliability. In most natural convection studies, the base fluid in the enclosure has a low thermal conductivity, which limits the rate of heat transfer. However, the continuing miniaturization of electronic devices requires further heat transfer improvements from an energy saving viewpoint. An innovative technique, which uses a mixture of nanoparticles and the base fluid, was first introduced by Choi in order to develop advanced heat transfer fluids with substantially higher conductivities. The resulting mixture of the base fluid and nanoparticles having unique physical and chemical properties is referred to as a nanofluid. It is expected that the presence of the nanoparticles in the nanofluid increases the thermal conductivity and therefore substantially enhances the heat transfer characteristics of the nanofluid [1].

Increased thermal conductivity will result in higher heat transfer than that of the base (pure) fluid without dispersed nanoparticles. Measurements of the heat transfer coefficients of fluids have show that the heat trasfer capability of water increased by 15% with a dispersion of less than 1 vol% copper oxide nanoparticles (Zussman, 1997). Recently, we have seen about 80% improvements in heat transfer with the dispersion of less than 3 vol% alumina nanoparticles. It should be noted that the observed heat transfer rates of nanofluids are much higher than those predicted by conventional heat transfer correlations, even when changes in thermophysical properties such as thermal conductivity, density, specific heat, and viscosity are considered. It appears that the effect of particle size and number becomes predominant in enhancing heat transfer in nanofluids. All of these results on thermal conductivity and heat transfer enhancement were from nanofluids containing metallic oxide nanoparticles. Even greater effects are expected for nanofluids that contain metal nanoparticles (such as Cu, Ag) rather than oxides. Therefore, there is great potential to "engineer" ultra-energy-efficient heat transfer fluids by choosing the nanoparticle material, as well as by controlling particle size and loading.

On the contrary, natural convection heat transfer research using nanofluids is scarce and has received very little attention. In view of this, there is still a debate on the role that nanoparticles play on the heat transfer enhancement in natural convection applications.

Examples of controversial results are found in the results reported by Khanafer et al. who studied Cu–water nanofluids in a two-dimensional rectangular enclosure. These authors reported an augmentation in heat transfer with an increment percentage of the suspended nanoparticles at any given Grashof number. Oztop and Abu-Nada showed similar results, where an enhancement in heat transfers was registered by the addition of nanoparticles.

However, contradictory experimental findings were reported by Putra et al. using Al_2O_3 and CuO water nanofluids. These authors found that the natural convection heat transfer coefficient was lower than that for a clear fluid. Moreover, another experimental work in natural convection conducted by Wen and Ding, highlighted deterioration in heat transfer by the addition of nanoparticles. Most recently, Abu-Nada et al. demonstrated that the enhancement of heat transfer in natural convection depends mainly on the magnitude of Rayleigh number [1].

1.1 Objective of Study

The aim of this experimental study is investigation natural convection of nanofluid in a rectangular cavity.

Natural convection heat transfer is affected by nanofluid properties such as viscosity and thermal conductivity.These parameters are affected by both liquid and solid phases in nanofluid, also volume fraction of nanoparticles affect these thermophysical properties. Some ideal assumptions about properties of nanofluid were made in simulation of natural convection of nanofluid by some researchers. Because of these assumptions there is a paradox in results of numerical and experimental studies.

In the present experimental study, all of the thermophysical properties of nanofluid such as thermal conductivity, viscosity, density, heat capacity and thermal expansion were calculated by experimental datas.According to these important calculated parameters base on experimental datas, an accurate formulation of heat transfer coefficient of nanofluid will be possible.

The present results were comprised with others experimental and numerical studies about natural convection of nanofluids in the past years.

1.2 Thesis Organization

In chapter 2, a background of nanofluids, using nanofluids in different application, some kind of nanofluid, natural convection of nanofluid and also how we are able to find thermophysical properties of nanofluid to find formulation of problem were introduced in general.

In chapter 3, which is the most important chapter of the thesis, whole experimental procedure of the work from beginning to the end were considered. At the end of this chapter we found the whole thermophysical properties of 3 samples of nanofluids.

In chapter 4, some figures as our experimental results were shown and some comparison between our work and other researchers work were made in this chapter.

Finally chapter 5 contains some conclusions and summarizing of other chapters

Chapter 2

BACKGRAUND INFORMATION AND LITERATURE SURVEY

2.1 Nanofluids

Heat transfer fluids such as water, minerals oil and ethylene glycol play an important role in many industrial sectors including power generation, chemical production, air-conditioning, transportation and microelectronics. The performance of these conventional heat transfer fluids is often limited by their low thermal conductivities. According to industrial needs of process intensification and device miniaturization, development of high performance heat transfer fluids has been a subject of numerous investigations in the past few decades [2].

It is well known that at room temperature, metallic solids possess an order-of-magnitude higher thermal conductivity than fluids. For example, the thermal conductivity of copper at room temperature is about 700 times greater than that of water and about 3000 times greater than that of engine oil (Fig 2. 1). Therefore, the thermal conductivities of fluids containing suspended solid metallic or nonmetallic (Metallic oxide) particles would be expected to be significantly higher than those of conventional heat transfer fluids[3].

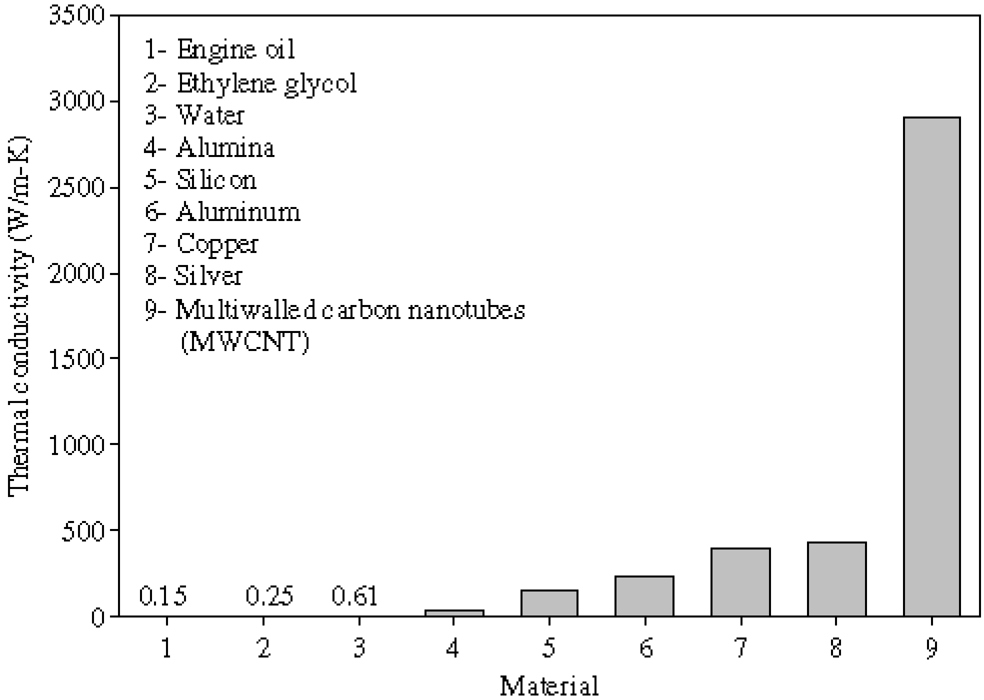


Figure 2.1: Thermal conductivity of typical materials (solids and liquids) at 300 °K [3].

An inventive way of improving the heat transfer performance of common fluids is to suspend various types of small solid particles, such as metallic, nonmetallic and polymeric particles, in conventional fluids to form colloidal. However, suspended particles of the order of μm (micrometer) or even mm (millimeter) may cause some problems in the flow channels, increasing pressure drop, causing the particles to quickly settle out of suspension.

In recent years, modern nanotechnology has been discovered. Particles of nanometer dimensions dispersed in base liquids are called nanofluids. This term was first introduced by Choi in 1995 at the Argonne National Laboratory.

Compared with millimeter or micrometer sized particle suspensions, nanofluids have shown a number of potential advantages such as better long-term stability and rheological properties, and can have significantly higher thermal conductivities.

A number of researchers have researched and reported the correlations for predicting the thermal conductivity, density, viscosity and specific heat of the nanofluids. Understanding the physical and thermal properties of nanofluid is important before using nanofluids in practical applications. There are a few important correlations for predicting the thermo physical properties of nanofluids that are often cited by a number of researchers. Their works have both experimentally and theoretically investigated the heat transfer behavior of the nanofluids [4].

2.1.1 Types of Nanofluids

Some nanoparticle materials that have been used in nanofluids are oxide ceramics (Al_2O_3, CuO, Cu_2O), nitride ceramics (AIN, SiN), carbide ceramics (Sic, TiC), metals (Ag, Au, Cu, Fe), semiconductors (TiO_2), single, double or multi-walled carbon (SWCNT, DWCNT, NWCNT), and composite materials such as nanoparticle core-polymer shell composites. In addition new materials and structures are attractive for use in nanofluids where the particle-liquid interface is doped with various molecules.

The base fluids which are used in nanofluids are common heat transfer fluids such as water, engine oil, Ethylene glycol and ethanol [5].

Generally in the most researchs, the following three kind of nanoparticles were considered as the solid phase of nanofluid :

I)<u>CuO and Cu_20 base nanofluids:</u>

Cu_2O is a p-type semiconductor that has received appreciable attentions recently due to its potential applications in fields such as solar cells, pigments, and catalysts. Nanoscaled Cu_2O is expected to possess improved properties than its bulk one. Although Cu_2O nanocrystals have been successfully synthesized by different methods, few approaches to synthesize shape-controlled Cu_2O nanocrystals at mild conditions have been reported [6-10].

Xiaohao Wei et al. [6] indicated that Cu_2O nanofluids can be synthesized by using the chemical solution method (CSM). The nanoparticle can be varied from a spherical shape to an octahedral one by adjusting some synthesis parameters. The nanofluid thermal conductivity can also be controlled by either the synthesis parameters or its temperature.

The reaction between cupric-sulfate ($CuSO_4$) and sodium-hydrate (NaOH) yields cupric-hydroxide (Cu $(OH)_2$) and sodium-sulfate (Na_2SO_4)[6] .

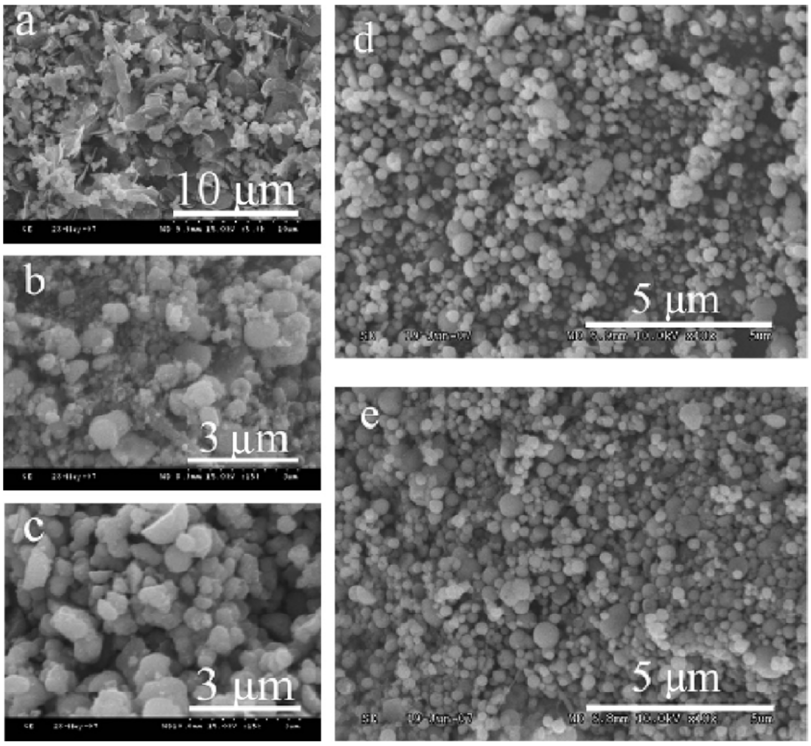


Figure 2.2: The SEM images of Cu_2O nanoparticles obtained by photolysis of Cu $(Ac)_2$ in different solvents: (a) water; (b) methanol; (c) ethanol; (d) ethylene glycol; (e) dodecanol [7].

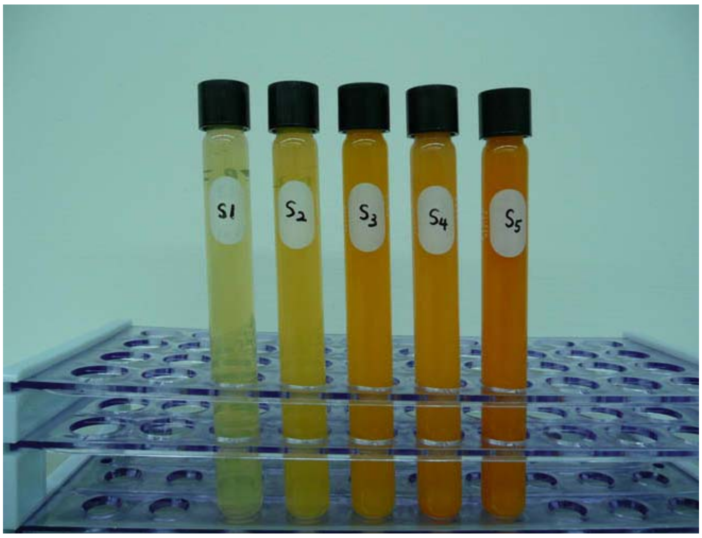


Figure 2.3: Octahedral-Cu_2O nanofluids 24 h after their preparation ($CuSO_4$ molar concentration from 0.0025 mol/L to 0.002 mol/L) [7].

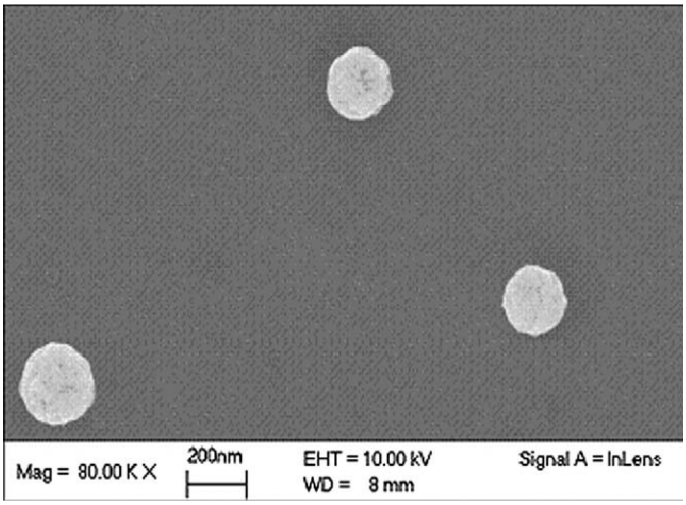


Figure 2.4: SEM image of some spherical Cu_2O nanoparticles ($CuSO_4$ molar concentration: 0.01 mol/L; at ambient temperature) [6].

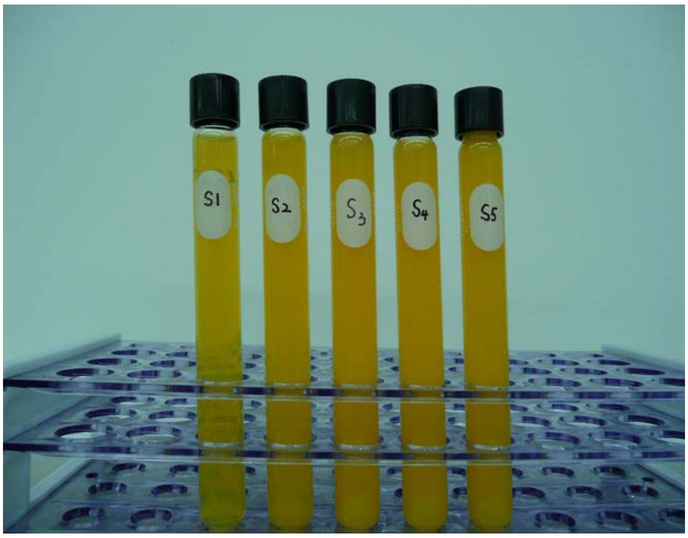


Figure 2.5: Spherical-Cu_2O nanofluids 24 h after their preparation ($CuSO_4$ molar concentration from 0.01 mol/L to 0.05 mol/L) [6].

II) Al and Al_2O_3 base nanofluids:

Comparing micron-sized and nano-sized alumina particles, nano-alumina has many advantages. A smaller particle size would provide a much larger surface area for molecular collisions and therefore increase the rate of reaction, making it a better catalyst and reactant. Finer abrasive grains would enable finer polishing, and this would also give rise to new applications areas like nano-machining and nano-probes. In terms of coatings, the use of nano-sized alumina particles would significantly increase the quality and reproducibility of these coatings.

There are several methods to synthesize nano-alumina, and these are categorized into physical and chemical methods. Physical methods include mechanical milling, laser ablation, flame spray and thermal decomposition in plasma. Chemical methods include sol–gel processing, solution combustion decomposition and vapor deposition. Most of the chemical methods have resulted in extremely low yield rates, and thus cannot be adapted to mass manufacturing. Physical methods like mechanical milling are not efficient as the size of the nanoparticles cannot be easily controlled, and these methods are only limited to certain materials. Other methods such as laser ablation, vapor deposition and sol–

gel are very costly as they require specialized equipment such as vacuum systems, high power lasers as well as expensive precursor chemicals. Finally, most systems are only possible for a specific range of materials [11].

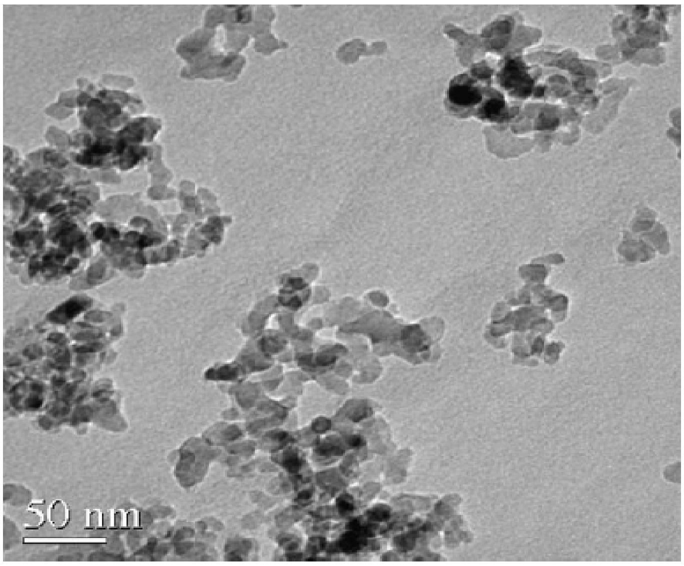


Figure 2.6: TEM micrograph of as-sprayed alumina nano-particles [11].

III) TiO_2 base nanofluids:

Titanium dioxide (TiO_2) is a very useful semiconducting transition metal oxide material and exhibits unique characteristics such as low cost, easy handling and non toxicity, and resistance to photochemical and chemical erosion. The properties of TiO_2 are significantly dependent on the crystalline phase, i.e. anatase, rutile, or brookite[12].

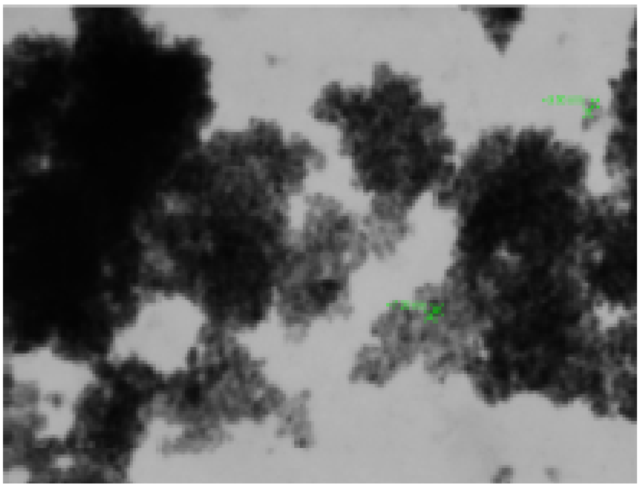


Figure 2.7: XRD patterns of TiO_2 [12].

2.1.2 Thermopysical Properties of Nanofluids

Some important thermophysical properties of nanofluids are density, viscosity, thermal conductivity and thermal diffusivity. These three properties cause that a nanofluid act very different from its base fluid in cooling applications.

- Density of nanofluids (ρ_{nf}):

The effective density of a fluid containing suspended particles at a reference temperature is given by

$$\rho_{nf} = (1-\phi)\rho_f + \phi \rho_s \quad (2.1)$$

Where ρ_f, ρ_s and ϕ are the density of clear fluid, density of the particles, and the volume fraction of the nanoparticles, respectively[5].

- Viscosity of nanofluids (μ_{eff}):

Some review articles emphasized the significance of investigating the viscosity of nanofluids, very few studies on effective viscosity were reported. It is believed that viscosity is as critical as thermal conductivity in engineering systems that employ fluid flow. Pumping power is proportional to the pressure drop, which in turn is related to fluid viscosity. In laminar flow, the pressure drop is directly proportional to the viscosity. All reported results show that the viscosity of nanofluids is increased anomalously and cannot be predicted by classical models such as by Einstein, Krieger and Dougherty, Nielsen, and Batchelor. No firm conclusion can be drawn from the above fluctuating data of several nanofluids [3].

In the most experimental studies, Brinkman formula were used.The effective viscosity of a fluid of viscosity μ_f containing a dilute suspension of small rigid spherical particles is given by Brinkman [13] as:

$$\mu_{eff} = \frac{\mu_f}{(1-\phi)^{2.5}} \tag{2.2}$$

- Thermal conductivity of nanofluids $(k_{eff})_{stagnant}$:

From the reported results, it is clear that nanofluids exhibit much higher thermal conductivities than their base fluids even when the concentrations of suspended nanoparticles are very low and they increase significantly with nanoparticle volume fraction[3].

In the most experimental studies of nanofluid, when the samples are dilute (ϕ< 5%) and the shape of nanoparticles are spherical , the effective stagnant thermal conductivity of the solid–liquid mixture is calculated using Maxwell equitation which Depends on the thermal conductivities of both phases and volume fraction of solid as:

$$\frac{(k_{eff})_{stagnant}}{k_f} = \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + 2k_f + \phi(k_f - k_s)} \tag{2.3}$$

- Thermal diffusivity of nanofluids (α_{nf}):

While the determination and prediction of the effective thermal conductivity of nanofluids have attracted much attention in recent years, very little work has been performed on the effective thermal diffusivity of nanofluids, which is especially important in convective heat transfer applications. Xuan and

Roetzel[14] discussed the effective thermal diffusivity tensor for fluids under both laminar and turbulent flow conditions. However, neither experimental nor theoretical result for the effective thermal diffusivity of nanofluids was provided in their paper. Wang et al. [15] measured the thermal conductivity and specific heat of some nanofluids and thereby calculated their effective thermal diffusivity. Their calculated results were also found to fluctuate severely with volume fraction. Murshed et al.[16] studied the effective thermal diffusivity of several types of nanofluids at different volume percentages (1–5%) of titanium dioxide (TiO_2), aluminum oxide (Al_2O_3) and aluminum (Al) nanoparticles in ethylene glycol and engine oil. The thermal diffusivities of these nanofluids measured directly by a novel transient double hot-wire technique were found to increase substantially with increased volume fraction of nanoparticles in base fluids. For example, for maximum 5% volumetric loading of TiO_2 nanoparticles of 15 nm and 10 - 40 nm in ethylene glycol, the maximum increase in effective thermal diffusivity was observed to be 25% and 29%, respectively. Nanofluids with aluminum nanoparticles in ethylene glycol and engine oil showed substantial enhancement of thermal diffusivity i.e. maximum 49% and 36%, respectively compared to their base fluids. The effects of particle shape and base fluid were also observed in their study.

Generally α_{nf} can calculated as follow:

$$\alpha_{nf} = (k_{eff})_{stagnant} / (\rho c_p)_{nf} \quad (2.4)$$

2.2 Applications of Nanofluids

2.2.1 Potential Benefits of Nanofluids

When the nanoparticles are properly dispersed, nanofluids can offer numerous benefits besides the anomalously high effective thermal conductivity. These properties 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 immediately available for thermal interaction. 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. 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. The better stability of nanofluids will prevent rapid settling and reduce clogging in the walls of heat transfer devices. The high thermal conductivity of nanofluids translates into higher energy efficiency, better performance, and lower operating costs. They can reduce energy consumption for pumping heat transfer fluids. Miniaturized systems require smaller inventories of fluids where nanofluids can be used. Thermal systems can be smaller and lighter. In vehicles, smaller components result in better gasoline mileage, fuel savings, lower emissions, and a cleaner environment[3].

2.2.2 Engineering Applications of Nanofluids

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

(a) Nanofluids in transportation: The transportation industry has a strong demand to improve performance of vehicle heat transfer fluids and enhancement in cooling technologies is also desired. Because engine coolants, engine oils, automatic transmission fuids, and other synthetic high temperature fluids currently possess essentially 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 highpower 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 could 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[3].

2.2.3 Medical Applications of Nanofluids

Magnetic nanoparticles in body fluids (biofluids) can be used as delivery agents 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 [3].

Three applications of nanotechnology are particularly suited to biomedicine: diagnostic techniques, drugs, and prostheses and implants. Interest is booming in biomedical applications for use outside the body, such as diagnostic sensors and “labon-a-chip” techniques, which are suitable for analyzing blood and other samples, and for inclusion in analytical instruments for R&D on new drugs. For inside the body, many companies are developing nanotechnology applications for anticancer drugs, implanted insulin pumps, and gene therapy. Other researchers are working on prostheses and implants that include nanostructured materials.

There are several kinds of nanoparticles that can be used as biosensors components. Most of them work as probes recognizing and differentiating an analyte of interest for diagnostic and screening purposes. In such applications biological molecular species are attached to the nanoparticles through a proprietary modification procedure. The probes are used then to bind and signal the presence of a target in a sample by their colour, mass, or other physical properties[17].

2.3 Natural Convection of Nanofluids

There are two general categories for study the natural convection of fluid: Experimental studies, Numerical studies.

2.3.1 Experimental Studies

One of the most common experimental studies is investigated using a cavity. The natural convection in a square cavity plays a very important role in a lot of engineering applications, such as the solar energy system, the cooling of the electronic circuits, the conditioning of the air and many others. Therefore it is essential for the applied research[18]. The shape of the wall, flow and heat transfer problems inside enclosure have numerous engineering applications like solar-collectors, double-wall insulation, electric machinery, cooling system of electronic devices, natural circulation in the atmosphere, etc.

In natural convection processes, the thermal and the hydrodynamic are coupled and both are strongly influenced by the fluid thermophysical characteristics, the temperature differences and the system geometry[18] .

Differentially heated enclosures are extensively used to simulate natural convection heat transfer within systems using nanofluids . Experimental results have been reported in the literature that dispersion of nanoparticles in the base fluid may result in considerable decrease in heat transfer. Putra et al and Wen and Ding found a systematic and definite deterioration in the heat transfer for a particular range of Rayleigh numbers and density and concentration of nanoparticles. Similar results were also obtained by Santra et al.[19] who modeled the nanofluid as a non-Newtonian fluid.

In Figure 2.8 the experimental results of Wen and Ding [20] can be seen. The Nusselt number decreases with the Rayleigh number during the transient heating period. Similar phenomena were also observed by Tso et al. [21]and Bhowmik and Tou [22]for cooling of electronic chips through natural convection in a vertical rectangular channel.

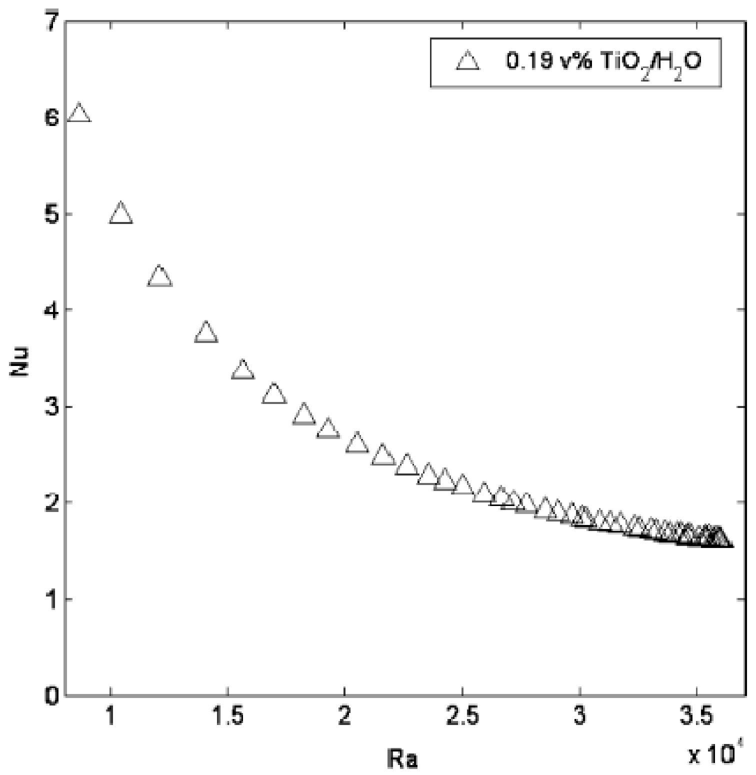


Figure 2.8: Experimental results of Wen and Ding (2005) [20].

2.3.2 Numerical Studies

One of the most common references in study the natural convection of nanofluid is Khanafer et al.[23]. Research studies consider a two-dimensional enclosure of height H and width L filled with a nanofluid as shown in Figure 2.9. The horizontal walls are assumed to be insulated, non conducting and impermeable to mass transfer. The nanofluid in the enclosure is Newtonian, incompressible and laminar. The nanoparticles are assumed to have a uniform shape and size. Moreover, it is assumed that both the fluid phase and nanoparticles are in thermal equilibrium state and they flow at the same velocity. The left vertical wall is maintained at a high temperature (T_H) while the right vertical wall is kept at a low temperature (T_L).

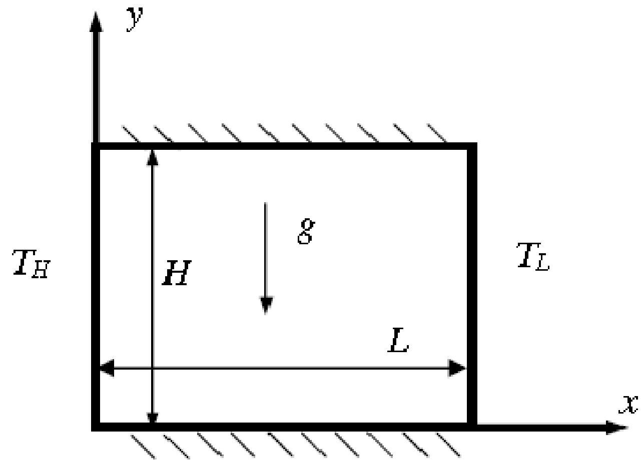


Figure 2.9: Schematic for the physical model [23].

According to Khanafer et al.[23]Numerical results the average Nusselt number along the hot vertical wall is correlated in terms of the Grashof number and the particles volume fraction.The correlation of Khanafer et al. can be expressed as [23]:

$\overline{Nu} = 0.5163(0.4436 + \phi^{1.0809})Gr^{0.3123}$ for $10^3 \leq Gr \leq 10^5$ and $0 \leq \phi \leq 0.25$

Santra et al. (2007)[24] Presented the numerical results of the simulation of natural convection in a differentially heated square cavity using copper–water nanofluid for $10^4 \leq Ra \leq 10^7$ and $0.05 \leq \phi \leq 5$ according to Figure 2.10 as:

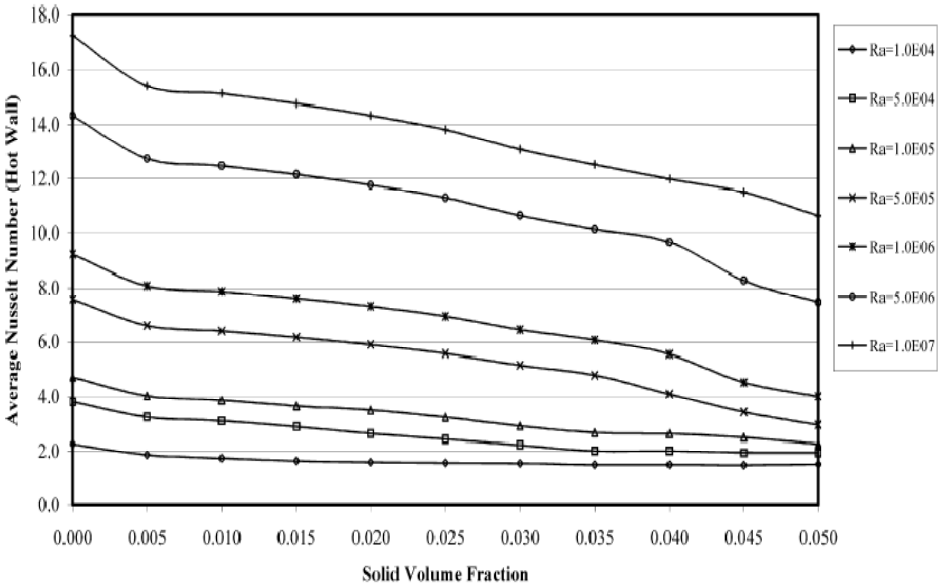


Figure 0.10: Variation of average Nusselt number with solid volume fraction for different *Ra* (Santra et al.)[24].

Ho et al. (2008) [24] also did a simulation of natural in the enclosure filled with alumina–water Nanofluid and found another correlation as:

$\overline{Nu} = C(1+\phi)^m Ra^n$ for $10^4 \le Ra \le 10^6$ and $0 \le \phi \le 0.04$

And they found parameters C, m and n in different four models of simulation according to Table 2.1 as:

Table 2.1: Values of coefficient C and exponents m, n for different models according to numerical results of Ho et al.[24].

Model	C	m	n
1	0.149	1.624	0.297
2	0.148	-0.561	0.298
3	0.148	2.067	0.300
4	0.145	-0.261	0.300

2.3.3 Comparison and Disscussion

Few studies have been carried on natural convective heat transfer. Khanafer et al. (2003) numerically investigated the heat transfer behaviour of nanofluids in a two-dimensional horizontal enclosure. The random motion of nanoparticles was considered through a dispersion model similar to thermal dispersion models for flows through porous media. The simulations showed that suspended nanoparticles substantially increased heat transfer at any given Grashof number. Such enhancement increased with particle concentration, which was thought to be the increased energy exchange from enhanced irregular and random movements of particles. However different experimental results have been observed by Putra et al. (2003) for natural convective heat ransfer of aqueous CuO and Al_2O_3 nanofluids and by Wen and Ding (2005) for natural convective heat ransfer of aqueous TiO_2 nanofluid. Unlike the results of thermal conduction and forced convection, experiments at Rayleigh number from 10^6 to 10^9 showed a systematic and significant deterioration in natural convective heat transfer. The deterioration increased with particle concentration and was more pronounced for CuO nanofluids.

The above short review shows that heat transfer behavior of nanofluids is very complicated and application of nanofluids for heat transfer intensification should not be decided only by the effective thermal conductivity. Many other factors such as particle size, morphology and distribution of particles in the fluids could significantly influence the flow and heat transfer behaviour of nanofluids. The simulations of numerical researchers in the field of natural convection of nanofluids were based on some ideal assumptions of (a)nanofluid was Newtonian, incompressible and the flow was in the laminar regime. (b) nanoparticles were uniform in shape and size. (c) there was no slip between liquid and particle phases in terms of both velocity and temperature, and (d) nanofluids had constant thermophysical properties except for density variation that gave rise to the buoyancy. The assumption of (c) and (d) are very difficult to be satisfied for real nanofluids. Although nanofluids behave more like pure fluids than suspensions of large particles, fundamentally speaking, they still exhibit two-phase characteristics that need to be considered for thorough understanding of nanofluids heat transfer.

Chapter 3

DESIGNING THE EXPERIMENT

3.1 Experimental Equipment

The experiments have been done in an enclosure(Figure 3.1) having the dimensions of 11 cm (length) and 11 cm (height) and 8 cm (width) which has the aspect ratio (H/L) of 1. The cavity was full of nanofluid. Figure 3.2 shows a picture of cavity.

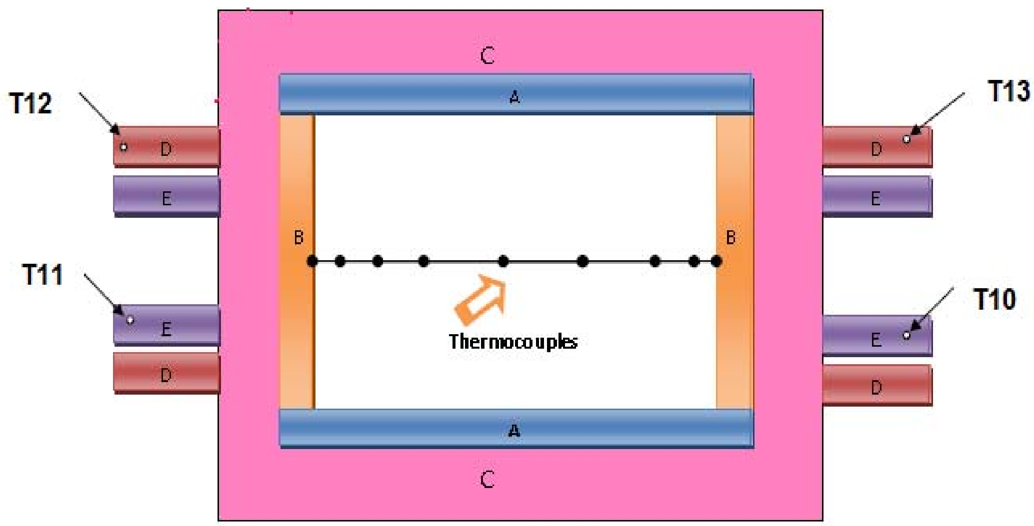


Figure 3.1: A top view of cavity: [A] Plexiglas Plates, [B] Heat exchangers(right side is hot wall and left side is cold wall), [C] Insulation Material, [E] Output Pipes,[D]Input Pipes, [T10 to T13] Pipe Thermocouples

The front, back, bottom and top sides of the enclosure are made of Plexiglas which has 1 cm thickness. Left and right sides of the enclosure consist of brass plates (Heat Exchanger) in which water passages are engraved.

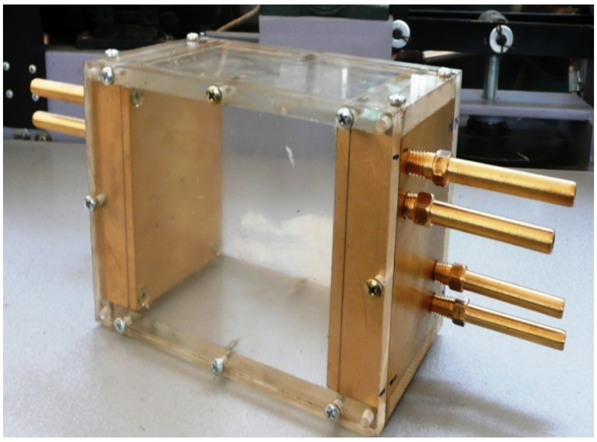


Figure 3.2: A photo of cavity

Each brass heat exchanger contains two brass plates (see Fig 3.3) that one of them is smooth which is used as the uniform temperature plate and the other has some grooves. The brass plates were kept isothermal by passing water through grooves engraved in each plate to form counter flows. The water flows in the two passage in opposite directions to provide constant temperature in the brass plate. Total thickness of each brass heat exchanger is 2.8 cm.

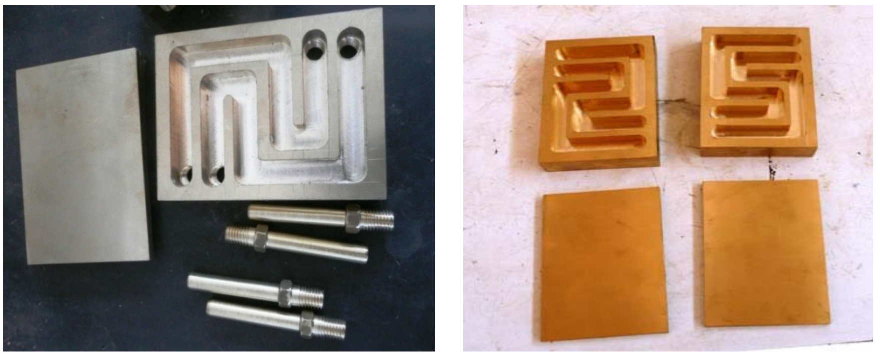


Figure 3.3: Brass plates of heat exchangers

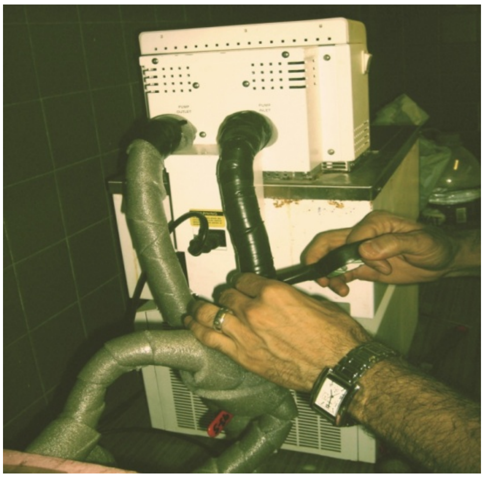
Water is supplied from two separate constant-temperature baths. Hot water bath from right side and cold water bath from left part of cavity are connected by flexible tubes.

There are four holes in front of cavity and five holes at the back of it that thermocouples passed through them and fixed exactly in the middle of cavity(y=W/2) to a horizontal nylon wire with thickness of 0.1 cm that comes from centers of hot and cold plate. In addition of these nine thermocouples we have four others to measure input and output temperatures of cold and hot bathes. Also there is one thermocouple to measure ambient air temperature. The first and last thermocouples on the horizontal nylon wire are fixed on the surface of hot and cold plates to sense temperature of these sides.

In order to change and control the mass flow rate of water, two valves are used for input pipes as shown in Figure 3.4.

Figure 3.4: Situation of valves.

The whole sides of cavity are insulated by foam with thickness of 4cm. Also all flexible tubes are insulated by Styrofoam which has 0.5 cm thickness as shown in Figure 3.5.

(a) (b)

(c)

Figure 3.5: Picture (a) and (b) show tubes and picture (c) shows cavity after insulation.

All thermocouples were calibrated about 31.5 °C with 0.15 °C tolerances. The thermocouples are T-type which is made of 36 gauge copper and constantan wires. The temperature readings are collected by a data acquisition system interfaced to personal computer. This data acquisition system is MultiScan/1200 which is a high-speed instrument that can measure temperatures through 96 channels. Also there is software for this data acquisition system which is called ChartView. Figure 3.6 shows a schematic diagram of the experimental apparatus.

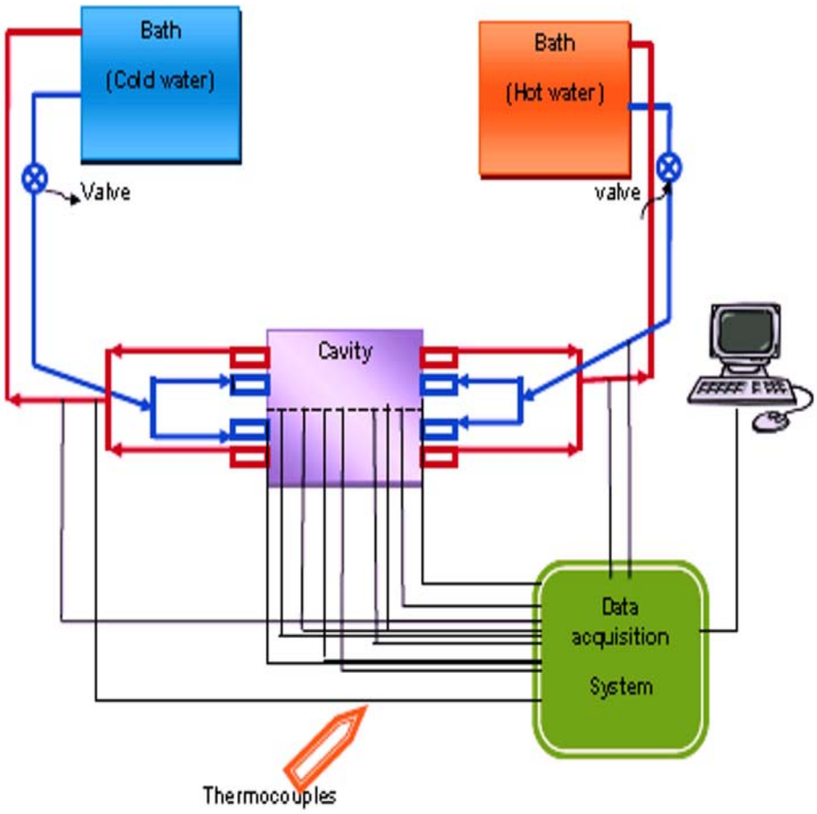


Figure 3.6: Schematic diagram of the experimental apparatus.

3.2 Nanofluid Used in Experiment

Purchase of nanofluid has become more common and cost effective over the past few years. Several companies list nanofluids as products. These companies produce many nanofluid products with varying quality. The candidate for this project which is purchased is a dispersion of Cu_2O nanospheres in ethanol as base fluid. Two bottle of the dispersion of nanofluid which each of them contained 25 ml of ready dispersion of nanofluid were purchased. Table 3.1 shows some information about the nanofluid which used in present study.

Table 3.1 : Copper (I) Oxide dispersion nanofluid (Sigma Aldrich Co.).

Linear Formula:	Cu_2O
Molecular Weight:	143.09
Application	Used to make CuO gas sensors and CuO nanospheres.
form	dispersion
concentration	1.5 % (w/v) in ethanol
particle size	<350 nm

3.3 Making Nanofluid Ready to Use

3.3.1 Making Dilution of Main Sample of Nanofluid

Each bottle of product contains 25 ml of concentrate nanofluid then we need to make a dilute solution of main product to fill in cavity.

Figure 3.7: Nanofluid before making dilute samples

Pure ethanol is added to 10, 15 and 25 ml of main nanofluid till the total volume of solution arrive to 968 ml (volume of cavity: 11×11×8) after that we have 3 different solution of main nanofluid S_1 , S_2 and S_3 .

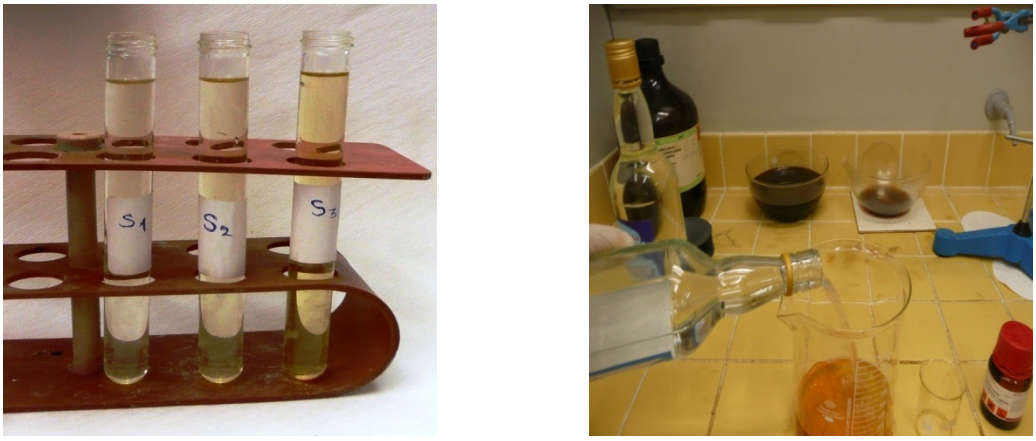


Figure 3.8: Left photo shows making dilution of nanofluid and right photo shows the three dilute samples: S_1, S_2 and S_3.

3.3.2 Density of Samples

Because mass and volume of each sample is measurable, the density of the samples can be calculated according to Formula 3.1 as:

$$\rho_{nf} = \frac{m_{sample}}{v_{sample}} \tag{3.1}$$

Figure 3.9: Measuring weight of a sample which volume is known to calculate density of the sample

Table 3.2: Density of Pure Nanofluid and Dilute Samples at T=28°C.

No.	Sample	m(gr)	v(ml)	ρ_{nf} (gr/ml)
1	Pure Nanofluid	20.06	25	0.8026
2	S_1	33.86	50	0.6772
3	S_2	34.24	50	0.6849
4	S_3	34.62	50	0.6924

3.3.3 PH of Samples

Also PH of samples is important to some chemical application of nanofluid. We can measure PH of samples using a PH meter.

Figure 3.10: Measuring PH of samples

Table 3.3: PH of Distilled Water, Pure Nanofluid and Dilute Samples at T=28°C.

No.	Sample	PH
1	Distilled Water	6.83
2	Pure Ethanol	5.28
3	Pure Nanofluid	10.12
4	S_1	11.23
5	S_2	11.7
6	S_3	11.94

3.4 Experimental Measurement Method

A typical experiment involved cleaning of the test region by distilled water many times followed by filling with the nanofluids. Great care was needed during the filling process to prevent the formation of gas bubbles in the cavity. Heating and data requisition were then started until steady state was reached. Both transient and steady state signals from thermocouple were collected.

The unsteady experiments were performed for 3 different samples of nanofluid and for each of them in 5 different $(\Delta T)_{bath}$ = 10ºC, 15 ºC, 20 ºC, 25 ºC and 30 ºC. Temperature data were collected ten seconds by ten seconds by data acquisition system in one Microsoft Excel file during each test. After one hour that data were collected in excel file, we need to check the last 30 temperature and if the temperature difference between first and last one of them was less than 0.1 ºC, the experiment can be stopped because we have reached steady state situation.

Table 3.4: Location of each thermocouple.

Thermocouples No.	Location
1	In to the cavity and 0.5 cm from hot wall
2	In to the cavity and 3.5 cm from hot wall
3	Exact in the middle of cavity
4	In to the cavity and 1.5 cm from cold wall
5	On the cold wall
6	On the hot wall
7	In to the cavity and 1.5 cm from hot wall
8	In to the cavity and 3.5 cm from cold wall
9	In to the cavity and 0.5 cm from cold wall
10	Inlet tube of hot wall
11	Inlet tube of cold wall
12	Outlet tube of cold wall
13	Outlet tube of hot wall
14	Ambient air

3.5 Experimental Errors and Uncertainty

3.5.1 Types of Error

1. Systematic errors have assignable causes and definite values. They are often unidirectional (causeresults to be either too large or too small). Types of these errors include:

a) Instrumental uncertainties (Calibration procedures can usually eliminate these.)

b) Method uncertainties (nonideal behavior of substances, slowness of reactions, instability of species, etc.)

c) Personal uncertainties (personal judgments, bias, and mistakes).

2. Random errors or random fluctuations in results occur when replicate experimental data are collected.The specific causes are unknown because they have many sources, none large enough to be identified/detected.

3.5.2 Calibrating the Thermocouples to Find Errors

Before starting the experiment, Whole thermocouples should be calibrated to understand their error in showing the temperatures.

First, the cavity was filled with water and then all fourteen thermocouples were put into the water of cavity. Also a thermometer was put into the water of cavity but not in contact with the bottom of it. After that the data acquisition system was turned on and started to gathering the data in excel files.

In the Appendix B of this work, the excel files which is made by data acquisition are shown. First the data acquisition was set on the Calibration mode and then start gathering data. Using the average of each column , fourteen value of temperatures were collected which each of them belongs to each thermocouples, If the average value of these fourteen are calculated , A value as an average temperature of cavity will be obtained. This value for the present experiment is 31.5 °C. The differences between this value and average temperatures of each column shows the related thermocouples errors which for the thermocouples in this study the value of error is in the range of ± 0.15 °C.

An abstract to find of thermocouples errors is as follow:

Step 1: Calculate average temperature of each column: $T_{Ave}(i)$

Which parameter i is the number of thermocouples.(i=1, 2,3 ....,14)

Step 2: Calculate an average value of above values: $T_{Calibration}$

$$T_{Calibration} = \frac{\sum T_{Ave}(i)}{14}$$

Step 3: Calculate values of errors for each thermocouples: ε(i)

$\varepsilon(i) = T_{Calibration} - T_{Ave}(i)$

3.5.3 Error in Measuring the Mass Flow Rate of Hot Bath ($\dot{m}$)

Using a Measuring cylinder as shown in figure 3.11 and a chronometer, the mass flow rate of hot bath was measured. The measuring Cylinder has the volume of 1000 ml and its error is ± 10 ml.

Figure 3.11: Measuring cylinder

First the valve was closed at time t=0 s, then the valve was opened and the Measuring cylinder was filled with water till it reached 500 ml and the valve is closed and chronometer was stopped. The procedure was done five times according to Table 3.5. These datas are collected at T= 32.2°C Then the density of water is 0,995 gr/ml.

Table 3.5: Measuring mass flow rate of hot bath.

No.	v(ml)	m(gr)=ρ*v	t(s)	$\dot{m}$ =m/t (gr/s)	$\dot{m}$ (Kg/s)
1	100	99.5	20	4.98	0.0050
2	100	99.5	20.22	4.92	0.0049
3	110	109.45	21.55	5.08	0.0051
4	90	89.55	18.98	4.72	0.0047
5	100	99.5	20.63	4.82	0.0048

$\dot{m}_{\text{ave}} = 0.0049$

The standard deviation is a significant measure of precision. The standard deviation for a small number of measurements is:

$$S = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{N-1}}$$

Where $(x_i - \bar{x})^2$ are the individual deviations from the mean and N represents the number of individual measurements.

For the present study :

$\bar{x} = \dot{m}_{\text{ave}} = 0.0049$

x_i =0.0050, 0.0049, 0.0051, 0.0047, 0.0048

N= 5

S = 1.5811 x 10^{-4}

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Data Analysis

First of all we need some thermo physical properties of both solid and fluid at the base temperature i.e. at 20 ºC; they have been summarized in Table 4.1.

Table 4..1: Thermo physical properties of both solid and fluid.

Property	Base fluid (Ethanol)	Nano particles (Cu_2O)
Cp (J/kg ºC)	2439	474
ρ (kg/m^3)	789	6090
k (w/m ºC)	0.169	20
μ (kg/m s)	1.77×10^{-3}	
β (1/ ºC)	750×10^{-6}	4.95×10^{-5}
α (m^2/s)	8.782×10^{-8}	
υ_f (Kinematic viscosity m^2/s)	2.20×10^{-6}	

The problem is assumed to done in an adiabatic cavity.

Step 1:

L (Length of cavity) = 0.11 (m)

H (Height of cavity) = 0.11 (m)

W (Width of cavity) = 0.08 (m)

$\dot{m}$ (Mass flow rate of hot water) = 0.005 (kg/s)

T_{aveW}=Average temperature of water of inlet and outlet of hot wall of cavity:

$$\frac{T(13)+T(10)}{2}+273.15 \quad (4.1)$$

According to the tables at the end of heat transfer book , heat capacity of hot water for different temperature are estimated with 2 polynomial function , each one for one range of temperature:

If T_{aveW} < 310 ºK → $(C_p)_w$ = 4178 +0.44 × (310 - T_{aveW})

If T_{aveW} > 310 ºK → $(C_p)_w$ = 4188 -0.33 × (340 - T_{aveW}) (4.2)

In order to calculate the value of heat flux and Nusselt number for the hot wall:

$Q = \dot{m} \times (C_p)_w \times [T(13) - T(10)]$ (J/s) (4.3)

$$Nu = \frac{Q \times L}{W \times H \times (T_H - T_C) \times (k_{eff})_{stagnant}} \quad (4.4)$$

T_H = Temperature on the hot wall: T (6)

T_C =Temperature on the cold wall: T (5)

According to calculate Nusselt number, step 2 must follow.

Step 2:

ρ_{Cu2O} = 6.09 gr/cm^3

In each pack of nanofluid there is 25 ml of nanofluid that 1.5 % of it belongs to Cu_2O Nanospheres then in each pack of n anofluid there is 37.5 (25×1.5) gr of Cu_2O Nanospheres.

Sample 1 contains 10 ml (v_{sample}) of base nanofluid then: 10 ×1.5=15 gr Cu_2O Nanospheres(m_{sample}).

$$v_{nanoparticles} = \frac{m_{sample1}}{\rho_{Cu2O}} = \frac{15}{6.09} = 2.463 \text{ (ml)}$$

Volume fraction of samples (ϕ) are as:

$$\phi_{sample1}(\%) = \frac{v_{nanoparticles}}{v_{cavity}} \times 100 = \frac{2.463}{968} \times 100 = 0.254$$

Sample 2 and sample 3 contains 15 ml and 25 ml of base nanofluid respectively.

Then volume fractions of samples are according to table 4.2:

Table 4.2: Volume fraction of samples ϕ(%).

Sample	ϕ (%)
S_1	0.245
S_2	0.381
S_3	0.636

As our samples are dilute ($\phi <$ 5%) and the shape of nanoparticles are spherical , the effective stagnant thermal conductivity of the solid–liquid mixture is calculated using Maxwell equitation which depends on the thermal conductivities of both phases and volume fraction of solid as:

$$\frac{(k_{eff})_{stagnant}}{k_f} = \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + 2k_f + \phi(k_f - k_s)} \qquad (4.5)$$

$k_s = k_{Cu_2O}$ =20 (w/m°K)

$k_f = k_{Ethanol}$=0.169 (w/m°K)

The effective stagnant thermal conductivity of samples are in Table 4.3 as follow:

Table 4.3: The effective stagnant thermal conductivity of Samples

Sample	$(k_{eff})_{stagnant}$
S_1	0.1702
S_2	0.1708
S_3	0.1721

At the end of step 2 we are able to calculate Nusselt number.

Step 3:

According to Raleigh number formula[26]:

$$Ra_{nf} = \frac{g\,\beta_{nf}\,(T_H - T_C)\,H^3}{\nu_{nf} \times \alpha_{nf}} \quad (4.6)$$

We have to calculate some parameters such as β_{nf}, α_{nf} and ν_{nf} .In order to calculate these parameters, we need to calculate some thermophysical properties at average temperature of nanofluid inside cavity.

Average temperature of nanofluid inside cavity = $T_{Ave\ 1\text{-}9}$

There are 9 thermocouples inside the cavity which named as number 1 to 9 where their places are according to table 3.4.Then $(\rho c_p)_{nf}$, β_{nf} and μ_{eff} will be calculated at $T_{Ave\ 1\text{-}9}$.

Calculating $(\rho c_p)_{nf}$

According to formulas:

$$(\rho c_p)_{nf} = (1-\phi)\,(\rho c_p)_f + \phi\,(\rho c_p)_s \quad (4.7)$$

And as our samples are dilute then $(\rho c_p)_{nf}$ is a function of $(\rho c_p)_f$.

$(\rho c_p)_f = \rho_f (c_p)_f$, both ρ_f and $(c_p)_f$ are related to Temperature $T_{Ave\ 1\text{-}9}$.

Calculating ρ_f

Table 4.4 shows density of ethanol at various temperatures (kg/m^3). Data obtained from Lange's Handbook of Chemistry, 10th Ed[27].

Table 4.4: Density of Ethanol at various temperatures (kg/m3).

Temperature	Viscosity	Temperature	Viscosity	Temperature	Viscosity
3°C	803.74	16°C	792.83	29°C	781.82
4°C	802.90	17°C	791.98	30°C	780.97
5°C	802.07	18°C	791.14	31°C	780.12
6°C	801.23	19°C	790.29	32°C	779.27
7°C	800.39	20°C	789.45	33°C	778.41
8°C	799.56	21°C	788.60	34°C	777.56
9°C	798.72	22°C	787.75	35°C	776.71
10°C	797.88	23°C	786.91	36°C	775.85
11°C	797.04	24°C	786.06	37°C	775.00
12°C	796.20	25°C	785.22	38°C	774.14
				39°C	773.29

Also according to specific gravity of ethanol we can find density of ethanol at other temperatures because density of water at different temperatures is available.

Specific gravity of ethanol (SG) = $\frac{\rho_{Ethanol}}{\rho_{Water}} = 0.814$ (4.8)

Calculating $(c_p)_f$

A correlation for heat capacity of liquid is a series expansion in temperature:

$c_p = A + BT + CT^2 + DT^3$ (4.9)

Where:

c_p : Heat capacity of liquid (J/mol ºK)

A, B, C and D: Regression coefficients for chemical compound

T: Temperature (ºK)

According to Lange's Handbook of Chemistry, 10th Ed[27], regression coefficients A, B, C and D for ethanol are as follows:

A= 59.342

B= 3.6358×10^{-1}

C= - 1.2164×10^{-3}

D= 1.8030×10^{-6}

Calculating β_{nf}

According to formula:

$$(\rho\beta)_{nf} = (1-\phi)\,(\rho\beta)_f + \phi\,(\rho\beta)_s \qquad (4.10)$$

And because of the low concentration of nanoparticles then $(\rho\beta)_{nf}$ is a function of $(\rho\beta)_f$.

β_f is not changing in various temperature but ρ_f is changing in different temperature

Calculating μ_{eff}

As our samples are dilute and the shape of nanoparticles is spherical, we can use Brinkman[13] equation as:

$$\mu_{eff} = \frac{\mu_f}{(1-\phi)^{2.5}} \qquad (4.11)$$

According to above formula viscosity of nanofluid is a function of base fluid viscosity and nanoparticles volume fraction. Viscosity of Ethanol as base fluid is changing in difference temperatures. (According to table 4.5)

Table 4.5: Viscosity of Ethanol at different temperature.

Ethanol Viscosity	
Temperature (°C)	μ_f (kg/m s)
0	1.773×10^{-3}
10	1.466×10^{-3}
20	1.200×10^{-3}
30	1.003×10^{-3}
40	0.834×10^{-3}
50	0.702×10^{-3}
60	0.592×10^{-3}
70	0.504×10^{-3}

4.2. Transient temperature and heat transfer coefficient

At t=0 the temperature at the right side of the cavity is suddenly raised by applying a temperature difference $(\Delta T)_{bath}$. Examples of transient temperature signals for different concentration of Cu_2O nanofluids every 10 seconds are shown in Fig. 4.1 under $(\Delta T)_{bath}$ = 10 °C . To make a quantitative comparison, the heating surface temperature of cold plate was found to increase with nanoparticles concentrations.

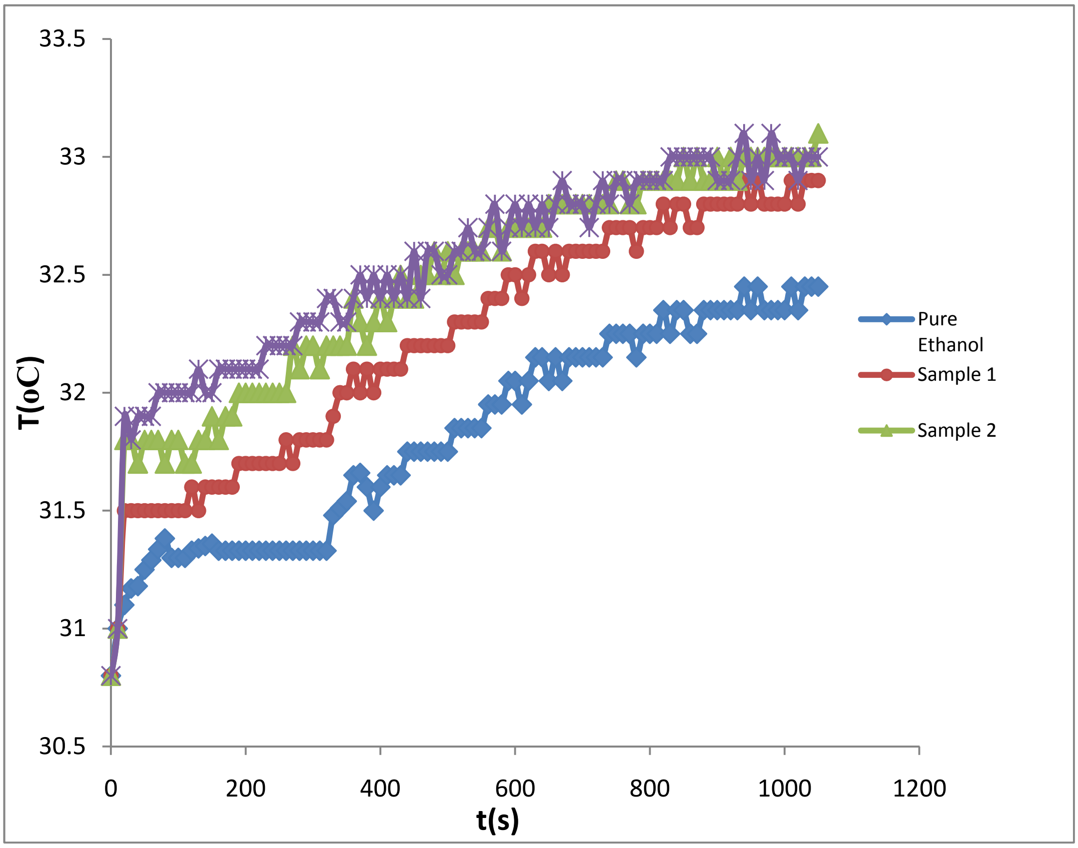


Figure 4.1: Effect of nanoparticles concentrations on the cold surface temperature for the three samples at $(\Delta T)_{bath} = 10$ °C.

The variations of Nusselt and Rayleigh numbers as a function of time are illustrated in the next two figures. It can be seen that the Nusselt number decreases continuously with time (Fig.4.2) while the Rayleigh number increases during the heating period (Fig.4.3). As a result, the Nusselt number decreases with the Rayleigh number during the transient heating period (Figure4.4).

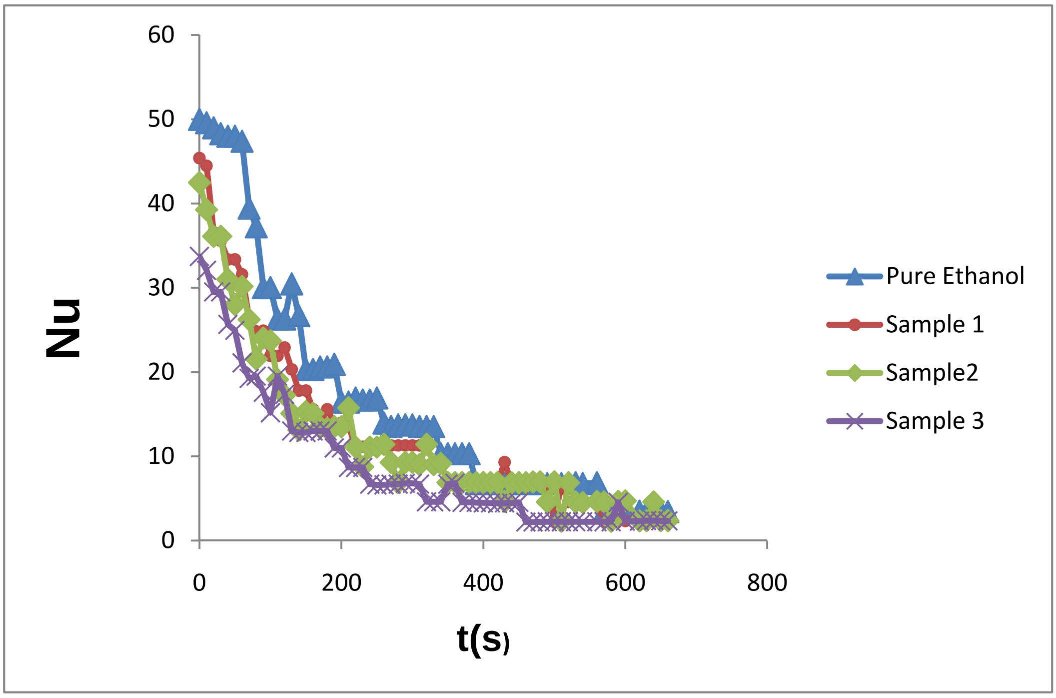


Figure 4.2: Transient Nusselt number as a function of time for the three samples at $(\Delta T)_{bath}$ = 10 °C.

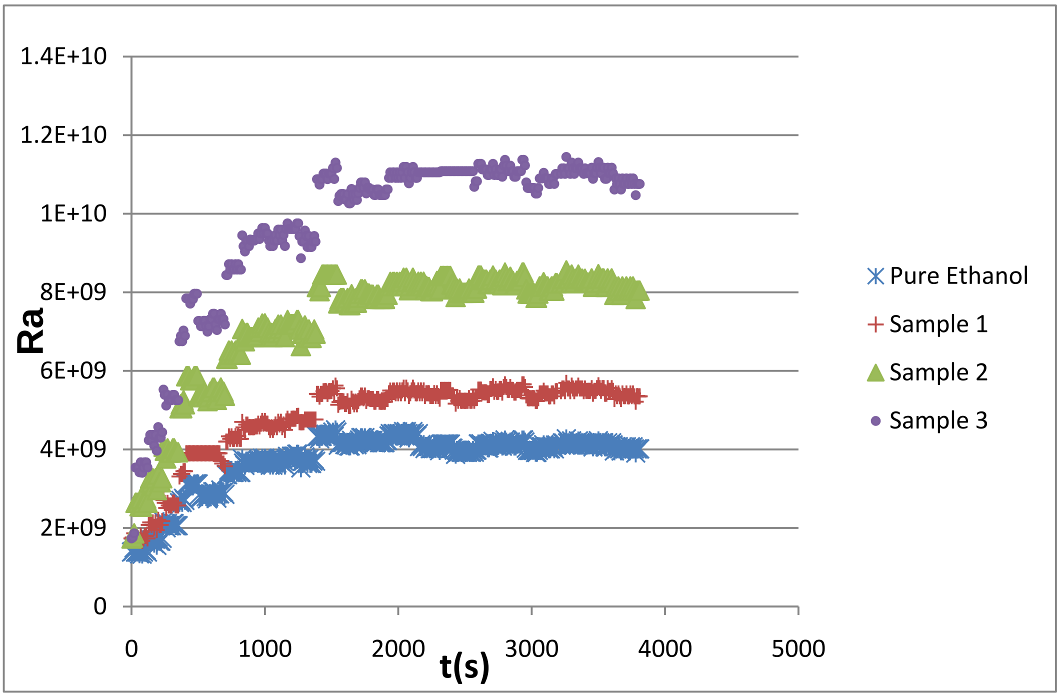


Figure 4.3: Transient Raleigh number as a function of time for the three samples at $(\Delta T)_{bath}$ = 10 °C.

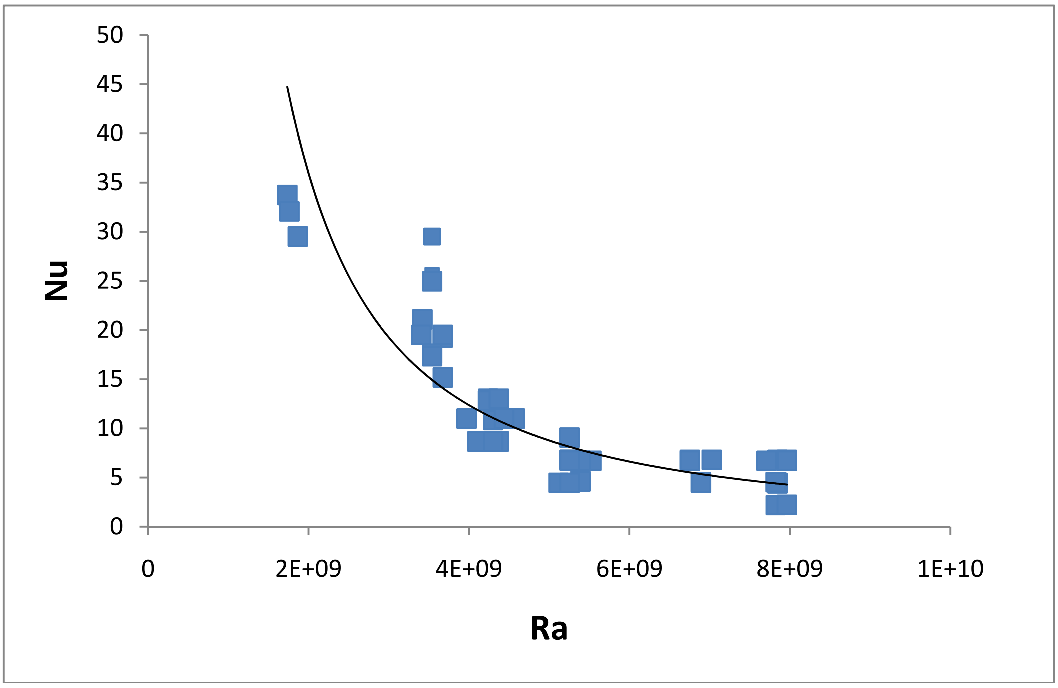


Figure 4.4: Transient Nusselt number versus Rayleigh number for the sample S_3 at $(\Delta T)_{bath}$ = 10 °C.

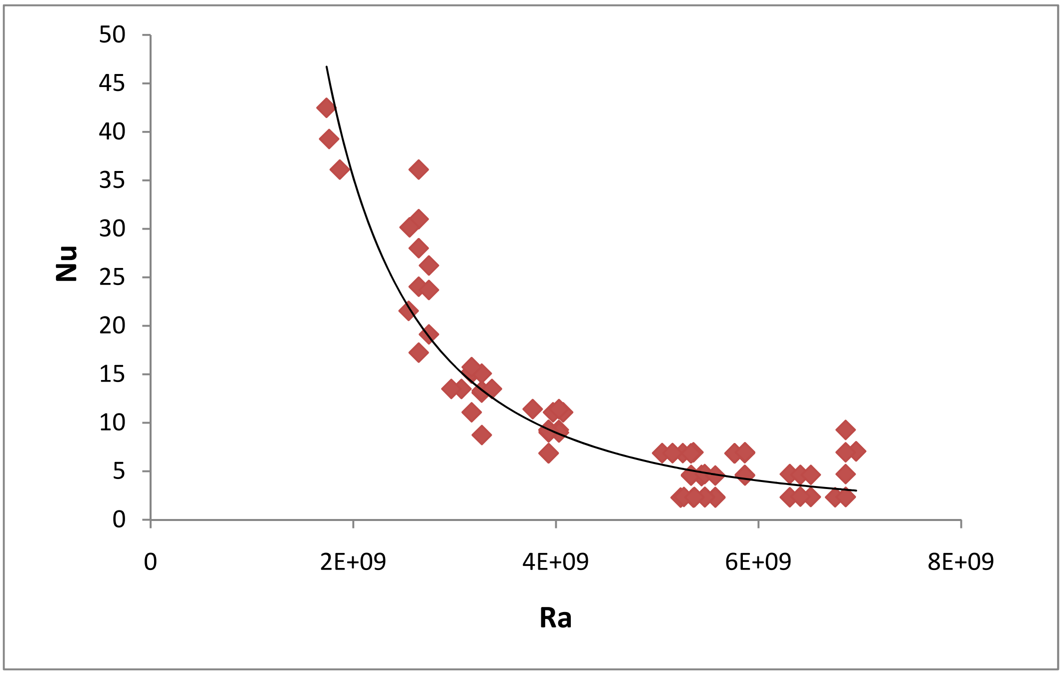


Figure 4.5: Transient Nusselt number versus Rayleigh number for the sample S_2 at $(\Delta T)_{bath}$ = 10 °C.

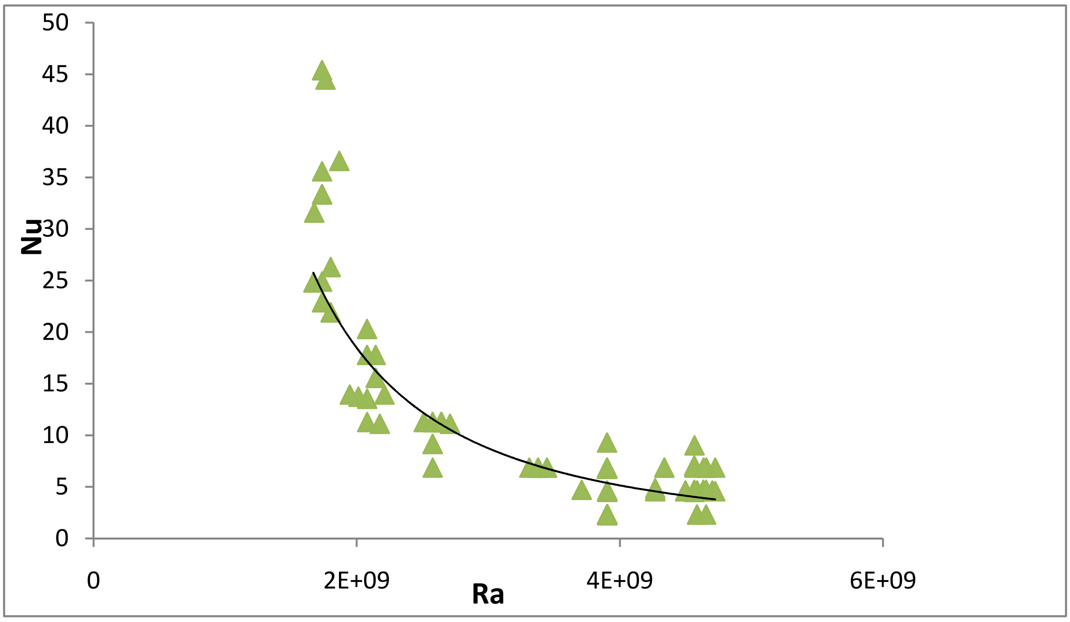


Figure 4.6: Transient Nusselt number versus Rayleigh number for the sample S_1 at $(\Delta T)_{bath} = 10$ °C.

Using results from Figures 4.3 to 4.5 we are able to find constants c and n in correlation Nu= c Ra^n for 3 samples at $\Delta T = 10$ °C as:

Table 4.6: Constants c and n in correlation Nu= c Ra^n

Sample	c	n
S_1	8E+15	-1.54
S_2	8E+19	-1.97
S_3	8E+18	-1.84

4.3. Temperature Distribution in Cavity at Various Times

One of the subjects that have studied by krane and Jesse [28], Khanafer etal. [23] and Abu-Nada and Oztop [29,30]was temperature distribution in cavity by numerical experiments.

We are also able to show our experimental results to analyze Temprature distribution in cavity at various times. To make a comparison between our experimental results and present numerical studies we have to use dimensionless temperature (θ) and also dimensionless length (X).

$$\theta = \frac{T - T_L}{T_H - T_L} = \frac{T - T_5}{T_6 - T_5}$$

X =x/H and H (Height of cavity) = 0.11 (m)

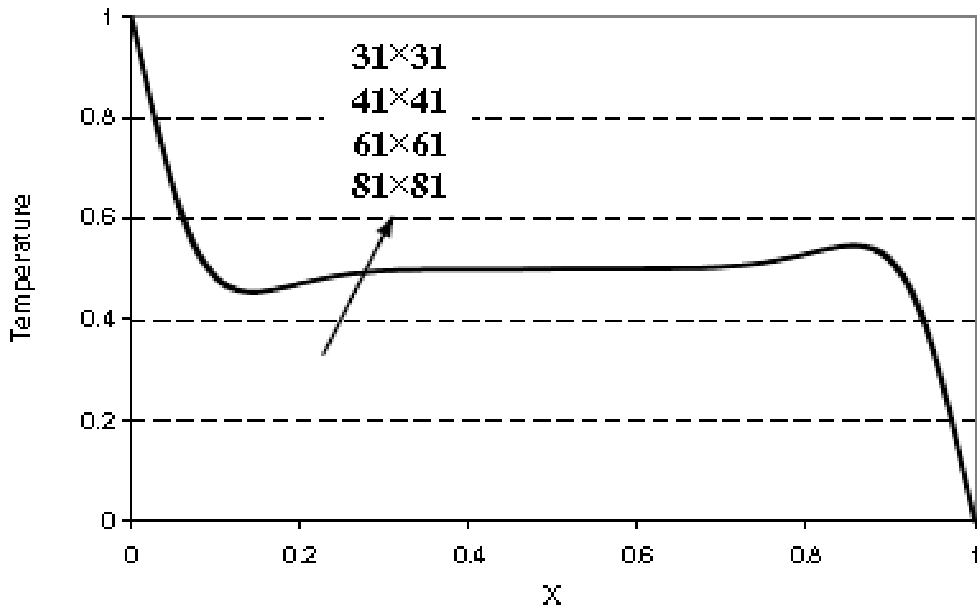


Figure 4.7: Numerical studies were performed by krane and Jesse (1983), Khanafer et al. (2003) and Abu-Nada and Oztop (2009) to analyze Temperature distribution of nanofluid in cavity for various mesh sizes: 31x31, 41x41, 61x61 and 81x81.

According to Figure 4.8 , All three researchers find the same results for various mesh sizes: 31x31, 41x41, 61x61 and 81x81 and as our results shows in Figures 4.8 to 4.22 , the experimental results are agree with their numerical analysis in this case (Temperature distribution of nanofluid in cavity).

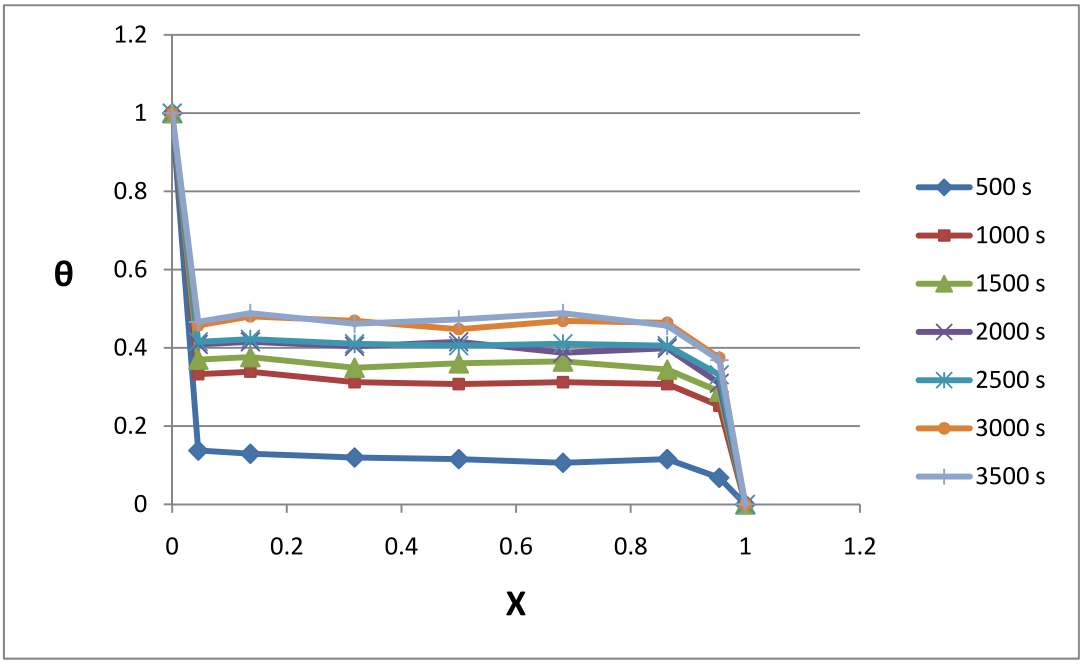


Figure 4.8: Temperature distribution in cavity at various times for the Sample S_1 at $(\Delta T)_{bath}$ = 10 °C.

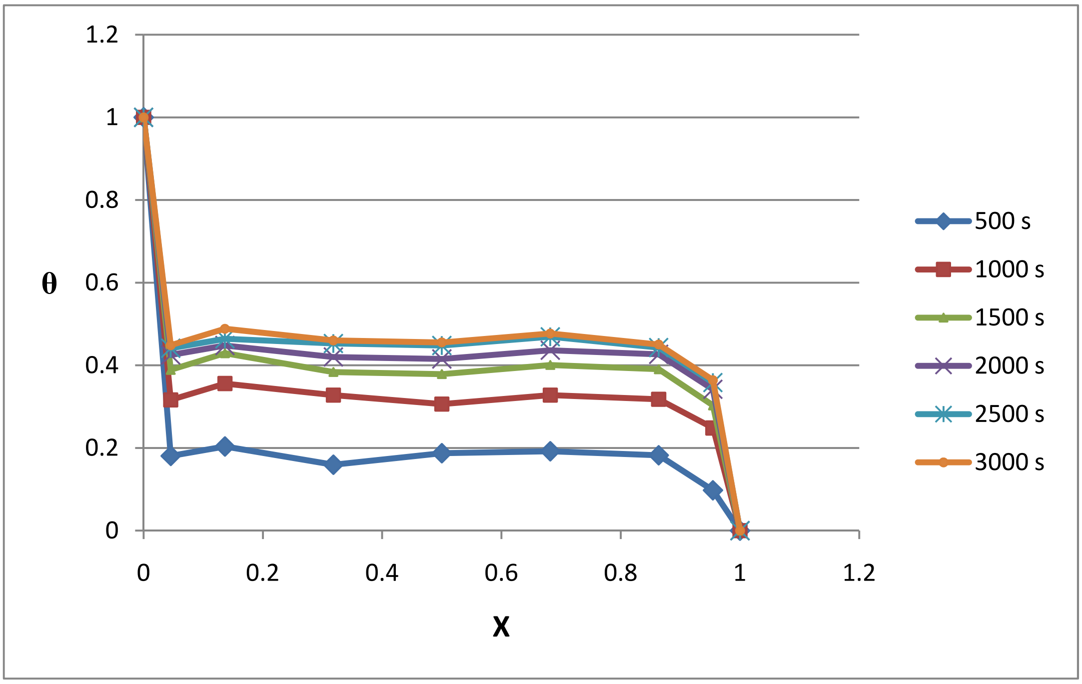


Figure 4.9: Temperature distribution in cavity at various times for the Sample S_2 at $(\Delta T)_{bath}$ = 10 °C.

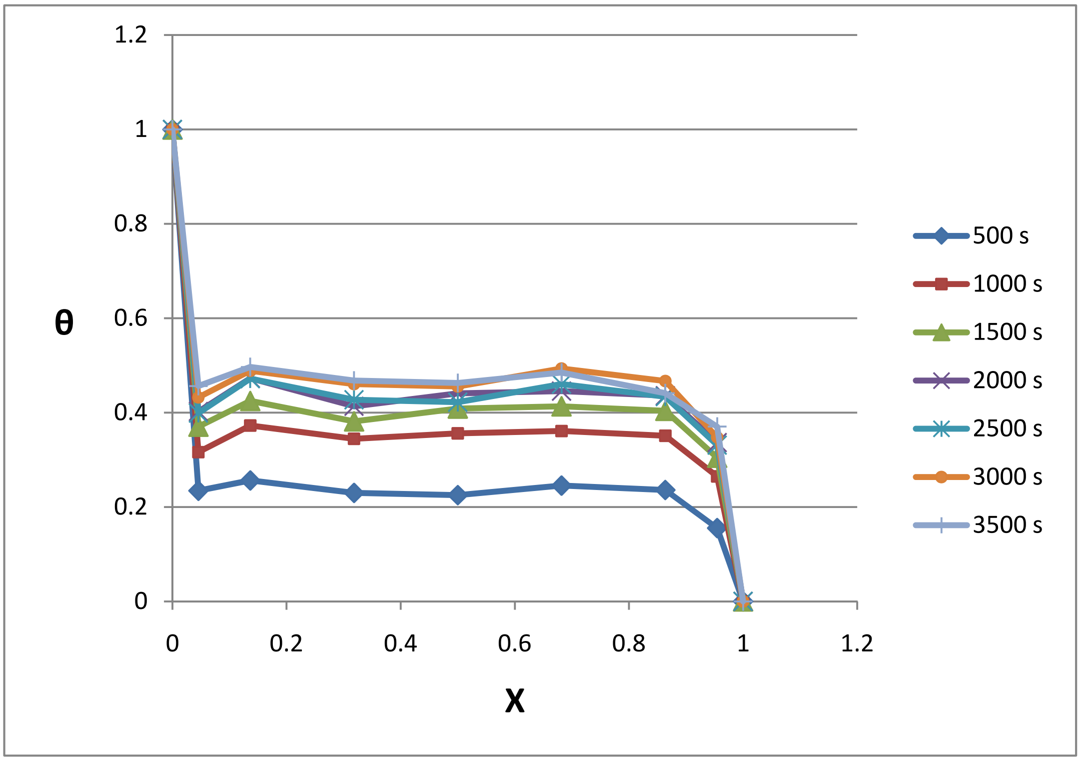


Figure 4.10: Temperature distribution in cavity at various times for the Sample S_3 at $(\Delta T)_{bath}$ = 10 °C.

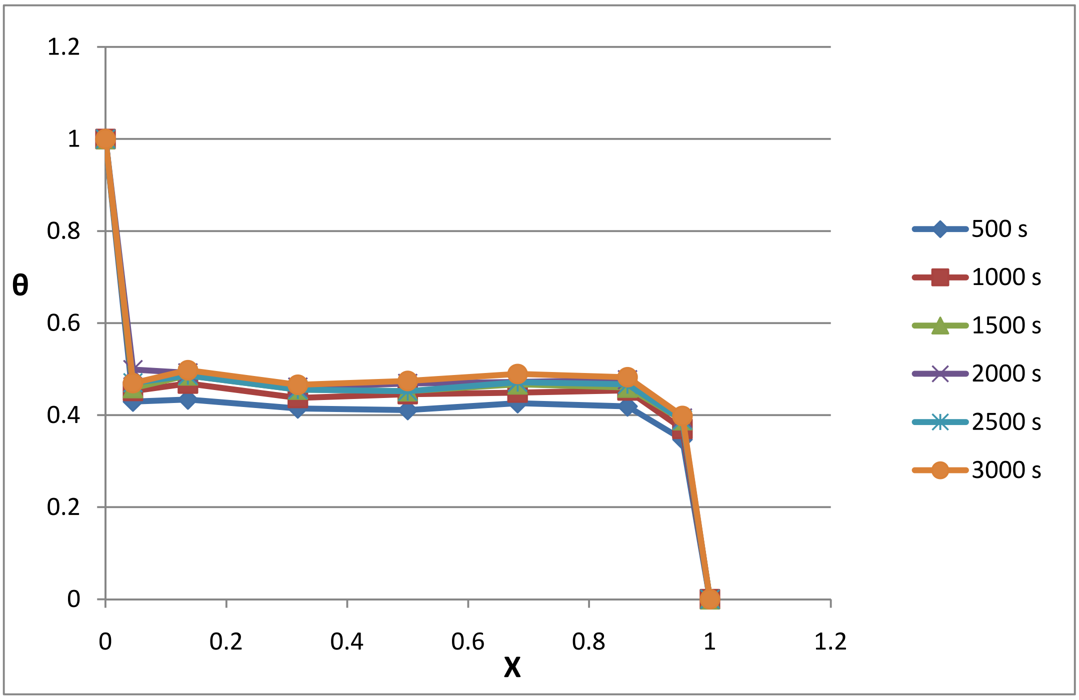


Figure 4.11: Temperature distribution in cavity at various times for the Sample S_1 Hazne at $(\Delta T)_{bath}$ = 15 °C.

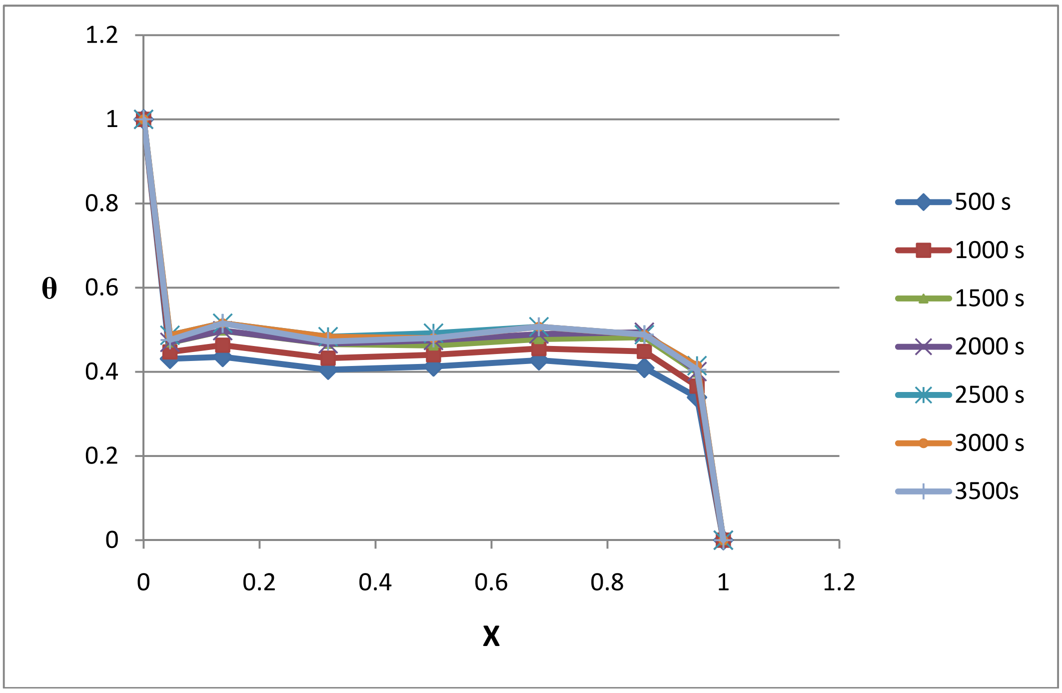


Figure 4.12: Temperature distribution in cavity at various times for the Sample S_2 at $(\Delta T)_{bath} = 15$ °C.

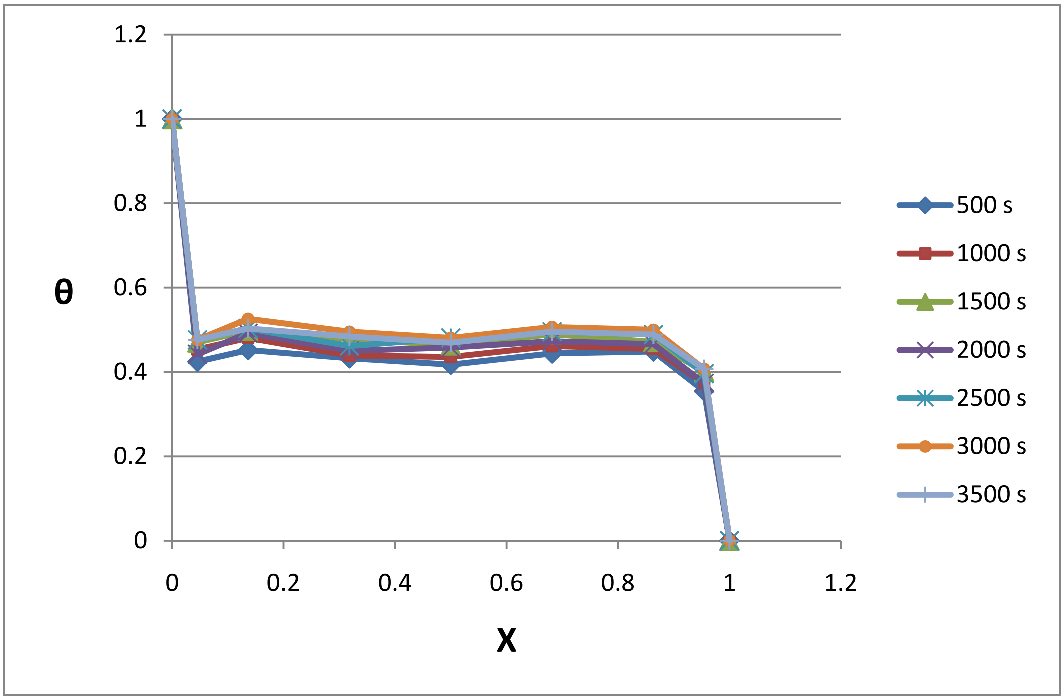


Figure 4.13: Temperature distribution in cavity at various times for the Sample S_3 at $(\Delta T)_{bath} = 15$ °C

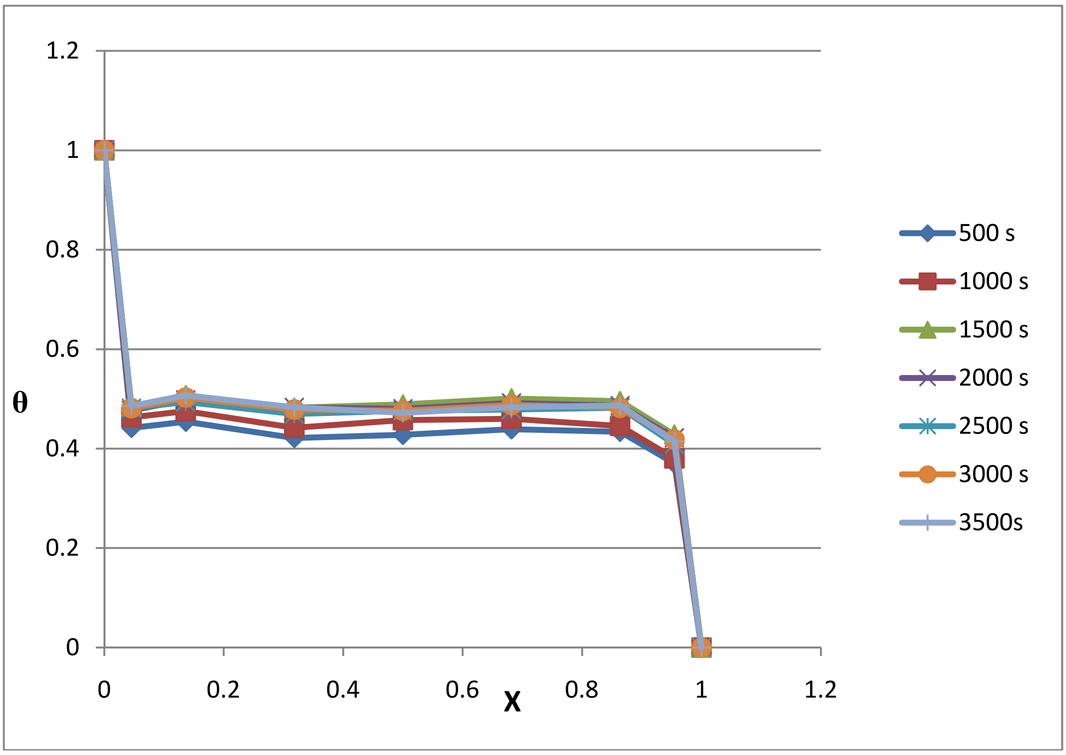


Figure 4.14: Temperature distribution in cavity at various times for the Sample S_1at $(\Delta T)_{bath}$ = 20 °C.

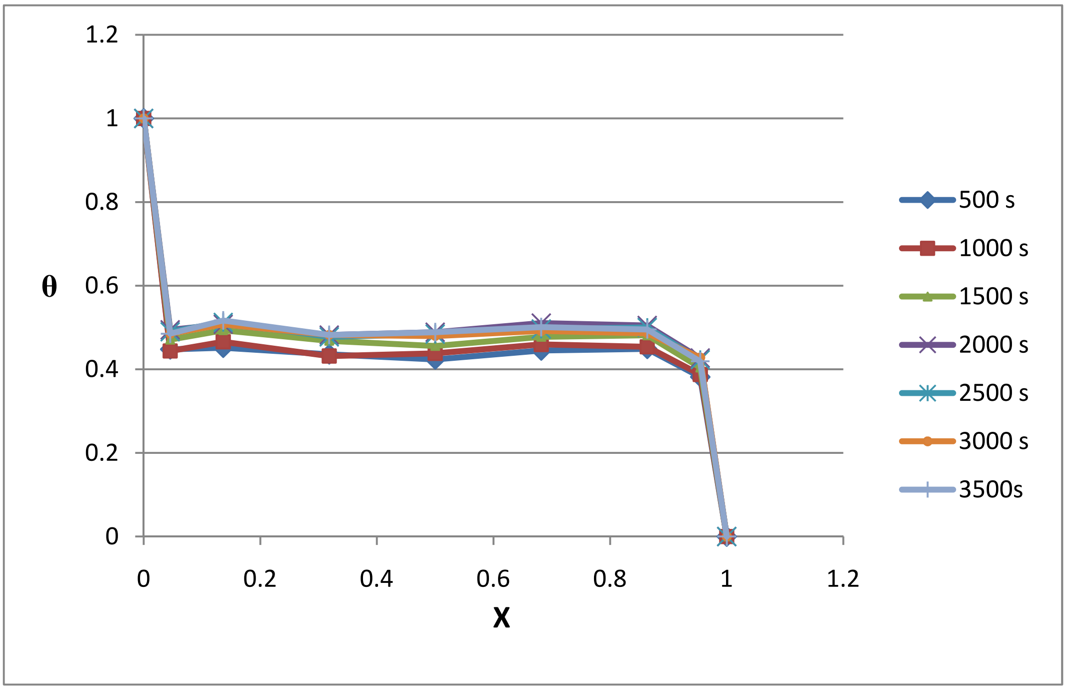


Figure 4.15: Temperature distribution in cavity at various times for the Sample S_2 at $(\Delta T)_{bath}$ = 20 °C.

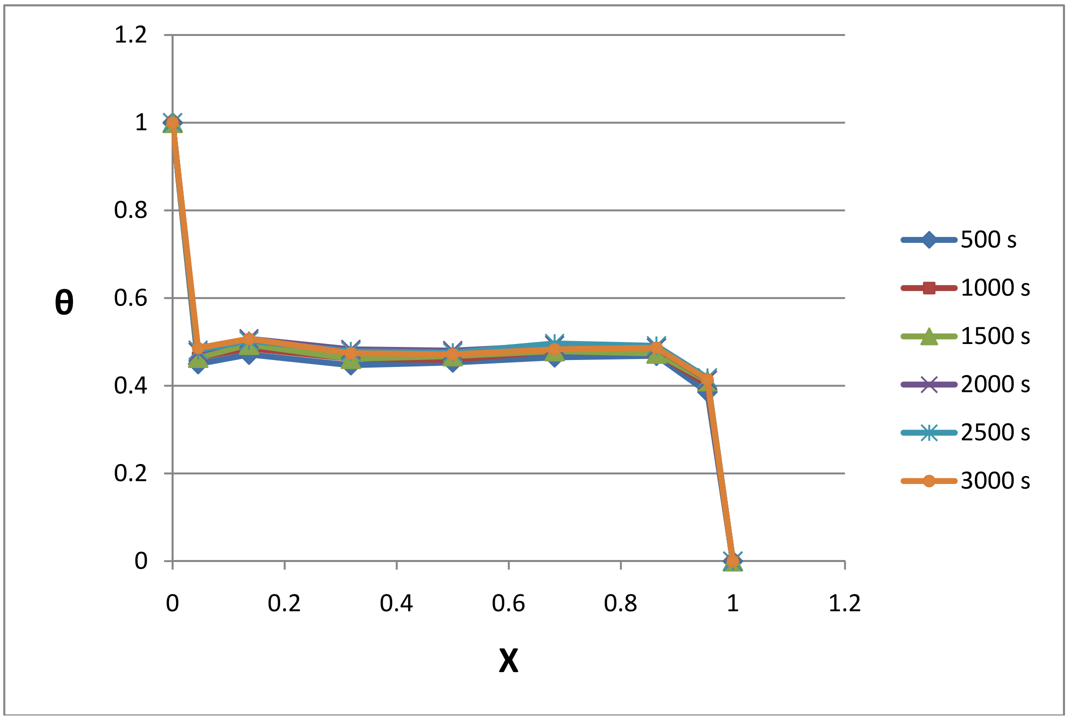


Figure 4.16: Temperature distribution in cavity at various times for the Sample S_3 at $(\Delta T)_{bath}$ = 20 °C.

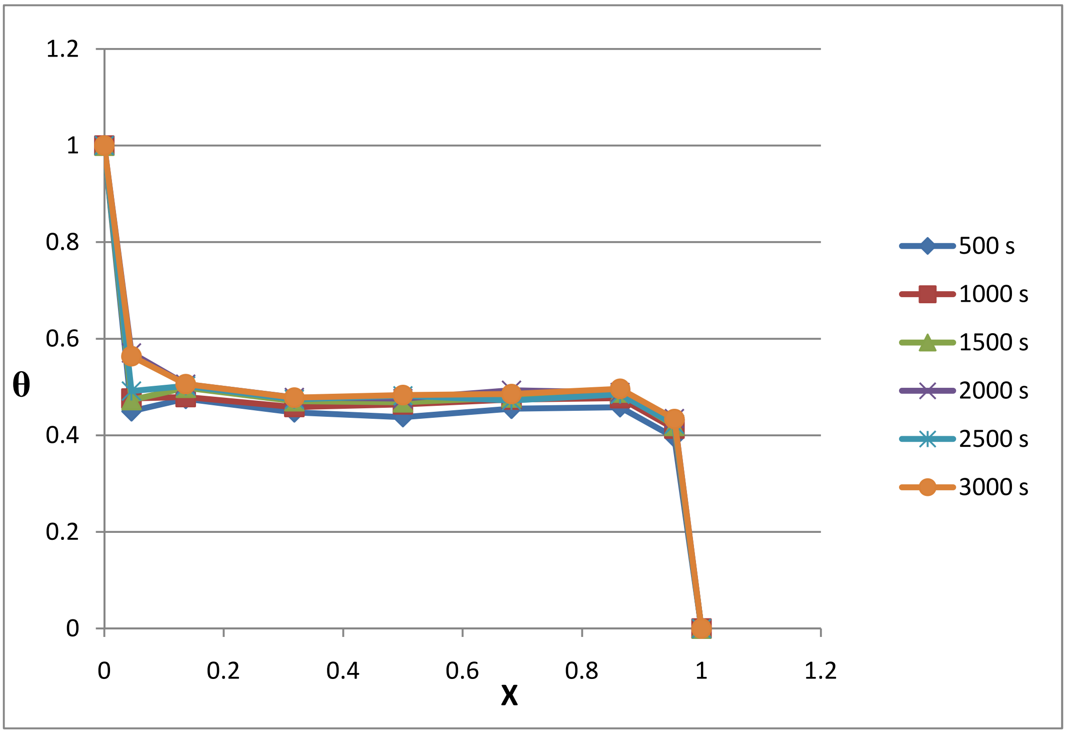


Figure 4.17: Temperature distribution in cavity at various times for the Sample S_1 at $(\Delta T)_{bath}$ = 25 °C.

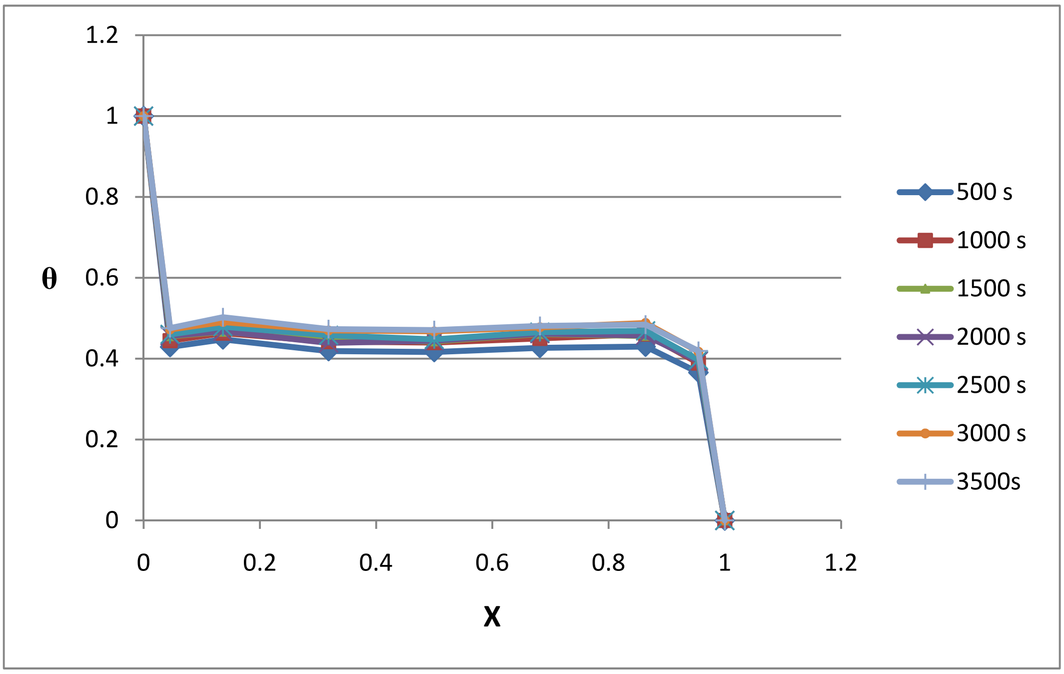


Figure 4.18: Temperature distribution in cavity at various times for the Sample S_2 at $(\Delta T)_{bath} = 25°C$.

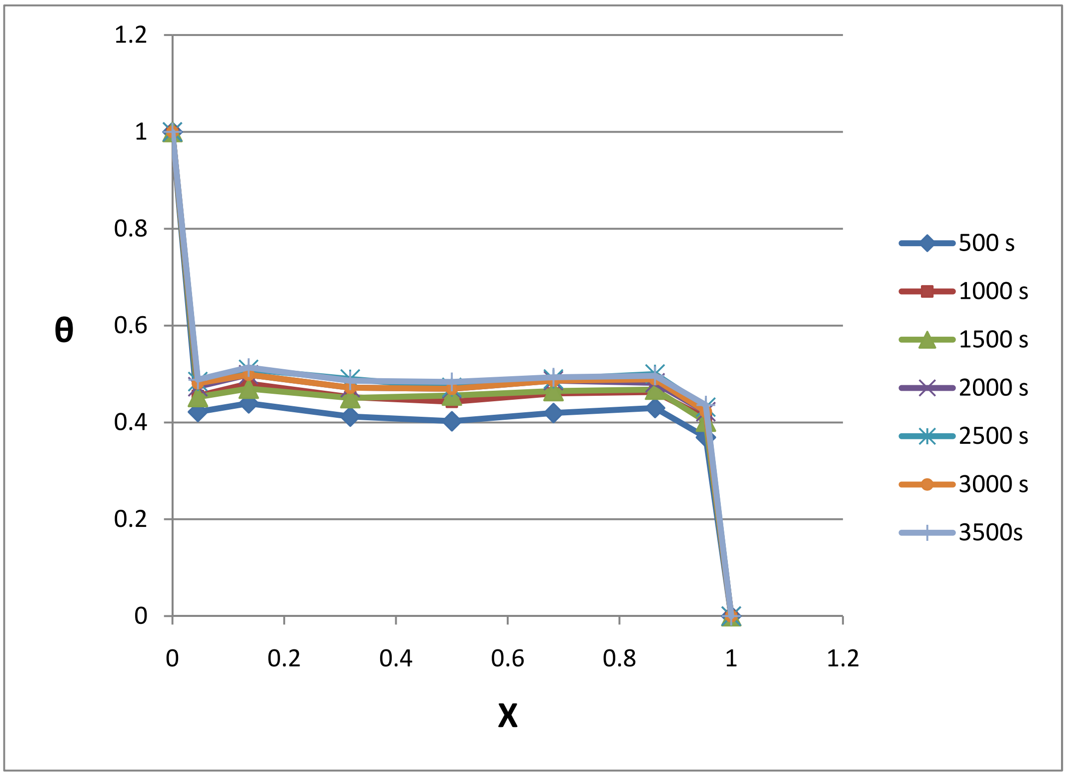


Figure 4.19: Temperature distribution in cavity at various times for the Sample S_3 at $(\Delta T)_{bath} = 25$ °C.

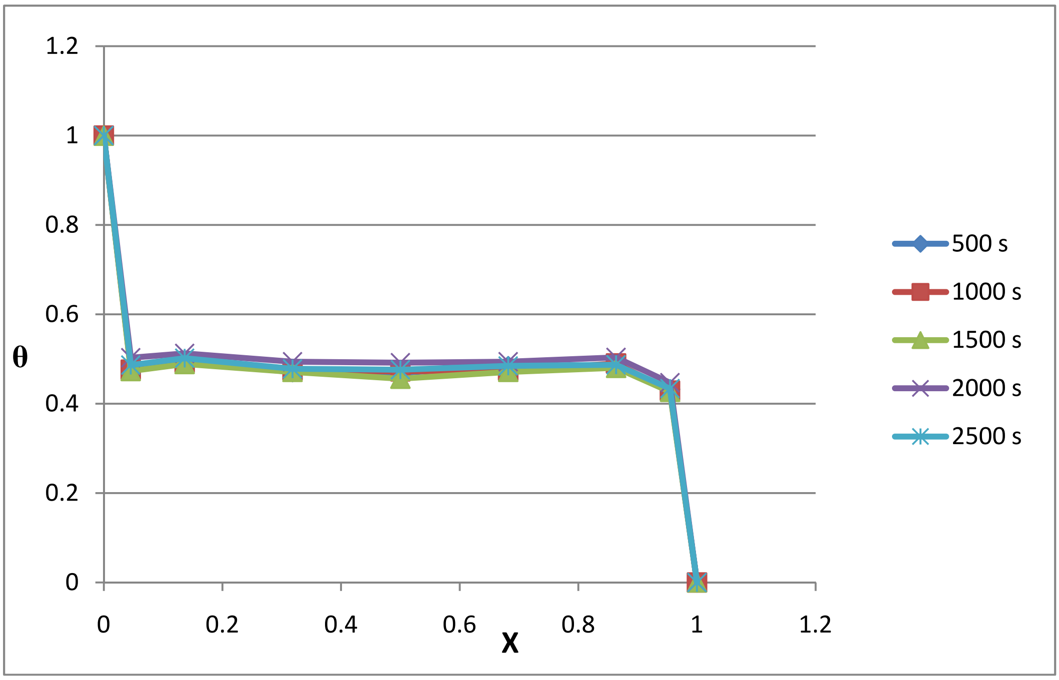


Figure 4.20: Temperature distribution in cavity at various times for the Sample S_1 at $(\Delta T)_{bath} = 30$ °C.

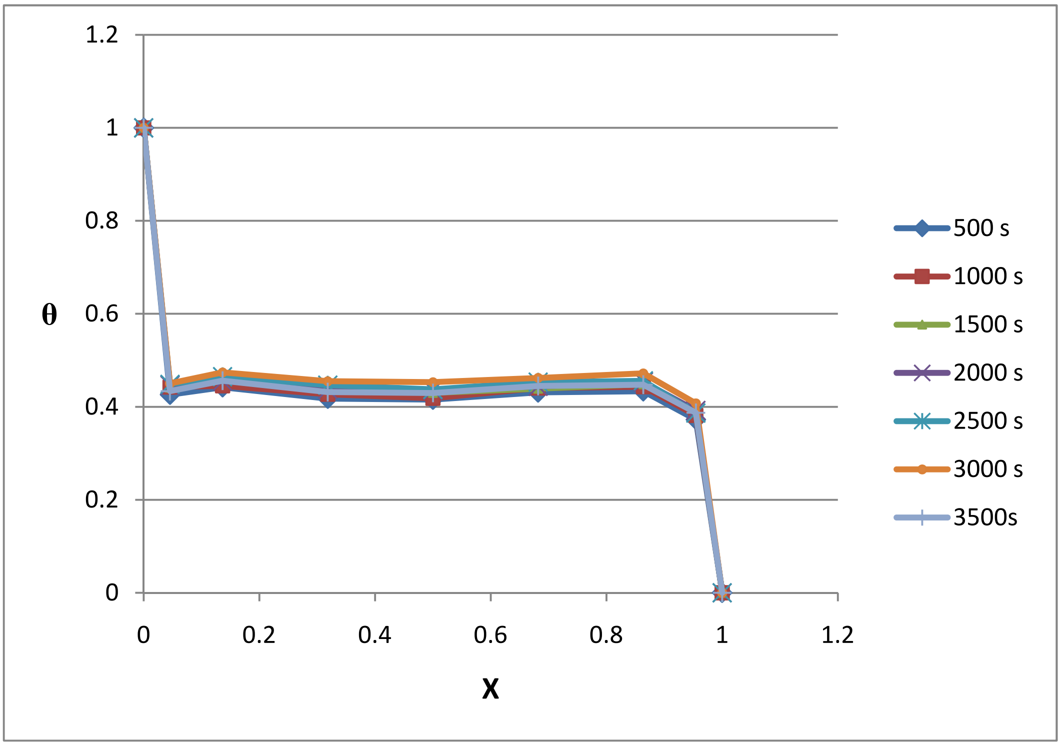


Figure 4.21: Temperature distribution in cavity at various times for the Sample S_2 at $(\Delta T)_{bath} = 30$ °C.

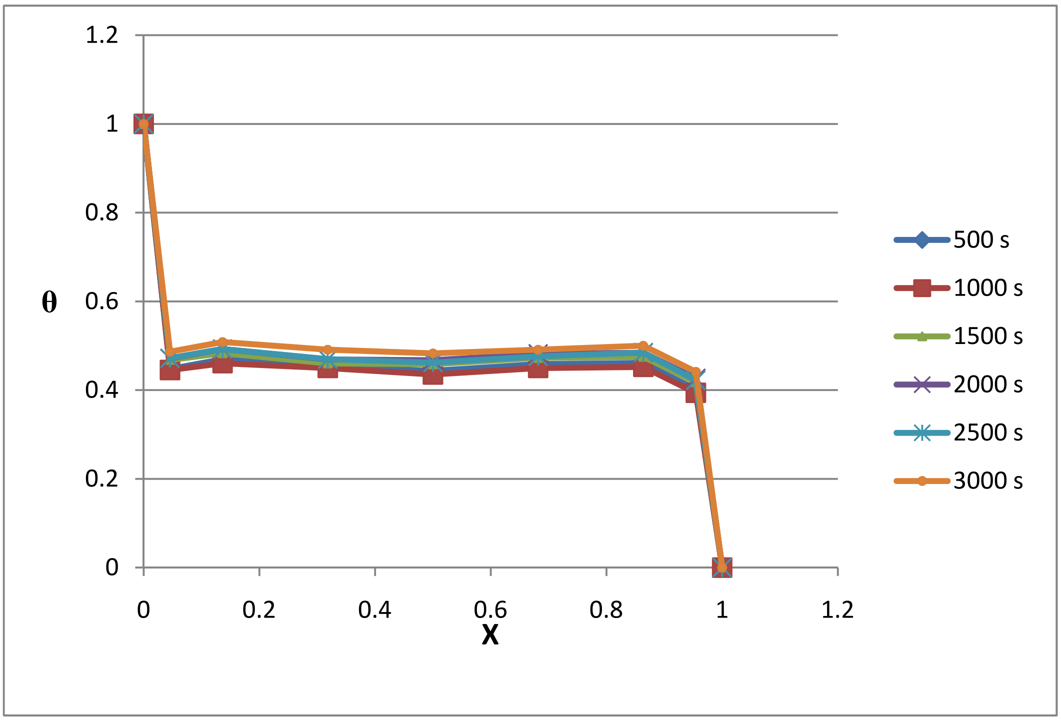


Figure 4.22: Temperature distribution in cavity at various times for the Sample S_3 at $(\Delta T)_{bath}$ = 30 °C.

According to Figure 4.7 to 4.22, It's clear that Temperature distribution of nanofluid is affected by some parameters such as concentration of nanoparticles and also $(\Delta T)_{bath}$ (Temperature difference between hot and cold bathes at various time), For example at same concentration of nanofluid, If we increase $(\Delta T)_{bath}$ then we will find that the temperature distribution in cavity (θ) is not a function of time and experimental results are closer to numerical results.

Chapter 5

CONCLUSION

The experiment has been carried out on a rectangular cavity which filled nanofluid (Cu_2O nanoparticles dispersed in ethanol).The opposing vertical walles have different but uniform temperature.

Three different concentration samples of nanofluid were used in the present work which each of them had different thermophysical properties.

To make a comparison between pesent work and previous studies that have done by other researchers in the field of natural convection of nanofluid, there are two methods of analyzing the problem: Experimental methods and numerical methods.

In the case of temperature distribution of nanofluid in cavity, both numerical and experimental analyzing is agreeing each other. According to our experimental results, It's clear that Temperature distribution of nanofluid is affected by some parameters such as concentration of nanoparticles and also $(\Delta T)_{bath}$ (Temperature difference between hot and cold baths at various time), For example at same concentration of nanofluid, If $(\Delta T)_{bath}$ is increased, the temperature distribution in cavity (θ) is not a function of time and experimental results are closer to numerical results.

The present results and also other experimental results are opposing numerical results in the case of the transient Ra and Nu numbers. Present experimental results show that using nanofluid in cavity cause decreasing heat transfer coefficients. The numerical results are not accurate to find a correlation like Nu= c Ra^n because the simulations were based on some ideal assumptions of (a) nanofluid was Newtonian, incompressible and the flow was in the laminar regime; (b) nanoparticles were uniform in shape and size; (c) there was no slip between liquid and particle phases in terms of both velocity and temperature; and (d) nanofluids had constant thermophysical properties except for density variation that gave rise to the buoyancy. The assumption of (c) and (d) are very difficult to be satisfied for real nanofluids. Although nanofluids behave more like pure fluids than suspensions of large particles and also some thermophysical properties like viscosity , thermal conductivity and density of nanofluid cannot be constant in various times.

At the end of present study, constants c and n in the correlation Nu= c Ra^n are found for three samples of nanofluid at $(\Delta T)_{bath}$ = 10 °C.

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APPENDICES

Appendix A: Experiment Matrix

Table A.1: Experiment Matrix

Sample (ϕ%)	**Pure Ethanol**	**S_1(0.245)**	**S_2(0.381)**	**S_3(0.636)**
$(\Delta T)_{bath}$ (°C)	10	10	10	10
	15	15	15	15
	20	20	20	20
	25	25	25	25
	30	30	30	30

Appendix B: Raw Data

Table B.1: The Excel file which made by data acquisition system for the sample of pure ethanol at $(\Delta T)_{bath}$= 10°C (Date: 15/07/09, Time: 10:43:44)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	31.3	31.5	31.7	32.0	31.6	39.0	32.0	32.0	31.0	41.2	31.7	31.7	42.0	40.1
100s	31.3	31.5	31.9	32.0	31.5	39.0	32.0	32.0	32.0	41.7	31.9	32	42.1	41.2
200s	32.0	32.1	32.4	32.0	31.9	39.0	33.0	33.0	32.0	41.7	32.0	31.9	41.9	41.7
300s	32.6	32.7	33	33.0	32.1	39.0	33.0	33.0	33.0	41.7	32.1	31.9	41.8	42.1
400s	33.1	33.4	33.5	34.0	32.3	39.0	34.0	34.0	33.0	41.8	32.2	32.1	41.9	42.8
500s	33.5	33.8	34.1	34.0	32.4	39.0	34.0	34.0	34.0	41.9	32.3	32.2	42.0	43.3
600s	33.8	34.1	34.5	35.0	32.6	40.0	35.0	35.0	34.0	42.1	32.4	32.1	42.0	43.8
700s	34.1	34.4	34.7	35.0	32.6	40.0	35.0	35.0	34.0	42.0	32.4	32.3	42.0	44.2
800s	34.3	34.7	34.9	35.0	32.7	40.0	35.0	35.0	35.0	42.1	32.4	32.2	42.0	44.6
900s	34.5	34.9	35.1	35.0	32.8	40.0	35.0	36.0	35.0	42.2	32.4	32.2	42.1	44.8
1000s	34.7	35.0	35.4	36.0	32.9	40.0	36.0	36.0	35.0	42.0	32.5	32.3	42.0	45.2
1100s	34.7	35.1	35.5	36.0	33.0	40.0	36.0	36.0	35.0	42.2	32.5	32.3	42.0	45.4
1200s	35.0	35.4	35.6	36.0	33.0	40.0	36.0	36.0	35.0	42.2	32.5	32.3	42.0	45.8
1300s	35.1	35.4	35.8	36.0	33.1	40.0	36.0	36.0	35.0	42.1	32.5	32.2	42.0	46
1400s	35.3	35.5	35.8	36.0	33.1	40.0	36.0	36.0	36.0	42.2	32.5	32.4	41.9	46.1
1500s	35.2	35.6	35.9	36.0	33.1	40.0	36.0	36.0	36.0	42.3	32.6	32.3	42.0	46.1
1600s	35.4	35.7	35.9	36.0	33.1	40.0	36.0	36.0	36.0	42.3	32.5	32.4	42.0	46.4
1700s	35.5	35.7	36.1	36.0	33.3	40.0	36.0	37.0	36.0	42.2	32.5	32.4	42.0	46.6
1800s	35.5	35.8	36.1	36.0	33.2	40.0	36.0	36.0	36.0	42.2	32.7	32.3	42.0	46.9
1900s	35.6	35.8	36.2	36.0	33.3	40.0	36.0	37.0	36.0	42.3	32.6	32.3	41.9	47
2000s	35.6	35.8	36.2	36.0	33.3	40.0	36.0	37.0	36.0	42.3	32.6	32.3	41.9	47

Table B.2: The Excel file which made by data acquisition system for the sample of pure ethanol at $(\Delta T)_{bath}$= 15°C (Date: 15/07/09, Time: 12:10:24)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	37.5	37.7	38.0	38.1	34.2	43.8	38.3	38.3	37.6	46.7	32.6	32.1	46.9	34.2
100s	37.9	37.9	38.2	38.3	34.4	43.4	38.5	38.5	37.8	46.4	32.7	32.3	46.5	34.5
200s	38.0	38.1	38.3	38.4	34.5	43.6	38.5	38.6	37.9	46.6	32.7	32.4	46.7	34.2
300s	38.1	38.2	38.5	38.5	34.5	43.9	38.6	38.6	38.0	46.9	32.9	32.4	46.9	34.5
400s	38.2	38.3	38.5	38.7	34.6	43.9	38.8	38.8	38.2	47.1	32.9	32.4	47.0	34.2
500s	38.2	38.3	38.6	38.7	34.6	43.7	38.8	38.9	38.2	47.0	33.0	32.4	46.9	34.5
600s	38.4	38.4	38.7	38.9	34.7	43.9	38.9	39.0	38.3	46.9	32.9	32.4	46.8	34.5
700s	38.5	38.6	38.7	39.0	34.8	43.9	39.0	39.0	38.5	46.9	32.8	32.5	47.0	34.4
800s	38.5	38.7	38.8	39.0	34.8	44.0	39.1	39.1	38.4	47.0	32.8	32.4	46.9	34.8
900s	38.5	38.8	38.8	39.1	34.8	44.1	39.2	39.2	38.5	47.0	32.9	32.5	46.9	35.2
1000s	38.6	38.7	39.0	39.1	34.9	44.0	39.2	39.2	38.6	47.0	33.1	32.4	46.9	34.7
1100s	38.7	38.8	38.8	39.2	34.8	44.0	39.3	39.2	38.6	47.0	32.9	32.5	46.9	34
1200s	38.8	38.8	39.0	39.1	34.8	44.0	39.3	39.3	38.6	47.0	33.0	32.5	46.9	35
1300s	38.8	38.8	39.1	39.3	34.7	44.1	39.3	39.2	38.8	46.9	33.1	32.5	46.9	34.8
1400s	38.8	38.8	39.0	39.3	34.8	44.2	39.4	39.4	38.8	47.0	33.0	32.5	47.0	35.1
1500s	38.8	38.9	39.0	39.4	34.9	44.1	39.5	39.5	38.8	47.1	33.0	32.5	47.0	35
1600s	38.8	38.9	39.2	39.4	35.0	44.0	39.5	39.4	38.8	47.0	32.9	32.5	46.9	34.8
1700s	38.9	39.0	39.0	39.3	34.9	44.1	39.5	39.5	38.8	47.0	33.0	32.5	46.9	34.8
1800s	38.9	39.0	39.2	39.3	35.0	44.2	39.5	39.5	38.8	47.0	33.0	32.4	47.0	34.9
1900s	38.8	39.0	39.2	39.4	34.9	44.1	39.5	39.5	38.8	47.0	32.9	32.6	46.9	35
2000s	38.8	39.0	39.2	39.4	34.9	44.1	39.5	39.5	38.8	47.0	32.9	32.6	46.9	35

Table B.3: The Excel file which made by data acquisition system for the sample of pure ethanol at $(\Delta T)_{bath}$= 20°C (Date: 15/07/09, Time: 13:41:55)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	40.3	40.6	40.7	41.0	35.8	47.5	41.1	41.1	40.3	51.3	32.4	32.1	52.0	33.8
100s	40.4	40.6	40.8	41.0	35.8	47.3	41.2	41.2	40.4	51.0	32.5	32.3	51.5	34.4
200s	40.6	40.6	40.9	41.1	35.9	47.6	41.2	41.2	40.6	51.3	32.7	32.3	51.8	33.9
300s	40.7	40.9	40.9	41.3	36.0	47.6	41.4	41.3	40.7	51.6	32.7	32.4	52.1	34.5
400s	40.9	40.9	41.1	41.3	36.1	47.6	41.5	41.4	40.7	51.6	32.7	32.3	52.2	33.6
500s	41.0	41.1	41.2	41.4	36.2	47.4	41.6	41.6	40.9	51.6	32.6	32.4	52.1	34.6
600s	41.0	41.2	41.2	41.6	36.2	47.7	41.7	41.5	41.0	51.5	32.7	32.4	51.9	34.6
700s	41.1	41.2	41.4	41.6	36.1	47.8	41.7	41.6	41.0	51.5	32.8	32.5	51.9	34.8
800s	41.2	41.2	41.4	41.6	36.3	47.8	41.8	41.7	41.0	51.6	32.9	32.5	52.0	34.4
900s	41.3	41.3	41.5	41.7	36.3	47.8	41.8	41.8	41.1	51.6	32.9	32.4	51.9	34.1
1000s	41.3	41.3	41.5	41.8	36.3	47.9	41.9	41.8	41.1	51.6	32.8	32.5	52.0	33.5
1100s	41.3	41.3	41.6	41.8	36.3	48.0	41.8	41.9	41.1	51.5	32.8	32.4	52.0	33.9
1200s	41.4	41.4	41.6	41.8	36.3	47.9	41.9	41.9	41.3	51.6	32.7	32.4	52.0	34.3
1300s	41.4	41.4	41.6	42.0	36.3	48.0	42.0	42.0	41.2	51.6	32.8	32.5	51.9	34.9
1400s	41.5	41.4	41.7	41.9	36.4	48.0	42.0	42.1	41.4	51.4	32.9	32.4	51.9	34.4
1500s	41.5	41.5	41.6	41.9	36.4	48.0	42.1	42.1	41.3	51.6	32.8	32.4	52.0	34.6
1600s	41.6	41.5	41.8	41.9	36.4	48.0	42.2	42.1	41.4	51.5	32.8	32.5	51.9	34.7
1700s	41.6	41.6	41.7	42.0	36.4	48.1	42.1	42.0	41.4	51.5	32.8	32.5	51.9	35.2
1800s	41.6	41.6	41.8	42.0	36.5	48.0	42.2	42.1	41.4	51.6	32.8	32.4	51.9	35.2
1900s	41.6	41.7	41.9	42.2	36.4	48.1	42.2	42.2	41.5	51.6	32.9	32.5	52.0	32.6
2000s	41.6	41.7	41.9	42.2	36.4	48.1	42.2	42.2	41.5	51.6	32.9	32.5	52.0	32.6

Table B.4: The Excel file which made by data acquisition system for the sample of pure ethanol at $(\Delta T)_{bath}$= 25°C (Date: 15/07/09, Time: 15:10:27)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	42.9	43.0	43.2	43.5	38.0	51.0	43.7	43.6	43.0	55.5	32.6	32.2	56.5	34.1
100s	43.1	43.0	43.2	43.7	38.0	51.3	43.8	43.7	43.0	55.8	32.7	32.4	56.8	33.7
200s	43.3	43.0	43.4	43.8	38.0	51.4	44.0	43.9	43.0	56.2	32.8	32.4	57.1	33.9
300s	43.4	44.0	43.7	44.1	38.0	51.6	44.1	44.0	43.0	56.2	32.9	32.3	57.1	34.0
400s	43.4	44.0	43.7	44.0	38.0	51.5	44.1	44.1	43.0	56.2	32.8	32.3	56.9	34.2
500s	43.6	44.0	43.7	44.0	38.0	51.3	44.1	44.1	44.0	56.1	32.9	32.4	56.9	34.1
600s	43.7	44.0	43.8	44.1	38.0	51.2	44.1	44.1	44.0	56.1	32.8	32.4	56.8	34.3
700s	43.7	44.0	43.8	44.1	38.0	51.5	44.2	44.2	44.0	56.1	32.8	32.4	56.9	34.0
800s	43.8	44.0	43.9	44.2	38.0	51.5	44.3	44.2	44.0	56.2	32.8	32.4	56.9	34.2
900s	43.8	44.0	43.9	44.3	38.0	51.6	44.4	44.2	44.0	56.2	32.8	32.5	56.9	34.2
1000s	43.9	44.0	43.9	44.3	38.0	51.5	44.4	44.3	44.0	56.1	32.8	32.5	57.0	34.4
1100s	43.9	44.0	44.0	44.2	38.0	51.7	44.4	44.4	44.0	56.1	32.8	32.5	56.9	34.3
1200s	43.9	44.0	44.0	44.4	38.0	51.6	44.4	44.3	44.0	56.1	32.9	32.5	56.9	34.6
1300s	43.9	44.0	44.1	44.4	38.0	51.2	44.5	44.5	44.0	56.1	32.8	32.4	56.9	34.2
1400s	44.0	44.0	44.2	44.4	38.0	51.2	44.5	44.5	44.0	56.1	32.8	32.5	56.9	35.0
1500s	44.0	44.0	44.2	44.6	38.0	51.6	44.6	44.6	44.0	56.1	32.8	32.5	56.9	34.0
1600s	44.0	44.0	44.2	44.6	38.0	51.6	44.5	44.5	44.0	56.1	32.8	32.5	56.7	32.5
1700s	44.0	44.0	44.2	44.6	38.0	51.7	44.6	44.5	44.0	56.1	32.8	32.5	56.8	34.1
1800s	44.1	44.0	44.2	44.6	38.0	51.6	44.6	44.6	44.0	56.2	32.9	32.5	56.8	34.2
1900s	44.1	44.0	44.2	44.6	38.0	51.7	44.7	44.6	44.0	56.2	32.8	32.6	56.8	33.4
2000s	44.1	44.0	44.2	44.6	38.0	51.7	44.7	44.6	44.0	56.2	32.8	32.6	56.8	33.4

Table B.5: The Excel file which made by data acquisition system for the sample of pure ethanol at $(\Delta T)_{bath}$= 30°C (Date: 15/07/09, Time: 15:59:32)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	44.9	44.8	45	45.4	39.0	54.6	45.4	45.4	44.7	60.6	32.7	32.1	62.2	32.7
100s	45.1	45.1	45.2	45.7	38.9	54.6	45.7	45.6	44.9	60.6	32.6	32.3	61.9	34.6
200s	45.3	45.2	45.5	45.8	39.2	54.8	45.9	45.8	45.1	60.6	32.6	32.4	61.9	34.1
300s	45.6	45.5	45.8	46.1	39.3	54.5	46.1	46	45.3	60.7	32.8	32.5	61.9	33.6
400s	45.6	45.7	45.8	46.3	39.6	54.8	46.3	46.2	45.5	60.8	32.8	32.5	62.0	34.1
500s	45.9	45.9	45.9	46.4	39.5	54.9	46.5	46.3	45.7	60.9	32.8	32.6	62.0	33.5
600s	46.1	46.0	46.3	46.6	39.6	55.0	46.6	46.6	45.9	60.8	32.9	32.4	61.9	33.9
700s	46.3	46.1	46.3	46.8	39.5	55.1	46.8	46.6	46.1	60.8	32.9	32.5	61.9	33.6
800s	46.2	46.4	46.6	46.9	39.8	54.7	47.0	46.8	46.3	61.0	32.9	32.6	61.9	33.6
900s	46.3	46.5	46.6	47.1	39.8	55.3	47.1	47.0	46.3	60.9	33.0	32.5	62.1	33.9
1000s	46.4	46.6	46.7	47.2	39.9	55.2	47.3	47.2	46.4	61.0	32.9	32.5	62.0	33.6
1100s	46.5	46.7	46.8	47.2	40.0	55.4	47.3	47.2	46.4	61.0	32.9	32.5	62.0	33.3
1200s	46.5	46.6	46.9	47.3	39.9	55.4	47.3	47.2	46.5	61.0	32.9	32.5	62.1	34.0
1300s	46.4	46.7	47.0	47.3	40.0	54.8	47.4	47.3	46.6	61.1	33.0	32.4	62.1	33.5
1400s	46.6	46.8	47.1	47.4	39.9	55.4	47.5	47.5	46.5	61.0	33.0	32.5	62.2	33.7
1500s	46.6	46.7	47.0	47.4	39.8	55.4	47.5	47.3	46.6	61.0	32.9	32.5	62.1	33.8
1600s	46.6	46.7	47.0	47.5	40.1	55.6	47.5	47.4	46.8	61.1	32.9	32.5	62.1	33.8
1700s	46.7	46.8	47.1	47.4	40.2	55.3	47.5	47.4	46.7	61.0	32.9	32.4	62.1	33.3
1800s	46.6	46.9	47.0	47.5	40.1	55.0	47.6	47.5	46.7	61.1	32.9	32.5	62.0	33.3
1900s	46.7	46.8	47.2	47.4	40.1	55.4	47.5	47.5	46.7	61.1	32.9	32.4	62.0	33.2
2000s	46.7	46.8	47.2	47.4	40.1	55.4	47.5	47.5	46.7	61.1	32.9	32.4	62.0	33.2

Table B.6: The Excel file which made by data acquisition system for the sample S_1 at $(\Delta T)_{bath}$= 10°C (Date: 17/07/09, Time: 10:11:15)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	31.0	31.0	31.0	31.2	31.3	38.4	31.0	31.0	31.2	40.1	31.6	31.6	42.2	32.2
100s	31.1	31.1	31.0	31.2	31.5	38.5	31.0	31.0	31.2	41.2	31.8	31.9	42.2	33.1
200s	31.4	31.5	32.0	31.7	31.5	38.5	32.0	32.0	31.6	41.3	32.0	32.0	41.8	33.5
300s	32.0	32.2	32.0	32.3	31.8	38.5	32.0	32.0	32.2	41.4	32.0	32.1	41.8	32.9
400s	32.5	32.7	33.0	32.9	32.1	38.8	33.0	33.0	32.7	41.6	32.1	32.1	41.8	33.9
500s	33.2	33.2	33.0	33.4	32.2	39.0	34.0	33.0	33.3	41.8	32.1	32.1	41.9	33.1
600s	33.6	33.7	34.0	33.9	32.5	39.1	34.0	34.0	33.7	41.9	32.2	32.1	42.0	33.3
700s	33.9	34.0	34.0	34.2	32.6	39.1	34.0	34.0	34.0	42.0	32.1	32.1	42.0	33.2
800s	34.3	34.2	34.0	34.5	32.7	39.4	35.0	35.0	34.3	41.9	32.1	32.2	42.0	33.2
900s	34.4	34.6	35.0	34.7	32.8	39.3	35.0	35.0	34.6	42.0	32.1	32.2	42.0	34.9
1000s	34.6	34.7	35.0	34.9	32.8	39.5	35.0	35.0	34.7	42.0	32.2	32.3	41.9	33.5
1100s	34.9	34.9	35.0	35.1	32.8	39.6	35.0	35.0	35.0	42.0	32.3	32.3	42.0	34.9
1200s	35.0	35.1	35.0	35.2	33.1	39.7	35.0	35.0	35.1	42.2	32.2	32.3	42.1	34.2
1300s	35.1	35.2	35.0	35.3	33.0	39.8	36.0	35.0	35.2	42.2	32.2	32.4	42.0	34.2
1400s	35.2	35.3	35.0	35.5	33.1	39.7	36.0	36.0	35.3	42.2	32.3	32.3	42.0	34.5
1500s	35.4	35.4	36.0	35.6	33.1	39.8	36.0	36.0	35.5	42.2	32.3	32.3	42.0	34.8
1600s	35.4	35.5	36.0	35.7	33.2	39.8	36.0	36.0	35.5	42.3	32.4	32.4	42.0	34.6
1700s	35.5	35.7	36.0	35.9	33.3	39.8	36.0	36.0	35.6	42.4	32.3	32.3	42.0	34.0
1800s	35.7	35.7	36.0	35.9	33.3	39.9	36.0	36.0	35.7	42.3	32.4	32.3	42.0	33.7
1900s	35.7	35.9	36.0	36	33.4	39.9	36.0	36.0	35.8	42.4	32.3	32.3	42.0	35.1
2000s	35.7	35.9	36.0	36	33.4	39.9	36.0	36.0	35.8	42.4	32.3	32.3	42.0	35.1

Table B.7: The Excel file which made by data acquisition system for the sample S_1 at $(\Delta T)_{bath}$= 15°C (Date: 17/07/09, Time: 11:11:15)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	37.1	36.9	37.0	37.0	33.9	43.0	37.1	37.1	36.3	47.8	32.7	33.7	47.0	33.8
100s	37.2	37.1	37.1	37.2	34.0	42.4	37.4	37.3	36.5	47.5	32.7	34.0	46.2	34.2
200s	37.3	37.3	37.4	37.4	34.0	42.6	37.6	37.5	36.7	47.7	32.8	34.0	46.4	34.1
300s	37.5	37.5	37.5	37.4	34.1	43.0	37.7	37.7	36.8	48.0	32.8	34.1	46.7	34.2
400s	37.6	37.6	37.6	37.6	34.2	42.7	37.9	37.7	37.0	48.2	32.8	34.1	46.8	34.5
500s	37.9	37.83	37.8	37.8	34.2	42.8	38	37.9	37.2	48.1	32.8	34.1	46.7	34.5
600s	38.1	37.9	37.9	37.9	34.3	42.9	38.1	38.0	37.3	48.1	33.0	34.1	46.7	34.2
700s	38.1	38.0	38.1	38.0	34.4	43.0	38.3	38.13	37.3	48.1	32.9	34.1	46.7	34.3
800s	38.1	38.1	38.2	38.1	34.4	43.0	38.4	38.2	37.5	48.0	33.0	34.1	46.7	35.2
900s	38.2	38.23	38.3	38.3	34.4	43.2	38.4	38.3	37.6	48.1	33.0	34.2	46.6	34.2
1000s	38.3	38.2	38.3	38.3	34.4	43.0	38.5	38.3	37.6	48.0	32.9	34.1	46.7	34.4
1100s	38.3	38.4	38.4	38.4	34.4	42.9	38.6	38.5	37.7	48.1	33.0	34.2	46.6	34.8
1200s	38.5	38.4	38.5	38.4	34.4	43.2	38.6	38.5	37.7	48.1	33.0	34.1	46.7	34.6
1300s	38.4	38.43	38.5	38.5	34.6	43.1	38.7	38.6	37.8	48.1	33.0	34.1	46.7	34.8
1400s	38.5	38.4	38.6	38.6	34.6	43.1	38.8	38.6	37.8	48.2	32.9	34.1	46.7	34.3
1500s	38.5	38.5	38.5	38.5	34.5	43.2	38.8	38.6	37.9	48.1	33.0	34.1	46.6	34.4
1600s	38.6	38.5	38.6	38.5	34.6	43.4	38.8	38.6	37.9	48.1	33.0	34.1	46.7	34.8
1700s	38.6	38.6	38.5	38.5	34.6	43.4	38.9	38.7	38.0	48.2	33.0	34.1	46.7	34.7
1800s	38.6	38.5	38.6	38.6	34.5	43.2	38.9	38.6	37.9	48.1	32.8	34.1	46.6	34.9
1900s	38.6	38.7	38.7	38.7	34.6	43.1	38.9	38.7	38.1	48.1	33.0	34.1	46.6	34.8
2000s	38.6	38.7	38.7	38.7	34.6	43.1	38.9	38.7	38.1	48.1	33.0	34.1	46.6	34.8

Table B.8: The Excel file which made by data acquisition system for the sample S_1 at $(\Delta T)_{bath}$= 20°C (Date: 17/07/09, Time: 12:24:17)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	37.1	36.9	37.0	37.0	33.9	43.0	37.1	37.1	36.3	47.8	32.7	33.7	47.0	33.8
100s	37.2	37.1	37.1	37.2	34.0	42.4	37.4	37.3	36.5	47.5	32.7	34.0	46.2	34.2
200s	37.3	37.3	37.4	37.4	34.0	42.6	37.6	37.5	36.7	47.7	32.8	34.0	46.4	34.1
300s	37.5	37.5	37.5	37.4	34.1	43.0	37.7	37.7	36.8	48.0	32.8	34.1	46.7	34.2
400s	37.6	37.6	37.6	37.6	34.2	42.7	37.9	37.7	37.0	48.2	32.8	34.1	46.8	34.5
500s	37.9	37.8	37.8	37.8	34.2	42.8	38.0	37.9	37.2	48.1	32.8	34.1	46.7	34.5
600s	38.1	37.9	37.9	37.9	34.3	42.9	38.1	38.0	37.3	48.1	33.0	34.1	46.7	34.23
700s	38.1	38.0	38.1	38.0	34.4	43.0	38.3	38.1	37.3	48.1	32.9	34.1	46.7	34.3
800s	38.1	38.1	38.2	38.1	34.4	43.0	38.4	38.2	37.5	48.0	33.0	34.1	46.7	35.2
900s	38.2	38.2	38.3	38.3	34.4	43.2	38.4	38.3	37.6	48.1	33.0	34.2	46.6	34.2
1000s	38.3	38.2	38.3	38.3	34.4	43.0	38.5	38.3	37.6	48.0	32.9	34.1	46.7	34.4
1100s	38.3	38.4	38.4	38.4	34.4	42.9	38.6	38.5	37.7	48.1	33.0	34.2	46.6	34.8
1200s	38.5	38.4	38.5	38.4	34.4	43.2	38.6	38.5	37.7	48.1	33.0	34.1	46.7	34.6
1300s	38.4	38.4	38.5	38.5	34.6	43.1	38.7	38.6	37.8	48.1	33.0	34.1	46.7	34.8
1400s	38.5	38.4	38.6	38.6	34.6	43.1	38.8	38.6	37.8	48.2	32.9	34.1	46.7	34.3
1500s	38.5	38.5	38.5	38.5	34.5	43.2	38.8	38.6	37.9	48.1	33.0	34.1	46.6	34.4
1600s	38.6	38.5	38.6	38.5	34.6	43.4	38.8	38.	37.9	48.1	33.0	34.1	46.7	34.8
1700s	38.6	38.6	38.5	38.5	34.6	43.4	38.9	38.7	38.0	48.2	33.0	34.1	46.7	34.7
1800s	38.6	38.5	38.6	38.6	34.5	43.2	38.9	38.6	37.9	48.1	32.8	34.1	46.6	34.9
1900s	38.6	38.7	38.7	38.7	34.6	43.1	38.9	38.7	38.1	48.1	33.0	34.1	46.6	34.8
2000s	38.6	38.7	38.7	38.7	34.6	43.1	38.9	38.7	38.1	48.1	33.0	34.1	46.6	34.8

Table B.9: The Excel file which made by data acquisition system for the sample S_1 at $(\Delta T)_{bath}$= 25°C (Date: 17/07/09, Time: 13:42:25)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	39.7	39.5	39.6	39.6	35.3	46.5	39.8	39.7	38.9	52.3	32.7	33.6	52.0	33.5
100s	40.0	39.9	39.9	39.9	35.5	46.0	40.1	40.0	39.1	52.2	32.8	33.9	51.2	34.0
200s	40.0	40.0	40.1	40.1	35.6	46.1	40.3	40.2	39.4	52.4	32.8	34.0	51.3	34.6
300s	40.4	40.2	40.3	40.2	35.7	46.7	40.4	40.3	39.5	52.6	32.9	34.0	51.6	34.6
400s	40.5	40.4	40.5	40.4	35.6	46.6	40.7	40.4	39.7	52.6	32.9	34.0	51.7	34.5
500s	40.6	40.4	40.5	40.5	35.6	46.9	40.8	40.6	39.8	52.7	32.8	34.1	51.7	34.3
600s	40.7	40.6	40.6	40.6	35.7	46.7	40.9	40.7	39.9	52.7	32.9	34.1	51.6	34.1
700s	40.7	40.7	40.7	40.8	35.7	46.7	40.9	40.8	40.0	52.6	32.9	34.0	51.6	34.6
800s	40.8	40.8	40.8	40.8	35.8	46.7	41.2	40.9	40.2	52.7	32.9	34.1	51.7	34.7
900s	41.0	40.8	40.9	40.9	35.9	46.9	41.2	41.0	40.2	52.7	33.0	34.1	51.6	34.9
1000s	41.1	40.9	41.1	40.9	36.0	47.0	41.3	41.1	40.2	52.7	32.9	34.1	51.6	34.6
1100s	41.1	41.0	41.1	41.1	36.0	47.0	41.2	41.2	40.4	52.8	32.9	34.1	51.7	34.8
1200s	41.1	41.1	41.1	41.2	35.9	46.9	41.4	41.1	40.4	52.7	32.8	34.1	51.6	34.4
1300s	41.3	41.1	41.1	41.2	36.0	46.8	41.4	41.2	40.5	52.8	32.9	34.1	51.7	34.2
1400s	41.2	41.1	41.2	41.3	35.9	46.7	41.5	41.3	40.5	52.7	32.9	34.1	51.6	34.4
1500s	41.2	41.2	41.3	41.3	36.0	46.7	41.5	41.4	40.6	52.7	32.8	34.0	51.6	33.6
1600s	41.9	41.3	41.4	41.3	36.1	46.9	41.6	41.4	40.6	52.7	32.8	34.0	51.6	33.3
1700s	41.3	41.3	41.3	41.3	36.0	47.1	41.7	41.4	40.6	52.8	32.8	34.1	51.7	34.4
1800s	41.4	41.2	41.4	41.4	36.1	47.1	41.6	41.5	40.6	52.7	32.8	34.1	51.6	34.1
1900s	41.3	41.3	41.4	41.4	36.0	47.2	41.6	41.4	40.6	52.7	32.8	34.1	51.6	34.4
2000s	41.3	41.3	41.4	41.4	36.0	47.2	41.6	41.4	40.6	52.7	32.8	34.1	51.6	34.4

Table B.10: The Excel file which made by data acquisition system for the sample S_1 at $(\Delta T)_{bath}$= 30°C (Date: 17/07/09, Time: 15:05:07)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	42.2	42.1	42.2	42.2	36.7	50.1	42.4	42.2	41.5	57.0	32.8	33.8	56.8	34.2
100s	42.5	42.4	42.4	42.4	36.8	50.4	42.7	42.5	41.8	57.2	32.8	34.0	56.7	34.1
200s	42.6	42.6	42.7	42.7	37.1	49.7	43.0	42.8	42.0	57.2	32.9	34.1	56.5	34.8
300s	42.9	42.8	42.8	42.9	37.2	50.3	43.1	42.9	42.1	57.3	32.8	34.2	56.6	34.8
400s	43.1	42.9	43.0	43.0	37.2	50.2	43.3	43.1	42.3	57.3	32.9	34.1	56.6	34.9
500s	43.2	43.2	43.1	43.3	37.3	50.4	43.6	43.3	42.5	57.4	32.9	34.1	56.6	35.1
600s	43.3	43.3	43.3	43.4	37.6	50.6	43.6	43.4	42.5	57.4	32.9	34.2	56.7	35.3
700s	43.4	43.4	43.4	43.5	37.5	50.8	43.7	43.4	42.7	57.4	32.9	34.2	56.7	35.1
800s	43.6	43.5	43.5	43.5	37.4	50.6	43.8	43.6	42.8	57.3	32.9	34.1	56.6	34.9
900s	43.6	43.6	43.6	43.6	37.4	50.4	43.9	43.6	42.9	57.4	32.9	34.2	56.6	35.0
1000s	43.8	43.6	43.7	43.8	37.6	50.6	43.9	43.8	43.0	57.4	33.0	34.1	56.6	36.3
1100s	43.7	43.6	43.7	43.8	37.6	50.8	44.0	43.8	43.0	57.4	32.9	34.1	56.7	35.5
1200s	43.8	43.7	43.8	43.8	37.6	50.9	44.2	43.8	43.0	57.5	32.9	34.1	56.6	34.7
1300s	43.9	43.8	43.8	43.9	37.7	50.5	44.1	43.9	43.1	57.5	32.9	34.2	56.8	34.7
1400s	43.8	43.8	43.9	44.0	37.6	50.4	44.2	44.0	43.2	57.41	33.0	34.1	56.7	35.4
1500s	43.9	43.9	43.9	44.1	37.6	50.9	44.3	44.0	43.2	57.4	32.9	34.1	56.6	34.4
1600s	44.1	43.9	44.0	44.0	37.6	51.1	44.3	44.0	43.3	57.4	32.9	34.1	56.7	34.9
1700s	44.0	44.0	44.0	44.0	37.6	50.8	44.4	44.0	43.3	57.4	32.9	34.1	56.7	35.6
1800s	44.0	44.0	44.0	44.1	37.7	50.7	44.3	44.1	43.4	57.5	32.9	34.2	56.6	35.6
1900s	44.0	43.9	44.0	44.2	37.6	50.4	44.3	44.1	43.3	57.3	33.0	34.1	56.6	35.1
2000s	44.0	43.9	44.0	44.2	37.6	50.4	44.3	44.1	43.3	57.3	33.0	34.1	56.6	35.1

Table B.11: The Excel file which made by data acquisition system for the sample S_2 at $(\Delta T)_{bath}$= 10°C (Date: 22/07/09, Time: 10:01:19)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	30.8	30.7	30.7	30.6	31.1	37.7	30.7	30.7	30.4	41.2	31.8	33.2	42.1	32.6
100s	30.9	30.8	30.8	30.6	31.3	37.8	30.8	30.8	30.4	42.3	32.0	33.5	42.1	33.5
200s	31.2	31.2	31.3	31.1	31.3	37.8	31.2	31.1	30.8	42.4	32.2	33.6	41.7	33.9
300s	31.8	31.9	31.8	31.7	31.6	37.8	31.9	31.7	31.4	42.5	32.2	33.7	41.7	33.3
400s	32.3	32.4	32.4	32.3	31.9	38.1	32.5	32.3	31.9	42.7	32.3	33.7	41.7	34.3
500s	33.0	32.9	32.9	32.8	32.0	38.3	33.0	32.8	32.5	42.9	32.3	33.7	41.8	33.5
600s	33.4	33.4	33.3	33.3	32.3	38.4	33.4	33.2	32.9	43.0	32.4	33.7	41.9	33.7
700s	33.7	33.7	33.7	33.6	32.4	38.4	33.7	33.7	33.2	43.1	32.3	33.7	41.9	33.6
800s	34.1	33.9	34.0	33.9	32.5	38.7	34.1	34.0	33.5	43.0	32.3	33.8	41.9	33.6
900s	34.2	34.3	34.2	34.1	32.6	38.6	34.4	34.0	33.8	43.1	32.3	33.8	41.9	35.3
1000s	34.4	34.4	34.4	34.3	32.6	38.8	34.5	34.4	33.9	43.1	32.4	33.9	41.8	33.9
1100s	34.7	34.6	34.6	34.5	32.6	38.9	34.8	34.6	34.2	43.1	32.5	33.9	41.9	35.3
1200s	34.8	34.8	34.8	34.6	32.9	39.0	34.9	34.7	34.3	43.3	32.4	33.9	42.0	34.6
1300s	34.9	34.9	34.9	34.7	32.8	39.1	35.1	34.8	34.4	43.3	32.4	34.0	41.9	34.6
1400s	35.0	35.0	35.0	34.9	32.9	39.0	35.2	35.0	34.5	43.3	32.5	33.9	41.9	34.9
1500s	35.2	35.1	35.2	35.0	32.9	39.1	35.3	35.2	34.7	43.3	32.5	33.9	41.9	35.2
1600s	35.2	35.2	35.2	35.1	33.0	39.1	35.3	35.3	34.7	43.4	32.6	34.0	41.9	35.0
1700s	35.3	35.4	35.3	35.3	33.1	39.1	35.5	35.3	34.8	43.5	32.5	33.9	41.9	34.4
1800s	35.5	35.4	35.5	35.3	33.1	39.2	35.5	35.5	34.9	43.4	32.6	33.9	41.9	34.1
1900s	35.5	35.6	35.5	35.4	33.2	39.2	35.6	35.4	35.0	43.5	32.5	33.9	41.9	35.5
2000s	35.5	35.6	35.5	35.4	33.2	39.2	35.6	35.4	35.0	43.5	32.5	33.9	41.9	35.5

Table B.12: The Excel file which made by data acquisition system for the sample S_2 at $(\Delta T)_{bath}$= 15°C (Date: 22/07/09, Time: 11:15:26)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	30.8	30.7	30.7	30.6	31.1	37.7	30.7	30.7	30.4	41.2	31.8	33.2	42.1	32.6
100s	30.9	30.8	30.8	30.6	31.3	37.8	30.8	30.8	30.4	42.3	32.0	33.5	42.1	33.5
200s	31.2	31.2	31.3	31.1	31.3	37.8	31.2	31.1	30.8	42.4	32.2	33.6	41.7	33.9
300s	31.8	31.9	31.8	31.7	31.6	37.8	31.9	31.7	31.4	42.5	32.2	33.7	41.7	33.3
400s	32.3	32.4	32.4	32.3	31.9	38.1	32.5	32.3	31.9	42.7	32.3	33.7	41.7	34.3
500s	33.0	32.9	32.9	32.8	32.0	38.3	33.0	32.8	32.5	42.9	32.3	33.7	41.8	33.5
600s	33.4	33.4	33.3	33.3	32.3	38.4	33.4	33.2	32.9	43.0	32.4	33.7	41.9	33.7
700s	33.7	33.7	33.7	33.6	32.4	38.4	33.7	33.7	33.2	43.1	32.3	33.7	41.9	33.6
800s	34.1	33.9	34.0	33.9	32.5	38.7	34.1	34.0	33.5	43.0	32.3	33.8	41.9	33.6
900s	34.2	34.3	34.2	34.1	32.6	38.6	34.4	34.0	33.8	43.1	32.3	33.8	41.9	35.3
1000s	34.4	34.4	34.4	34.3	32.6	38.8	34.5	34.4	33.9	43.1	32.4	33.9	41.8	33.9
1100s	34.7	34.6	34.6	34.5	32.6	38.9	34.8	34.6	34.2	43.1	32.5	33.9	41.9	35.3
1200s	34.8	34.8	34.8	34.6	32.9	39.0	34.9	34.7	34.3	43.3	32.4	33.9	42.0	34.6
1300s	34.9	34.9	34.9	34.7	32.8	39.1	35.1	34.8	34.4	43.3	32.4	34.0	41.9	34.6
1400s	35.0	35.0	35.0	34.9	32.9	39.0	35.2	35.0	34.5	43.3	32.5	33.9	41.9	34.9
1500s	35.2	35.1	35.2	35.0	32.9	39.1	35.3	35.2	34.7	43.3	32.5	33.9	41.9	35.2
1600s	35.2	35.2	35.2	35.1	33.0	39.1	35.3	35.3	34.7	43.4	32.6	34.0	41.9	35.0
1700s	35.3	35.4	35.3	35.3	33.1	39.1	35.5	35.3	34.8	43.5	32.5	33.9	41.9	34.4
1800s	35.5	35.4	35.5	35.3	33.1	39.2	35.5	35.5	34.9	43.4	32.6	33.9	41.9	34.1
1900s	35.5	35.6	35.5	35.4	33.2	39.2	35.6	35.4	35.0	43.5	32.5	33.9	41.9	35.5
2000s	35.5	35.6	35.5	35.4	33.2	39.2	35.6	35.4	35.0	43.5	32.5	33.9	41.9	35.5

Table B.13: The Excel file which made by data acquisition system for the sample S_2 at $(\Delta T)_{bath}$= 20°C (Date: 22/07/09, Time: 12:31:04)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	40.2	40.3	40.3	40.3	35.8	46.3	40.6	40.4	39.6	52.3	32.9	34.2	51.6	37.4
100s	40.4	40.4	40.4	40.5	35.8	46.6	40.6	40.6	39.8	52.1	33.0	34.3	51.2	37.7
200s	40.6	40.5	40.5	40.7	35.9	46.7	40.8	40.7	39.9	52.3	33.0	34.4	51.5	38.0
300s	40.6	40.7	40.6	40.7	35.9	46.5	41.0	40.8	40.0	52.7	33.1	34.4	51.9	38.0
400s	40.7	40.8	40.8	40.9	36.1	46.7	41.1	40.8	40.2	52.9	33.0	34.5	51.9	37.9
500s	41.0	40.9	40.8	41.0	36.2	46.9	41.1	41.0	40.3	52.8	33.1	34.4	51.8	38.0
600s	41.0	41.0	41.0	41.1	36.3	47.0	41.3	41.1	40.3	52.8	33.1	34.3	51.8	38.0
700s	41.0	41.1	41.0	41.2	36.3	46.9	41.3	41.1	40.4	52.8	33.1	34.4	51.8	39.2
800s	41.1	41.1	41.2	41.2	36.3	46.8	41.4	41.2	40.4	52.8	33.1	34.4	51.8	38.3
900s	41.1	41.1	41.2	41.3	36.2	46.6	41.5	41.4	40.6	52.8	33.0	34.4	51.8	38.3
1000s	41.2	41.1	41.2	41.3	36.4	47.2	41.5	41.4	40.6	52.8	33.1	34.5	51.8	38.2
1100s	41.2	41.3	41.2	41.3	36.2	47.1	41.6	41.3	40.6	52.8	33.1	34.4	51.8	38.3
1200s	41.2	41.3	41.3	41.4	36.4	47.0	41.6	41.4	40.6	52.8	33.0	34.5	51.8	38.1
1300s	41.3	41.3	41.3	41.4	36.3	47.0	41.6	41.4	40.7	52.8	33.1	34.4	51.9	38.3
1400s	41.3	41.4	41.4	41.4	36.4	46.7	41.6	41.5	40.6	52.8	33.1	34.3	51.7	38.1
1500s	41.4	41.4	41.3	41.5	36.4	47.0	41.7	41.5	40.7	52.8	33.1	34.5	51.8	38.1
1600s	41.4	41.5	41.4	41.4	36.3	47.3	41.8	41.6	40.7	52.7	33.0	34.4	51.9	38.3
1700s	41.4	41.4	41.5	41.5	36.4	47.2	41.8	41.6	40.8	52.8	33.0	34.5	51.8	38.3
1800s	41.4	41.4	41.5	41.5	36.2	46.9	41.9	41.6	40.7	52.8	33.0	34.5	51.9	38.4
1900s	41.4	41.3	41.5	41.6	36.4	47.1	41.8	41.6	40.7	52.8	33.0	34.4	51.8	38.2
2000s	41.4	41.3	41.5	41.6	36.4	47.1	41.8	41.6	40.7	52.8	33.0	34.4	51.8	38.2

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Table B.14: The Excel file which made by data acquisition system for the sample S_2 at $(\Delta T)_{bath}$= 25°C (Date: 22/07/09, Time: 13:45:05)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	42.7	42.6	42.6	42.7	37.2	49.9	42.9	42.8	42.0	57.1	32.8	34.0	56.9	36.9
100s	42.9	42.8	42.8	42.9	37.6	50.4	43.1	42.9	42.1	56.9	33.0	34.2	56.5	37.9
200s	43.1	43.0	43.0	43.1	37.5	50.1	43.3	43.2	42.3	57.1	33.1	34.3	56.6	37.8
300s	43.2	43.2	43.2	43.3	37.8	50.4	43.6	43.3	42.5	57.3	32.9	34.3	56.9	38.0
400s	43.3	43.4	43.3	43.4	37.6	50.4	43.7	43.4	42.6	57.4	33.0	34.5	56.9	38.1
500s	43.6	43.5	43.5	43.7	38.0	51.0	43.9	43.6	42.8	57.4	33.1	34.3	56.8	38.1
600s	43.5	43.6	43.5	43.7	38.0	50.5	43.9	43.8	42.9	57.4	32.9	34.5	56.8	38.2
700s	43.7	43.6	43.7	43.8	38.0	50.9	44.0	43.9	43.0	57.4	32.9	34.5	56.9	37.6
800s	43.7	43.7	43.6	43.8	38.0	50.9	44.0	43.8	43.0	57.3	33.2	34.4	56.8	38.2
900s	43.8	43.8	43.8	44.0	38.1	50.9	44.1	43.9	43.1	57.4	33.0	34.5	56.7	39.7
1000s	43.8	43.8	43.7	43.9	38.1	51.3	44.1	43.9	43.1	57.4	33.0	34.4	56.9	38.0
1100s	43.9	43.9	43.8	43.9	38.0	50.9	44.2	44.0	43.1	57.5	33.0	34.4	56.8	38.2
1200s	43.9	43.8	43.8	44.1	38.2	51.1	44.2	43.9	43.1	57.4	33.0	34.4	56.8	38.5
1300s	43.9	43.9	43.9	44.1	37.9	50.8	44.2	44.0	43.2	57.4	33.0	34.4	56.9	38.2
1400s	44.0	43.9	43.9	44.0	38.3	50.8	44.2	44.1	43.3	57.5	33.1	34.5	56.8	38.2
1500s	44.0	43.9	43.9	44.1	38.4	51.1	44.3	44.1	43.3	57.4	33.1	34.4	56.9	38.3
1600s	44.0	44.0	43.9	44.0	38.3	51.1	44.3	44.1	43.3	57.4	33.1	34.3	56.9	39.0
1700s	44.1	43.9	44.0	44.1	38.1	51.1	44.3	44.1	43.2	57.3	33.1	34.4	56.8	38.1
1800s	44.0	44.0	44.0	44.1	38.1	50.8	44.3	44.1	43.3	57.4	33.1	34.5	56.9	38.2
1900s	44.1	43.9	44.0	44.1	38.2	51.1	44.3	44.2	43.3	57.3	33.1	34.3	56.8	38.2
2000s	44.1	43.9	44.0	44.1	38.2	51.1	44.3	44.2	43.3	57.3	33.1	34.3	56.8	38.2

Table B.15: The Excel file which made by data acquisition system for the sample S_2 at $(\Delta T)_{bath}$= 30°C (Date: 22/07/09, Time: 15:05: 59)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	45.2	45.2	45.1	45.2	39.0	54.4	45.5	45.3	44.4	61.7	32.9	34.0	62.1	36.5
100s	45.5	45.3	45.3	45.6	39.2	54.1	45.8	45.5	44.7	61.6	33.1	34.2	61.7	38.0
200s	45.6	45.6	45.4	45.7	39.4	53.9	46.0	45.7	44.9	61.6	33.0	34.3	61.6	38.1
300s	45.86	45.8	45.7	45.9	39.4	54.0	46.0	45.8	45.0	61.8	33.0	34.4	61.8	37.9
400s	45.9	45.9	45.9	46.0	39.7	54.3	46.2	46.0	45.1	61.9	33.2	34.4	61.9	38.3
500s	46.1	46.0	46.0	46.2	39.7	54.7	46.4	46.2	45.3	61.9	33.1	34.4	61.9	38.2
600s	46.1	46.0	46.1	46.2	39.9	55.1	46.4	46.2	45.4	61.9	33.1	34.4	61.8	38.5
700s	46.2	46.2	46.1	46.3	39.9	54.7	46.5	46.3	45.5	62.0	33.1	34.4	61.8	38.1
800s	46.4	46.3	46.2	46.4	40.1	54.4	46.6	46.5	45.5	62.0	33.2	34.3	61.8	38.4
900s	46.4	46.4	46.3	46.5	40.0	54.8	46.7	46.5	45.7	61.9	33.2	34.3	61.8	38.2
1000s	46.6	46.4	46.3	46.6	40.0	54.9	46.7	46.6	45.7	61.9	33.2	34.4	61.9	39.3
1100s	46.6	46.5	46.4	46.6	40.0	54.8	46.9	46.7	45.8	62.0	33.2	34.4	61.8	38.7
1200s	46.9	46.6	46.6	46.7	40.0	54.8	46.9	46.6	45.9	62.0	33.1	34.4	61.7	38.1
1300s	46.6	46.53	46.5	46.7	39.9	54.8	46.9	46.6	45.8	62.0	33.0	34.4	61.9	38.2
1400s	46.6	46.6	46.5	46.7	40.2	55.0	46.9	46.7	45.8	62.0	33.1	34.4	61.9	38.5
1500s	46.6	46.6	46.5	46.7	40.2	54.7	47.0	46.6	45.9	62.0	33.1	34.3	61.9	38.7
1600s	46.6	46.6	46.5	46.7	40.2	55.1	47.0	46.7	45.8	62.1	33.2	34.4	61.8	38.2
1700s	46.7	46.6	46.6	46.8	40.0	54.6	47.0	46.8	46.0	61.9	33.1	34.4	61.8	38.8
1800s	46.7	46.6	46.7	46.8	39.9	54.7	47.0	46.7	45.9	62.0	33.2	34.3	61.8	38.3
1900s	46.7	46.7	46.7	46.8	40.1	54.9	47.0	46.8	45.8	62.0	33.1	34.3	61.8	38.5
2000s	46.7	46.7	46.7	46.8	40.1	54.9	47.0	46.8	45.8	62.0	33.1	34.3	61.8	38.5

Table B.16: The Excel file which made by data acquisition system for the sample S_3 at $(\Delta T)_{bath}$= 10°C (Date: 24/07/09, Time: 9:54: 25)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	32.0	32.1	32.1	32.0	31.6	38.3	32.1	32.0	31.6	41.61	32.2	33.7	42.0	35.1
100s	32.1	32.2	32.3	32.1	31.8	38.3	32.2	32.2	31.7	42.5	32.3	33.8	42.0	35.8
200s	32.3	32.5	32.5	32.4	31.9	38.3	32.6	32.5	32.0	42.5	32.3	34.0	41.8	35.9
300s	33.0	33.0	33.0	33.0	32.1	38.3	33.0	32.9	32.4	42.5	32.5	33.8	41.6	36.8
400s	33.4	33.4	33.5	33.5	32.2	38.5	33.6	33.4	32.9	42.7	32.5	33.9	41.7	36.7
500s	33.8	33.8	33.8	33.8	32.3	38.7	34.0	33.9	33.3	42.7	32.5	33.9	41.7	36.9
600s	34.1	34.1	34.2	34.1	32.6	38.7	34.4	34.2	33.6	42.8	32.5	33.9	41.6	37.6
700s	34.2	34.4	34.4	34.4	32.6	38.6	34.6	34.4	33.8	42.8	32.4	34.0	41.6	38.4
800s	34.5	34.6	34.6	34.6	32.7	38.7	34.8	34.7	34.1	42.8	32.4	34.0	41.6	36.9
900s	34.6	34.8	34.8	34.9	32.7	38.7	35.0	34.9	34.3	42.9	32.3	34.0	41.7	38.0
1000s	34.7	34.9	35.0	34.9	32.8	38.8	35.1	35.0	34.4	42.9	32.4	34.1	41.5	37.7
1100s	34.9	35.1	35.1	35.2	32.8	38.9	35.2	35.1	34.5	42.9	32.4	34.1	41.6	37.6
1200s	35.0	35.1	35.2	35.2	32.9	38.9	35.4	35.3	34.6	43.0	32.3	34.1	41.6	37.5
1300s	35.1	35.2	35.4	35.3	33.0	39.0	35.5	35.4	34.8	43.0	32.3	34.1	41.6	37.4
1400s	35.2	35.4	35.4	35.3	33.0	39.0	35.6	35.4	34.8	43.1	32.3	34.1	41.6	37.0
1500s	35.3	35.4	35.6	35.5	33.0	39.2	35.7	35.6	34.9	43.0	32.4	34.2	41.6	37.3
1600s	35.5	35.5	35.7	35.6	33.1	39.1	35.8	35.8	35.0	43.1	32.5	34.2	41.6	38.1
1700s	35.5	35.7	35.6	35.7	33.1	39.2	35.9	35.8	35.1	43.1	32.3	34.3	41.7	37.7
1800s	35.6	35.6	35.8	35.7	33.0	39.3	36.0	35.8	35.1	43.0	32.3	34.2	41.6	37.1
1900s	35.6	35.7	35.9	35.8	33.1	39.3	36.1	35.9	35.2	43.1	32.4	34.3	41.5	37.5
2000s	35.6	35.7	35.9	35.8	33.1	39.3	36.1	35.9	35.2	43.1	32.4	34.3	41.5	37.5

Table B.17: The Excel file which made by data acquisition system for the sample S_3 at $(\Delta T)_{bath}$= 15°C (Date: 24/07/09, Time: 11:01: 52)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	37.5	37.5	37.6	37.6	34.1	42.7	37.8	37.7	37.0	47.9	32.6	34.4	46.7	37.8
100s	37.6	37.7	37.6	37.7	34.3	43.0	38.0	37.9	37.1	48.0	32.6	34.4	46.9	37.7
200s	37.9	37.8	37.9	37.8	34.3	43.2	38.1	38.0	37.2	48.0	32.7	34.3	46.8	38.4
300s	38.0	37.9	38.0	38.1	34.3	43.2	38.3	38.2	37.3	48.0	32.7	34.4	46.8	37.6
400s	38.0	38.1	38.1	38.2	34.5	43.1	38.3	38.3	37.4	48.1	32.7	34.4	46.8	38.7
500s	38.1	38.2	38.1	38.3	34.4	43.1	38.4	38.3	37.5	48.1	32.7	34.4	46.7	38.0
600s	38.2	38.2	38.3	38.3	34.5	43.0	38.5	38.4	37.6	48.0	32.7	34.4	46.8	37.7
700s	38.3	38.4	38.4	38.4	34.4	43.1	38.6	38.5	37.7	48.0	32.6	34.4	46.8	38.2
800s	38.4	38.4	38.5	38.4	34.5	43.2	38.7	38.5	37.8	48.0	32.7	34.4	46.7	38.1
900s	38.4	38.5	38.5	38.6	34.6	43.4	38.8	38.6	37.8	48.1	32.6	34.4	46.9	37.9
1000s	38.6	38.5	38.5	38.6	34.6	43.4	38.9	38.7	37.9	48.1	32.6	34.5	46.8	37.8
1100s	38.5	38.6	38.6	38.6	34.5	43.4	38.9	38.7	37.9	48.0	32.7	34.4	46.8	37.93
1200s	38.5	38.6	38.7	38.7	34.6	43.5	38.9	38.8	37.9	48.1	32.6	34.5	46.8	37.9
1300s	38.5	38.7	38.6	38.8	34.6	43.3	39.0	38.8	38.0	48.1	32.7	34.4	46.8	38.0
1400s	38.6	38.7	38.7	38.7	34.6	43.3	38.9	38.9	38.1	48.0	32.7	34.5	46.7	38.4
1500s	38.7	38.8	38.7	38.7	34.6	43.3	39.0	38.9	38.1	48.1	32.7	34.4	46.8	38.3
1600s	38.7	38.7	38.8	38.8	34.6	43.2	39.0	38.9	38.1	48.1	32.8	34.5	46.7	37.7
1700s	38.8	38.8	38.8	38.7	34.7	43.2	39.0	38.8	38.1	48.1	32.8	34.4	46.7	38.1
1800s	38.8	38.8	38.8	38.8	34.6	43.5	39.1	39.0	38.2	48.1	32.7	34.3	46.7	38.1
1900s	38.7	38.8	39	38.9	34.7	43.4	39.2	39.0	38.1	48.2	32.7	34.4	46.8	38.0
2000s	38.7	38.8	39	38.9	34.7	43.4	39.2	39.0	38.1	48.2	32.7	34.4	46.8	38.0

Table B.18: The Excel file which made by data acquisition system for the sample S_3 at $(\Delta T)_{bath}$= 20°C (Date: 24/07/09, Time: 12:18: 51)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	40.6	40.6	40.5	40.7	35.8	47.0	40.9	40.7	39.9	52.4	32.6	34.1	51.9	36.6
100s	40.8	40.7	40.8	40.8	35.8	46.5	41.0	40.9	40.1	52.0	32.8	34.2	51.2	38.0
200s	40.9	40.8	40.8	41.0	35.9	47.0	41.1	40.9	40.1	52.1	32.9	34.3	51.3	37.8
300s	40.8	40.9	40.9	40.9	35.9	47.3	41.2	41.0	40.1	52.5	32.8	34.4	51.8	39.2
400s	41.0	41.0	41.0	41.1	35.9	47.3	41.3	41.1	40.2	52.7	32.8	34.3	51.9	37.8
500s	41.0	41.0	41.1	41.2	36.0	47.1	41.3	41.2	40.3	52.7	32.9	34.4	51.8	37.9
600s	41.1	41.0	41.0	41.2	35.9	47.4	41.4	41.2	40.4	52.7	32.9	34.4	51.8	38.1
700s	41.2	41.1	41.2	41.3	36.0	47.4	41.5	41.3	40.5	52.6	32.9	34.5	51.8	38.2
800s	41.3	41.2	41.2	41.3	36.1	47.3	41.5	41.4	40.5	52.7	32.9	34.4	51.7	38.8
900s	41.3	41.2	41.3	41.4	36.1	47.2	41.6	41.4	40.6	52.7	32.8	34.5	51.8	38.9
1000s	41.3	41.3	41.3	41.4	36.0	47.4	41.6	41.5	40.6	52.6	32.8	34.4	51.9	38.0
1100s	41.4	41.4	41.3	41.4	36.1	47.6	41.7	41.5	40.7	52.7	32.9	34.3	51.7	38.8
1200s	41.4	41.4	41.5	41.4	36.0	47.4	41.7	41.6	40.7	52.6	32.8	34.3	51.8	38.2
1300s	41.4	41.4	41.4	41.4	36.0	47.3	41.7	41.6	40.7	52.7	32.9	34.4	51.8	38.3
1400s	41.4	41.4	41.4	41.5	36.1	47.3	41.7	41.6	40.7	52.7	32.8	34.4	51.8	38.8
1500s	41.4	41.4	41.5	41.5	36.1	47.5	41.8	41.6	40.8	52.8	32.8	34.4	51.8	38.1
1600s	41.4	41.5	41.5	41.6	36.2	47.5	41.8	41.6	40.8	52.7	32.8	34.5	51.7	38.0
1700s	41.5	41.4	41.5	41.6	36.2	47.4	41.7	41.6	40.7	52.7	32.9	34.4	51.7	38.2
1800s	41.4	41.5	41.6	41.6	36.2	47.3	41.8	41.0	40.8	52.7	32.9	34.4	51.7	38.0
1900s	41.5	41.6	41.5	41.6	36.1	47.2	41.9	41.7	40.9	52.6	33.0	34.4	51.7	38.4
2000s	41.5	41.6	41.6	41.6	36.2	47.3	41.9	41.7	40.8	52.7	32.9	34.4	51.7	38.2

Table B.19: The Excel file which made by data acquisition system for the sample S_3 at $(\Delta T)_{bath}$= 25°C (Date: 24/07/09, Time: 13:19: 54)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	42.7	42.7	42.7	42.8	37.2	50.8	43.0	42.8	42.0	56.9	32.9	34.2	56.5	37.5
100s	42.9	42.8	42.8	43.0	37.4	51.1	43.2	43.0	42.1	56.8	32.9	34.2	56.3	38.1
200s	43.0	42.9	43.0	43.1	37.3	51.0	43.3	43.1	42.2	57.1	32.9	34.4	56.6	38.9
300s	43.1	43.1	43.0	43.2	37.3	50.9	43.4	43.3	42.4	57.2	32.9	34.3	56.9	38.9
400s	43.3	43.3	43.2	43.3	37.6	51.2	43.6	43.4	42.6	57.4	32.9	34.3	56.8	38.0
500s	43.4	43.3	43.2	43.5	37.7	51.2	43.7	43.4	42.7	57.3	32.9	34.4	56.9	38.4
600s	43.3	43.4	43.4	43.5	37.5	50.9	43.7	43.7	42.7	57.3	33.0	34.4	56.9	38.8
700s	43.5	43.6	43.5	43.6	37.4	51.0	43.9	43.6	42.7	57.2	32.9	34.4	56.8	38.2
800s	43.6	43.6	43.5	43.7	37.6	51.4	43.9	43.7	42.9	57.3	32.8	34.4	56.8	38.2
900s	43.7	43.6	43.5	43.7	37.7	51.2	44.0	43.8	43.0	57.2	33.0	34.3	56.8	38.6
1000s	43.7	43.7	43.6	43.8	37.6	51.0	44.1	43.8	43.1	57.2	33.0	34.4	56.8	38.3
1100s	43.8	43.7	43.8	43.8	37.6	51.1	44.1	44.0	43.0	57.3	33.0	34.3	56.8	38.3
1200s	43.8	43.9	43.6	43.8	37.6	51.5	44.2	43.8	43.0	57.4	33.0	34.4	56.8	38.3
1300s	43.9	43.8	43.9	44.1	37.8	51.3	44.3	44.0	43.2	57.4	32.9	34.4	56.9	38.2
1400s	43.9	43.8	43.8	44.0	37.6	51.1	44.2	44.0	43.1	57.4	33.0	34.4	56.9	37.9
1500s	43.9	43.9	44.0	44.1	37.6	51.5	44.2	44.1	43.2	57.4	32.9	34.4	56.8	38.7
1600s	44.0	44.0	44.0	44.1	37.6	51.5	44.3	44.1	43.3	57.3	33.0	34.4	56.8	38.1
1700s	44.0	44.0	44.0	44.2	37.6	51.0	44.4	44.2	43.2	57.3	33.0	34.4	56.8	37.6
1800s	44.2	44.1	44.1	44.2	37.7	51.5	44.5	44.3	43.3	57.4	33.0	34.4	56.8	39.0
1900s	44.1	44.1	44.1	44.2	37.6	51.5	44.5	44.2	43.4	57.4	33.1	34.4	56.7	38.5
2000s	44.1	44.1	44.1	44.2	37.6	51.3	44.5	44.3	43.4	57.4	33.1	34.3	56.8	38.3

Table B.20: The Excel file which made by data acquisition system for the sample S_3 at $(\Delta T)_{bath}$= 30°C (Date: 24/07/09, Time: 14:49: 04)

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14
0s	45.9	45.8	45.9	46.0	39.3	54.4	46.2	46.0	45.0	61.1	32.9	34.0	61.3	37.2
100s	46.0	45.9	45.9	46.0	39.4	54.6	46.3	46.1	45.2	61.1	33.0	34.2	61.2	38.1
200s	46.0	46.0	45.9	46.1	39.2	54.2	46.4	46.1	45.3	61.4	32.9	34.3	61.5	38.1
300s	46.1	46.0	46.1	46.3	39.4	55.1	46.4	46.3	45.3	61.6	33.1	34.4	61.7	38.1
400s	46.2	46.2	46.1	46.3	39.2	55.2	46.5	46.3	45.4	61.8	33.1	34.4	61.9	38.7
500s	46.2	46.3	46.2	46.4	39.3	54.7	46.6	46.4	45.5	61.9	33.2	34.4	61.8	37.8
600s	46.4	46.3	46.3	46.5	39.3	55.2	46.7	46.5	45.5	61.9	33.1	34.3	61.8	38.1
700s	46.3	46.3	46.3	46.5	39.9	54.7	46.7	46.5	45.6	61.8	33.2	34.4	61.8	37.9
800s	46.6	46.5	46.4	46.6	39.3	55.0	46.8	46.6	45.7	61.8	33.0	34.5	61.8	38.3
900s	46.5	46.5	46.4	46.7	39.2	55.3	46.9	46.6	45.8	61.9	33.2	34.4	61.8	37.8
1000s	46.5	46.6	46.4	46.6	39.5	55.2	46.8	46.6	45.7	62.0	33.2	34.3	61.8	38.7
1100s	46.5	46.5	46.5	46.7	39.3	54.8	46.9	46.7	45.7	61.9	33.0	34.4	61.8	38.4
1200s	46.7	46.6	46.4	46.8	39.2	55.5	47.0	46.7	45.8	61.8	33.1	34.3	61.7	37.9
1300s	46.6	46.6	46.5	46.8	39.4	55.2	46.9	46.8	45.8	61.9	33.1	34.4	61.8	38.6
1400s	46.7	46.7	46.7	46.8	39.3	55.7	47.1	46.8	45.9	61.9	33.2	34.4	61.9	39.3
1500s	46.7	46.6	46.6	46.8	39.2	55.2	47.0	46.8	45.9	61.9	33.1	34.4	61.8	38.6
1600s	46.7	46.8	46.7	46.9	39.3	55.0	47.1	46.9	45.9	61.9	33.1	34.4	61.8	38.5
1700s	46.8	46.8	46.8	46.9	39.3	55.4	47.2	46.9	46.0	61.9	33.1	34.4	61.8	39.0
1800s	46.8	46.8	46.7	46.9	39.3	55.4	47.3	46.9	46.1	61.9	33.2	34.4	61.8	39.2
1900s	46.9	46.9	46.8	47.0	39.2	55.2	47.2	47.0	46.0	61.9	33.2	34.4	61.8	39.0
2000s	46.8	46.8	46.8	47.0	39.7	55.2	47.2	47.0	46.1	61.9	33.1	34.4	61.7	38.2