

SOME STUDIES ON HEAT TRANSFER AND PRESSURE DROP CHARACTERISTICS OF NANOFUIDS

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Submitted by

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DECLARATION

I hereby declare that the work being presented in the thesis report entitled **Some Studies On Heat Transfer And Pressure Drop Characteristics Of Nanofluids** by me in the partial fulfillment of the requirements for the award of degree of Masters of Technology in Chemical Engineering, from Department of Chemical Engineering, Thapar University, Patiala, is an authentic record of my own work carried under the supervision of **Dr. D. Gangacharyulu**, Professor, Department of Chemical Engineering, Thapar University, Patiala. The matter presented in this report has not been submitted in any other University/Institute for the award of Masters of Technology or any other degree.

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CERTIFICATE


This is to certify that the thesis report entitled **Some Studies on Heat Transfer And Pressure Drop Characteristics of Nanofluids** being submitted by **Ms. Richa Saxena** in partial fulfillment for the requirement of degree of **Master of Technology** in **Chemical Engineering** in the **Department of Chemical Engineering, Thapar University, Patiala** is a record of candidate's own work carried out by her under my supervision. To the best of our knowledge, the content of this thesis does not form a basis for the award of any other degree.


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ABSTRACT

Nanofluids are suspensions of nanometer-sized solid particles in base fluids which have been proposed as a route for surpassing the performance of heat transfer fluids. The heat transfer and pressure drop characteristics of nanofluid is being studied in this thesis work. Various aspects of nanofluid including synthesis of nanofluid, applications, experimental and analytical studies on the thermal conductivity, viscosity, density and heat transfer coefficient have been carried out.

For nanofluids, nanoparticles of Alumina (Al_2O_3) and carbon nanotubes (MWCNT) and distilled water is used as base fluid. The volume fractions of nanoparticles used are 0.1% and 0.50%. The Thermal conductivity is measured by KD2 pro thermal property analyzer, viscosity and density is measured by Ubbelohde viscometer and pycnometer, respectively. Heat transfer coefficient and pressure drop is measured by using an experimental setup at various flow rates and power inputs for distilled water, 0.1 volume% and 0.5 volume% alumina/distilled water nanofluid. Reynolds number and Nusselt number have also been calculated for the same above.

Results show that the alumina/distilled water nanofluid has a good stability while MWCNT/distilled water nanofluid after using a surfactant is not stable for more than 2 hours. Therefore, for further work alumina/water nanofluid is selected. Thermal conductivity is increasing with increase in temperature and also with particle concentration. Density and viscosity is decreasing with temperature but increasing with increase in particle concentration.

The temperatures of nanofluids, surface temperatures of pipe and pressure drop of nanofluids are measured at steady state for different flow rates and power inputs. The heat transfer coefficients and friction factors are calculated for above experimental data. With increase in flow rate and power input, heat transfer coefficient of 0.1 volume % and 0.5 volume % of alumina/water nanofluid is much higher than that of distilled water. Heat transfer coefficient is increasing with increase in flow rate and particle concentration. Pressure drop of distilled water is higher than that of alumina/distilled water nanofluid but it is increasing with increase in particle concentration.

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ABBREVIATIONS

Abbreviation	Description
HVAC	Heating, cooling & air conditioning
CHF	Critical heat flux
DI	Deionized water
DW	Distilled water
NM	Nanometer
CNT	Carbon nanotubes
MWCNT	Multiwall carbon nanotubes
EG	Ethylene glycol
HTC	Heat transfer coefficient
PID	Proportional integral derivative
SANSS	Submerged arc nano-synthesis system
SANS	Small angle neutron scattering
SDS	Sodium dodecyl Sulfate
SEM	Scanning electron microscopy
TEM	Transmission electron microscopy
DLS	Dynamic light scattering

SYMBOLS

Symbol	Description	Units
A	Area	m ²
C _p	Specific heat	J/Kg.K
ρ	Density	kg/m ³
D	Diameter	m
h	Heat Transfer coefficient	W/m ² .K
k	Thermal conductivity	W/m.K
m	Mass	kg
t	Time	s
T	Temperature	K
μ	Viscosity	kg/(m.s)

CHAPTER – 1

INTRODUCTION

The design of energy-efficient heat transfer equipment, as well as the research for enhancing thermal capability of conventional fluids, contributes to the effort for better energy management. In the past, the thermal conductivity of working fluids has been augmented by suspending millimeter or micrometer sized particles in a base fluid. However, it has not been of interest for practical applications due to problems such as sedimentation, erosion, clogging, fouling and increased pressure drop of the flow channel. Lately, technological progress has led to the development and production of metal particles in nanometer scale, which, when dispersed in a conventional base fluid, appreciably enhance its thermal conductivity. Water, ethylene glycol and various kinds of oils are usually employed as base fluids. These suspensions, called nanofluids, can possibly overcome the aforementioned problems, because the particles are ultra-fine and are usually used at low particle concentrations.

Nanofluids, suspension of nanometer-sized particles, have recently been demonstrated to have thermal conductivities far superior to that of the fluid alone. This and their other distinctive features offer unprecedented potential for many applications in various fields including energy, bio- and pharmaceutical industry, and chemical, electronic, environmental, material, medical and thermal engineering.

1.1 What are nanofluids

Nanofluid is the term proposed by Choi [1] to describe stable colloidal suspensions of nano sized (1–100 nm) solid particles in common base fluids such as water and ethylene glycol. Nanofluids prepared by dispersing nanoparticles into conventional heat transfer fluids are proposed as the next generation heat transfer fluids as they offer exciting new possibilities to enhance heat transfer performance compared to conventional fluids. Therefore, nanofluids have attracted great interest due to their potential benefits for numerous applications such as microelectronics, energy supply, transportation and HVAC. From experimental investigations reported by various researchers in the past decade, nanofluids were found to exhibit substantially higher thermal properties particularly thermal conductivity even when the concentrations of suspended nanoparticles are very low [2 and 3].

Keblinski et al. [4] listed four possible explanations for the cause of an anomalous increase of thermal conductivity such as Brownian motion of the nanoparticles, molecular-level layering of

the liquid at the liquid/particle interface, the nature of heat transport in the nanoparticles, and the effects of nanoparticles clustering. While the study of the effective thermal conductivity of nanofluids have received much attention in recent years, very less number of studies have been reported on effective viscosity, which influences the flow and heat transfer characteristics [5].

1.2 Nanoparticles

Nanoparticles are defined as particulate dispersions or solid particles with a size in the range of 10-100 nm [6]. At these length scales, materials begin to exhibit distinct properties that affect biological, chemical, and physical behaviors. A wide variety of nanoparticles exists with organic or inorganic composition, most being metals. Examples include: silica (SiO₂), silver, iron nanoparticles, carbon black, aluminum, zinc oxides, titanium dioxide (TiO₂), polystyrene and nanoclays etc.

1.2.1 Nanoparticles versus Microparticles

The surface area of nanoparticles is 1000 times higher than that of microparticles. The high surface area of nanoparticles enhances the heat conduction of nanofluid, since heat transfer occurs on the surface of the particle. Nanoparticles are very small in size so they reduce erosion, clogging, decreases pumping power, reduce inventory of heat transfer fluid, and significantly save energy. Comparison of nanoparticles and microparticles is shown in table 1.1. Nanoparticles stay suspended much longer as compared to microparticles; therefore, these unique properties of nanoparticles lead to develop nanofluids with combination of the two features most highly desired for heat transfer systems: extreme stability and ultrahigh thermal conductivity.

Table 1.1: Comparison between Microparticles and Nanoparticles [7]

S.No.	Description	Micro-Particle	Nano-Particle
1.	Stability	Settle	Stable(remain suspended for long time)
2.	Surface to volume ratio	1	1,000 times larger than that of microparticles
3.	Thermal Conductivity	Low	High
4.	Clogging	Yes	No

1.3 Base Fluid

Base fluids mostly used in the preparation of nanofluids are the common working fluids of heat transfer applications include water, organic liquids (e.g. ethylene, tri-ethylene-glycols, refrigerants, etc.), oils and lubricants, bio-fluids, polymeric solutions and other common liquids.

1.4 Advantages of nanofluids

Nanofluids are engineered colloids made of a base fluid and nanoparticles (1-100 nm). Compared to conventional solid-liquid suspensions for heat transfer intensifications, properly engineered thermal nanofluids possess the following advantages [8]:

- High specific surface area and therefore more heat transfer surface between particles and fluids.
- High dispersion stability with predominant Brownian motion of particles.
- Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.
- Reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization.
- Adjustable properties, including thermal conductivity and surface wettability, by varying particle concentrations to suit different applications.

Owing to their enhanced properties as thermal transfer fluids for instance, nanofluids can be used in engineering applications ranging from use in the automotive industry to the medical arena to use in power plant cooling systems as well as computers and biomedical applications

1.5 Heat transfer in nanofluids

The practical utility of nanofluids as heat transfer fluids is best determined by its convective heat transfer coefficient. Increase in effective thermal conductivity as well as changes in density, specific heat, and viscosity are important indications of improved heat transfer behavior of nanofluids, the net benefit of nanofluids as heat transfer fluids is determined through the heat transfer coefficient. If nanofluids can improve the heat transfer coefficient of thermal energy systems, then they can facilitate the reduction in size of such systems and lead to increased energy and fuel efficiencies, lower pollution, and improved reliability, then it is essential to directly measure the heat transfer performance of nanofluids under flow conditions typical of specific applications.

Heat transfer studies under convective conditions are rather scarce. Choi [9] presented a theoretical background for the estimation of heat transfer enhancement, which essentially means a dramatic decrease of pumping power for a given heat transfer system. Xuan and Roetzel [10] were the first to indicate a mechanism for heat transfer in nanofluids. They proposed thermal dispersion as a major mechanism of heat transfer in flowing fluid, along with the enhancement of

nanofluid thermal conductivity. However, no evidence was presented in its support. Pak and Cho [11] presented the somewhat gloomy picture that in nanofluids, even though the Nusselt number increases, the heat transfer coefficient actually decreases by 3–12%. However, this may be due to the large increase in viscosity they observed. On the other hand, Eastman et al. [12] showed that with less than 1% volume fraction of CuO, the heat transfer rate increased by more than 15% in water. The work of Putra et al. [13] showed that natural convection in nanofluids deteriorated with particle concentration and was less than that in the pure fluid. Williams et al. [14] studied the turbulent convective heat transfer coefficient of alumina and zirconia nanofluids in a horizontal tube. They observed no significant heat transfer enhancement for nanofluid compared to base fluid. Also, they demonstrated that the convective heat transfer coefficient could be predicted by means of the traditional correlations.

Experiments showed that thermal conductivity increase is not the sole reason for heat transfer enhancement in nanofluids. However, the proper physical mechanism of heat transfer enhancement has not been established till date. Experiments showed significant heat transfer enhancement with little penalty of pressure drop also. The heat transfer enhancement using nanofluids may also be affected by several factors such as gravity, Brownian motion, Brownian diffusion, friction force between the fluid and nanoparticles, sedimentation and dispersion, layering at the solid/liquid interface [15].

1.6 Applications of nanofluids

Nanofluids can be used to cool automobile engines and welding equipments and to cool high heat flux device such as high power microwave tubes, and high power laser diode array. Nanofluid could flow through the tiny passage in MEMS to improve the efficiency. Some common applications are [16]:

- Engine cooling
- Engine transmission oil
- Cooling of electronic circuits
- Solar water heating
- Thermal storage
- Refrigeration (domestic and chillers)
- Defence and Space applications
- Nuclear system cooling
- Bio-medical applications
- Drilling and lubrications

The measurement of nanofluid critical heat flux (CHF) in a forced convection loop is useful for the nuclear applications [17]. If nanofluid improves the chiller efficiency by 1%, a saving of 320 billion KWh of electricity or equivalent 5.5 million barrel of oil per year would be released in US alone. The nanofluids find the potential for deep drilling operations. A nanofluid can also be used

for increasing the dielectric strength and life of transformer oil by dispersing nanodiamonds particles.

1.7 Conclusion

The nanofluids have unique thermal properties due to their reduced size. A lot of work has been done on its thermo-physical properties i.e. thermal conductivity, density and viscosity but there is a little amount of research work has been done on the heat transfer coefficient and pressure drop of nanofluid. Therefore, substantial amount of work on experimental research is still required in this area. Unlike past research activities which have focused on thermal conductivity, the study of convective heat transfer of nanofluids still needs to be explored in more detail.

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CHAPTER – 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, preparation methods of nanofluids, properties of nanofluids, experimental efforts on synthesis process and on its properties, experimental measurements of thermal conductivity, viscosity, density and heat transfer rates are discussed, which lays a basis for further work in this area and detailed explanation of the experiments and experimental results carried out by many researchers will be reviewed and discussed.

2.2 Nanofluids

Nanofluids coined by Choi [1], are a new class of nanotechnology-based heat transfer fluids that are engineered by stably suspending a small amount of particles, fibers, or tubes with dimension on the order of 1–100 nm. Nanofluids consisting of such particles suspended in liquids (typically conventional heat transfer liquids) have been shown to enhance the thermal conductivity and convective heat transfer performance of the base liquids. The thermal conductivities of the particle materials are typically an order-of-magnitude higher than those of the base fluids such as water, ethylene glycol, and light oils, and nanofluids, even at low volume concentrations, resulting in significant increases in thermal performance [2 & 3]. Nanofluids have the potential to reduce such thermal resistances, and the industrial groups that would benefit from such improved heat transfer fluids are quite varied. They include transportation (coolant, fuel, and oil), electronics, medical (Nanodrug delivery, Cancer Therapeutics, Cryopreservation, Nano-cryo surgery, Sensing and Imaging), food, defense, nuclear, space and manufacturing of many types [4]. The nanofluid does not mean a simple mixture of solid particles and base fluid. In order to prepare the nanofluids by dispersing the nanoparticles in a base fluid, proper mixing and stabilization of the particles is required. Normally, there are three effective methods used to attain stability of the suspension against sedimentation of the nanoparticles, which are summarized as follows [5]: (1) control of the pH value of the suspensions, (2) addition of surface activators or surfactants and (3) use of ultrasonic vibration. All of these techniques aim at changing the surface properties of the suspended nanoparticles and suppressing the formation of clusters of particles in order to obtain stable suspensions

2.3 Need of nanofluids

Nanofluids are needed due to following reasons [6]:

- Due to nano size particles, pressure drop is minimum.

- Higher thermal conductivity of nano particles will increase the heat transfer rate.
- Successful employment of nanofluid will lead to lighter and smaller heat exchanger.
- Drastic change in the properties of the base fluid, by suspending nanofluids.
- Heat transfer rate increases due to large surface area of the nano particles in the base fluid.
- Nanofluids are most suitable for rapid heating and cooling systems.
- Due to nano size particles, fluid is considered as integral fluid.

2.4 Preparation of Nanofluids

Large variety of combinations of nanoparticles and heat transfer fluids can be used to synthesize stable nanofluids with improved thermal transport properties. Nanoparticles made from metals, oxides, carbides and carbon nanotubes can be dispersed into heat transfer fluids, such as water, ethylene glycol, hydrocarbons and fluorocarbons with or without the presence of stabilizing agents [7].

In most experimental studies, nanofluids are synthesized in a two-step process [8, 9 & 10], which is the first and the most classic synthesis method of nanofluids. In the first step, nanoparticles are prepared by mechanical comminuting, chemical reaction, vapor condensation or decomposition of organic complex [11]. Then it is followed by the second step in which the produced nanoparticles are dispersed into base heat transfer fluids with mechanical agitation (stirring) or ultrasonication [12]. Nanofluids are homogenized using or not using surfactants depending on the properties of interfaces between nanoparticles and base fluids. The main advantage of this two-step synthesis method is that it produces nanoparticles under clean conditions, without undesirable surface coatings and other contaminants [13]. The major problem is that agglomeration of nanoparticles may occur. When finely divided solid nanoparticles are immersed in liquids, they often do not form a stable dispersion. Summary of nanofluids prepared with this method and their stability and observations is shown in Table 2.1. Many of the particles aggregate together in forms of clumps. Though these particles can be easily re-dispersed in liquids by mechanical dispersion, they soon clump together again to form large aggregates that will settle out of the suspension quickly.

Uniform dispersions can be significantly stabilized by steric barriers surrounding the nanoparticles to form a coating layer that is sterically bulky, for example, polymeric surfactant [14]. When absorbed on the surfaces of solid particle, the surfactant molecules can produce a barrier to prevent aggregation of nanoparticles and impart solubility to particles in base fluids, so that the prepared nanofluids can sustain the stability without visible precipitation for months or even years. Oxide nanoparticles are firstly used for nanofluids, mainly because they are easy to

produce, chemically stable and easy to be dispersed into water due to their less hydrophobic nature.

Table 2.1: Summary of nanofluids prepared with dispersion method [15]

S. No.	Nanofluid	Preparation condition	Volume fraction (Volume %)	Observations on stability
1.	Al ₂ O ₃ /water	mixing and shaking	1-5	some large agglomerates
2.	Al ₂ O ₃ /water	ultra sonication for 3 hrs	2-10	several days
3.	Al ₂ O ₃ /water	pH =3 mixing (10000rpm) 2 hrs	1-10	stable for more than 6 days
4.	Al ₂ O ₃ /EG	mixing and shaking	1-5	some large agglomerates
5.	CuO/water	mixing and shaking	1-5	some large agglomerates
6.	CuO/water	ultra-sonication for 3 hrs	2-10	several days
7.	CuO/water	Cu(OH) ₂ as precursor, act as dispersant, ultrasonic and microwave irradiation	0.1-10	several weeks
8.	CuO/EG	mixing and shaking	1-5	some large agglomerates
9.	CuO/EG	ultra-sonication for 1-30 hrs	0.001-5	some clusters, ultrasonic time affect stability
10.	CNTs/water	SDS as dispersant, ultra-sonication 20-490 minutes	0.6	ultrasonic time affect stability
11.	CNTs/water	pH = 2-11, GA as dispersant, ultra-sonication, high-shear mixing	0.1-0.5	several months
12.	CNTs/water	acid treatment, ultra-sonication	0.2-1.0	2 months
13.	CNTs/EG	acid treatment, ultra-sonication	0.2-1.0	2 months

Agglomeration is greatly reduced in a one-step method by combining together the synthesis process and the subsequent dispersing process into a single step [16]. This one-step method employs a direct evaporation condensation technique, which is a modified inert gas condensation process that has been used in ANL (Eastman 1998; Eastman et al. 1996; Eastman et al. 2001). There are four steps in the process in this one-step process,

1. A cylinder containing a heat transfer fluid such as water or ethylene glycol is rotated so that a thin film of the fluid is constantly being transported over the top of the chamber.
2. A piece of the metallic material as the source of nanoparticle is evaporated by heating on a crucible.
3. Evaporated particles contact the fluid overhead and condense as nanoparticles.

4. The fluid is cooled at the base of the chamber to prevent any unwanted evaporation of the fluid.

The presence of surfactants in the carrying liquid can further suppress the agglomeration of nanoparticles. The main advantages of this process are [17]:

1. It enables producing nanoparticles without undesirable and less conductive oxide layers, which increase the thermal resistance between the particles and liquids.
2. The size of the produced nanoparticle is as small as <10 nm and the size distribution of particle is in a narrow range.
3. The nanoparticle yield is high due to the high evaporation rate.
4. The agglomeration of nanoparticles is substantially reduced and the nanofluids are very stable.

However, this method has limitations that the base fluids must have a low vapor pressure (usually below 1 torr), and oxidation may occur at the surface of pure metallic particles. High liquid vapor pressures of base fluids may lead to apparent aggregation of nanoparticles.

Another method of nanofluid synthesis is the laser ablation method which has been used to produce alumina nanofluids [18]. Laser ablation is another much sought, single-step technique that simultaneously makes and disperses nanoparticles directly in the base fluids. A variety of nanofluids have been prepared by laser ablation method [19,20] by ablating solid metals, semiconductors, etc which are submerged in the base fluid (water, lubrication oils, etc). By creating a nanofluid in this way, stable nanofluids resulted without using any property-changing dispersants. This method is also useful for further splitting of nanoparticles present in the nanofluids to study effect of particle size on thermal conductivity.

Pure chemical synthesis is also an option which has been used by Patel et al. [21] to prepare gold and silver nanoparticle nanofluids. Zhu et al. [16] also use a one-step pure chemical synthesis method to prepare nanofluids of Cu nanoparticles dispersed in ethylene glycol. Chemical approach [22] using wet technology, a single-step approach, is emerging as a powerful method for growing nanostructures of different metals, semiconductors, non- metals, and hybrid systems. Raykar et al. [23] gives another one step approach that is adopted for nanofluids synthesis based on microwave irradiation and is a quick method of nanofluid synthesis. Lo et al. [24] used submerged arc nano-synthesis system (SANSS) for preparing nanofluids. Summary of nanofluids prepared with other methods is shown in Table 2.2.

Table 2.2: Summary of nanofluid prepared with the other methods [25]

Method	Nanofluid	Preparation condition	Particle size (nm)	Volume fraction (vol. %)	Observations on stability
Direct evaporation condensation method	Cu/EG	Cu vapor condensed into nanoparticles by contacting with EG	10	0.1-0.3	little agglomeration
SANSS method	CuO/water CuO/water+EG Cu/EG	Cu bars were heated and vaporized by arc sparking, Cu aerosol was condensed to particles in the dielectric liquid	20-80 20-40 10		well dispersed
One-step chemical Method	Cu/EG	Reducing CuSO ₄ with NaH ₂ PO ₂ in EG under microwave irradiation using PVP as protective agent	10-20	<0.2	3 weeks well dispersed
	Au/water Ag/water	using citrate as reducing agent	10-20 60-80	0.0026 0.001	well dispersed
	Cu/water	reducing copper acetate with N ₂ H ₄ in water without surfactant	75-100	<0.2	not stable
	Ag/oil	thermal decomposition of silver lactate in mineral oil using korantin as stabilizer	9.5	0.001-0.3	1 month

2.5 Characterization

Characterization of nanofluid systems is composed of characterization of nanoparticles and characterization of nanofluids. The characterization of nanoparticles includes investigation of particle size and geometry, and characterization of particle microstructures. The characterization of nanofluids includes investigation of nanofluid stability, measurement of mobility of nanoparticles in base fluids.

Transmission electron microscopy (TEM) is a straightforward method to observe the dimensions and geometry of nanoparticles. The main limitation of TEM observation of nanoparticles is that the viewing field of TEM is relatively small, which potentially raise the possibility that the region to be analyzed may not be characteristic of the whole sample. Several (more than 6) different places are observed and averaged information is obtained and analyzed in order to overcome this drawback.

Dynamic light scattering (DLS) technique is used to measure the mobility of nanoparticles in nanofluids. Actually, dynamic light scattering can be used to determine the size distributions of these small particles in solution, which is called “hydrodynamic radius”. A proper amount of surfactant maybe added when the nanoparticles are dispersed into base fluids and the surfactant molecules are tightly bound at the surface of nanoparticles, the “hydrodynamic radius” measured by DLS are different from the results of TEM. Theoretical results have been reported that the anomalous enhancement in thermal conductivity of nanofluids is attributed to Brownian motion.

2.6 Properties of nanofluids

2.6.1 Thermal Conductivity

Since thermal conductivity is the most important parameter responsible for enhanced heat transfer, many experimental works have been reported on this aspect. The transient hot wire method [26], the steady-state parallel-plate technique [27] and the temperature oscillation technique [28] have been employed to measure the thermal conductivity of nanofluids. Among them the transient hot wire method has been used most extensively. Because in general nanofluids are electrically conductive, it is difficult to apply the ordinary transient hot-wire technique directly.

A modified hot-wire cell and electrical system was proposed by Nagasaka and Nagashima [29] by coating the hot wire with an epoxy adhesive which has excellent electrical insulation and heat conduction. However, Das et al. [30] pointed that possible concentration of ions of the conducting fluids around the hot wire may affect the accuracy of such experimental results. The oscillation method was proposed by Roetzel et al. [31] and further developed by Czarnetski and Roetzel [32]. This method is purely thermal and the electrical components of the apparatus are removed from the test sample. Hence ion movement should not affect the measurement. Alumina (Al_2O_3) and copper oxide are the most common and inexpensive nanoparticles used by many researchers in their experimental investigations. All the experimental results have demonstrated the enhancement of the thermal conductivity by addition of nanoparticles. Eastman et al. [13] measured the thermal conductivity of nanofluids containing Al_2O_3 , CuO, and Cu nanoparticles with two different base fluids: water and oil. A 60% improvement of the thermal conductivity was achieved as compared to the corresponding base fluids for only 5 vol% of nanoparticles. They also showed that the use of Cu nanoparticles results in larger improvements than that of CuO.

Lee et al. [33] suspended CuO and Al₂O₃ (18.6 and 23,6 nm, 24.4 and 38.4 nm for them, respectively) with two different base fluids: water and ethylene glycol (EG) and obtained four combinations of nanofluids: CuO in water, CuO in EG, Al₂O₃ in water and Al₂O₃ in EG. Their experimental results showed that nanofluids have substantially higher thermal conductivities than the same liquids without nanoparticles. The CuO/EG mixture showed enhancement of more than 20% at 4 vol% of nano particles. In the low volume fraction range (<0.05 in test), the thermal conductivity ratios increase almost linearly with volume fraction. Many of the researchers have done a lot of work on thermal conductivity of nanofluids using different nanoparticles with different base fluids. The studies conducted by different authors and their findings are shown in Table 2.3.

2.6.2 Viscosity

Viscosity of nanofluids is less investigated than thermal conductivity; however, the rheological properties of liquid suspensions had been studied since Einstein (Einstein 1906). Pak et al. [41] firstly measured the viscosity of their Al₂O₃-water nanofluids as a function of shear rate and concentration. The Al₂O₃ nanoparticles have an average diameter of 13 nm and the concentration is up to 10 vol. %. It is observed that nanofluids show a Newtonian behavior, i.e., the viscosity is independent of the shear rate and the maximum viscosity of nanofluids is up to 300 times higher than that of the base fluid.

Wang et al. [42] only observed a 90% increase in viscosity in same Al₂O₃ in water nanofluids with similar concentrations and particle dimensions. Though Wang et al. measured the viscosity of Al₂O₃ nanofluids and did not find any non-Newtonian effect, many nanofluid systems show non-Newtonian behavior, unlike the corresponding base fluids.

Das et al. [43] measured the viscosity of water based nanofluids containing Al₂O₃ nanoparticles and they observed slightly change in viscosity as the shear rate increased and exhibited Newtonian behavior. They also investigated the temperature dependence of the viscosity and found similar to that of base fluids. The maximum viscosity of nanofluids was found in nanofluid at highest particle loading and lowest temperature.

Table 2.3 Summary of studies conducted on thermal conductivity

Author	Nanofluid Used	Studies Conducted
Xuan and Li [34]	Cu nanoparticles dispersed in water	Thermal conductivity ratio varies from 1.24 to 1.78 if volume percent of Cu nanoparticles increase from 2.5 to 7.5%
Eastman et al. [13]	Cu nanoparticles dispersed in ethylene glycol	Effective thermal conductivity of ethylene glycol improved by up to 40% through the dispersion on 0.3% Cu nanoparticles
Patel et al. [21]	Ag and Au nanoparticles dispersed in water and toluene	0.011 vol% of Au nanoparticles dispersed toluene nanofluid shows enhancement in thermal conductivity 7% at 30°C and 14% at 60°C.
Das et al. [30]	Al ₂ O ₃ nanoparticles dispersed in water	4 vol% Al ₂ O ₃ dispersed water nanofluids thermal conductivity raise 9.4% to 24.3% with increase in Temperature from 21 to 51 °C
Choi et al. [34]	Carbon nanotubes dispersed in oil	Thermal conductivity ratio exceeded 2.5 at 1 vol% nanotubes.
Xie et al. [36]	Carbon nanotubes dispersed in distilled water and ethylene glycol	At 1 volume %, the thermal conductivity enhancements are 12.7% and 7.0% for CNT in ethylene glycol and distilled water, respectively
Assael et al. [37]	MWCNT dispersed in water using SDS	By dispersing 0.6 vol.% carbon nanotubes in water, thermal conductivity enhancement is 38%.
Chang et al. [38]	Al ₂ O ₃ dispersed in water	Dispersing 1 vol.% Al ₂ O ₃ , 29% enhancement in water based nanofluid
Hong et al. [39]	Nano-Fe dispersed in ethylene glycol .	10% enhancement by dispersing 0.55 volume % Fe nanoparticles in ethylene glycol
Hwang et al. [40]	CuO-water based nanofluid	Dispersing 1 volume % CuO, 5% enhancement in water based nanofluid

2.7 Heat Transfer in nanofluids

Trisaksri and Wongwises [44] revealed that the practical utility of nanofluids as heat transfer fluids is best determined by its convective heat transfer coefficient. Nanoparticles have great potential to more effectively improve the thermal transport properties of heat transfer fluids than micrometer and millimeter sized particles. This is mainly due to the tininess of nanoparticles or other nanostructures, which not only improves the stability and the applicability of liquid suspensions, but also increases the specific surface area and the diffusion mobility of Brownian

motion of nanoparticles. Furthermore, the tininess of nanoparticles can provide nanofluids a potential to be used in miniaturized electronic cooling and microchannels, where larger particles would either clog the channels or settle out from the carrying fluids quickly. Nanofluids were an improvement on previous suspensions, because they suffered from less sedimentation, large pressure drops, and were less corrosive. The development of nanofluids as a new class of heat transfer with the use of nanotechnology has been the subject of much attention in recent years.

Hwang et al. [45] investigated the convective heat transfer coefficient and pressure drop of Al_2O_3 /water nanofluids inside a circular tube in the fully developed laminar flow regime with constant heat flux. They reported that, convective heat transfer coefficient increased by up to 8% at 0.3% volume concentration.

Fotukian et al. [46] experimentally investigated turbulent convective heat transfer of dilute Al_2O_3 /water inside circular tubes. The nanofluid Al_2O_3 /water with dilute loading of 0.03% and 0.054% were studied. The Reynolds number was varied from 6000 to 31000. The experimental results indicated that addition of small amount of nanoparticles to pure water improves the heat transfer performance significantly. The maximum value of 48% increase in the heat transfer coefficient compared to pure water for 0.054% volume concentration at Reynolds number of 10000 was observed. Increasing the particle concentration did not show much heat transfer enhancement in the turbulent region. The ratio of convective heat transfer coefficient of nanofluid to that of pure water decreases with the Reynolds number. The pressure drop of the nanofluid with 0.135% volume concentration with showed 30% increase at Reynolds number of 20000 compared to pure water.

Nasiri et al. [47] measured heat transfer of nanofluid through annular duct. The nanofluids were Al_2O_3 and TiO_2 with water as the base fluid. The range of the Reynolds number for both the nanofluids were 4000 and 13000. The volume concentration for both fluids was 0.1%, 0.5%, 1.0%, and 1.5% of Al_2O_3 and TiO_2 . Both nanofluids shows higher Nusselt number than those of the base fluids and enhancement increases with the particle concentration. At Peclet number about 24400, the enhancement of Nusselt number for $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ nanofluid with concentration of 0.1%, 0.5%, 1.0%, 1.5% are 2.2%, 9%, 17% and 23.8% respectively. For $\text{TiO}_2/\text{H}_2\text{O}$ nanofluid, at Peclet number 53200 the increment in the Nusselt number with particle concentration of 0.1, 0.5, 1.0, and 1.5% are 1%, 2%, 5.1%, and 10.1%. Relative enhancement in the heat transfer coefficient is increased by increasing in the nanoparticle concentration for both nanofluids. This may be due to

thermal conductivity of the nanofluid, the presence of the Brownian motion, nanoparticle migration in nanofluid, possible slip at the wall, and thinner boundary layer thickness.

Saeedinia et al. [48] studied heat transfer and pressure drop of nanofluids flow in horizontal coiled wire inserted tube at constant heat flux. The nanofluid is prepared by dispersion of CuO in base oil. Particles volume fraction ranging from 0.07% to 0.3% is used. Five coiled wires having pitch of 25-35 mm and wire diameter 0.9-1.5 mm were put one by one in the test section. Effects of different parameters such as Reynolds number, wire diameter, coil pitch, particle concentration were studied. Result shows that there is an increase of 45% in heat transfer coefficient and penalty of 63% in the pressure drop was observed for the coiled tubes. Nanofluids have better heat transfer performance when they flow inside the tubes with wire coil inserts instead of flowing through plain tubes. For 0.3% vol. concentration for the highest wire diameter 40.2% enhancement in the heat transfer is achieved.

Heris et al. [49] performed experimental investigation of convective heat transfer of alumina/water nanofluid in circular tubes. The test section consists of 6 mm diameter tube of 1 m length with 0.5 mm thickness. Nanofluid flows inside the tubes while saturated steam entered the annular section in order to maintain the constant wall temperature. The Nusselt number and Reynolds number was obtained for the different particle concentration. The experimental results were compared to the theoretical values by the use of Seider-Tate equation. The increase in the heat transfer rate is due to the higher thermal conductivity of the nanoparticles. Some other factors are dispersion and chaotic movements of nanoparticles. The Brownian motion and migration of the particles plays an important role in the heat transfer enhancement.

Pak and Cho [35] studied the heat transfer enhancement in a circular tube, using Al_2O_3 and TiO_2 nanoparticle fluid mixtures as the flowing medium. They observed an increase in the Nusselt number with the increasing volume fraction and Reynolds number. Putra et al. [37] studied the natural convection of nanofluids inside horizontal cylinder heated from one end and cooled from the other. An apparently paradoxical behavior of heat transfer deterioration was observed in the experimental study. The nature of this deterioration and its dependence on parameters such as particle concentration, material of the particles, and geometry of the containing cavity was investigated. Bang et al. [50] studied boiling heat transfer characteristics of Al_2O_3 -based nanofluids. Pool boiling heat transfer coefficients and phenomena of nanofluids are compared with those of pure water, which are acquired on a smooth horizontal flat surface (roughness of a few tens of nanometers). The experimental results showed that these nanofluids have poor heat transfer performance compared to pure water in natural convection and nucleate boiling. On the

other hand, CHF has been enhanced in not only horizontal but also vertical pool boiling. This is related to a change of surface characteristics by the deposition of nanoparticles

Abbasian and Amani [51] studied experimentally the effect of TiO₂-water nanofluid on heat transfer and pressure drop. The particle size selected was of 30 nm. The experimentation was performed for the volume fraction of 0.002 and 0.02, the Reynolds number was in between 8000 to 51000. The apparatus was in the form of horizontal double tube counter-flow heat exchanger. It is observed that by increasing the Reynolds number or nanoparticle volume fraction, the Nusselt number increases. Meanwhile all nanofluids have a higher Nusselt number compared to distilled water. It is observed that by use the nanofluid at high Reynolds number (say greater than 30,000) more power compared to low Reynolds number needed to compensate the pressure drop of nanofluid, while increments in the Nusselt number for all Reynolds numbers are approximately equal. Therefore using nanofluids at high Reynolds numbers compared with low Reynolds numbers, have lower benefits. It is also seen that, the maximum thermal performance factor of 1.8 is found with the simultaneous use of the TiO₂- water nanofluid with 0.02% volume and at Reynolds number of 47,000.

Sundar and Sharma [52] studied experimentally the heat transfer enhancements of low volume concentration of Al₂O₃ nanofluid and with longitudinal strip inserts in a circular tube. The main aim is to study the convective heat transfer and friction factor for Al₂O₃/water nanofluid with different aspect ratio. Experiments are conducted with water and nanofluid in the range of $3000 < Re < 22,000$, particle volume concentration $0 < u < 0.5\%$ and longitudinal strip aspect ratios of $0 < AR < 18$. The friction factor of 0.5% volume concentration nanofluid with longitudinal strip insert having $AR = 1$ is 5.5 times greater at 3000 Reynolds number and 3.6 times at 22,000 Reynolds number when compared to water or nanofluid flowing a tube. The heat transfer coefficient of 0.5% volume concentration Al₂O₃ nanofluid with longitudinal strip insert having $AR = 1$ is 50.12% and 55.73% greater at Reynolds number of 3000 and 22,000, respectively compared to the same fluid and 76.20% and 80.19% greater compared to water flowing in a plain tube. Li and Xuan [53] experimentally investigated the convective heat transfer and flow characteristics of the Cu-H₂O nanofluid under laminar flow in a straight brass tube of the inner diameter of 10 mm and the length of 800 mm. The effects of the volume fraction of suspended nanoparticles and the Reynolds number on the heat transfer and flow characteristics were observed. The experimental results showed that the suspended nanoparticles remarkably increase the convective heat transfer coefficient of the base fluid and the nanofluid has larger heat transfer coefficient than pure water under the same Reynolds number. Compared with the base fluid, for example, the convective heat transfer coefficient is increased about 60% for the nanofluid with

2.0 vol. % Cu nanoparticles at the same Reynolds number. The heat transfer feature of a nanofluid increases with the volume fraction of nanoparticles.

Anoop et al. [54] carried out experimental investigation on the convective heat transfer characteristics in the developing region of tube flow with constant heat flux with alumina–water nanofluids. The primary objective was to evaluate the effect of particle size on convective heat transfer in laminar developing region. Two particle sizes were used, one with average particle size off 45 nm and the other with 150 nm. They observed that in the developing region, both nanofluids showed higher heat transfer characteristics than the base fluid and the nanofluid with 45 nm particles showed higher heat transfer coefficient than that with 150 nm particles. With increase in particle concentration and flow rate the average heat transfer coefficient value was increased. Faulkner et al. [55] reported heat transfer enhancement in a micro-channel at very low Reynolds number and particle volume concentrations between 1.1–4.4 volume%. Ding et al. [56] reported heat transfer enhancement at intermediate Reynolds number (800–1200) and low particle volume concentration (0.05 vol %). Although both of these papers reported heat transfer enhancement, however, the heat transfer enhancement trends with respect to particle volume concentration in one paper was found to contradict the other work. Therefore, it can be said that substantial amount of work is still required in this area.

Ashtiani et al. [57] investigated effect of MWCNT inside tube at uniform wall temperature condition. The test section consists of copper tube surrounded by a steam chamber to keep temperature of the wall constant. Weight fraction of 0.0%, 0.1%, 0.2%, and 0.4% were selected. Copper tube of 14.5 mm ID and test section of oblong shape with inside height of 13.4mm, 11.7mm, 10.6mm, 8.6mm were used. The heat transfer without the nanofluid is carried out so as to compare it with nanofluids. The results shows that the Nusselt number rises suddenly by 132% at the Peclet number of 420000 for 0.4wt.% whereas the corresponding value for the 0.2 wt. % nanofluid is approximately 58% for the same range of Peclet number. It can be concluded that the Nusselt number and hence the heat transfer rate goes up by increasing the nanoparticle weight fraction.

2.8 Application of nanofluids

Tzeng et al. [58] revealed that experimentally and theoretically nanofluids have been shown to possess improved heat transport properties and higher energy efficiency in a variety of thermal exchange systems for different industrial applications, such as transportation, electronic cooling, military, nuclear energy, aerospace etc. Nanofluid research could lead to a major impact in

developing next generation coolants for numerous engineering and medical applications. Summary of work done on cooling application of nanofluid is shown in Table 2.4.

Table 2.4: Summary of cooling applications of nanofluids

S.No.	Author	Year	Application
1.	Tzeng et al. [58]	2005	Dispersed Cu and Al ₂ O ₃ nanoparticles into engine transmission oil. The results indicated that CuO nanofluids resulted in the lowest transmission temperatures both at high and low rotating speeds
2.	Singh et al. [59]	2006	Determined that the use of high-thermal conductive nanofluids in radiators can lead to a reduction in the frontal area of the radiator by up to 10%.
3.	Ma et al. [60]	2006	Introduced diamond nanoparticles into high performance liquid chromatography (HPLC) water. The movement of the OHP keeps the nanoparticles from settling and thus improving the efficiency of the cooling device
4.	Nguyen et al. [61]	2007	Investigated the heat transfer enhancement and behavior of Al ₂ O ₃ -water nanofluid with the intention of using it in a closed cooling system designed for microprocessors or other electronic devices.
5.	Lin et al. [62]	2008	Investigated nanofluids in pulsating heat pipes by using silver nanoparticles. The silver nanofluid improved heat transfer characteristics of the heat pipes
6.	Routbort et al.[63]	2008	Employed nanofluids for industrial cooling that could result in great energy savings and resulting emissions reductions.
7.	Shen et al.[64]	2010	Water-based alumina and diamond nanofluids were applied in the MQL grinding process and the grinding results were compared with those of pure water. Later he used oil based nanofluids
8.	Zhang et al. [65]	1997	Reported that surface-modified nanoparticles stably dispersed in mineral oils are effective in reducing wear and enhancing load-carrying capacity
9	Tzeng et al. [58]		<p>Electronics cooling The power dissipation of IC (Integrated Circuits) and microelectronic components has dramatically increased due to their size reduction. Nanofluids have been considered as working fluids in heat pipes for electronic cooling application.</p> <p>Military applications Military hardware both mechanical and electrical devices dissipates a large amount of heat and consequently requires high heat flux cooling fluids having sufficient cooling capacity. Nanofluids have the capability to provide the required cooling capacity in</p>

		<p>such applications, as well as in other military applications, including submarines and high power laser.</p> <p>Medical application Nanofluids are now being developed for medical applications, including cancer therapy. Iron based nanoparticles can be used as delivery vehicle for drugs or radiation without damaging the neighboring healthy tissues by guiding the particles up the blood stream to the tumor locations with magnets. Nanofluids could be used to produce higher temperatures around tumors, to kill cancerous cells without affecting the nearby healthy cells.</p>
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2.8.1 Heat transportation

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

Tzeng et al. [58] have conducted research to study the effects of nanofluids in the cooling of automatic transmission. They dispersed CuO & Al₂O₃ nanoparticles and antifoam agents in the transmission fluid, and then, the transmission fluid was used in real time four wheel automatic transmissions. The results show that CuO nanofluids have the lowest temperature distribution at both high and low rotating speed and accordingly the best heat transfer effect.

Tsai et al. [66] were probably the first to show experimentally that the thermal performance of the heat pipe can be enhanced when nanofluids are used. Gold nanoparticles with a particle size of 17nm dispersed in water were used as a working fluid in a disk shaped miniature heat pipe. The result shows that the thermal resistance of the disk shaped miniature heat pipe is reduced by nearly 40% when nanofluids are used instead of de-ionized (DI) water.

Kang et al. [67] measured the temperature distribution and thermal resistance of a conventional grooved circular heat pipe with water based nanofluids containing 1 to 50 ppm of 35nm silver nanoparticles. The result shows that at the same charge volume, the thermal resistance of the heat

pipe with nanofluids is reduced by 10% to 80% compared with that of DI water at an input power of 30 to 60 W. The results are compared with those of Wei et al. [68]. They show that the maximum reduction in the thermal resistance of the heat pipe is 50% for 10nm silver nanoparticles and 80% for 35nm silver nanoparticles.

Chein and Huang [69] numerically tested the performance of nanofluids as coolants in silicon micro channels. The nanofluids they used were water suspensions of Cu nanoparticles at various particle loadings. They found that the performance of the micro channel heat sink was greatly improved due to the increased thermal conductivity and thermal dispersion effects, as well as that the presence of the nanoparticles in water did not cause much pressure drop due to the small volume fraction of the solid particles.

Ma et al. [60] were the first to develop an ultrahigh performance chip cooling device called the nanofluid oscillating heat pipe. The conventional heat pipe with an oscillating motion generated by the variable frequency shaker dramatically increased the heat removal rate in capillary tubes.

2.9 Conclusions

This chapter presents an overview of the recent developments in the study on heat transfer coefficient using nanofluids, preparation of nanofluids and experimental study on properties of nanofluids. Many important and interesting phenomena of heat transfer characteristics of nanofluids have been reported in literature. Experimental studies on heat transfer coefficient using various setups by many researchers have been reported in literature, but the development in this field is rather scarce. The use of nanofluids in a wide range of applications appears promising.

Gaps identified from the literature survey:

Pak and Cho [35] studied the heat transfer enhancement in a circular tube, using Al_2O_3 and TiO_2 nanoparticle fluid mixtures as the flowing medium. They observed an increase in the Nusselt number with the increasing volume fraction and Reynolds number.

Fotukian et al. [46] experimentally investigated turbulent convective heat transfer of dilute Al_2O_3 /water inside circular tubes. The nanofluid Al_2O_3 /water with dilute loading of 0.03% and 0.054% were studied. The Reynolds number was varied from 6000 to 31000. The maximum value of 48% increase in the heat transfer coefficient compared to pure water for 0.054% volume concentration was observed.

Hwang et al. [45] investigated the convective heat transfer coefficient and pressure drop of Al_2O_3 /water nanofluids inside a circular tube in the fully developed laminar flow regime with constant heat flux. They reported that, convective heat transfer coefficient increased by up to 8% at 0.3% volume concentration

Heris et al. [49] performed experimental investigation of convective heat transfer of alumina/water nanofluid in circular tubes. The Nusselt number and Reynolds number were obtained for the different particle concentration. The experimental results were compared to the theoretical values by the use of Seider-Tate equation. The increase in the heat transfer rate is due to the higher thermal conductivity of the nanoparticles

Ashtiani et al. [57] investigated effect of MWCNT inside tube at uniform wall temperature condition. The heat transfer without the nanofluid is carried out so as to compare it with nanofluids. The result shows that the Nusselt number rises suddenly by 132%.

The experiments conducted by the many of the above researchers are focused on measurement of heat transfer coefficient at various flow rates at a particle concentration below 0.1 volume % of alumina/water nanofluid and at a particular power input.

The scope of the work:

1. Preparation of alumina/water and carbon nanotubes (CNT) nanofluid and investigation of its thermal conductivity, viscosity and density at different temperatures.
2. To find out the heat transfer coefficient, Nusselt number, Reynolds number and pressure drop of prepared nanofluid.

The objectives of the present work are to study the:

1. To find out the thermal conductivity of distilled water (DW), alumina/distilled water and CNT/distilled water nanofluid at different temperatures.
2. The density and viscosity of above nanofluids and its variation with temperature.
3. Calculation of heat transfer coefficient and pressure drop at various flow rates and power input using an experimental setup.

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CHAPTER - 3

EXPERIMENT AND METHODOLOGY

3.1 Introduction

The objective of the present work is to prepare nanofluid of alumina (Al_2O_3) and carbon nanotube (CNT) nanoparticles with distilled water as base fluid, measurement of thermo-physical properties (thermal conductivity, viscosity and density), heat transfer coefficient of nanofluid and pressure drop. These measurements are performed by using KD2 pro thermal property analyzer, Ubbelohde viscometer, pycnometer for density measurement and an experimental setup for measurement of heat transfer coefficient and pressure drop.

In this chapter, methodology adopted for nanofluid preparation, measurement of thermal conductivity, viscosity and density is discussed followed by the description of experimental setup which is used for measurement of heat transfer coefficient and pressure drop. Firstly, the synthesis method for nanofluid is discussed and then there is a brief discussion on the working principle of KD2 pro thermal property analyzer, Ubbelohde viscometer and pycnometer for measurement of thermal conductivity, viscosity and density respectively. In section 3.6, the description of experimental setup is discussed and in next section, equations used for the calculation of heat transfer coefficient are discussed.

3.2 Synthesis of nanofluids

For the present work alumina (Al_2O_3) and carbon nanotubes (CNT) nanoparticles are used for the preparation of the nanofluid and distilled water is used as base fluid. Work is done on two volume fractions i.e. 0.1% and 0.5%. Alumina/water nanofluid is prepared without use of any surfactant while for the CNT/water nanofluid surfactant has been used.

3.2.1 Materials required for preparing nanofluids

- Al_2O_3 nanoparticles
- Carbon Nanotubes (Multiwall)
- Distilled water
- Gum Arabic (GA)

3.2.1.1 Background of alumina (Al_2O_3)

Aluminum oxide (Al_2O_3) commonly referred to as alumina, white crystalline powder that is found

as balls or lumps of various mesh sizes, possesses strong ionic inter-atomic bonding giving rise to its desirable material characteristics. Alumina is most cost effective and one of the most versatile of refractory ceramic oxides. The raw materials from which this high performance technical grade ceramic is made are readily available and reasonably priced, resulting in good value for the cost in fabricated alumina shapes [1]. With an excellent combination of properties and an attractive price, it is no surprise that fine grain technical grade alumina has a very wide range of applications like gas laser tubes, wear pads, seal rings, high temperature and high voltage electrical insulators etc.

3.2.1.2 Background of multiwall carbon nanotubes (MWCNT)

Carbon nanotubes are unique tubular structures of nanometer diameter and large length/diameter ratio. The nanotubes may consist of one up to tens and hundreds of concentric shells of carbons with adjacent shells separation of 0.34 nm. The carbon network of the shells is closely related to the honeycomb arrangement of the carbon atoms in the graphite sheets. The nanotubes can be metallic or semiconducting depending on their structural parameters. Carbon nanotubes have exceptionally higher thermal conductivity and unique thermo-physical properties.

3.2.2 Methodology for the preparation of nanofluids

3.2.2.1 Alumina/water nanofluid

The size of alumina nanoparticles is 40-45 nm as it was mentioned by the company. Nanofluid is prepared by two step process. First of all, weigh the exact amount of alumina nanoparticles as per volume fraction i.e. 0.1% and 0.5% with the help of digital weighing balance machine. Then, take 50 ml distilled water in a beaker, and pour the calculated amount of alumina nanoparticles in the beaker very gently, avoiding the sticking of nanoparticles on the beaker wall. Then place this beaker in ultra sonicator for at least 2-3 hours for proper mixing. The prepared alumina/water nanofluid for both of the concentrations is shown in Fig. 3.1.



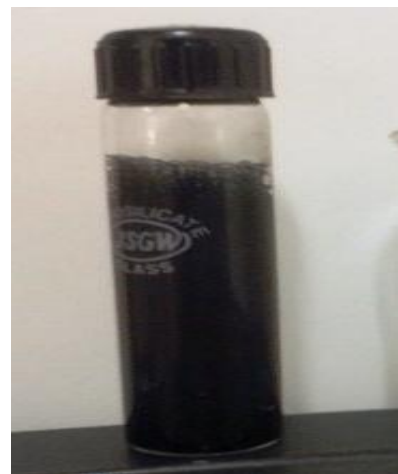
Fig. 3.1: Alumina and distilled water based nanofluids; (0.1% and 0.5%)

3.2.2.2 CNT/water nanofluid

As carbon nanotubes are very much hydrophobic in nature, two different surfactants have been used for stable suspension of CNT in water. Weigh the calculated amount of CNT as per volume fraction i.e. 0.1% and 0.5% with the help of digital weighing balance machine. Then, take 50 ml distilled water in a beaker, add the surfactant and pour CNT in the beaker very gently, avoiding the sticking of nanoparticles on the beaker wall. Then place this beaker in ultra sonicator for at least 2-3 hours for proper mixing. Fig. 3.2 (a) & (b) shows the prepared CNT/water nanofluid without using any surfactant and with using surfactant respectively.



Fig. 3.2 (a) MWCNT/water nanofluid without surfactant



(b) MWCNT/water nanofluid with surfactant

3.2.3 Ultra sonicator

Sonication is the act of applying sound (usually ultrasound) energy to agitate particles in a sample, for various purposes. In the laboratory, it is usually applied using an ultrasonic bath known as a sonicator. Sonication can be used to speed dissolution, by breaking intermolecular interactions. Sonication is commonly used in nanotechnology for evenly dispersing nanoparticles in liquids. The front view of ultrasonicator is shown in Fig.3.3.



Fig. 3.3: Front View of Ultra Sonicator

3.3 Thermal conductivity measurement

Thermal conductivity is measured by using KD2 pro thermal properties analyzer. KD2 pro is supplied by Decagon Devices, Inc. 2365 NE Hopkins Ct. Pullman, WA 99163 USA. The KD2 Pro is a battery-operated, menu-driven and handheld device used to measure thermal properties. It consists of a handheld controller and sensors that can be inserted into the medium you wish to measure. The single-needle sensors measure thermal conductivity and resistivity; while the dual-needle sensor also measures volumetric specific heat capacity and diffusivity. The KD2 Pro has been designed for ease of use and maximum functionality.

Specifications:

Operating environment:

Controller: 0 to 50 °C

Sensors: -50 to +150 °C

Power: 4 AA cells

Battery Life: At least 500 readings in constant use or 3 years with no use (battery drain in sleep mode < 50 uA)

Case Size: 15.5 cm x 9.5 cm x 3.5 cm

Display: 3 cm x 6 cm, 128 x 64 pixel graphics LCD

Keypad: 6 key, sealed membrane

Data Storage: 4095 measurements in flash memory (both raw and processed data are stored for download)

Interface: 9-pin serial

Read Modes: Manual and auto read.

Sensors: The specifications of all the 3 sensors are given below.

1. 60 mm (small) single-needle (KS-1):

Size: 1.3 mm diameter x 60 mm long

Thermal conductivity range: 0.02 to 2.00 W/(m·K)

Thermal resistivity: 50 to 5000 °C·cm/W

Accuracy (conductivity): ± 5% from 0.2 - 2 W/(m·K), ±0.01 W/(m·K) from 0.02 - 0.2W/(m.K)

Cable length: 0.8

2. 100 mm (large) single-needle (TR-1):

Size: 2.4 mm diameter x 100 mm long

Thermal conductivity range: 0.10 to 4.00 W/(m· K)

Thermal resistivity range: 25 to 1000 °C·cm/W

Accuracy (conductivity): $\pm 10\%$ from 0.2 - 4 W/(m· K) ± 0.02 W/(m· K) from 0.1 - 0.2 W/(m· K)

Cable length: 0.8 m

3. 30 mm dual-needle (SH-1):

Size: 1.3 mm diameter x 30 mm long, 6 mm spacing

Thermal conductivity range: 0.02 to 2.00 W / (m· K)

Thermal resistivity: 50 to 5000 °C·cm/W

Diffusivity: 0.1 to 1 mm²/s

Volumetric specific heat: 0.5 to 4 mJ/(m³K)

Accuracy: (Conductivity) $\pm 10\%$ from 0.2 - 2 W/(m· K) ± 0.01 W/(m· K) from 0.02 - 0.2 W/(m·K)

Cable length: 0.8 m

3.3.1 Key points for KS-1 sensor

As in present work, only KS-1 sensor is used. So, some key points for the same can be discussed as: The KD2 pro KS-1 sensor (Fig. 3.4) is specially designed to add a very small amount of heat to the sample during measurement and thereby minimize problems with free convection. In high viscosity liquids (e.g. oils, glycerin), free convection is generally not an issue. However, in low viscosity liquids like water or aqueous solutions, there are several important steps that will aid in accurate measurements.

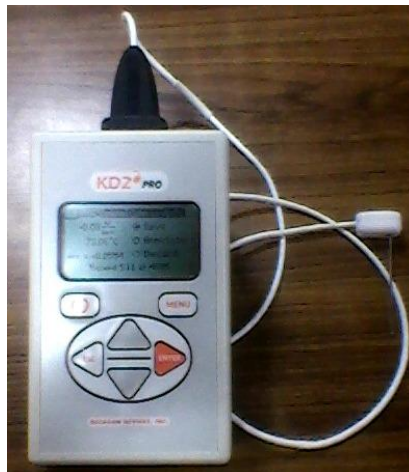


Fig. 3.4: KD2 pro thermal properties analyzer

- When dealing with low viscosity liquid samples, the duration of the read time should be minimized to minimize the amount of heat added to the sample.

- The default read time for the KS-1 sensor is 1 minute. If you are measuring in low viscosity liquids, use this read time.
- In liquid samples, the KS-1 sensor needle should be oriented vertically during the measurement to help prevent free convection.
- Never use the KS-1 sensor in high power mode in liquids. The sensor must be configured in low power mode to prevent free convection.

Note: All the above data and Fig. 3.4 is taken from KD2 pro thermal properties analyzer, Operator’s Manual (Version 10), supplied by Decagon Devices, Inc., WA 99163 USA [1].

3.3.2 Principle of measurement

KD2 Pro has 5% accuracy over the 5°C to 40°C temperature range. It consists of a handheld microcontroller and sensor needles. The KD2’s sensor needle contains both a heating element and a thermistor. The controller module contains a battery, a 16-bit microcontroller/AD converter, and power control circuitry. The thermal conductivity measurement assumes several things like: (i) the long heat source can be treated as an infinitely long heat source; (ii) the medium is both homogeneous and isotropic, and at uniform initial temperature. Although these assumptions are not true in the strict sense, they are adequate for accurate thermal properties measurements [5]. The KS-1 sensor needle can be used for measuring thermal conductivity of fluids in the range of 0.2–2 W/m k with accuracy of ±5%. Each measurement cycle consists of 90 s. During the first 30 s, the instrument will equilibrate which is then followed by heating and cooling of sensor needle for 30 s each. At the end of the reading, the controller computes the thermal conductivity using the change in temperature (ΔT)–time data from

$$k = \frac{q(\ln t_2 - \ln t_1)}{4\pi(\Delta T_2 - \Delta T_1)} \quad (3.1)$$

Where, q is constant heat rate applied to an infinitely long and small “line” source, ΔT_1 and ΔT_2 are the changes in the temperature at times and respectively.

3.3.3 Thermal conductivity measurement at different temperatures

Firstly, the whole process is done for base fluids i.e. distilled water, then this process is repeated for the samples of nanofluids. It is found that in the laboratory environment water starts boiling above 90°C. Therefore, keep the temperature of water in the water bath below it. First of all, put the sample in fluken tube, then placed it in the stand. Then with the help of cello tape, put the KD2’s KS-1 sensor needle in the upper part of fluken tube. Then place this whole arrangement in

the water bath and then wait for steady state, after this note the readings at different temperatures. The readings are taken from 30 °C to 60 °C because above 60°C, KD2 pro gives large errors.

3.4 Density measurement

For the measurement of density of nanofluids, pycnometer as shown in Fig. 3.5 has been used. A detailed description and use of pycnometer is explained below as :



Fig. 3.5: Pycnometer

3.4.1 Pycnometer

Pycnometer is also known as specific gravity bottle or relative density bottle. Density determination by pycnometer is a very precise method. It uses a working liquid with well-known density, such as water. We will use distilled water, for which temperature dependent values of density is known. The pycnometer is a glass flask with a close-fitting ground glass stopper with a capillary hole through it. This fine hole releases a spare liquid after closing a top-filled pycnometer and allows for obtaining a given volume of measured and/or working liquid with a high accuracy.

First of all, weigh the empty pycnometer with digital weighing balance machine. Then, fill the pycnometer with distilled water. The volume of distilled water that is filling the pycnometer and the stopper is

$$V = \frac{m_{H_2O}}{\rho_{H_2O}} \quad (3.2)$$

Where, m_{H_2O} is experimentally determined weight of water (empty pycnometer weight subtracted). We repeat the procedure for the liquid with unknown density ρ_L and determine its weight m_L (measured weight minus weight of empty pycnometer). Volume V obtained in this measurement is the same as the volume of water determined from equation 3.1. It follows alternated equation

$$V = \frac{m_L}{\rho_L} \quad (3.3)$$

Combining equations (3.2) and (3.3).

$$\frac{m_{H_2O}}{\rho_{H_2O}} = \frac{m_L}{\rho_L} \quad (3.4)$$

This yields a relation that provides the density of measured liquid

$$\rho_L = \frac{m_L}{m_{H_2O}} \rho_{H_2O} \quad (3.5)$$

3.4.2 Density measurement at different temperatures

Before doing any measurement, first of all, pycnometer is to be filled with potassium dichromate solution for at least 12 hours. As potassium dichromate solution is good cleaning agent. So, it removes any kind of dust particles in the pycnometer. Then, it is cleaned with distilled water, and then it is to be dried in Oven at above 120 °C for at least 4-5 hours. So, that no water particles left in it. Now, it is ready to use. Now, First of all, weigh the empty pycnometer with the digital weighing balance machine. Then pour the exactly 5 ml sample of nanofluid in the pycnometer by micro pipette. Then weigh the pycnometer again. Now this will give the weight of 5 ml sample of nanofluid sample by subtracting the empty pycnometer weight from the total weight. So, density of this 5 ml sample can be found by the following equation:

$$\rho = \frac{\text{weight of nanofluid sample (gm/cm}^3\text{)}}{5} \quad (3.6)$$

The above procedure is for density measurement by pycnometer at room temperature. But for different temperature, we use hot plate. Firstly, the whole process is done for base fluids i.e. distilled water, and then the process is repeated for samples of nanofluids. The readings are taken from 30 °C to 80 °C.

3.5 Viscosity measurement

For the measurement of viscosity of nanofluids, Ubbelohde viscometer is used. This apparatus is cheap and easily available, but still no one had find viscosity through this viscometer. A detailed description and use of Ubbelohde viscometer is explained below as:

3.5.1 Ubbelohde viscometer

An Ubbelohde type viscometer or suspended-level viscometer is a measuring instrument which uses a capillary based method of measuring viscosity. The advantage of this instrument is that the

values obtained are independent of the total volume. The device was invented by the German chemist Leo Ubbelohde (1877-1964).

The Ubbelohde viscometer is closely related to the Ostwald viscometer. Both are u-shaped pieces of glassware with a reservoir on one side and a measuring bulb with a capillary on the other. Liquid is introduced into the reservoir then sucked through the capillary and measuring bulb. The liquid is allowed to travel back through the measuring bulb and the time it takes for the liquid to pass through two calibrated marks is a measure for viscosity. The Ubbelohde device has a third arm extending from the end of the capillary and open to the atmosphere. In this way the pressure head only depends on a fixed height and no longer on the total volume of liquid.

The viscosity of the test liquid is determined by measuring the time it takes for the sample, whose volume is defined by two ring-shaped marks to flow in laminar pattern through a capillary under the influence of gravity. Hence, the friction within the liquid with high viscosity needs more time to pass the distance between the two measuring marks within the capillary tube. In accurate measurements these time is mostly measured by stopwatches. The time taken for a liquid to flow between two marks is a function both of dynamic viscosity and density. The relationship between dynamic viscosity and density is called kinematic viscosity and is defined as

$$\text{Kinematic Viscosity} = \frac{\text{Dynamic viscosity}}{\text{Density}}$$

The Ubbelohde Viscometer therefore, measure kinematic viscosity. The viscosity of nanofluid sample can be compared with the one whose viscosity is known (e.g. Water) and the viscosity calculated in this way. Thus, the viscosity of the nanofluid may be calculated from

$$\mu_{nf} = \mu_w \frac{t_{nf} \rho_{nf}}{t_w \rho_w} \quad (3.7)$$

Where,

μ = Dynamic Viscosity (Pa-sec)

ρ = Density (kg/m³)

t= time (sec.)

Subscripts *nf* and *w* and represents nanofluid and water respectively.

3.5.2 Viscosity measurement at different temperatures

Firstly, the whole process is done for base fluid i.e. distilled water, then the process is repeated for the samples of nanofluids. First of all, water is filled in a glass beaker and insulated with aluminum foil. So that heat transfer from the environment can be minimized. Then place this beaker on the hot plate. This will work as a hot water bath for the viscometer. Please ensure that the beaker should be fully filled with water. Place a thermometer inside this beaker with the help of a clamp and stand. Then with the help of another stand put the Ubbelohde viscometer in the beaker and then with the help of a flask, pour the nanofluid sample in the reservoir or filling tube. Now, with the help of a suction pump, suck this nanofluid sample through the capillary tube and when it comes down, then note down the time with the help of stopwatch very precisely between two ring-shaped calibrated marks. Repeat this for different temperature and different volume fraction of nanofluids. The readings are taken from 30 °C to 80 °C.

3.6 Experimental setup

An experimental set up used to measure heat transfer coefficient is shown in Fig. 3.6. It consist of a copper test section with heating facility, heat exchanger, a manometer, a rotameter, a magnetic drive pump, a PID controlled heater in storage tank and power supply:

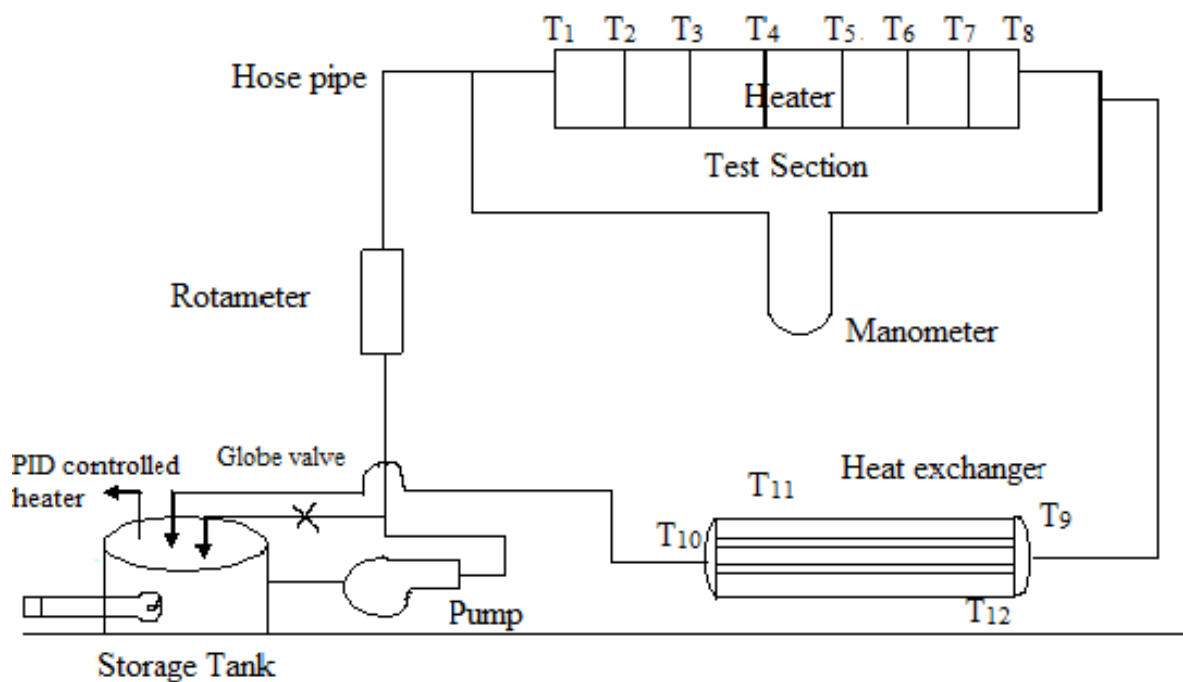


Fig. 3.6: Schematic diagram of experimental setup

3.6.1 Description

A photographic view of the experimental setup used to investigate the heat transfer enhancement of nanofluid is shown in Fig. 3.7. It consists of a storage tank having a capacity of 3 liters in which a PID controlled heater is fitted, a magnetic drive pump, which helps to circulate the hot water to the test section. The test section is a 1.5m long copper pipe containing 8 RTD Pt-100 sensors, followed by a small heat exchanger. A small rotameter is fitted for hot water flow control and a manometer is provided to measure the pressure difference across the test section. There are total 12 RTD Pt-100 sensors used in the setup i.e. T_1 , T_2 , T_3 , T_4 , T_5 , T_6 , T_7 , T_8 , T_9 , T_{10} , T_{11} and T_{12} . T_1 and T_2 are on the inlet and outlet of the test section respectively, while total 6 RTD Pt-100 sensors are on the surface of the test section, located at a distance of 2 mm to each other, a heat exchanger of stainless steel with counter current flow type pattern.



Fig. 3.7 Photographic view of experimental setup

Where,

T_1 = Temperature of the inlet water or nanofluid to the test section.

T_8 = Temperature of the outlet water or nanofluid from the test section.

T_2 , T_3 , T_4 , T_5 , T_6 , T_7 = Test section surface RTD sensors.

T_9 = Temperature of the outlet hot water or nanofluid to the heat exchanger.

T_{10} = Temperature of the outlet hot water or nanofluid from the heat exchanger.

T_{11} = Temperature of the inlet cold water to the heat exchanger.

T_{12} = Temperature of the outlet cold water from the heat exchanger.

3.6.1.1 Utilities Required [3]

- Water supply 10 lit/min (approx.) and drain.
- Electricity Supply: 1Phase, 220 V AC, 3 kW.
- Floor area 2 m x 0.6m.

Table 3.1: Technical details of experimental setup [3]

Test section	Copper pipe, length- 1.5 meter, embedded with 8 temperature sensors, 6 on surface, 1 each at inlet & outlet.
External heater	A coil heater of 250 watts is wrapped over the test piece with variac for controlled external heating of section
Heat exchanger	Pipe in pipe type
Water flow measurement	Measuring cylinder & stop watch with rotameter.
Hot water tank	Made of Stainless steel.
Hot water circulation	Magnetic pump made of Polypropylene to circulate hot water. Maximum working temperature is 75°C
Heaters	Nichrome wire heater
Temperature sensors.	RTD PT-100 type 12 in number.
Manometer	For pressure difference across test length.
Control panel	Digital Temperature Controller: 0-199.9°C (For hot water tank), Digital Temperature Indicator: 0-199.9°C, with multi-channel switch, On/Off switch, mains indicator etc

3.6.2 Experimental Procedure

The storage tank is filled with distilled water, fixed the flow rate of the water by rotameters and then with the help of magnetic drive pump it is circulated to the test section. The PID controlled heater fitted in the storage tank is kept switched off. The test section is coiled with heater, so as the water moves along its length, the temperature of the water keeps on rising. This hot water then, through a hose pipe enters the heat exchanger, where the cold water is continuously circulating. Hot and cold water are contacted in a counter current flow pattern. After attaining steady state condition, the temperature indicated by all the 12 temperature sensors, pressure drop across the test section and the flow rates are measured. Then the volume flow rate was varied but the voltage input kept constant and the corresponding values are noted down. After replacing distilled water by the Al_2O_3 nanofluid, the volume concentration was varied and their respective concordant values were noted. This procedure is repeated for different voltage inputs and for different volumetric flow rates.

3.7 Equations used for measurement of heat transfer coefficient

The data obtained from the experiment were used to calculate the heat transfer coefficient. The thermal conductivity, density and viscosity of nanofluids for various concentrations were measured. Specific heat was estimated using theoretical models.

$$C_{P_{nf}} = \phi C_{P_s} + (1-\phi)C_{P_{bf}} \quad (3.8)$$

Where,

C_p = Specific heat

ϕ = Volume fraction of nanoparticles

Subscript *nf*, *s* and *bf* stands for nanofluid, solid nanoparticles and base fluid respectively.

The Heat exchange rate between hot and cold fluid can be determined easily for the measured temperature difference, volumetric flow rate and voltage of the test fluid with the help of the equation given below:

$$Q = \dot{m} C_p \Delta T \quad (3.9)$$

or

$$Q = \dot{m} C_p (T_8 - T_1)$$

(4.0)

Where Q is the heat exchange rate of water or nanofluid, \dot{m} is the mass flow rate of water or nanofluid, and T_8 and T_1 are the temperatures at the entry and exit points of the water or nanofluid, respectively.

The test section is cylindrical in shape, therefore,

$$Q = 2\pi k L \frac{(T_{so} - T_{si})}{\ln(r_o / r_i)} \quad (4.1)$$

$$r_o = d_o / 2 \quad (4.2)$$

$$r_i = d_i / 2 \quad (4.3)$$

$$T_{so} = \frac{(T_2 + T_3 + T_4 + T_5 + T_6 + T_7)}{6} \quad (4.4)$$

By using the numerical value of Q from equation (4.0), T_{si} can be calculated

Where,

T_{so} = Outside surface temperature of test section ($^{\circ}\text{C}$)

T_{si} = Inside surface temperature of test section ($^{\circ}\text{C}$)

r_o = Outside radius of the test section (m)

r_i = Inside radius of the test section (m)

k = thermal conductivity of nanofluid

L = length of the test section

Then, heat transfer coefficient of water or nanofluid can be calculated as:

$$Q = h_i A_i (T_{si} - \bar{T}_b) \quad (4.4)$$

$$A_i = \pi d_i L \quad (4.5)$$

$$\bar{T}_b = \frac{T_8 + T_1}{2} \quad (4.6)$$

Where, h_i = inside heat transfer coefficient (W/m².K)

A_i = inside area of test section (m²)

T_{si} = inside surface temperature (°C)

\bar{T}_b = bulk mean temperature (°C)

Dimensionless numbers i.e. Reynolds number and Nusselt number can be calculated as:

Reynolds number:

$$Re = \frac{d_i v_i \rho_i}{\mu_f}$$

(4.7)

Where,

d_i = inside diameter of test section (m)

μ_f = viscosity of the fluid inside the test section (Pa.s)

v_i = velocity of the fluid inside the test section (m/s)

ρ_i = density of the fluid inside the test section (kg/m³)

Nusselt number:

$$Nu = \frac{h_i d_i}{k_f} \quad (4.8)$$

Where,

h_i = inside heat transfer coefficient (can be calculated using equation 4.4)

k_f = thermal conductivity of fluid (W/m.K)

Friction factor can be calculated as:

$$\Delta p = f \left(\frac{L}{d_i} \right) \left(\frac{\rho u^2}{2} \right) \quad (4.9)$$

Where, Δp = Pressure drop (Pa)
L = length of pipe (m)
 d_i = inner diameter of pipe (m)
u = velocity (m/s)

3.8 Conclusion

In this chapter, methodology of preparation of alumina/distilled water and MWCNT/distilled water nanofluid, working principles of various instruments like KD2 Pro, Ubbelohde viscometer and Pycnometer have been discussed. Description of experimental setup for measurement of heat transfer coefficient with its schematic diagram, experimental procedure and equations used to calculate the heat transfer coefficient are also discussed. In next chapter, all the results obtained by these measurements are discussed thoroughly.

Reference

1. Chandrasekar, M., Suresh, S., and Bose, A. C., Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al_2O_3 /water nanofluid, *Experimental Thermal and Fluid Science*, vol. 34, pp. 210-216, 2010.
2. KD2 Pro Thermal Properties Analyzer, *Operator's Manual (Version 10)*, supplied by Decagon Devices, Inc., WA 99163 USA.
3. Experimental setup; Instruction Manual, supplied by MASS INTERNATIONAL, 93 Preet Nagar, Jagadhri Road, Ambala Cantt, 133001.

CHAPTER - 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, all the results from the experiments conducted on the experimental setup and all observations found during the preparation of nanofluids, calculation of heat transfer coefficient, Nusselt number, Reynolds number pressure drop and friction factor are discussed. The thermo-physical properties of nanofluids are evaluated at different temperatures by using KD2 pro thermal properties analyzer, Ubbelohde viscometer and pycnometer for thermal conductivity, viscosity and density, respectively, as mentioned in previous chapter.

4.2 Observations of prepared nanofluid

4.2.1 Alumina/water nanofluid

- Alumina nanoparticles dispersed in distilled water by sonicating it for 2.5 hours continuously, without adding any surfactant.
- It remains stable for 3 weeks, after that nanoparticle started to settle down, the alumina/distilled water nanofluid is shown in Fig 4.1.



Fig. 4.1: Alumina/distilled water nanofluid

4.2.2 MWCNT/ water nanofluid

- Firstly, the MWCNT/distilled water nanofluids were prepared without use of any surfactant, but MWCNT was not dispersed properly due to hydrophobic nature of carbon nanotubes. The MWCNT/distilled water nanofluid without use of any surfactant is shown in Fig. 4.2.

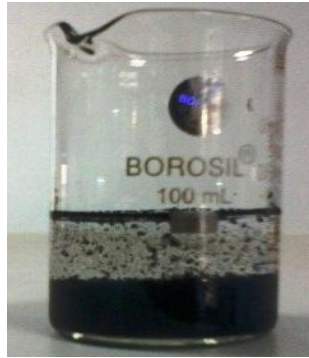


Fig. 4.2: MWCNT/water nanofluid without use of any surfactant.

- For preparation of MWCNT/distilled water with surfactant, Gum Arabic is used as surfactant. This surfactant was added in distilled water first and then MWCNT nanoparticles were added in it and sonicated for 2.5 hours continuously. But still the nanoparticles were not dispersed properly. It remains stable for 1-2 hours only and then nanoparticles start to settle down. The MWCNT/distilled water nanofluid with surfactant is shown in Fig 4.3.



Fig 4.3: MWCNT/water nanofluid with surfactant.

4.3 Thermal conductivity measurement

Thermal conductivity of nanofluids is measured by using KD2 pro thermal property analyzer and KD2's KS-1 sensor needle is used in present work. The thermal conductivity is measured in the temperature range of 30°C (i.e. room temperature) to 76 °C for base fluids i.e. distilled water, as shown in Table 4.1.

Table 4.1: Thermal conductivity of distilled water

S.No.	Temperature (°C)	Thermal conductivity (W/m-K)
1	30.24	0.628
2.	37.99	0.632
3.	40.52	0.645
4.	45.66	0.65
5.	49.12	0.655
6.	53.91	0.659
7.	57.11	0.664
8.	61.33	0.688
9.	67.01	0.701
10.	72.02	0.744
11.	76.11	0.748

4.3.1 Thermal conductivity of alumina/water nanofluid

The thermal conductivity of 0.1% and 0.5% volume fractions of alumina/distilled water nanofluids at different temperatures is given in Table 4.2 and Table 4.3. The variation of thermal conductivity with temperature is shown in Fig. 4.4.

Table 4.2: Thermal conductivity of 0.1 volume% alumina/water nanofluid

S.No.	Temperature (°C)	Thermal conductivity (W/m-K)
1.	32.18	0.631
2.	36.59	0.642
3.	41.10	0.651
4.	46.19	0.655
5.	50.01	0.66
6.	55.91	0.664
7.	60.21	0.673
8.	66.01	0.691
9.	71.11	0.707
10	76.24	0.766

Table 4.3: Thermal conductivity of 0.5 volume% alumina/water nanofluid

S.No.	Temperature (°C)	Thermal conductivity (W/m-K)
1	30.46	0.635
2	36.24	0.658
3.	39.56	0.679
4.	45.69	0.693
5.	50.27	0.699
6.	56.21	0.712
7.	61.04	0.718
8.	65.01	0.722
9.	70.23	0.734
10.	75.86	0.772

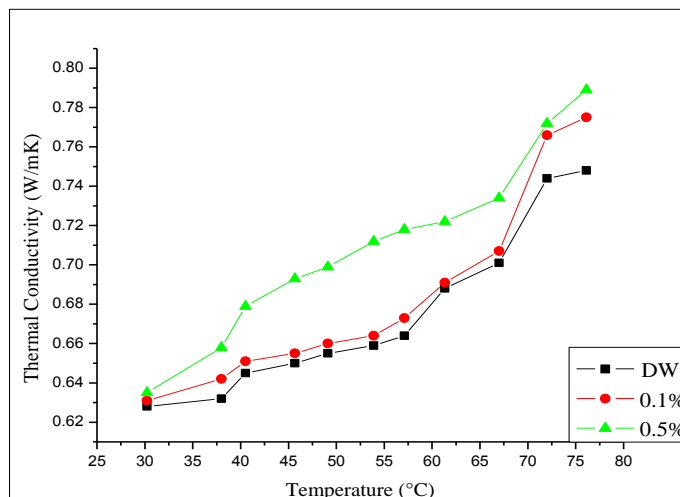


Fig. 4.4: Temperature variation of thermal conductivity

It can be seen from the Fig 4.4 that at ambient temperature, with the increase in the concentration of nanoparticles from 0.1% to 0.5% thermal conductivity of alumina/water based nanofluids increases compared to base fluid because the thermal conductivity of the water is 0.612 W/ (m.K) and thermal conductivity of alumina is 237 W/ (m.K), therefore the resultant thermal conductivity of alumina/water nanofluid is higher than that of water.

4.4 Density measurement

Density has been measured using pycnometer at a temperature range from 25°C to 70°C.

4.4.1 Density measurement of alumina/distilled water nanofluid

The value of weight of distilled water, 0.1% and 0.5% volume fraction of alumina (Al_2O_3)/ water nanofluids are respectively given in Table 4.4. The calculated density of DW and alumina/water nanofluids is shown in Table 4.5.

Table 4.4: Weight of distilled water and alumina/water nanofluids (gm)

S.No.	Temperature (°C)	DW	0.1%	0.5%
1	25	4.919	5.211	5.305
2	35	4.905	5.201	5.300
3	40	4.888	5.193	5.291
4	45	4.880	5.184	5.279
5	50	4.867	5.173	5.264
6	55	4.860	5.159	5.252
7	60	4.856	5.138	5.239
8.	70	4.849	5.120	5.225

Table 4.5: Density of distilled water and alumina/water nanofluids (Kg/m³)

S.No.	Temperature (°C)	DW	0.1%	0.5%
1	25	983.8	1042.2	1061.0
2	35	981.0	1040.0	1060.0
3	40	977.6	1038.6	1058.2
4	45	976.0	1036.8	1055.8
5	50	973.4	1034.8	1052.8
6	55	972.0	1031.2	1050.4
7	60	971.2	1027.6	1047.8
8.	70	969.8	1024.0	1045.0

It can be seen from the Fig 4.5, with the increase in the concentration of nanoparticles from 0.1% to 0.5%, density of alumina/water based nanofluids increases as compared to base fluid i.e. distilled water but with the increase in temperature, density of alumina and distilled water based nanofluids decreases.

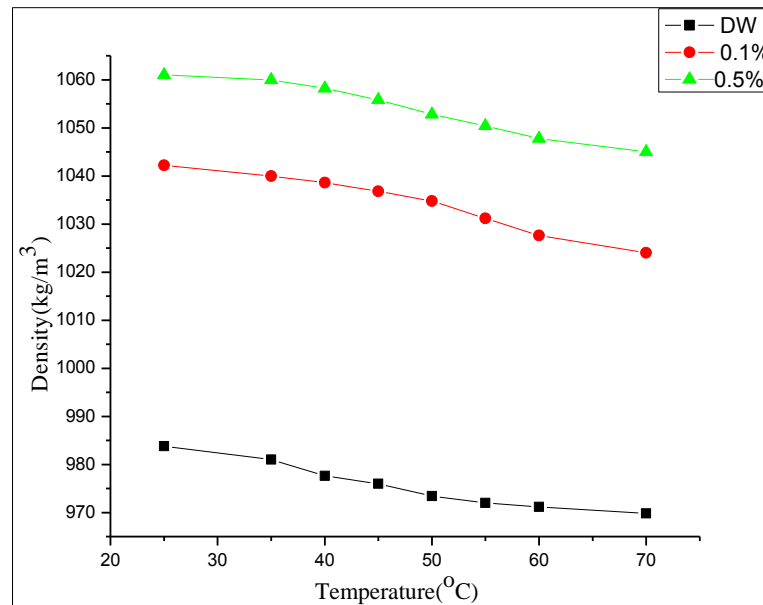


Fig 4.5: Temperature variation of density

4.5 Viscosity measurement

Viscosity has been measured using Ubbelohde viscometer at different temperature range from 30°C to 80 °C for the samples. In the Ubbelohde viscometer, the viscosity of any sample can be compared with the one whose viscosity is known (eg. distilled water) and then the viscosity of that sample is find out with the help of following formula.

$$\mu_{nf} = \mu_w \frac{t_{nf} \rho_{nf}}{t_w \rho_w} \quad (4.1)$$

Where, μ = Dynamic Viscosity (Pa-sec)

ρ = Density (kg/m³)

t = time (sec.)

Subscripts *nf* and *w* and represents nanofluid and water respectively

4.5.1 Viscosity of alumina/water nanofluids

The average time taken to cover the distance between two ring-shaped calibrated marks for the distilled water, and 0.1% and 0.5% volume fraction of alumina /distilled water nanofluids is given by Table 4.6 and the viscosities for the same are given by Table 4.7.

Table 4.6: Average time taken to cover the distance between two calibrated marks (sec.)

S. No	Temperature (°C)	DW	0.1%	0.5%
1.	30	113	119	149
2.	40	101	110	131
3.	50	90	95	115
4.	60	82	87	109
5.	70	73	76	94
6.	80	60	66	88

Table 4.7: Viscosities of distilled water and alumina/water based nanofluids (cP)

S.No	Temperature (°C)	DW	0.1%	0.5%
1.	30	0.790	0.835	1.110
2.	40	0.651	0.693	0.871
3.	50	0.550	0.583	0.729
4.	60	0.470	0.502	0.639
5.	70	0.400	0.428	0.523
6.	80	0.359	0.371	0.467

It can be seen from the Fig 4.6 that, with the increase in the concentration of nanoparticles from 0.1% to 0.5%, viscosity of alumina and distilled water nanofluids increases as compared to distilled water. And with the increase in temperature, viscosity of alumina and distilled water based nanofluids decreases

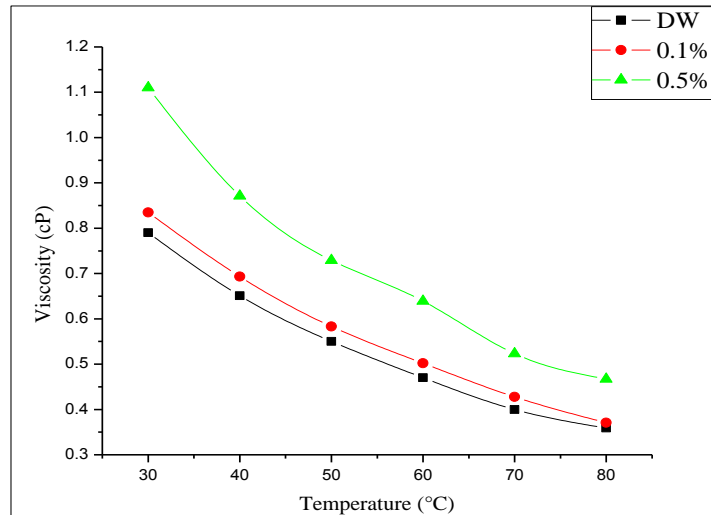


Fig 4.6: Temperature variation of viscosity

4.6 Readings of experimental setup

4.6.1 Steady state temperature readings at V= 112.0V and current = 1.95A

The steady state temperatures at voltage 112 V and current 1.95 A at four different flow rates i.e. 0.5, 1.0, 1.5 & 2.0 LPM of distilled water (DW), 0.1 volume% and 0.5 volume % alumina/distilled water nanofluids are shown in Table 4.8 and the pressure drop and friction factor are shown in Table 4.9 while the calculated heat transfer coefficient, Reynolds number and Nusselt number for the same above is shown in Table 4.10.

Table 4.8: Steady state temperatures at V = 112 V and I = 1.95 A

P=V×I (W)	Flow rates (LPM)		T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)
218.4	0.5	DW	33.6	38.5	39.1	41.8	55.3	63.6	61.1	39.7	37.2	35.5	26.9	32.3
		0.1%	35.7	40.1	41.3	43.7	58.2	66.6	63.3	42.1	39.5	37.6	28.1	34.4
		0.5%	40.1	42.4	44.5	44.7	60.2	71.6	69.4	41.3	39.8	28.7	35.5	41.3
218.4	1.0	DW	46.5	56.1	56.7	64.2	80.0	91.5	84.0	60.5	52.4	48.4	28.3	37.1
		0.1%	54.9	64.6	66.2	67.3	81.9	93.1	89.4	64.2	62.6	61.3	29.5	48.1
		0.5%	55.7	65.1	67.7	67.5	83.0	94.4	90.1	66.7	64.4	62.1	29.1	47.1
218.4	1.5	DW	52.4	61.3	62.1	61.6	78.3	86.7	82.6	57.9	56.8	54.9	29.2	39.9
		0.1%	53.2	64.9	66.6	64.4	75.9	85.3	84.3	60.1	57.1	55.3	27.3	41.2
		0.5%	56.1	65.3	68.9	68.5	78.1	88.3	80.1	62.4	58.5	56.6	27.0	40.3
218.4	2.0	DW	48.9	61.9	63.3	63.4	76.0	87.5	82.8	55.2	53.2	52.8	28.6	38.1
		0.1%	57.2	65.1	69.1	69.1	81.0	89.0	85.5	63.9	61.6	60.2	28.9	42.6
		0.5%	60.5	66.2	70.1	71.0	83.6	90.1	87.4	67.7	65.5	61.1	27.0	43.3

Table 4.9 Pressure drop and friction factor at V = 112 V and I = 1.95 A

P=V×I (W)	Flow rate (LPM)	Pressure drop (Pa)			Friction factor		
		DW	0.1 volume %	0.5 volume %	DW	0.1 volume %	0.5 volume %
218.4	0.5	147.1	78.5	147.1	0.0480	0.0245	0.0459
218.4	1.0	245.2	156.9	196.2	0.0200	0.0122	0.0150
218.4	1.5	274.6	196.2	245.2	0.0099	0.0068	0.0083
218.4	2.0	294.3	245.2	284.4	0.0060	0.0047	0.0054

The variation in friction factor with Reynolds number is shown in Fig. 4.7. From the graph, generalized equations for friction factor and Reynolds number can be obtained as

$$f = f(Re)$$

For DW,

$$f = -8E-06Re + 0.0527 \quad (4.2)$$

For 0.1 volume % Alumina/water nanofluid,

$$f = -4E-06Re + 0.0301 \quad (4.3)$$

For 0.5 volume % Alumina/water nanofluid

$$f = -7E-06Re + 0.0516 \quad (4.4)$$

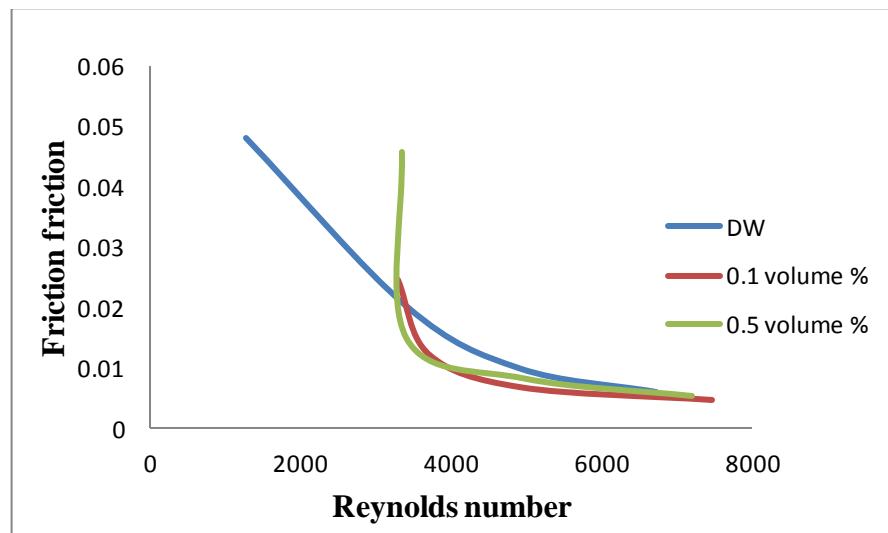


Fig. 4.7: Friction factor variation Reynolds number (V = 112, I = 1.95 A)

Table 4.10: Heat transfer coefficient, Re and Nu

P=V×I (W)	Flow rate (LPM)	Heat transfer coefficient (W/m ² K)			Reynolds number			Nusselt number		
		DW	0.1%	0.5%	DW	0.1%	0.5%	DW	0.1%	0.5%
218.4	0.5	369.2	371.6	512.8	1282	1328.5	3356.0	6.86	6.90	8.98
	1.0	526.2	1330.2	1514.8	3427.6	3709.8	3415.3	21.9	23.26	24.68
	1.5	1080.1	1437.9	1896.4	4914	4920.9	4978.8	19.35	25.37	31.0
	2.0	1686.8	3470.5	7809.9	6721.8	7450.7	7200	30.36	60.2	127.7

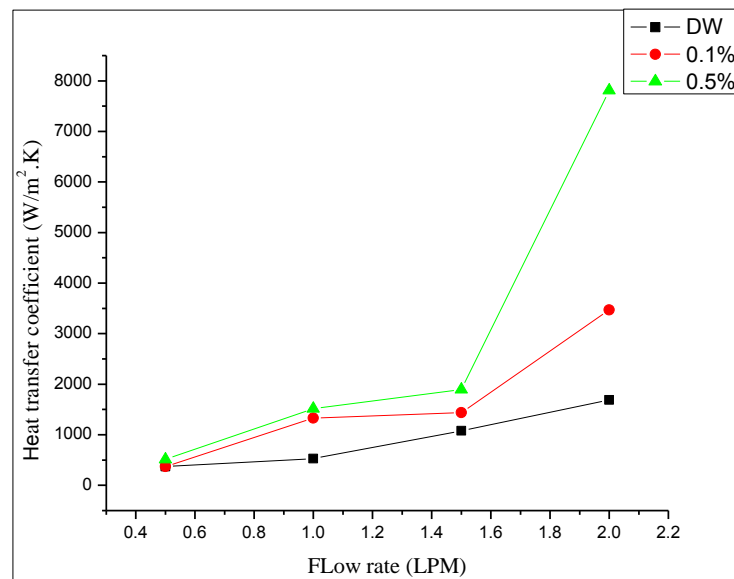


Fig. 4.8: Variation in heat transfer coefficient with flow rates

The variation in heat transfer coefficient at different flow rates of distilled water and 0.1 volume % and 0.5 volume % alumina/water nanofluid is shown in Fig. 4.8. The heat transfer coefficient is increasing from distilled water to 0.1 volume % to 0.5 volume % nanofluid. Heat transfer coefficient of 0.5 volume % of alumina/water nanofluid is much higher than that of distilled water.

At 0.5 LPM flows rate of nanofluid, there is an increment of 0.644% in heat transfer coefficient at 0.1 volume% concentration of alumina/water nanofluid and 38.8% increment in heat transfer coefficient at 0.5 volume% concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

At 1 LPM flow rate of nanofluid, there is an increment of 152.7% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 189.86% increment in heat transfer

coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

At 1.5 LPM flow rate of nanofluid, there is an increment of 33.12% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 75.5% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

At 2.0 LPM flow rate, there an increment of 105.7% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 363.0% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

Therefore, it can be said that with increase in flow rate, the heat transfer coefficient increases and it is also increasing with increase in alumina nanoparticle concentration. The abrupt increase in heat transfer coefficient of 0.5 volume % of alumina/water nanofluid i.e. 363.0% as compared to water may be considered as an experimental error.

In Fig. 4.9, a graph has been plotted between Re and Nu for DW, 0.1 volume% and 0.5 volume% alumina/distilled water nanofluid. From the graph, a generalized equation can be obtained as $Nu = f(Re)$

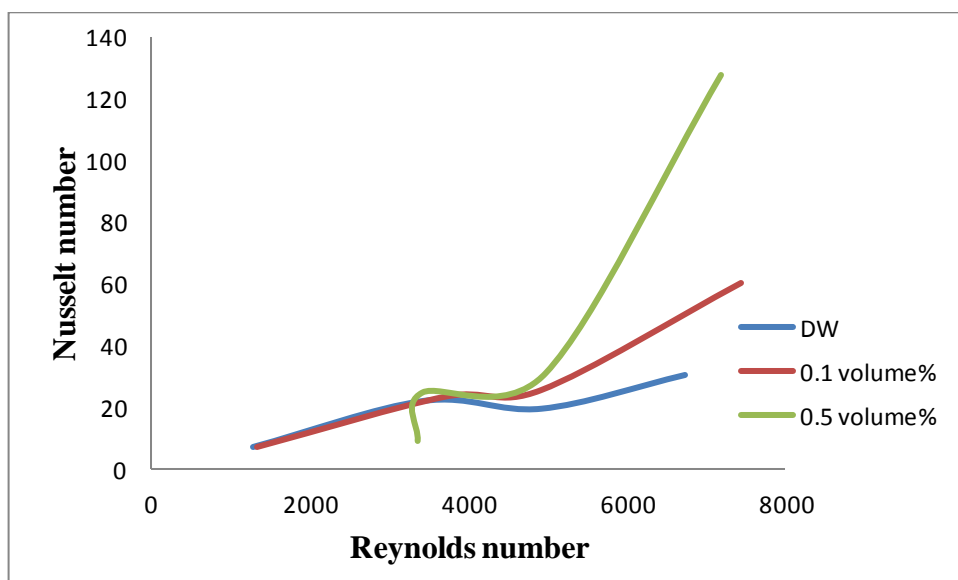


Fig. 4.9 Variation of Nusselt number with Reynolds number

For DW,

$$Nu = 0.0039Re + 3.6192 \quad (4.5)$$

For 0.1 volume% alumina/water nanofluid

$$Nu = 0.0116Re - 27.356 \quad (4.6)$$

For 0.5 volume% alumina/water nanofluid

$$Nu = 0.0283Re - 86.058 \quad (4.7)$$

4.6.2 Steady state temperature readings at V= 136.9V and current = 2.03A

The steady state temperatures at voltage 136.9V and current 2.03A at four different flow rates i.e. 0.5, 1.0, 1.5 & 2.0 LPM of distilled water (DW), 0.1 volume% and 0.5 volume % alumina/distilled water nanofluids are shown in Table 4.11 and the pressure drop and friction factor are shown in Table 4.12 while the calculated heat transfer coefficient, Reynolds number and Nusselt number for the same flow rates are shown in Table 4.13.

Table 4.11: Steady state temperatures at V =136.9 and I = 2.03 A

P=V×I (W)	Flow rates (LPM)		T₁ (°C)	T₂ (°C)	T₃ (°C)	T₄ (°C)	T₅ (°C)	T₆ (°C)	T₇ (°C)	T₈ (°C)	T₉ (°C)	T₁₀ (°C)	T₁₁ (°C)	T₁₂ (°C)
277.9	0.5	DW	44.4	58.3	59.6	65.1	79.0	92.8	83.5	57.7	55.8	49.8	26.8	39.9
		0.1%	48.3	65.3	68.6	69.1	83.2	93.2	91.1	63.8	61.3	59.8	27.7	46.3
		0.5%	50.5	67.3	70.1	69.9	85.5	95.6	92.0	67.5	62.1	60.0	27.9	47.5
277.9	1.0	DW	34.5	40.6	41.3	43.0	51.4	57.7	53.1	40.3	39.1	37.6	28.3	32.6
		0.1%	36.3	41.2	43.6	44.0	60.3	68.1	64.9	43.7	39.9	38.8	26.7	34.1
		0.5%	40.3	43.5	45.3	45.1	61.6	72.2	70.0	49.6	41.8	40.5	27.4	36.2
277.9	1.5	DW	36.4	42.5	44.1	44.2	53.5	60.3	63.9	42.1	40.5	39.6	27.9	32.9
		0.1%	36.9	43.6	47.3	47.1	55.2	68.0	66.7	44.5	41.3	39.9	26.9	34.9
		0.5%	41.5	44.6	47.1	47.2	64.4	74.1	71.3	49.9	44.1	42.5	29.3	37.3
277.9	2.0	DW	37.1	42.7	44.9	45.0	55.3	61.2	62.4	43.2	40.9	39.8	29.2	33.3
		0.1%	37.8	44.2	48.1	48.2	56.1	69.4	68.7	45.1	41.3	39.9	26.9	34.9
		0.5%	38.2	45.5	48.6	48.9	64.9	74.8	73.6	50.2	45.0	43.6	29.2	37.5

Table 4.12: Pressure drop and friction factor at $V = 136.9$ and $I = 2.03$ A

P=V×I (W)	Flow rate (LPM)	Pressure drop (Pa)			Friction factor		
		DW	0.1 volume %	0.5 volume %	DW	0.1 volume %	0.5 volume %
277.9	0.5	147.1	98.1	127.5	0.0480	0.0306	0.0398
277.9	1.0	196.2	147.1	156.9	0.0160	0.0115	0.0120
277.9	1.5	264.8	186.3	196.2	0.0096	0.0064	0.0067
277.9	2.0	323.7	245.2	264.8	0.0066	0.0047	0.0050

The variation in friction factor with Reynolds number is shown in Fig. 4.10. From the graph, generalized equations for friction factor and Reynolds number can be obtained as

$$f = f(Re)$$

For DW,

$$f = -1E-05Re + 0.048 \quad (4.8)$$

For 0.1 volume % Alumina/water nanofluid,

$$f = -9E-06Re + 0.0373 \quad (4.9)$$

For 0.5 volume % Alumina/water nanofluid

$$f = -1E-05Re + 0.0672 \quad (4.10)$$

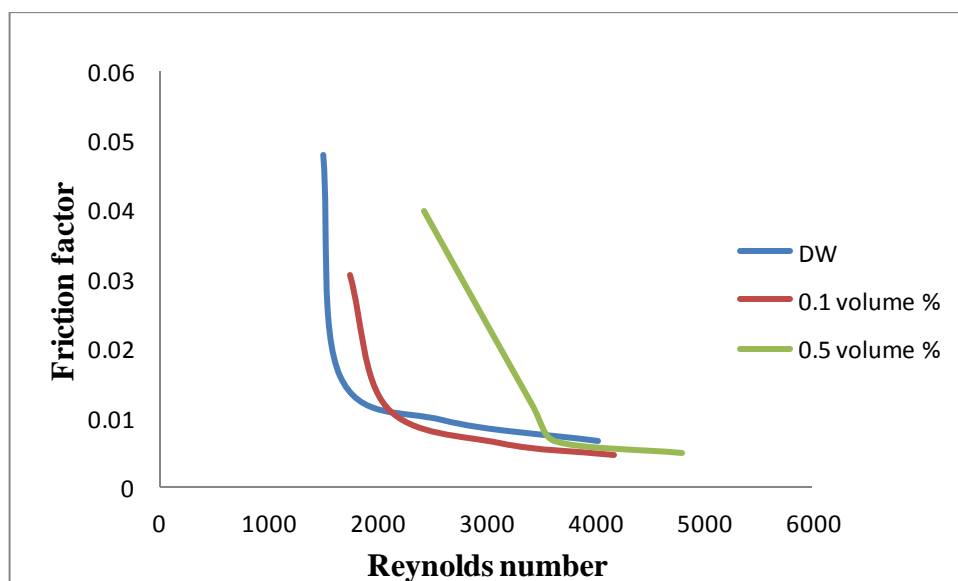


Fig. 4.10 Friction factor variation with Reynolds number at ($V = 136.9 = 2.03$ A)

Table 4.13: Heat transfer coefficient, Re and Nu

P=V×I (W)	Flow rate (LPM)	Heat transfer coefficient (W/m ² K)			Reynolds number			Nusselt number		
		DW	0.1%	0.5%	DW	0.1%	0.5%	DW	0.1%	0.5%
277.9	0.5	516.46	588.22	725.83	1502	1755	2435	9.31	10.3	11.8
	1.0	1249.9	1477.4	3365.1	1656	2095	3422	23.2	27.3	57.3
	1.5	2644.2	3616.5	9089.7	2607	3132	3633	48.7	64.9	153.4
	2.0	3849.3	4537.2	11,345	4031	4175	4,796	68.9	78.4	195.2

The variation in heat transfer coefficient at different flow rates of distilled water, 0.1 volume % and 0.5 volume % alumina/water nanofluid is shown in Fig. 4.11. The heat transfer coefficient is increasing from distilled water to 0.1 volume % to 0.5 volume % nanofluid. Heat transfer coefficient of 0.5 volume % of alumina/water nanofluid is quite higher than that of distilled water.

At 0.5 LPM flows rate of nanofluid, there is an increment of 13.89% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 40.55% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

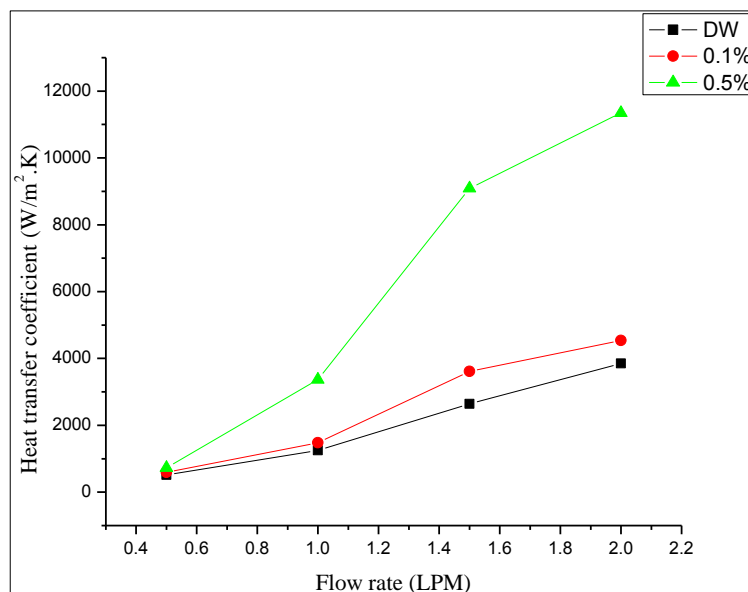


Fig. 4.11: Variation in heat transfer coefficient with flow rates

At 1 LPM flow rate of nanofluid, there is an increment of 18.20% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 169.2% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

At 1.5 LPM flow rate of nanofluid, there is an increment of 36.77% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 243.7% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

At 2.0 LPM flow rate, there an increment of 17.87% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 194.7% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

Therefore, it can be said that with increase in flow rate, the heat transfer coefficient increases and it is also increasing with increase in alumina nanoparticle concentration. The abrupt increase in heat transfer coefficient of 0.5 volume % at 1.5 LPM of alumina/water nanofluid i.e. 243.7% as compared to water may be considered as an experimental error

In Fig. 4.12, a graph has been plotted between Re and Nu for DW, 0.1 volume% and 0.5 volume% alumina/distilled water nanofluid. From the graph, a generalized equation can be obtained as $Nu = f(Re)$

For DW,

$$Nu = 0.0221Re - 16.536 \quad (4.11)$$

For 0.1 volume% alumina/water nanofluid,

$$Nu = 0.0282Re - 33.478 \quad (4.12)$$

For 0.5 volume% alumina/water nanofluid,

$$Nu = 0.0804Re - 182.7 \quad (4.13)$$

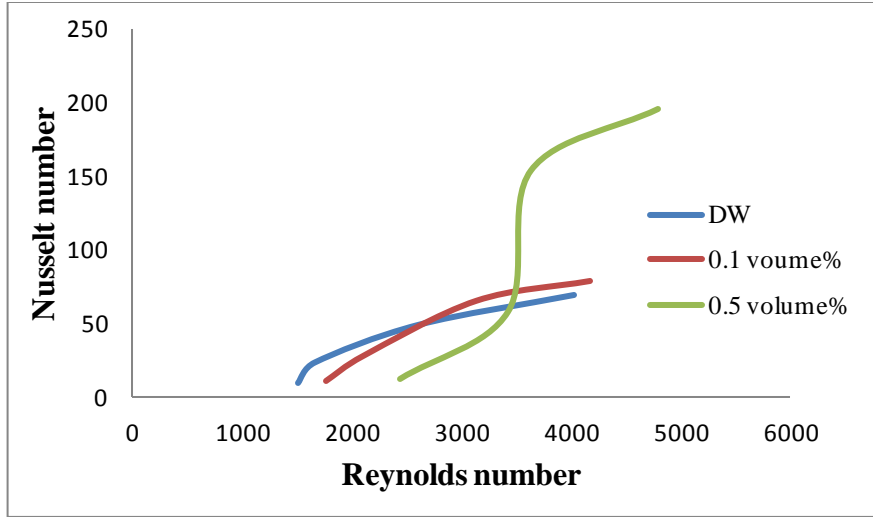


Fig. 4.12: Variation of Nusselt number with Reynolds number

4.6.3 Steady state temperature readings at V= 185.1V and current = 2.57 A

The steady state temperatures at voltage 185.1V and current 2.57A at four different flow rates i.e. 0.5, 1.0, 1.5 & 2.0 LPM of distilled water (DW), 0.1 volume% and 0.5 volume % alumina/distilled water nanofluids are shown in Table 4.14 and the pressure drop and friction factor are shown in Table 4.15 while the calculated heat transfer coefficient, Reynolds number and Nusselt number are shown in Table 4.16.

Table 4.14: Steady state temperatures at V = 185.1 and I = 2.57 A

P=V×I (W)	Flow rates (LPM)		T₁ (°C)	T₂ (°C)	T₃ (°C)	T₄ (°C)	T₅ (°C)	T₆ (°C)	T₇ (°C)	T₈ (°C)	T₉ (°C)	T₁₀ (°C)	T₁₁ (°C)	T₁₂ (°C)
475.7	0.5	DW	39.4	41.4	42.2	42.3	58.4	67.1	64.4	47.1	39.1	36.7	28.5	31.8
		0.1%	40.2	43.2	44.0	44.2	60.4	69.9	65.7	48.3	41.5	40.4	29.3	33.5
		0.5%	43.6	45.3	47.1	47.5	63.5	72.4	68.7	52.8	44.4	42.3	28.1	33.7
475.7	1.0	DW	41.9	43.7	44.5	44.7	61.2	69.9	66.2	50.1	42.1	41.1	28.8	34.5
		0.1%	43.8	45.6	47.7	47.9	63.8	72.1	68.8	53.2	44.5	43.1	29.2	33.2
		0.5%	45.1	46.1	48.2	48.9	68.1	76.0	69.2	54.6	46.1	45.9	28.7	33.6
475.7	1.5	DW	42.5	46.3	48.0	48.1	66.4	75.5	70.4	51.2	42.9	42.0	28.1	34.3
		0.1%	43.6	47.2	49.6	49.5	67.7	78.1	73.6	52.6	45.1	44.2	28.5	34.5
		0.5%	45.2	49.1	51.2	51.4	66.6	81.2	76.2	54.8	46.5	46.0	29.1	34.9
475.7	2.0	DW	43.7	55.6	55.7	75.6	83.6	74.5	52.7	51.6	43.1	42.8	27.8	34.7
		0.1%	46.1	56.0	58.4	58.8	79.9	89.8	75.7	56.2	45.6	44.8	28.4	35.0
		0.5%	48.7	58.2	61.4	61.7	81.2	90.9	78.3	59.2	46.9	46.2	28.9	35.3

Table 4.15: Pressure drop and friction factor at $V = 185.1V$ and $I = 2.57A$

P=V×I (W)	Flow rate (LPM)	Pressure drop (Pa)			Friction factor		
		DW	0.1 volume %	0.5 volume %	DW	0.1 Volume %	0.5 volume %
475.7	0.5	166.7	98.1	147.1	0.0547	0.0300	0.0450
475.7	1.0	245.2	147.1	196.2	0.0200	0.0116	0.0152
475.7	1.5	294.3	215.8	245.2	0.0100	0.0075	0.0084
475.7	2.0	333.5	245.2	294.3	0.0068	0.0048	0.0057

The variation in friction factor with Reynolds number is shown in Fig. 4.13. From the graph, a generalized equation for friction factor and Reynolds number can be obtained as

$$f = f(Re)$$

For DW,

$$f = -9E-06Re + 0.0593 \quad (4.14)$$

For 0.1 volume% alumina/water nanofluid,

$$f = -5E-06Re + 0.0321 \quad (4.15)$$

For 0.5 volume% alumina/water nanofluid,

$$f = -1E-05Re + 0.0559 \quad (4.16)$$

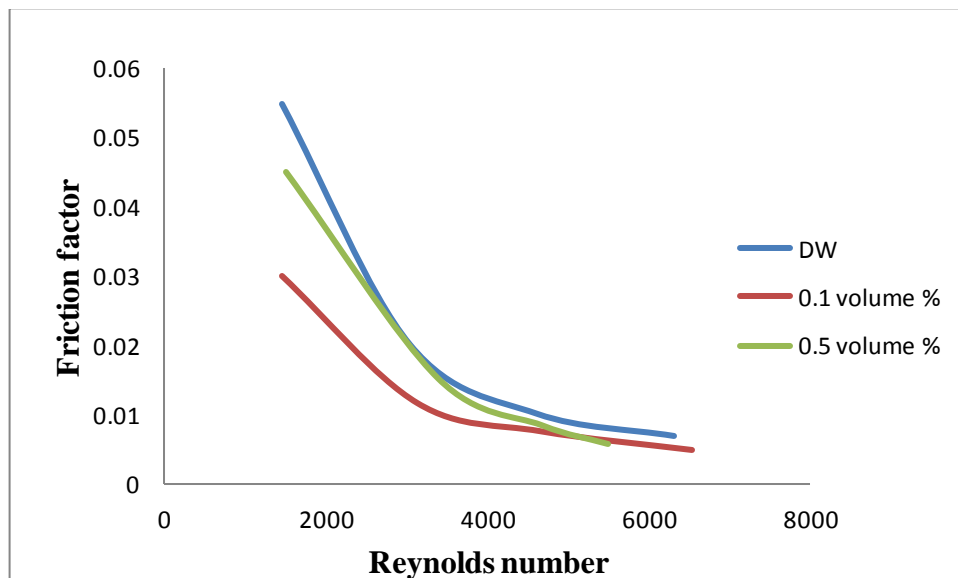


Fig. 4.13: Friction factor variation with Reynolds number ($V = 185.1 = 2.57 A$)

Table 4.16: Heat transfer coefficient, Re and Nu

P=V×I (W)	Flow rate (LPM)	Heat transfer coefficient (W/m ² K)			Reynolds number			Nusselt number		
		DW	0.1%	0.5%	DW	0.1%	0.5%	DW	0.1%	0.5%
475.7	0.5	732.2	842.20	1050.9	1449.17	1456.0	1505.2	15.415	13.32	17.83
	1.0	8407.2	15,180	22,707	3035.4	3132.6	3388.0	153.0	276.2	380
	1.5	13055.8	30,976	32,898	4613.7	4666	4677.5	237.5	564.0	567.7
	2.0	23,393	33,832	42,252	6310.2	6535.9	5494.8	424	609.7	699.2

The following Fig.4.14 shows the variation in heat transfer coefficient at different flow rates of distilled water, 0.1 volume % and 0.5 volume % alumina/water nanofluid. The heat transfer coefficient is increasing from distilled water to 0.1 volume % to 0.5 volume % nanofluid. Heat transfer coefficient of 0.5 volume % of alumina/water nanofluid is much higher than that of distilled water.

At 0.5 LPM flows rate of nanofluid, there is an increment of 0.0205% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 43.26% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient

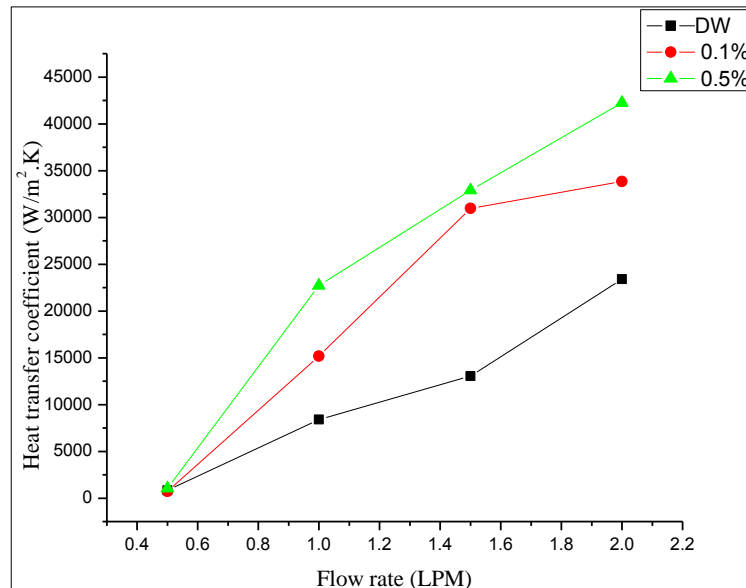


Fig. 4.14: Heat transfer coefficient variation with flow rates

At 1 LPM flow rate of nanofluid, there is an increment of 80.55% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 170.1% increment in heat transfer

coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

At 1.5 LPM flow rate of nanofluid, there is an increment of 137.2% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 151.97% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

At 2.0 LPM flow rate, there an increment of 44.26% in heat transfer coefficient at 0.1 volume % concentration of alumina/water nanofluid and 80.61% increment in heat transfer coefficient at 0.5 volume % concentration of alumina/water nanofluid as compared to distilled water heat transfer coefficient.

In Fig. 4.15, a graph has been plotted between Re and Nu for DW, 0.1 volume% and 0.5 volume% alumina/distilled water nanofluid. From the graph, a generalized equation can be obtained as $Nu = f(Re)$

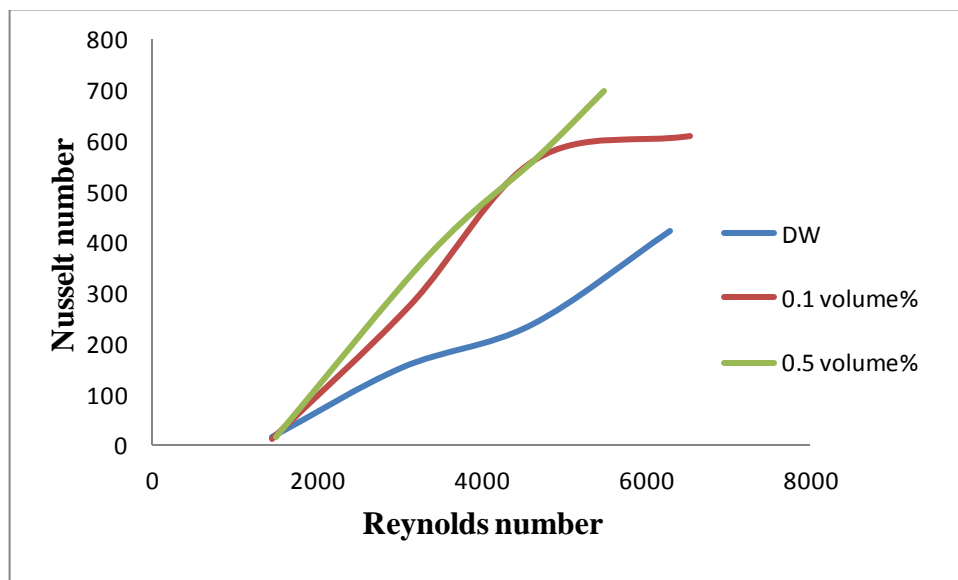


Fig. 4.15: Variation of Nusselt number with Reynolds number

For DW,

$$Nu = 0.0812Re - 105.42 \tag{4.17}$$

For 0.1 volume% alumina/water nanofluid,

$$\text{Nu} = 0.1224\text{Re} - 117.55 \quad (4.18)$$

For 0.5 volume% alumina/water nanofluid,

$$\text{Nu} = 0.1699\text{Re} - 223.74 \quad (4.19)$$

4.7 Conclusion

This chapter discussed all the results coming from thermal conductivity, density, viscosity and heat transfer coefficient measurements. Results of thermo-physical properties vary with the concentration as well as with the temperature. Heat transfer coefficient is increasing with increase in flow rate and power input. Pressure drop of DW is higher than that of nanofluid but it is increasing with increase in particle concentration.

CHAPTER – 5

CONCLUSIONS

This chapter explains the conclusions drawn from the research work carried out are as follows:

1. Nanofluids are prepared by two-step process i.e. dispersing the nanoparticles into base fluids. An ultra sonicator is used to disperse the particles properly and to minimize particle agglomeration to get a uniform stable suspension. Surfactant is also used to prepare MWCNT/ water nanofluids.
2. Two types of nanoparticles are used for preparing nanofluid i.e. alumina (Al_2O_3) and carbon nanotubes (MWCNT) for the base fluid as distilled water. Alumina/distilled water nanofluid are prepared without use of any surfactant but MWCNT/distilled water nanofluids are prepared with and without use of surfactant for 0.1 volume% and 0.5 volume%.
3. Alumina/distilled water nanofluid remain stable for 3 weeks while MWCNT do not disperse in distilled nanofluid without use of surfactant. When gum arabic is added in small quantity in MWCNT/ distilled water nanofluid then it shows a stable suspension only for 1-2 hours. After that it starts to settle down in the bottom. Therefore, for further experimental work alumina nanoparticles are selected due to their good stability in distilled water.
4. Alumina/distilled water nanofluids of 0.1 volume% and 0.5 volume% are subjected to 2.5 hours of sonication. Then their thermo-physical properties i.e. thermal conductivity, density and viscosity have been measured at different temperatures using KD2 pro thermal property analyzer, pycnometer and Ubbelohde viscometer respectively.
5. Results show that the thermal conductivity of alumina/distilled water nanofluid increases up to 2.40% for 0.1 volume% and 0.328% for 0.5 volume% of alumina/distilled water as compared to distilled water.
6. Density of alumina/distilled water nanofluid is increases as compared to distilled water and it also increases with increase in particle concentration at a particular temperature. But as temperature increases density decreases. At 0.1 volume% concentration of alumina in

distilled water, an increment of 5.58% and an increment of 7.754% at 0.5 volume % are found.

7. Viscosity results are also in an increasing pattern. Alumina/distilled water nanofluid for both concentrations have shown higher viscosities than distilled water. At 0.1 volume % there is an increment of 3.34 % and at 0.5 volume % increment of 30.1 % is found.
8. The temperatures and pressure drops of nanofluids as well as pipe surface temperatures are measured at steady state by using an experimental setup at different flow rates and power inputs.
9. Results show that the heat transfer coefficient of 0.1 volume % and 0.5 volume % of alumina/distilled water nanofluid, at a particular flow rate is much higher than that of distilled water.
10. For 0.1 volume % of alumina/distilled water nanofluid, an increment from 0.205 % to 152.2 % in heat transfer coefficient is found and for 0.5 volume % of alumina/distilled water nanofluid an increment from 38.8 % to 243.3 % in heat transfer coefficient is found as compared to distilled water.
11. Pressure drop of nanofluid is lower than that of water. For 0.1 volume % concentration, pressure drop is lower than that of water but at 0.5 volume % of nanofluid, pressure drop is higher than that of 0.1 volume % but lower than water.
12. So, it can be concluded that, with increase in flow rate, power input and particle concentration, the heat transfer coefficient increases. Pressure drop of nanofluid is lower than that of water but it is increasing with increase in particle concentration.

FUTURE SCOPE OF WORK

1. Experiments can be extended with higher particle concentrations for measurement of heat transfer coefficients. Variation in stability of alumina/water nanofluid with increase in particle concentration can also be studied.
2. Experiments can also be extended for different base fluids e.g. transformer oil, ethylene glycol etc for investigation of heat transfer characteristics.
3. Carbon nanotubes (CNT) have very high thermal conductivity i.e. around 3000 W/(m.K) . So, CNT/water nanofluid can be studied with different surfactants at various particle concentrations. Limited work has been reported on the cooling applications of nanofluid using carbon nanotubes (CNT).

Experimental observations**Voltage = 112, Current = 1.95A**

Flow rate = 0.5 LPM

Table 1: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	30.2	35.3	37.6	38.8	52.3	61.0	59.2	36.3	34.1	33.2	30.4	31.2	15
2.	15	31.3	35.5	37.9	39.3	52.6	61.1	59.6	36.8	34.6	33.9	29.8	31.6	15
3.	30	31.6	36.1	38.0	39.8	53.1	61.5	60.1	37.1	35.1	34.1	29.6	31.7	15
4.	45	32.0	36.7	38.4	40.0	53.9	62.1	60.4	37.7	35.8	34.3	29.4	31.9	15
5.	60	32.5	37.6	38.7	41.3	54.1	62.3	60.7	37.8	36.5	34.5	28.6	32.0	15
6.	75	32.8	38.4	38.9	41.4	54.8	62.9	61.2	39.3	36.8	35.1	28.6	32.3	15
7.	90	33.6	38.5	39.1	41.8	55.3	63.3	61.6	39.7	37.2	35.5	26.9	32.3	15
8.	105	33.6	38.5	39.1	41.8	55.3	63.3	61.6	39.7	37.2	35.5	26.9	32.3	15
9.	120	33.6	38.5	39.1	41.8	55.3	63.3	61.6	39.7	37.2	35.5	26.9	32.3	15

Table 2: Temperature and pressure drop readings of 0.1% nanofluid

S.No	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	32.5	37.4	39.2	40.5	54.4	62.5	60.6	37.6	36.3	34.2	29.7	31.1	8
2.	15	32.7	37.7	39.9	40.8	55.6	63.9	60.8	38.0	36.9	34.7	29.5	31.8	8
3.	30	32.9	38.2	40.0	41.7	55.8	64.2	61.7	38.9	37.1	35.4	29.0	32.7	8
4.	45	33.7	38.8	40.1	42.1	56.2	64.7	62.1	39.5	37.7	35.9	28.6	33.3	8
5.	60	34.3	39.0	40.5	42.4	57.3	65.0	62.6	39.8	38.3	36.4	28.3	33.7	8
6.	75	34.6	39.7	40.9	43.3	57.8	65.2	62.8	40.1	38.8	37.1	28.4	34.0	8
7.	90	35.7	40.1	41.3	43.7	58.2	66.6	63.3	42.1	39.5	37.6	28.1	34.4	8
8.	105	35.7	40.1	41.3	43.7	58.2	66.6	63.3	42.1	39.5	37.6	28.1	34.4	8
9.	120	35.7	40.1	41.3	43.7	58.2	66.6	63.3	42.1	39.5	37.6	28.1	34.4	8

Table 3: Temperature and pressure drop readings of 0.5% nanofluid

S.No	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	36.3	38.6	41.9	42.1	57.7	68.1	67.0	44.4	38.6	37.7	29.7	33.4	15
2.	15	36.7	38.7	42.1	42.3	58.0	68.6	67.4	44.7	39.1	38.1	29.7	33.8	15
3.	30	37.0	39.2	42.8	43.0	58.4	69.0	67.6	45.1	39.6	38.5	29.5	34.1	15
4.	45	37.6	39.6	43.3	43.4	58.8	69.7	68.1	45.8	39.9	38.7	29.0	34.7	15
5.	60	38.2	40.5	43.7	43.7	59.1	70.6	68.7	46.1	40.1	39.0	28.7	35.0	15
6.	75	38.7	41.9	44.1	44.3	59.8	71.3	69.2	46.5	40.6	39.2	28.7	35.2	15
7.	90	39.2	42.4	44.5	44.7	60.2	71.6	69.4	46.8	41.3	39.8	28.7	35.5	15
8.	105	39.2	42.4	44.5	44.7	60.2	71.6	69.4	47.2	41.3	39.8	28.7	35.5	15
9.	120	40.1	42.4	44.5	44.7	60.2	71.6	69.4	47.5	41.3	39.8	28.7	35.5	15

Voltage = 112, Current = 1.95A

Flow rate = 1.0 LPM

Table 4: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	43.8	53.4	54.1	62.2	77.7	89.5	81.8	58.1	50.3	46.4	30.0	35.1	25
2.	15	44.2	53.8	54.5	62.5	78.1	89.7	82.3	58.6	51.4	46.6	29.9	35.7	25
3.	30	44.7	54.3	55.0	62.8	78.8	89.3	82.6	59.2	51.7	46.9	29.6	35.9	25
4.	45	45.0	54.9	55.4	63.1	79.5	89.5	83.0	59.6	51.1	47.2	29.5	36.2	25
5.	60	45.6	55.1	55.8	63.4	79.5	90.9	83.6	59.8	51.4	47.5	28.4	36.6	25
6.	75	46.0	55.7	56.0	63.9	79.8	91.3	83.8	60.1	51.9	48.0	28.4	36.8	25
7.	90	46.5	56.1	56.7	64.2	80.0	91.5	84.0	60.5	52.4	48.4	28.3	37.1	25
8.	105	46.5	56.1	56.7	64.2	80.0	91.5	84.0	60.5	52.4	48.4	28.3	37.1	25
9.	120	46.5	56.1	56.7	64.2	80.0	91.5	84.0	60.5	52.4	48.4	28.3	37.1	25

Table 5: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	52.7	62.3	64.9	65.3	79.4	89.2	87.2	62.4	58.8	58.3	27.7	45.7	16
2.	15	53.0	62.7	64.1	65.8	79.9	89.7	87.5	62.8	59.0	58.8	27.5	45.9	16
3.	30	53.4	63.1	64.7	66.0	80.3	90.2	87.8	63.1	59.5	59.3	27.1	46.1	16
4.	45	53.9	63.5	65.1	66.2	80.7	91.9	88.1	63.4	59.6	59.8	26.9	46.4	16
5.	60	54.0	63.9	65.6	66.6	81.0	92.3	88.6	63.8	60.9	60.3	26.7	47.5	16
6.	75	54.6	64.1	65.9	66.8	81.1	92.8	88.7	64.0	61.2	60.5	26.7	47.9	16
7.	90	54.9	64.6	66.2	67.3	81.9	93.1	89.4	64.2	62.6	61.3	29.5	48.1	16
8.	105	54.9	64.6	66.2	67.3	81.9	93.1	89.4	64.2	62.6	61.3	29.5	48.1	16
9.	120	54.9	64.6	66.2	67.3	81.9	93.1	89.4	64.2	62.6	61.3	29.5	48.1	16

Table 6: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	53.1	63.1	64.8	65.4	80.7	89.6	88.1	64.6	59.0	59.1	28.3	44.6	20
2.	15	53.4	63.5	65.0	65.9	81.2	89.9	88.3	64.9	59.4	59.6	28.1	44.9	20
3.	30	53.6	63.9	66.2	66.1	81.6	90.4	88.5	65.1	59.9	59.8	27.7	45.1	20
4.	45	54.1	64.1	66.6	66.1	81.8	91.8	89.1	65.5	60.7	60.0	27.8	45.6	20
5.	60	54.4	64.4	67.2	66.6	82.0	92.5	89.4	65.9	61.2	61.4	27.4	45.7	20
6.	75	54.8	64.7	67.5	67.2	82.3	93.9	89.9	66.2	63.1	61.9	27.4	46.2	20
7.	90	55.7	65.1	67.7	67.5	83.0	94.4	90.1	66.7	64.4	62.1	29.1	47.1	20
8.	105	55.7	65.1	67.7	67.5	83.0	94.4	90.1	66.7	64.4	62.1	29.1	47.1	20
9.	120	55.7	65.1	67.7	67.5	83.0	94.4	90.1	66.7	64.4	62.1	29.1	47.1	20

Voltage = 112, Current = 1.95A

Flow rate = 1.5 LPM

Table 7: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	34.1	39.9	42.8	43.1	52.1	57.9	62.2	39.6	38.2	36.5	27.9	31.0	28
2.	15	34.4	41.0	43.1	43.4	52.2	58.0	62.5	39.9	38.5	36.8	27.6	31.6	28
3.	30	34.5	41.3	43.3	43.5	52.3	58.3	62.8	41.0	38.9	37.2	27.3	32.0	28
4.	45	34.9	41.6	43.6	43.7	52.7	58.5	63.1	41.1	39.1	38.1	26.2	32.3	28
5.	60	35.3	41.9	43.9	43.6	52.9	58.9	63.6	41.8	39.6	38.8	26.3	32.4	28
6.	75	35.8	42.4	44.0	43.9	53.3	60.1	63.7	42.1	39.9	39.5	26.3	32.7	28
7.	90	36.4	42.5	44.1	44.2	53.5	60.3	63.9	42.1	40.5	39.6	26.3	32.8	28
8.	105	36.4	42.5	44.1	44.2	53.5	60.3	63.9	42.1	40.5	39.6	26.3	32.8	28
9.	120	36.4	42.5	44.1	44.2	53.5	60.3	63.9	42.1	40.5	39.6	26.3	32.8	28

Table 8: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	50.1	60.4	59.6	59.0	76.3	84.1	79.1	55.3	54.0	51.9	28.1	37.3	20
2.	15	50.7	60.8	60.2	59.3	76.7	84.3	79.5	55.5	54.3	52.1	27.9	37.7	20
3.	30	51.2	61.2	60.7	59.8	77.0	84.8	80.6	56.1	55.0	52.5	27.8	38.3	20
4.	45	51.5	62.5	61.0	60.1	77.2	85.2	80.8	56.7	55.2	53.8	27.5	38.8	20
5.	60	51.8	62.8	61.4	60.4	77.7	85.6	81.2	56.8	55.9	54.1	27.1	39.1	20
6.	75	52.0	63.0	61.8	60.9	78.0	85.9	82.4	57.1	56.4	54.6	26.9	39.8	20
7.	90	52.4	61.3	62.1	61.6	78.3	86.7	82.6	57.9	56.8	54.9	29.2	39.9	20
8.	105	52.4	61.3	62.1	61.6	78.3	86.7	82.6	57.9	56.8	54.9	29.2	39.9	20
9.	120	52.4	61.3	62.1	61.6	78.3	86.7	82.6	57.9	56.8	54.9	29.2	39.9	20

Table 9: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	54.0	62.8	65.2	65.0	76.5	86.2	78.5	59.2	56.3	54.3	30.2	38.1	25
2.	15	54.5	63.1	65.5	65.6	76.8	86.5	78.8	59.6	56.5	55.0	30.0	38.4	25
3.	30	54.9	63.6	65.9	66.1	77.1	86.9	79.1	60.2	56.9	55.3	29.7	38.8	25
4.	45	55.3	63.9	66.4	66.5	77.5	87.3	79.5	61.7	57.1	55.7	29.3	38.9	25
5.	60	55.6	64.1	66.7	66.8	77.8	87.7	79.8	61.9	57.6	55.9	29.3	39.0	25
6.	75	56.0	64.8	67.0	67.1	78.0	87.9	80.0	62.0	57.8	56.1	29.3	39.2	25
7.	90	56.1	65.3	68.9	68.5	78.1	88.3	80.1	62.4	58.5	56.6	27.0	40.3	25
8.	105	56.1	65.3	68.9	68.5	78.1	88.3	80.1	62.4	58.5	56.6	27.0	40.3	25
9.	120	56.1	65.3	68.9	68.5	78.1	88.3	80.1	62.4	58.5	56.6	27.0	40.3	25

Voltage = 112, Current = 1.95A

Flow rate = 2.0 LPM

Table 10: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	46.1	58.7	61.1	61.2	74.0	85.1	79.2	53.3	50.8	51.1	29.4	36.1	30
2.	15	46.7	59.1	61.5	61.4	74.1	85.5	79.5	53.4	51.0	51.5	29.1	36.5	30
3.	30	47.0	59.6	61.7	61.8	74.4	85.9	79.8	53.7	51.3	51.8	29.0	36.8	30
4.	45	47.4	60.9	62.2	62.2	74.8	86.3	80.1	54.1	51.7	52.1	28.8	37.0	30
5.	60	47.6	61.0	62.5	62.9	75.0	86.8	80.4	54.4	52.1	52.4	28.5	37.5	30
6.	75	48.7	61.7	62.9	63.1	75.3	87.1	81.8	54.9	52.5	52.7	28.2	37.7	30
7.	90	48.9	61.9	63.3	63.4	76.0	87.5	82.8	55.2	53.2	52.8	28.6	38.1	30
8.	105	48.9	61.9	63.3	63.4	76.0	87.5	82.8	55.2	53.2	52.8	28.6	38.1	30
9.	120	48.9	61.9	63.3	63.4	76.0	87.5	82.8	55.2	53.2	52.8	28.6	38.1	30

Table 11: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	54.9	63.6	67.0	66.9	79.5	87.2	84.2	61.1	59.3	58.5	29.5	40.1	25
2.	15	55.1	63.9	67.2	67.0	79.9	87.7	84.4	61.6	59.5	58.7	29.2	40.4	25
3.	30	55.4	64.1	67.4	67.1	80.0	88.1	84.7	62.1	59.8	59.0	29.1	40.9	25
4.	45	55.9	64.5	67.8	67.9	80.2	88.5	84.1	62.4	60.2	59.2	28.7	41.2	25
5.	60	56.2	65.9	68.1	68.0	80.6	98.6	84.8	62.9	61.6	59.8	28.6	41.7	25
6.	75	56.5	65.0	68.5	68.8	80.8	88.9	85.0	63.1	61.8	60.0	28.5	42.1	25
7.	90	57.2	65.1	69.1	69.1	81.0	89.0	85.5	63.9	61.6	60.2	28.9	42.6	25
8.	105	57.2	65.1	69.1	69.1	81.0	89.0	85.5	63.9	61.6	60.2	28.9	42.6	25
9.	120	57.2	65.1	69.1	69.1	81.0	89.0	85.5	63.9	61.6	60.2	28.9	42.6	25

Table 12: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	58.1	64.1	68.8	69.3	81.0	88.3	85.8	67.6	63.4	58.6	29.7	41.6	29
2.	15	58.5	64.4	69.0	69.6	81.5	88.7	85.0	67.9	63.6	59.0	29.3	41.8	29
3.	30	58.7	64.8	69.1	69.9	81.9	88.9	85.8	68.3	63.9	59.6	29.3	42.0	29
4.	45	59.0	65.1	69.4	70.1	82.4	89.1	86.0	68.9	64.1	59.9	29.3	42.3	29
5.	60	59.3	65.5	69.8	70.5	82.7	89.4	86.4	67.3	64.4	60.2	29.2	42.8	29
6.	75	59.9	65.9	69.0	70.9	83.0	89.7	86.6	67.5	64.7	60.8	29.2	43.0	29
7.	90	60.5	66.2	70.1	71.0	83.6	90.1	87.4	67.7	65.5	61.1	27.0	43.3	29
8.	105	60.5	66.2	70.1	71.0	83.6	90.1	87.4	67.7	65.5	61.1	27.0	43.3	29
9.	120	60.5	66.2	70.1	71.0	83.6	90.1	87.4	67.7	65.5	61.1	27.0	43.3	29

Voltage = 136.9 V, Current = 2.03A

Flow rate= 0.5LPA

Table 13: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	42.3	56.5	57.8	63.5	76.9	89.5	81.6	56.0	53.6	47.8	30.1	37.5	15
2.	15	42.7	56.9	58.1	63.7	77.3	89.7	82.1	56.2	54.1	48.1	29.7	37.9	15
3.	30	43.0	57.1	58.5	64.0	77.7	90.0	82.5	56.4	54.6	48.5	29.6	38.0	15
4.	45	43.4	57.4	58.8	64.4	78.1	90.7	82.7	56.8	54.9	48.7	29.1	38.4	15
5.	60	43.7	57.8	59.2	64.6	78.4	91.0	83.0	57.1	55.1	49.1	28.5	38.9	15
6.	75	44.1	58.1	59.4	65.0	78.8	91.4	83.2	57.3	55.5	49.4	28.5	39.3	15
7.	90	44.4	58.3	59.6	65.1	79.0	92.8	83.5	57.7	55.8	49.8	26.8	39.9	15
8.	105	44.4	58.3	59.6	65.1	79.0	92.8	83.5	57.7	55.8	49.8	26.8	39.9	15
9.	120	44.4	58.3	59.6	65.1	79.0	92.8	83.5	57.7	55.8	49.8	26.8	39.9	15

Table 14: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	46.1	62.8	66.8	67.0	81.4	91.1	89.2	62.1	59.1	58.0	29.7	44.2	10
2.	15	46.5	63.4	67.1	67.3	81.8	91.6	89.5	62.3	59.4	58.3	29.5	44.6	10
3.	30	46.8	63.7	67.3	67.9	82.0	91.7	89.7	62.7	59.8	58.6	29.0	45.0	10
4.	45	47.1	64.1	67.7	68.3	82.5	92.0	90.1	63.0	60.4	58.8	28.6	45.3	10
5.	60	47.8	64.4	68.0	68.6	82.7	92.7	90.4	63.2	60.7	59.2	28.3	45.9	10
6.	75	48.0	64.9	68.3	68.9	82.9	93.0	90.7	63.6	61.0	59.6	28.4	46.0	10
7.	90	48.3	65.3	68.6	69.1	83.2	93.2	91.1	63.8	61.3	59.8	27.7	46.3	10
8.	105	48.3	65.3	68.6	69.1	83.2	93.2	91.1	63.8	61.3	59.8	27.7	46.3	10
9.	120	48.3	65.3	68.6	69.1	83.2	93.2	91.1	63.8	61.3	59.8	27.7	46.3	10

Table 15: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	48.5	65.1	68.0	67.8	83.7	93.0	68.6	66.0	60.2	57.9	29.7	46.0	13
2.	15	48.8	65.9	68.4	68.0	84.0	93.7	68.8	66.2	60.4	58.0	29.7	46.4	13
3.	30	49.0	66.1	68.7	68.5	84.3	94.1	69.0	66.4	61.3	58.3	29.5	46.8	13
4.	45	49.5	66.4	69.2	68.8	84.6	94.4	69.3	66.9	61.6	59.1	29.0	47.2	13
5.	60	49.8	66.7	69.6	68.9	84.8	94.9	69.7	67.0	61.8	59.3	28.7	46.7	13
6.	75	50.0	67.0	69.8	69.1	85.0	95.1	70.1	67.3	62.0	59.7	28.7	46.9	13
7.	90	50.5	67.3	70.1	69.9	85.5	95.6	92.0	67.5	62.1	60.0	27.9	47.5	13
8.	105	50.5	67.3	70.1	69.9	85.5	95.6	92.0	67.5	62.1	60.0	27.9	47.5	13
9.	120	50.5	67.3	70.1	69.9	85.5	95.6	92.0	67.5	62.1	60.0	27.9	47.5	13

Voltage = 136.9 V, Current = 2.03A

Flow rate= 1LPA

Table 16: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	35.3	36.5	39.5	41.5	49.7	55.3	51.0	38.0	37.4	34.8	30.1	31.9	20
2.	15	35.7	38.9	39.7	41.7	50.0	55.9	51.2	38.2	37.6	35.1	29.7	32.2	20
3.	30	36.0	39.1	40.0	42.0	50.3	56.1	51.9	38.8	38.0	35.5	29.6	32.6	20
4.	45	36.4	39.4	40.2	42.4	50.5	56.7	52.2	39.1	38.2	35.7	29.1	32.9	20
5.	60	36.7	39.8	40.5	42.6	50.9	57.0	52.5	39.4	38.5	36.1	28.5	33.3	20
6.	75	34.1	40.1	41.0	42.8	51.1	57.3	52.9	39.9	38.9	36.4	28.5	33.6	20
7.	90	34.5	40.6	41.3	43.0	51.4	57.7	53.1	40.3	39.1	37.6	28.3	32.6	20
8.	105	34.5	40.6	41.3	43.0	51.4	57.7	53.1	40.3	39.1	37.6	28.3	32.6	20
9.	120	34.5	40.6	41.3	43.0	51.4	57.7	53.1	40.3	39.1	37.6	28.3	32.6	20

Table 17: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	34.1	39.8	42.4	42.5	58.7	67.6	63.8	42.1	38.6	37.0	29.9	32.2	15
2.	15	34.5	39.8	42.6	42.8	59.0	67.7	64.0	42.4	39.0	37.3	29.5	32.6	15
3.	30	34.8	40.1	42.8	42.9	59.2	68.2	64.6	42.8	39.1	37.6	29.3	33.0	15
4.	45	35.1	40.4	43.1	43.3	59.5	68.9	64.7	43.1	39.4	38.0	28.4	33.3	15
5.	60	35.4	40.8	43.4	43.6	59.7	69.1	65.1	43.4	39.7	38.2	28.3	33.9	15
6.	75	35.9	40.0	43.7	43.9	60.1	69.5	65.5	43.9	39.9	38.6	28.1	34.6	15
7.	90	36.3	41.2	43.6	44.0	60.3	68.1	64.9	43.7	39.9	38.8	26.7	34.1	15
8.	105	36.3	41.2	43.6	44.0	60.3	68.1	64.9	43.7	39.9	38.8	26.7	34.1	15
9.	120	36.3	41.2	43.6	44.0	60.3	68.1	64.9	43.7	39.9	38.8	26.7	34.1	15

Table 18: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	39.5	43.0	47.4	47.8	62.1	71.9	68.6	46.3	43.0	39.8	29.7	34.0	16
2.	15	39.8	43.6	47.9	48.0	62.6	72.0	68.8	46.8	43.4	40.1	29.7	34.4	16
3.	30	41.0	44.1	48.2	48.5	62.9	72.3	69.0	47.1	43.9	40.4	29.5	34.8	16
4.	45	41.1	44.4	48.6	48.8	63.1	72.6	69.3	47.6	44.0	40.6	29.0	35.4	16
5.	60	41.4	44.7	48.8	48.9	63.4	72.9	69.7	47.9	44.3	40.8	28.7	35.7	16
6.	75	41.8	45.0	49.0	49.1	63.8	73.1	70.1	48.0	44.7	41.0	28.7	35.9	16
7.	90	40.3	43.5	45.3	45.1	61.6	72.2	70.0	49.6	41.8	40.5	27.4	36.2	16
8.	105	40.3	43.5	45.3	45.1	61.6	72.2	70.0	49.6	41.8	40.5	27.4	36.2	16
9.	120	40.3	43.5	45.3	45.1	61.6	72.2	70.0	49.6	41.8	40.5	27.4	36.2	16

Voltage = 136.9 V, Current = 2.03A

Flow rate= 1.5LPA

Table 19: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	34.3	40.5	42.5	42.5	51.7	58.5	61.6	40.5	38.2	37.8	30.1	30.9	27
2.	15	34.7	40.9	42.7	42.7	52.0	58.7	61.8	40.7	38.4	38.1	29.7	31.2	27
3.	30	35.0	41.1	43.0	42.9	52.3	59.0	62.0	41.2	38.8	38.5	29.6	31.6	27
4.	45	35.4	41.4	43.2	43.4	52.5	59.2	62.7	41.4	39.2	38.7	29.1	31.9	27
5.	60	35.7	41.8	43.5	43.6	52.9	59.4	63.0	41.8	39.5	38.9	28.5	32.3	27
6.	75	36.1	42.1	43.9	43.8	53.1	59.9	63.2	42.0	39.9	39.4	28.5	32.6	27
7.	90	36.4	42.5	44.1	44.2	53.5	60.3	63.9	42.1	40.5	39.6	27.9	32.9	27
8.	105	36.4	42.5	44.1	44.2	53.5	60.3	63.9	42.1	40.5	39.6	27.9	32.9	27
9.	120	36.4	42.5	44.1	44.2	53.5	60.3	63.9	42.1	40.5	39.6	27.9	32.9	27

Table 20: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	35.1	41.8	45.4	45.5	53.7	65.6	64.8	42.5	38.6	38.0	29.7	32.2	19
2.	15	35.5	42.1	45.6	45.8	54.0	65.7	65.0	42.9	39.0	38.3	29.5	32.6	19
3.	30	35.8	42.5	45.8	45.9	54.2	66.2	65.6	43.0	39.1	38.6	29.0	33.0	19
4.	45	36.1	42.7	46.1	46.3	54.5	66.9	65.7	43.4	39.4	39.0	28.6	33.3	19
5.	60	36.4	43.0	46.4	46.6	54.7	67.1	66.1	43.9	39.7	39.2	28.3	33.9	19
6.	75	36.5	43.2	46.7	46.9	55.1	67.5	66.5	44.1	41.0	39.6	28.4	34.6	19
7.	90	36.9	43.6	47.3	47.1	55.2	68.0	66.7	44.5	41.3	39.9	26.9	34.9	19
8.	105	36.9	43.6	47.3	47.1	55.2	68.0	66.7	44.5	41.3	39.9	26.9	34.9	19
9.	120	36.9	43.6	47.3	47.1	55.2	68.0	66.7	44.5	41.3	39.9	26.9	34.9	19

Table 21: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	39.5	42.0	45.4	44.8	62.1	71.9	68.6	46.3	42.0	39.8	29.9	35.0	20
2.	15	39.8	42.6	45.9	45.0	62.6	72.0	68.8	46.8	42.4	40.1	29.7	35.4	20
3.	30	40.0	43.1	46.2	45.5	62.9	72.3	69.0	47.1	42.9	40.4	29.5	35.8	20
4.	45	40.6	43.4	46.6	45.8	63.1	72.6	69.3	47.6	43.0	40.6	29.0	36.4	20
5.	60	40.0	43.7	46.6	45.9	63.4	72.9	69.7	47.9	43.3	40.8	28.7	36.7	20
6.	75	41.3	44.0	46.9	46.1	63.8	73.1	70.1	48.0	43.7	41.0	28.7	36.9	20
7.	90	41.5	44.6	47.1	47.2	64.4	74.1	71.3	49.9	44.1	42.5	29.3	37.3	20
8.	105	41.5	44.6	47.1	47.2	64.4	74.1	71.3	49.9	44.1	42.5	29.3	37.3	20
9.	120	41.5	44.6	47.1	47.2	64.4	74.1	71.3	49.9	44.1	42.5	29.3	37.3	20

Voltage = 136.9 V, Current = 2.03A

Flow rate= 2 LPA

Table 22: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	35.1	40.5	43.5	43.5	53.7	59.5	59.6	42.0	37.7	36.8	30.1	31.9	33
2.	15	35.3	40.9	43.7	43.7	54.0	59.7	59.8	42.2	38.0	36.1	29.7	32.2	33
3.	30	35.7	41.1	43.6	44.2	54.3	59.9	61.0	42.4	38.6	37.5	29.6	32.6	33
4.	45	36.1	41.4	43.9	44.4	54.5	60.2	61.7	42.8	38.9	37.7	29.1	32.9	33
5.	60	36.5	41.8	44.1	44.6	54.9	60.4	61.9	43.1	39.5	38.1	28.5	33.3	33
6.	75	36.8	42.1	44.7	44.9	55.1	61.0	62.2	43.3	39.9	38.4	28.5	33.6	33
7.	90	37.1	42.7	44.9	45.0	55.3	61.2	62.4	43.2	40.9	39.8	29.2	33.3	33
8.	105	37.1	42.7	44.9	45.0	55.3	61.2	62.4	43.2	40.9	39.8	29.2	33.3	33
9.	120	37.1	42.7	44.9	45.0	55.3	61.2	62.4	43.2	40.9	39.8	29.2	33.3	33

Table 23: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	35.1	41.8	46.4	46.5	53.7	67.6	61.8	43.0	39.0	38.0	29.7	32.2	25
2.	15	35.5	42.1	46.6	46.8	54.2	67.7	62.0	43.1	39.4	38.3	29.5	32.6	25
3.	30	36.5	42.5	46.8	46.9	54.8	68.2	65.6	43.5	39.9	38.6	29.0	33.0	25
4.	45	36.7	42.7	47.1	47.3	55.0	68.9	65.7	43.8	40.4	39.0	28.6	33.3	25
5.	60	37.2	43.0	47.4	47.6	55.6	69.1	67.1	44.4	40.7	39.2	28.3	33.9	25
6.	75	37.5	43.2	47.7	47.9	55.9	69.5	67.5	44.9	41.0	39.6	28.4	34.6	25
7.	90	37.8	44.2	48.1	48.2	56.1	69.4	68.7	45.1	41.3	39.9	26.9	34.9	25
8.	105	37.8	44.2	48.1	48.2	56.1	69.4	68.7	45.1	41.3	39.9	26.9	34.9	25
9.	120	37.8	44.2	48.1	48.2	56.1	69.4	68.7	45.1	41.3	39.9	26.9	34.9	25

Table 24: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	36.5	43.0	47.0	47.8	62.9	72.9	69.0	47.3	43.0	41.8	29.7	35.0	27
2.	15	36.8	43.6	47.5	48.0	63.1	73.0	69.2	47.8	43.4	42.1	29.7	35.4	27
3.	30	37.0	44.1	47.7	48.5	63.4	73.7	69.7	48.1	43.9	42.4	29.5	35.8	27
4.	45	37.1	44.4	47.9	48.8	63.9	73.2	70.3	48.6	44.0	42.6	29.0	36.4	27
5.	60	37.4	44.7	48.1	48.9	64.4	73.9	71.7	48.9	44.3	42.8	28.7	36.7	27
6.	75	37.8	45.0	48.4	49.1	64.6	74.1	72.1	49.0	44.7	43.0	28.7	36.9	27
7.	90	38.2	45.5	48.6	48.9	64.9	74.8	73.6	50.2	45.0	43.6	29.2	37.5	27
8.	105	38.2	45.5	48.6	48.9	64.9	74.8	73.6	50.2	45.0	43.6	29.2	37.5	27
9.	120	38.2	45.5	48.6	48.9	64.9	74.8	73.6	50.2	45.0	43.6	29.2	37.5	27

Voltage = 185.1 V, Current = 2.57A

Flow rate= 0.5LPA

Table 25: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	37.3	39.5	40.5	40.5	56.7	65.5	62.6	45.0	37.4	34.8	30.1	31.9	17
2.	15	37.7	39.9	40.7	40.7	57.0	65.7	62.8	45.5	37.6	35.1	29.7	32.2	17
3.	30	38.0	40.1	41.0	41.2	57.3	66.0	63.0	45.8	38.0	35.5	29.6	32.6	17
4.	45	38.4	40.4	41.2	41.4	57.5	66.2	63.7	46.2	38.2	35.7	29.1	32.9	17
5.	60	38.7	40.8	41.5	41.6	57.9	66.4	64.0	46.5	38.5	36.1	28.5	33.3	17
6.	75	39.1	41.1	41.9	42.0	58.1	66.9	64.2	46.9	38.9	36.4	28.5	33.6	17
7.	90	39.4	41.4	42.2	42.3	58.4	67.1	64.4	47.1	39.1	36.7	28.5	34.0	17
8.	105	39.4	41.4	42.2	42.3	58.4	67.1	64.4	47.1	39.1	36.7	28.5	34.0	17
9.	120	39.4	41.4	42.2	42.3	58.4	67.1	64.4	47.1	39.1	36.7	28.5	34.0	17

Table 26: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	38.1	41.8	42.4	42.5	58.7	67.6	63.8	42.1	38.6	38.0	29.7	32.2	10
2.	15	38.5	42.1	42.6	42.8	59.0	67.7	64.0	42.4	39.0	38.3	29.5	32.6	10
3.	30	38.8	42.5	42.8	42.9	59.2	68.2	64.6	42.8	39.1	38.6	29.0	33.0	10
4.	45	39.1	42.7	43.1	43.3	59.5	68.9	64.7	43.1	39.4	39.0	28.6	33.3	10
5.	60	39.4	43.0	43.4	43.6	59.7	69.1	65.1	43.4	39.7	39.2	28.3	33.9	10
6.	75	39.9	43.2	43.7	43.9	60.1	69.5	65.5	43.9	41.0	39.6	28.4	34.6	10
7.	90	40.2	43.2	44.0	44.2	60.4	69.9	65.7	44.3	41.1	39.9	28.1	35.0	10
8.	105	40.2	43.2	44.0	44.2	60.4	69.9	65.7	44.3	41.1	39.9	28.1	35.0	10
9.	120	40.2	43.2	44.0	44.2	60.4	69.9	65.7	44.3	41.1	39.9	28.1	35.0	10

Table 27: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	39.5	43.0	47.4	47.8	62.1	71.9	68.6	46.3	43.0	39.8	29.7	34.0	15
2.	15	39.8	43.6	47.9	48.0	62.6	72.0	68.8	46.8	43.4	40.1	29.7	34.4	15
3.	30	41.0	44.1	48.2	48.5	62.9	72.3	69.0	47.1	43.9	40.4	29.5	34.8	15
4.	45	41.1	44.4	48.6	48.8	63.1	72.6	69.3	47.6	44.0	40.6	29.0	35.4	15
5.	60	41.4	44.7	48.8	48.9	63.4	72.9	69.7	47.9	44.3	40.8	28.7	35.7	15
6.	75	41.8	45.0	49.0	49.1	63.8	73.1	70.1	48.0	44.7	41.0	28.7	35.9	15
7.	90	42.1	45.3	49.4	49.3	64.2	73.5	70.1	48.0	45.1	41.4	28.7	36.1	15
8.	105	42.1	45.3	49.4	49.3	64.2	73.5	70.1	48.0	45.1	41.4	28.7	36.1	15
9.	120	42.1	45.3	49.4	49.3	64.2	73.5	70.1	48.0	45.1	41.4	28.7	36.1	15

Voltage = 185.1 V, Current = 2.57A

Flow rate= 1.0 LPM

Table 28: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	39.3	41.5	42.7	43.1	59.2	68.2	64.3	48.0	39.8	39.1	30.1	31.9	25
2.	15	39.7	41.9	43.2	43.5	59.6	68.5	64.8	48.2	40.1	39.4	29.7	32.2	25
3.	30	40.0	42.1	43.8	43.9	60.3	68.7	65.1	48.9	40.4	39.8	29.6	32.6	25
4.	45	40.4	42.4	43.9	44.0	60.5	69.2	65.4	49.2	40.7	40.3	29.1	32.9	25
5.	60	40.7	42.8	44.0	44.2	60.9	69.4	65.6	49.5	41.4	40.5	28.5	33.3	25
6.	75	41.1	43.1	44.2	44.6	61.1	66.9	66.0	49.8	41.9	40.9	28.5	33.6	25
7.	90	41.9	43.7	44.5	44.7	61.2	69.9	66.2	50.1	42.1	41.1	28.8	34.5	25
8.	105	41.9	43.7	44.5	44.7	61.2	69.9	66.2	50.1	42.1	41.1	28.8	34.5	25
9.	120	41.9	43.7	44.5	44.7	61.2	69.9	66.2	50.1	42.1	41.1	28.8	34.5	25

Table 29: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	41.7	43.8	45.9	45.8	61.4	69.6	66.8	51.1	39.3	41.0	29.7	32.2	15
2.	15	42.1	44.1	46.1	46.2	61.8	69.7	67.0	51.4	39.8	41.3	29.5	32.6	15
3.	30	42.5	44.5	46.5	46.4	62.0	70.2	67.2	51.8	40.1	41.6	29.0	32.9	15
4.	45	42.9	44.7	46.8	46.9	62.5	70.9	67.5	52.1	40.4	42.0	28.6	33.0	15
5.	60	43.0	45.0	47.1	47.1	62.7	71.1	67.9	52.4	40.7	42.2	28.3	33.1	15
6.	75	43.4	45.2	47.5	47.5	63.1	71.7	68.5	52.9	41.0	42.6	28.4	34.2	15
7.	90	43.8	45.6	47.7	47.9	63.8	72.1	68.8	53.2	44.5	43.1	29.2	33.2	15
8.	105	43.8	45.6	47.7	47.9	63.8	72.1	68.8	53.2	44.5	43.1	29.2	33.2	15
9.	120	43.8	45.6	47.7	47.9	63.8	72.1	68.8	53.2	44.5	43.1	29.2	33.2	15

Table 30: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	43.5	44.3	46.4	46.8	66.1	73.9	67.6	52.3	44.0	43.8	28.7	31.8	20
2.	15	43.8	44.6	46.9	47.0	66.6	74.0	67.8	52.8	44.4	44.1	28.4	32.0	20
3.	30	44.0	45.1	47.2	47.5	66.9	74.3	68.0	53.1	44.9	44.4	28.1	32.3	20
4.	45	44.1	45.4	47.6	47.8	67.1	74.9	68.3	53.6	45.0	44.7	29.0	32.9	20
5.	60	44.4	45.7	47.8	48.0	67.4	75.5	68.7	53.9	45.3	45.3	28.7	33.1	20
6.	75	44.8	46.0	48.0	48.4	67.8	75.9	69.1	54.1	45.7	45.5	28.7	33.4	20
7.	90	45.1	46.1	48.2	48.9	68.1	76.0	69.2	54.6	46.1	45.9	28.7	33.6	20
8.	105	45.1	46.1	48.2	48.9	68.1	76.0	69.2	54.6	46.1	45.9	28.7	33.6	20
9.	120	45.1	46.1	48.2	48.9	68.1	76.0	69.2	54.6	46.1	45.9	28.7	33.6	20

Voltage = 185.1 V, Current = 2.57A

Flow rate= 1.5 LPA

Table 31: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	41.0	44.5	46.5	46.2	64.5	73.7	68.7	49.3	41.1	40.0	30.1	31.9	30
2.	15	41.1	44.9	46.7	46.3	64.9	73.8	68.8	49.6	41.6	40.2	29.7	32.2	30
3.	30	41.4	45.1	47.0	46.9	65.0	74.1	69.1	49.9	41.7	40.6	29.6	32.6	30
4.	45	41.8	45.4	47.2	47.0	65.3	74.5	69.4	50.3	42.0	40.8	29.1	32.9	30
5.	60	42.0	45.8	47.5	47.5	65.8	74.9	69.8	50.8	42.3	41.3	28.5	33.3	30
6.	75	42.1	46.1	47.9	47.8	66.1	75.2	70.1	51.0	42.6	41.9	28.5	33.6	30
7.	90	42.5	46.3	48.0	48.1	66.4	75.5	70.4	51.2	42.9	42.0	28.1	34.3	30
8.	105	42.5	46.3	48.0	48.1	66.4	75.5	70.4	51.2	42.9	42.0	28.1	34.3	30
9.	120	42.5	46.3	48.0	48.1	66.4	75.5	70.4	51.2	42.9	42.0	28.1	34.3	30

Table 32: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	42.1	45.8	47.4	47.5	58.7	67.6	63.8	47.1	38.6	38.0	29.7	32.2	22
2.	15	42.5	46.1	47.6	47.8	59.0	67.7	64.0	47.4	39.0	38.3	29.5	32.4	22
3.	30	42.8	46.5	47.8	48.0	59.2	68.2	64.6	47.5	39.1	38.6	29.0	32.5	22
4.	45	43.1	46.7	48.1	48.3	59.5	68.9	64.7	47.9	39.4	39.0	28.6	32.9	22
5.	60	43.4	47.0	48.4	48.9	59.7	69.1	65.1	48.4	39.7	39.2	28.3	33.0	22
6.	75	43.3	47.2	48.7	49.3	60.1	69.5	65.5	48.1	41.0	39.9	28.4	33.3	22
7.	90	43.6	47.2	49.6	49.5	67.7	78.1	73.6	52.6	45.1	44.2	28.5	34.5	22
8.	105	43.6	47.2	49.6	49.5	67.7	78.1	73.6	52.6	45.1	44.2	28.5	34.5	22
9.	120	43.6	47.2	49.6	49.5	67.7	78.1	73.6	52.6	45.1	44.2	28.5	34.5	22

Table 33: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	43.5	48.0	49.1	49.8	64.8	79.3	75.1	52.4	44.7	44.1	31.7	32.0	25
2.	15	43.8	48.6	49.5	50.0	65.1	79.4	74.4	52.6	45.1	44.3	31.7	32.4	25
3.	30	44.0	48.1	49.8	50.3	65.6	79.6	74.9	53.2	45.3	44.8	31.5	32.8	25
4.	45	44.1	48.4	50.3	50.8	65.8	80.1	75.3	53.4	45.9	45.0	31.0	33.0	25
5.	60	44.4	48.7	50.5	50.9	66.0	80.4	75.8	53.9	46.0	45.4	30.7	33.3	25
6.	75	44.9	48.8	50.8	51.1	66.2	80.9	76.0	54.3	46.1	45.9	30.8	33.5	25
7.	90	45.2	49.1	51.2	51.4	66.6	81.2	76.2	54.8	46.5	46.0	29.1	34.9	25
8.	105	45.2	49.1	51.2	51.4	66.6	81.2	76.2	54.8	46.5	46.0	29.1	34.9	25
9.	120	45.2	49.1	51.2	51.4	66.6	81.2	76.2	54.8	46.5	46.0	29.1	34.9	25

Voltage = 185.1 V, Current = 2.57A

Flow rate= 2.0 LPA

Table 34: Temperature and pressure drop readings of water

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	41.9	53.9	54.1	73.8	82.0	72.5	51.1	49.0	41.1	39.8	30.1	31.9	35
2.	15	42.0	54.2	54.3	74.0	82.1	72.9	51.3	49.3	41.6	41.0	29.7	32.2	35
3.	30	42.3	54.4	54.5	74.2	82.4	73.2	51.6	49.7	41.9	41.5	29.6	32.6	35
4.	45	42.8	54.7	54.9	74.7	82.7	73.8	51.9	50.3	42.1	42.0	29.1	32.9	35
5.	60	43.1	55.1	55.3	75.1	83.0	74.0	52.0	50.8	42.5	42.4	28.5	33.3	35
6.	75	43.4	55.3	55.5	75.4	83.4	74.3	52.3	51.0	42.8	42.7	28.5	33.6	35
7.	90	43.7	55.6	55.7	75.6	83.6	74.5	52.7	51.6	43.1	42.8	28.5	34.0	35
8.	105	43.7	55.6	55.7	75.6	83.6	74.5	52.7	51.6	43.1	42.8	28.5	34.0	35
9.	120	43.7	55.6	55.7	75.6	83.6	74.5	52.7	51.6	43.1	42.8	27.8	34.7	35

Table 35: Temperature and pressure drop readings of 0.1% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	44.2	54.0	56.2	57.0	78.2	87.8	73.7	54.5	44.1	43.0	29.7	32.2	25
2.	15	44.8	54.2	56.9	57.3	78.4	88.0	74.1	55.0	44.4	43.4	29.5	32.6	25
3.	30	45.1	54.7	57.0	57.7	78.6	88.2	74.4	55.3	44.8	43.6	29.0	33.0	25
4.	45	45.3	55.1	57.3	58.0	78.9	88.8	74.9	55.6	45.1	44.1	28.6	33.3	25
5.	60	45.8	55.6	57.5	58.3	79.2	89.1	75.1	55.8	45.4	44.3	28.3	33.9	25
6.	75	45.9	55.8	58.1	58.5	79.6	89.5	75.6	56.0	45.6	44.7	28.4	34.6	25
7.	90	46.1	56.0	58.4	58.8	79.9	89.8	75.7	56.2	45.6	44.8	28.4	35.0	25
8.	105	46.1	56.0	58.4	58.8	79.9	89.8	75.7	56.2	45.6	44.8	28.4	35.0	25
9.	120	46.1	56.0	58.4	58.8	79.9	89.8	75.7	56.2	45.6	44.8	28.4	35.0	25

Table 36: Temperature and pressure drop readings of 0.5% nanofluid

S.No.	Time (min)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)	Δp (mm of water)
1.	0	46.2	56.0	59.4	47.8	78.4	89.2	76.5	57.1	44.7	44.3	29.7	34.0	30
2.	15	46.6	56.3	59.5	48.0	78.8	89.6	76.9	57.3	45.1	44.6	29.7	34.4	30
3.	30	47.0	56.7	59.8	48.5	79.1	89.8	77.1	57.9	45.4	45.0	29.5	34.8	30
4.	45	47.4	57.0	60.3	48.8	79.3	90.0	77.5	58.1	45.9	45.3	29.0	34.9	30
5.	60	47.9	57.5	60.7	48.9	79.7	90.4	77.8	58.6	46.3	45.8	28.7	35.0	30
6.	75	48.1	57.8	61.1	49.1	81.0	90.7	78.0	58.8	46.7	46.0	28.7	35.1	30
7.	90	48.7	58.2	61.4	61.7	81.2	90.9	78.3	59.2	46.9	46.2	28.9	35.3	30
8.	105	48.7	58.2	61.4	61.7	81.2	90.9	78.3	59.2	46.9	46.2	28.9	35.3	30
9.	120	48.7	58.2	61.4	61.7	81.2	90.9	78.3	59.2	46.9	46.2	28.9	35.3	30

Sample calculations

(A) For water

Steady state temperatures of distilled water at 0.5 LPM

P=V×I (W)	Fluid	Flow rate (LPM)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T ₄ (°C)	T ₅ (°C)	T ₆ (°C)	T ₇ (°C)	T ₈ (°C)	T ₉ (°C)	T ₁₀ (°C)	T ₁₁ (°C)	T ₁₂ (°C)
218.4	DW	0.5	33.6	38.5	39.1	41.8	55.3	63.6	61.1	39.7	37.2	35.5	26.9	32.3

Flow rate (Q) = 0.5 LPM = 8.33×10^{-6} m³/s

$$\text{Bulk mean temperature: } \bar{T}_b = \frac{T_8 + T_1}{2} \quad (1)$$

$$\bar{T}_b = (39.7 + 33.6) / 2 = 36.65^\circ\text{C}$$

Outside surface temperature can be calculated as:

$$T_{so} = \frac{(T_2 + T_3 + T_4 + T_5 + T_6 + T_7)}{6} \quad (2)$$

$$T_{so} = (38.5 + 39.1 + 41.8 + 55.3 + 63.6 + 61.1) / 6$$

$$T_{so} = 49.9^\circ\text{C}$$

At bulk mean temperature, $C_p = 4174$ J/kg.K

$$\rho = 993.3 \text{ kg/m}^3$$

$$\mu = 702.7 \times 10^{-6} \text{ Pa.s}$$

$$k = 0.629 \text{ W/m.K}$$

Mass flow rate, $m = (\text{Volumetric flow rate}) \times (\text{Density})$

$$\dot{m} = (8.33 \times 10^{-6} \text{ m}^3/\text{s}) \times (993.3)$$

$$\dot{m} = 0.008274 \text{ kg/s}$$

$$\text{Heat duty can be calculated as: } Q = \dot{m} C_p (T_8 - T_1) \quad (3)$$

$$Q = 0.008274 \times 4174 \times (39.7 - 33.6) = 210.06 \text{ W}$$

The test section is cylindrical in shape, therefore,

$$Q = 2\pi kL \frac{T_{so} - T_{si}}{\ln(r_o / r_i)} \quad (4)$$

$$Q = 210.06 \text{ W,}$$

$$k = 0.629 \text{ W/m.K,}$$

$$L = 1.5 \text{ m,}$$

$$r_o = 0.00585 \text{ m and } r_i = 0.00635 \text{ m}$$

Therefore, using equation (4), T_{s_i} can be calculated,

$$T_{s_i} = 46.99^\circ\text{C}$$

Then, heat transfer coefficient of distilled water can be calculated as:

$$Q = h_i A_i (T_{s_i} - \bar{T}_b)$$

$$h_i = \frac{Q}{A_i (T_{s_i} - \bar{T}_b)}$$

$$T_{s_i} = 46.99^\circ\text{C and } \bar{T}_b = 36.65^\circ\text{C}$$

$$A_i = \pi d_i L = 0.055107 \text{ m}^2$$

$$h_i = 210.06 / [0.055107 \times (46.99 - 36.65)]$$

$$h_i = 369.22 \text{ W/m}^2.\text{K}$$

Nusselt number:

$$Nu = \frac{h_i d_i}{k_f}; \quad h_i = 369.22 \text{ W/m}^2.\text{K}, \quad d_i = 0.0117 \text{ m and } k_f = 0.629 \text{ W/m.K}$$

$$Nu = 6.86$$

Reynolds number:

$$R_e = \frac{d_i v_i \rho_i}{\mu_f}; \quad v_i = 0.07745 \text{ m/s}, \quad \rho_i = 993.3 \text{ kg/m}^3 \text{ and } \mu_f = 702.7 \times 10^{-6} \text{ Pa.s}$$

$$R_e = 1282.0$$

Likewise other calculations of heat transfer coefficient, Reynolds number and Nusselt number has been done for distilled water at various flow rates and power inputs.

(B) For nanofluid

Steady state temperatures of 0.1 volume % at 0.5 LPM

P=V×I (W)	Flow rate (LPM)	T₁ (°C)	T₂ (°C)	T₃ (°C)	T₄ (°C)	T₅ (°C)	T₆ (°C)	T₇ (°C)	T₈ (°C)	T₉ (°C)	T₁₀ (°C)	T₁₁ (°C)	T₁₂ (°C)
218.4	0.5	35.7	40.1	41.3	43.7	58.2	66.6	63.3	42.1	39.5	37.6	28.1	34.4

Flow rate (Q) = 0.5 LPM = 8.33×10^{-6} m³/s

$$\text{Bulk mean temperature: } \bar{T}_b = \frac{T_8 + T_1}{2} \quad (1)$$

$$\bar{T}_b = (35.7 + 42.1) / 2 = 38.9^\circ\text{C}$$

Outside surface temperature can be calculated as:

$$T_{so} = \frac{(T_2 + T_3 + T_4 + T_5 + T_6 + T_7)}{6} \quad (2)$$

$$T_{so} = (40.1 + 41.3 + 43.7 + 58.2 + 66.6 + 63.6) / 6$$

$$T_{so} = 52.2^\circ\text{C}$$

At bulk mean temperature, C_p can be calculated using equation:

$$C_{P_{nf}} = \phi C_{P_s} + (1 - \phi) C_{P_{bf}} \quad (3)$$

$$C_{P_{nf}} = C_p \text{ of nanofluid}$$

$$C_{P_s} = C_p \text{ of solid alumina nanoparticle; } 880 \text{ J/kg.K}$$

$$C_{P_{bf}} = C_p \text{ of base fluid i.e } 4174 \text{ J/kg.K}$$

$$\phi = \text{Volume fraction of nanoparticle, } 0.1 \text{ volume \%}$$

Using equation (3), C_{P_{nf}} can be calculated

$$C_{P_{nf}} = 3844.6 \text{ J/kg.K}$$

Density, thermal conductivity and viscosity have been measured experimentally;

$$\rho = 1038.9 \text{ kg/m}^3$$

$$\mu = 708.6 \times 10^{-6} \text{ Pa.s}$$

$$k = 0.631 \text{ W/m.K}$$

Mass flow rate, m = (Volumetric flow rate) × (Density)

$$\dot{m} = (8.33 \times 10^{-6} \text{ m}^3/\text{s}) \times (1038.9)$$

$$\dot{m} = 0.008654 \text{ kg/s}$$

Heat duty can be calculated as: $Q = \dot{m} C_p (T_8 - T_1)$ (4)

$$Q = 0.008654 \times 3844.6 \times (42.1 - 35.6) = 216.2 \text{ W}$$

The test section is cylindrical in shape, therefore,

$$Q = 2\pi kL \frac{T_{so} - T_{si}}{\ln(r_o / r_i)} \quad (5)$$

$$Q = 216.2 \text{ W},$$

$$k = 0.631 \text{ W/m.K},$$

$$L = 1.5 \text{ m},$$

$$r_o = 0.00585 \text{ m and } r_i = 0.00635 \text{ m}$$

Therefore, using equation (5), T_{si} can be calculated,

$$T_{si} = 49.2^\circ\text{C}$$

Then, heat transfer coefficient of distilled water can be calculated as:

$$Q = h_i A_i (T_{si} - \bar{T}_b)$$

$$h_i = \frac{Q}{A_i (T_{si} - \bar{T}_b)}$$

$$T_{si} = 49.2^\circ\text{C and } \bar{T}_b = 38.9^\circ\text{C}$$

$$A_i = \pi d_i L = 0.055107 \text{ m}^2$$

$$h_i = 216.2 / [0.055107 \times (49.2 - 38.9)]$$

$$h_i = 372.5 \text{ W/m}^2.\text{K}$$

Nusselt number:

$$Nu = \frac{h_i d_i}{k_f}; \quad h_i = 372.5 \text{ W/m}^2.\text{K}, \quad d_i = 0.0117 \text{ m and } k_f = 0.631 \text{ W/m.K}$$

$$Nu = 6.90$$

Reynolds number:

$$R_e = \frac{d_i v_i \rho_i}{\mu_f}; \quad v_i = 0.07745 \text{ m/s}, \quad \rho_i = 1038.9 \text{ kg/m}^3 \text{ and } \mu_f = 708.6 \times 10^{-6} \text{ Pa.s}$$

$$R_e = 1328.5$$

Likewise other calculations of heat transfer coefficient, Reynolds number and Nusselt number has been done for nanofluid at various flow rates and power inputs.