HEAT TRANSFER PERFORMANCE INVESTIGATION OF A WATER COOLED CHILLER OPERATED WITH NANOFLUID

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FACULTY OF ENGINEERING

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ABSTRACT

Nanofluid is the suspension of nanoparticles in a base fluid. Nanofluids are promising fluids for heat transfer enhancement due to their anomalously high thermal conductivity. At present, there is a significant discrepancy in nanofluid thermal conductivity data obtained from various experimental models & researches conducted.

In the first part of this research report, a detailed study on nanofluid had been discussed and found that three properties of nanofluid are being a promising coolant which are increased thermal conductivity, increased single phase heat transfer and its stability.

Types of nanofluid that possibly be used as coolant for water chillers, properties of nanofluid and how it could improve in enhancement of heat transfer of water chillers using nanofluid had been discussed. Moreover, characteristics of nanofluid for the improvement of heat transfer rate due to the effect of some parameters such as particle size and shape, particle materials, and temperature on the thermal conductivity models are also explained. Mechanism of thermal conductivity of nanofluid, challenges and future development of nanofluid was also included in this study.

In the second part, studies on what is chiller, types of chillers, detail explanation of water chillers and its working principle had been performed. Adding on, the purpose of cooling system for water chillers, types of coolant used for heat transfer purposes, and advantages of using nanofluid in water chiller had been explained.

In the final part of this study, a comparison calculation had been performed for heat transfer performance investigation of water chiller using water and two different types of nanoparticles which is Al_2O_3 & TiO_2, which are used as coolant for water chillers in this research report.

It was observed that the highest heat transfer rate achieved using Al_2O_3 nanofluid was 29,128.62 W with 5.0 m/s inlet velocity by 0.5% particle volume fraction, followed by TiO_2 nanofluid 29,126.19 W with 0.5% particle volume fraction at 5m/s inlet velocity, and finally using pure water in water chiller with 26,661.18 W at 5.0m/s inlet velocity.

ABSTRAK

Nanofluid terdiri daripada nanopartikel di dalam bendalir asas. Nanofluid adalah cecair yang digunakan untuk meningkatkan kadar pemindahan haba disebabkan oleh kekonduksian haba mereka yang amat tinggi. Pada masa kini, terdapat satu perbezaan yang amat ketara dalam data kekonduksian haba nanofluid yang diperolehi daripada pelbagai model penyelidikan dan ujikaji yang dilaksanakan oleh para penyelidik.

Dalam bahagian pertama, kajian mengenai nanofluid telah dibincangkan dan didapati terdapat tiga ciri-ciri nanofluid dijadikan sebagai bahan penyejuk iaitu peningkatan kekonduksian haba, peningkatan fasa tunggal pemindahan haba dan kestabilannya.

Jenis nanofluid yang digunakan sebagai bahan penyejuk untuk pendingin air, sifat-sifat nanofluid dan cara ia dapat meningkatkan pemindahan haba bagi pendingin air menggunakan nanofluid telah dibincangkan. Selain itu, ciri-ciri nanofluid dikaji mengenai kesan penambahbaikan nanofluid disebabkan oleh factor seperti saiz zarah dan bentuk, bahan-bahan zarah, dan suhu diterangkan. Mekanisme keberalihan haba nanofluid, cabaran dan pembangunan masa depan nanofluid juga dibincangkan.

Dalam bahagian kedua, kajian mengenai pendingin air, iaitu jenis pendingin air, dan prinsip penggunaan pendingin air, telah dilakukan. Disamping itu, tujuan sistem penyejukan untuk pendingin air, jenis bahan penyejuk yang digunakan untuk pendingin air bagi tujuan pemindahan haba, dan kelebihan menggunakan nanofluid dalam pendingin air juga telah diterangkan.

Dalam bahagian terakhir pula, pengiraan perbandingan telah dilakukan bagi penyiasatan prestasi pemindahan haba pendingin air menggunakan air dan dua jenis nanopartikel iaitu Al_2O_3 & TiO_2, yang digunakan sebagai bahan penyejuk untuk pendingin air.

Didapati bahawa kadar pemindahan haba tertinggi dicapai dengan menggunakan Al_2O_3 nanofluid sebanyak 29,128.62 W dengan halaju masuk 5.0 m / s oleh zarah 0.5% jumlah pecahan, diikuti oleh TiO_2 nanofluid sebanyak 29,126.19 W dengan jumlah pecahan zarah 0.5% pada 5m / s masuk halaju, dan akhirnya menggunakan air tulen di dalam penyejuk air dengan sebanyak 26,661.18 W pada halaju masuk 5.0m /s.

ACKNOWLEDGEMENT

I would like to express my heartfelt thanks to God for blessing me with the privilege to study on heat transfer performance of a water cooled chiller operated with nanofluids and actually come up with this research report, as I complete my Masters in Mechanical Engineering. It is my firm belief in the almighty that has given me the inspiration to continue and push forward. Next I would like to thank my supervisor Associate Professor Dr Saidur Rahman, for his willingness to allow me to embark on this research as well as his tireless efforts in assisting me throughout this endeavor. Last but not least, I would like to thank my parents and friends for their wonderful encouragement and support throughout that has kept me going thus far.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Channel flow area (m^2)
P	Channel wet perimeter (m)
H_{ch}	Height of rectangular minichannel (m)
W_{ch}	Width of rectangular minichannel (m)
L_{ch}	Length of rectangular minichannel (m)
D_h	Hydraulic diameter of the fluid flow (m)
f	Friction factor
h	Heat transfer coefficient ($W/m^2.K$)
k_{bf}	Thermal conductivity of base fluid (W/m.K)
k_{nf}	Thermal conductivity of nanofluid (W/m.K)
k_p	Thermal conductivity of particle (W/m.K)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
Pr	Prandtl number
ΔP	Pressure drop (kPa)
Q	Heat transfer rate (W)
Re	Reynolds number
$\dot{V}$	Volumetric flow rate (m^3)
Tmax – Tmin	Maximum temperature difference (K)
U_m	Inlet velocity (m/s)
P	Pumping power (W)
N	Number of minichannel

μ	Viscosity of fluid ($N.s/m^2$)
ρ	Density (kg/m^3)
Ø	Particle volume fraction
bf	base fluid (water)
nf	nanofluid
p	particle

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the study

The purpose of this research report is to investigate the heat transfer performance of the water cooled chiller with nanofluid compared to water. This is achieved by using two different types of nanofluid, which are TiO_2 & Al_2O_3 particles with volume fractions, Ø of 0.5%, 0.8%, 1.5%, 2.0% and 4% used along with water, which is used as base fluid, to calculate and compare the heat transfer performance of the water chiller. The comparisons are done by comparing the nanofluid with pure water.

1.2 Overview

At present days, cooling system is the most pressing needs for most of the industrial technology due to ever increasing of heat generation rate at micro-level such as microprocessor and followed by macro level such as cooling for chillers and car engine, etc [Choi et al, 2008].

The air conditioning machine that cools the water is called a chiller. In the chiller, refrigerant that flows through the coils which will eventually cool the room's air. The chilled water is pumped through a piping loop to air handlers in the spaces to be cooled, where the heat it absorbed is released to the refrigerant through the chillers evaporator coil [Nadeem Ener, 2001]

As for water cooled chillers, water flows through the condenser to cool the hot discharge gas to condensing temperature. The normal temperature for chilled water leaving the chiller is about 44°C or 45°C [Adnot et al, 2003].

Today, there are many researches had been conducted by utilizing nanofluids that could provide a basis for an enormous innovation for heat transfer intensification, which is pertinent to a number of industrial sectors including micro-manufacturing, heating, cooling system, ventilation, and air-conditioning industry.

We could observe that the thermal performance and heat transfer in the water chillers are greatly improved with the presence of nanoparticles, based on experiment models which are discussed in the subsequent sections.

1.3 Objective

The objective of this study is to establish that water cooled chillers operated with nanofluid has better heat transfer performance as compared to water. The study is divided into three main parts, for the first part a detail study on nanofluid had been done, followed by part two which covers study on water chiller system and for part three, the calculation and discussions on heat transfer using water and nanofluid had been performed.

CHAPTER II

LITERATURE REVIEW

2.1 Nanofluid

Nanofluid is a fluid containing nanometer-sized particles, called nanoparticles. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid. The nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes. Common base fluids include water, ethylene glycol and oil [Cheng, 2009].

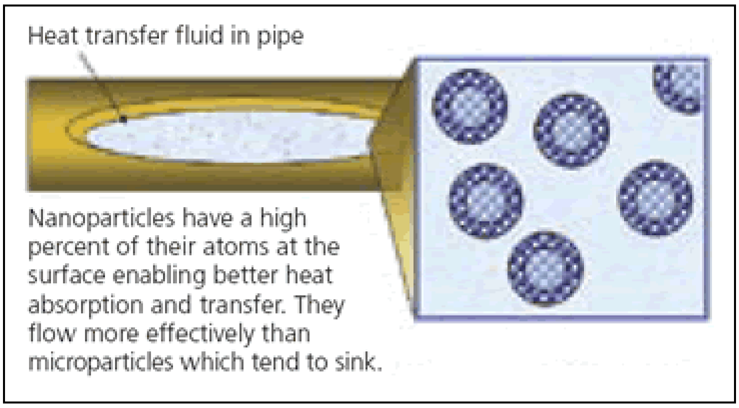

Figure 2.1: Nanofluids used for cooling purpose with the presence of nanoparticles

Nano technology is an emerging science in which new materials and tiny structures are built atom-by-atom, or molecule-by-molecule, instead of the more conventional approach of sculpting parts from pre-existing materials. Nano is a premix meaning one-billionth, so a nanometer is one-billionth of a meter. Just as antibiotics, the silicon transistor and plastics affected nearly every aspect of society in the 20th century. Nanotechnology is expected to have profound influences in the 21st century.

Nanofluids are conventional heat transfer liquids, such as water of glycol mixtures, which contain small volume fraction of suspended nanoparticles in a colloidal solution and studies have indicated that by adding nanoparticles to conventional fluids, they can alter the thermo physical and transport properties of the base fluid [Cheng, 2009].

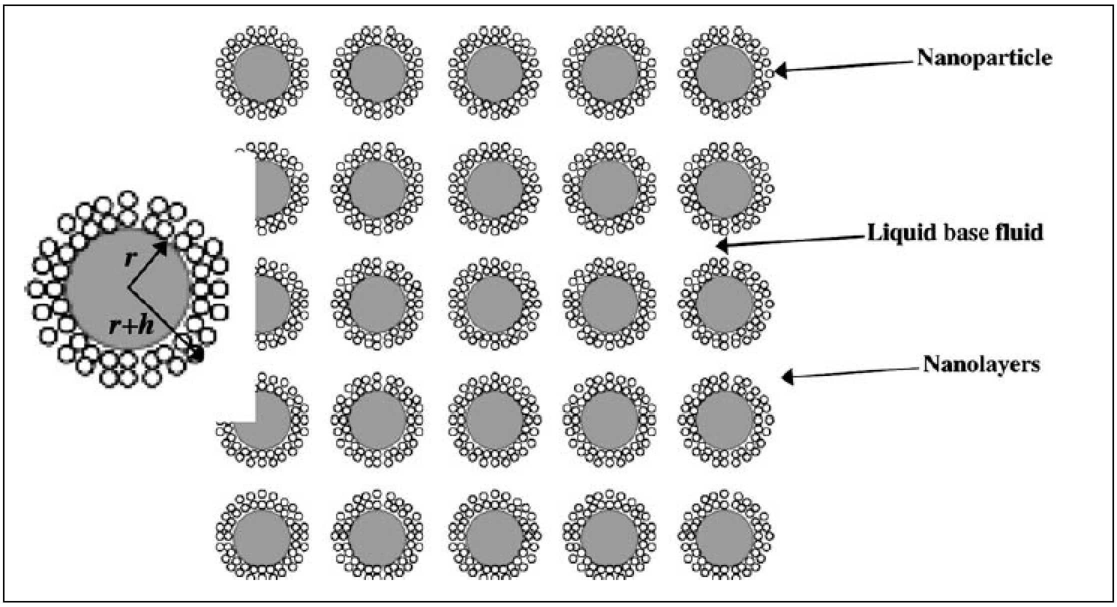

Figure 2.2 : Schematic cross section of Nanofluid structure

Numerous experiments on the thermal conductivity of these fluids have revealed a greater-than expected effective thermal conductivity, and thus there is a great interest in utilizing the nanofluids for heat transfer applications.

Compared to a conventional liquid and conventional two-phase mixture, the nanofluid has higher thermal conductivity, does not block flow channels, and induces a very small pressure drop. Solid particles are added as they conduct heat much better that a liquid. In addition, nanoparticles resist sedimentation, as compared to larger particles, due to

Brownian motion and interparticle forces and possess much higher surface area (1,000-time) which enhances the heat conduction of nanofluids since the heat transfer occurs on the surface of the fluid [Singh et al, 2009],[Raghu et al, 2005].

It has been identified thorough many researches that there are three properties that can make nanofluids promising coolant which are [Das et al, 2006] :-

(i) Increased thermal conductivity

(ii) Increased single-phase heat transfer, and

(iii) Increased critical heat flux.

2.2 Types of nanofluid

Nanofluid has many types, it can be categorized as tribology nanofluid, heat transfer nanofluid, pharmaceutical nanofluid, chemical nanofluid and process nanofluids.

The particles are made of stable metal (silver, gold, copper, etc), metal oxide (alumina, silica, titania, etc), oxide ceramic (Al_2O_3, CuO, etc), metal carbide, metal nitride, carbon in different forms (diamond, graphite, fullerene, carbon nanotubes, etc) [Cheng, 2009].

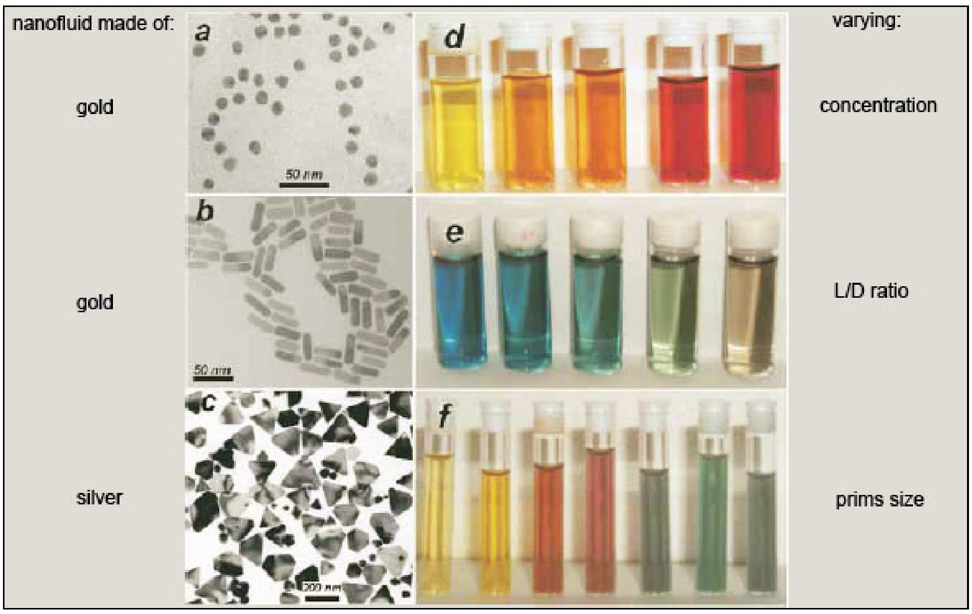

Figure 2.3 : Types of nanofluid made of different particles

Different mechanics has put forth to explain thermal transport enhancement such as interfacial resistance, nanoparticle motion, liquid layering at particle liquid interface and nanoparticle clustering, but the Brownian motion received more attention in researches so far.

2.3 Synthesis of Nanofluids

Choi et al, first prepared nanofluids by mixing nano particles with fluids. Since then, there has been a rapid development in the synthesis techniques for nanofluids. However, there is not yet a standard preparation method for nanofluids [Choi et al ,2008], [Xiang et al, 2008].

Different studies show different approaches in preparing nanofluids. However, there are two fundamental methods to obtain nanofluids [Choi et al, 2008],[Xiang et al, 2008]:

(a) Two-step process in which nanoparticles are first produced as a dry powder, typically by an inert gas. The resulting nanoparticles are then dispersed into a fluid. This method may result in a large degree of nanoparticle agglomeration.

(b) Chemical approach 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.

Moreover, nanofluids made using this method showed higher conductivity enhancement than the ones made using 2-step method. Furthermore, the base fluids contain other irons and reaction products that are difficult or impossible to separate from the fluids. Using either of these two approaches, nanoparticles are inherently produced from processes that involve reduction reactions or ion exchange.

2.4 Advantages of nanofluids

Compared to conventional solid-liquid suspensions for heat transfer intensifications, properly engineered thermal nanofluids possess the following advantages:

(i) High specific surface area and therefore more heat transfer surface between particles and fluids.

(ii) High dispersion stability with predominant Brownian motion of particles.

(iii) Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification

(iv) Reduced particle clogging as compared to conventional slurries, thus promoting system miniaturization

(v) Adjustable properties, including thermal conductivity and surface wet-ability, by varying particle concentrations to suit different applications.

2.5 Application of Nanofluid

Nanofluids are used for many applications [Xiang et al, 2008],[Kaufui et al, 2010]. Among those are :-

(i) **Automotive Application**

Nanofluids are used in Engine oils, automatic transmission fluids, coolants, lubrications, and other synthetic high-temperature heat transfer fluids found in conventional truck thermal systems-radiators, engines, heating, ventilation and air-conditioning (HVAC) – have inherently poor heat transfer properties. These could benefit from the high thermal conductivity offered by nanofluids that resulted form addition of nanoparticles.

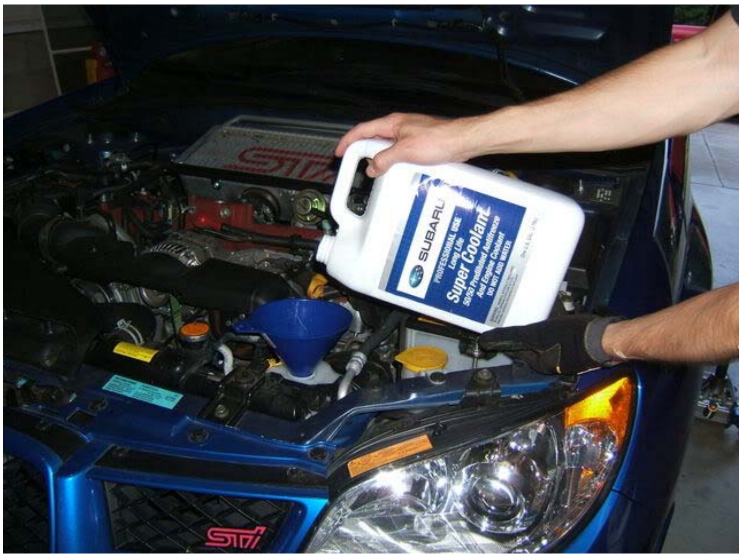

Figure 2.4 : Engine cooling using nanofluid coolant

(ii) **Biomedical Applications**

They are used for nano-drug delivery, for cancer therapeutics, cryopreservation, nanocryosurgery, sensing and imaging.

(iii) **Electronic Application**

Nanofluids are used for cooling of microchips in computers and elsewhere. They are also used in other electronic applications which use microfluidic applications.

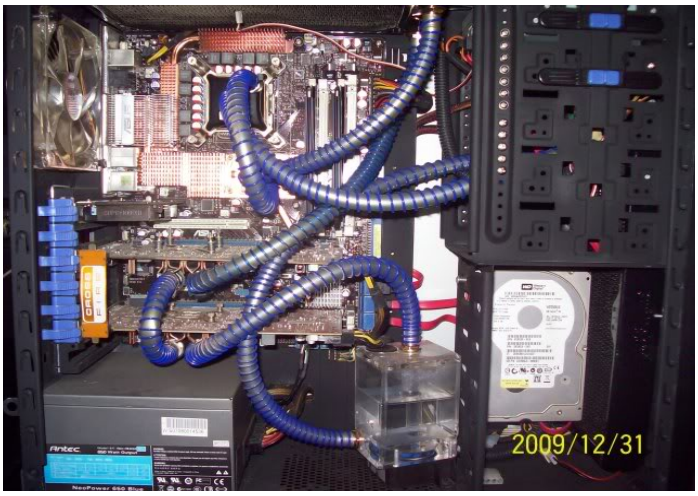

Figure 2.5 : Nanofluid used for cooling purposes in Computer (CPU Unit)

2.6 Challenges of Nanofluid

At current stage, research and development for nanofluid, it shows that most of the types of nanofluids which are been manufactured encounters many challenges [Cheng, 2009],[Saidur et al, 2011]. Among those are:-

(i) lack of agreement of results obtained by different researchers

(ii) lack of theoretical understanding of the mechanisms

(iii) responsible for changes in properties

(iv) poor characterization of suspensions

(v) stability of nanoparticles dispersion

(vi) increased pressure drop and pumping power

(vii) nanofluids thermal performance in turbulent flow and fully developed region

(viii) higher viscosity, lower specific heat

(ix) high cost of nanofluids

2.7 Properties that can help to enhance the nanofluid

Nanofluids have novel properties that make them potentially useful in many applications in heat transfer, as mentioned above in *Section 2.5*. They exhibit enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid.

The thermal conductivity of heat transfer fluid plays an important role in the development of energy-efficient heat transfer equipment's including electronics, HVAC, chemical processing, and transportation. Development of advanced heat transfer fluids is clearly essential to improve the effective heat transfer behavior of conventional heat transfer fluids. With a tiny addition of nanoparticle, significant rise of thermal conductivity is achieved without suffering considerable pressure drop penalty.

Here, we are going to discuss further on the characteristics of nanofluid that could potentially help to improve the current water chiller system and subsequently revolutionize the mathematical calculation based on the design of the water chiller itself using nanofluid in the subsequent parts.

2.7.1 Thermal Conductivity

The main characteristic of nanofluid, that is attracting a lot of interest, is basically the thermal conductivity it has; compared to the current water chiller coolant which is only water. It is said that nanofluid's thermal conductivity can be twice the conductivity of the pure base fluid [Choi et al,2008].

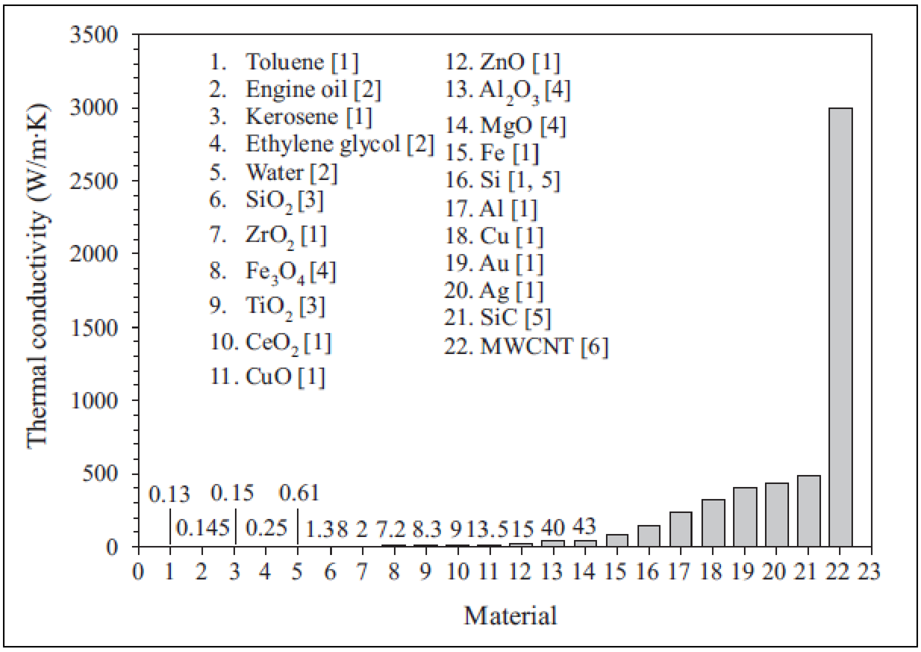

Figure 2.6 : Thermal conductivities of commonly used liquids and materials at room temperature

The main reason behind the increase in thermal conductivity of the fluid has to do with the addition of the nanoparticles into the base fluid [Kasaee et al, 2010]. The typical length of the particles added into the base fluid ranges from 1 to 100 nm and the particles have to have higher thermal conductivity than the fluid they will be dispersed into [Kasaee et al, 2010].

With the additional nanoparticle being augmented into the base fluid, it actually increases the thermal conductivity of the fluid, for example, by adding 1-5% of nanoparticle, the thermal conductivity could increase up to 20% [Maiga et al, 2006].

Table below shows a complete summary of experimental studies on thermal conductivity of various nanofluids together with their observations [Xiang et al, 2008].

Table 2.1 : Summary of experimental studies on thermal conductivity of nanofluids

Investigator	Particles	Size (nm)	Fluids	Observations
Eastman et al (1997)	Al_2O_3/CuO/Cu	33/36/18	water,HE-200 oil	60% improvement for 5 vol% CuO particles in water.
Lee et al (1999)	Al_2O_3/CuO	24.4,38.4/18.6,23.6	water,EG	20% improvement for 4 vol% Cuo/EG mixture.
Wang et al (1999)	Al_2O_3/CuO	28/23	water,EG,PO,EO	12% improvement for 3 vol% Al_2O_3/water nanofluids.
Das et al (2003c)	Al_2O_3/CuO	38.4/28.6	water	2-4 fold increase over range of 21°C to 52°C.
Xie et al (2002b)	Al_2O_3	12.2–302	water,EG,PO	pH value, SSA, crystalline phase
Li and Peterson (2006)	Al_2O_3/CuO	36/29	water	enhancement with volume fraction and temperature
Xuan and Li (2000)	Cu	100	water,oil	successful suspension of relatively big metallic nanoparticles
Eastman et al (2001)	Cu	<10	EG	40% increase for 0.3 vol% Cu-based nanofluids
Hong et al (2005)	Fe	10	EG	18% increase for 0.55 vol% Fe/EG nanofluids.
Patel et al (2003)	Au, Ag	4, 15/70	water, toluene	Size, temperature, and chemical characteristics.
Murshed et al (2005)	TiO_2	Ø10×40,Ø15	DW	33% and 30% increase at 5 vol% for Ø10×40 and Ø15, respectively.
Xie et al (2001, 2002b)	SiC	Ø26, 600	water, EG	15.8% increase at 4.2 vol% for Ø26 SiC-H_2O and 22.9% at 4 vol% for Ø600 SiC-H_2O
Choi et al (2001)	MWNTs	Ø25×50μm	oil	exceed 250% at 1.0 vol%.
Biercuk et al (2002)	SWNTs	Ø3-30	epoxy	125% at 1.0 wt%.
Xie et al (2003)	TCNTs	Ø15×30 μm	DW,EG,DE	19.6%, 12.7%, and 7.0% increase at 1.0 vol% for TCNT/DE, EG, and DW, respectively.
Choi et al (2003)	SWNTs	Ø20-30×200	epoxy	300% at 3 wt% SWNT loading.
Assaelet al (2003, 2004, 2005)	MWNTs, DWNTs	Ø130×10 μm	water	34% increase for 0.6 vol% suspension.
Liu et al (2005)	CNTs	Ø20-30 μm	EG,EO	12.4% for EG at 1 vol%, 30% for EO at 2 vol%.

Note: EG: ethylene glycol; PO: pump oil; EO: engine oil; DW: deionized water; DE: decene.

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There is also another study mentioned by Sakar and Selvam in their article that the thermal conductivity of a nanofluid could improve up to 150% with the addiction of maximum of 2% metal particles [Sarkar et al, 2007].

In general, it can be said that the thermal conductivity of a nanofluid is augmentation dependence means that the heat transfer efficiency of the fluid is very much proportional to the solid volume fraction of the added particle [Das et al, 2009].

This proves to be correctly demonstrated by Sakar and Selvam in their study of nanofluid as based on the experiment and calculations done by Green-Kubo method by EMD simulation, they discovered that the higher the percentage of the particles added, the higher the thermal conductivity be [Sarkar et al, 2007],[Chein et al, 2005]. In the experiment which they used copper as the added particles, they prepared 6 different types of solutions with 0.2%, 0.4%, 1%, 2%, 4% and 8% of copper loading and the finding agreed with what they had expected. The fluid with 0.4% of copper loading had its thermal conductivity measured at 0.145W/m-K while the fluid with 1% and 2% produced the results of 0.156 W/m-K and 0.165 W/m-K respectively [Sarkar et al, 2007]. The plot below shows the result obtained by Sakar and Selvam.

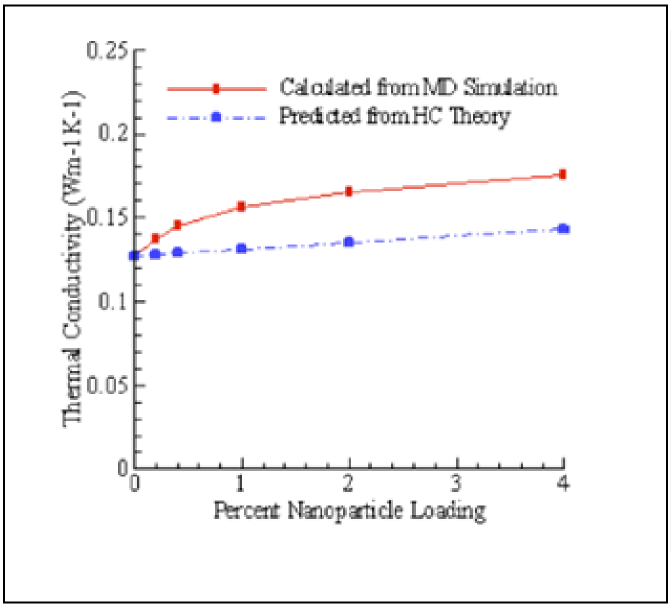


Figure 2.7 : Experiment conducted to show the effect of percentage of particle to thermal conductivity (Sakar & Selvam, 2007)

However, despite the fact that by dispersing more particles into the fluid will increase the thermal conductivity of the fluid, it could also increase the wall shear stress that could lead to higher pressure drop along the tube [Moghaddami et al, 2011]. Higher the pressure drop, it will have an impact on the pump as it will push the pump harder and could eventually end up breaking it.

2.7.2 Temperature

Temperature also plays an important role on nanofluid performance. In the study done by Das et al. they discovered that the nanofluids prepared using Al_2O_3, and CuO had the thermal conductivities increased almost (3) times as the fluid temperature increased from 21°C to 50°C [Das et al, 2006].

According to them, increase in thermal conductivity is proportional to the temperature due to the fact that as the temperature of the fluid increases, the energy absorbed by the particles increases as well and it resulted in a much more rapid movement of the particles. The more the particles move, the higher the frequency they collide with each other and the collision actually help to distribute the heat [Das et al, 2006].

Based on the Figure 2.8 below, it can be clearly noticed and proves that the thermal conductivity of Al_2O_3, and CuO is higher at higher temperature, with respect to volume concentration.

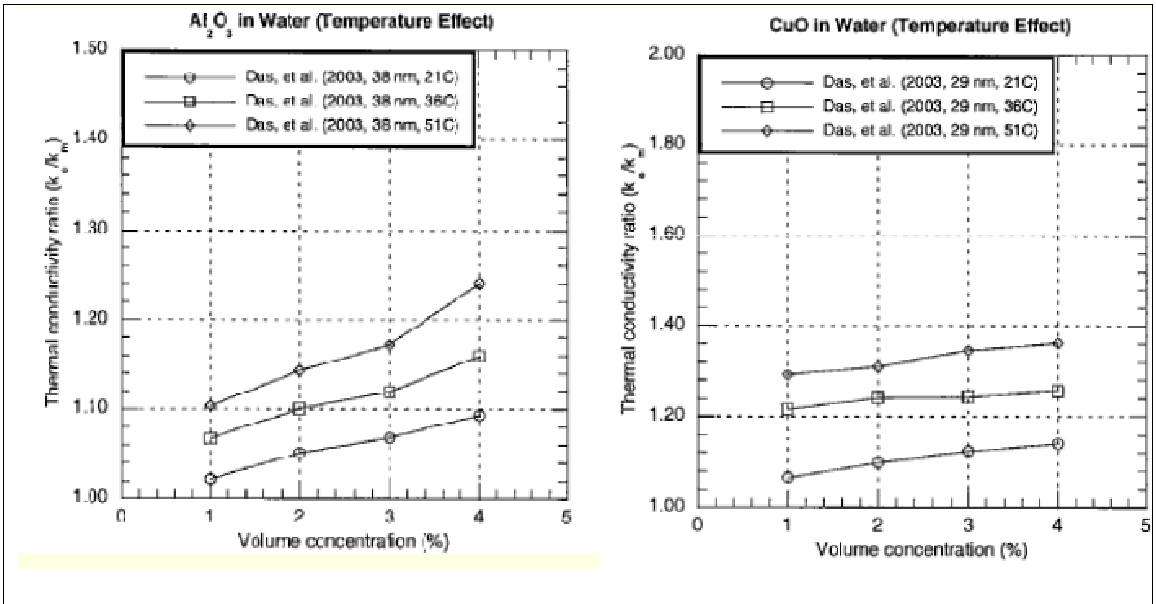


Figure 2.8 : Experiment research on nanofluid thermal conductivity effect to temperature

2.7.3 Stability

Nanofluids are not a simple mixture of liquid and solid particles. Nanoparticles tend to aggregate with the time elapsed for its high surface-activity. Another characteristic of nanofluid that is believed to be beneficial, if it is to be used as a water chiller coolant, is its stability. According to Das, Choi and Patel, due to the tiny size of the particles, mostly measured in nano meter (nm), the weight can be simply treated as negligible and thus the possibility of sedimentation to occur is less. [Das et al, 2006], [Anoop et al, 2009].

Stability of nanofluids can be determined using many methods such as sedimentation method where the variation of concentration with sediment time is obtained with a special apparatus [Yanjiao et al, 2009], [Mohammeda, et al, 2011].

It should be noted that proper method to produce stable nanofluids is still not fully achieved and many researches and standardized methods need to be established in order to obtain a systematic conclusion on stability of nanofluids. With this, the most vital factor in determining the stability of the nanoparticles suspensions is its concentrations, dispersant, viscosity of base fluid and pH values [Mohammeda et al, 2011].

2.7.3.1 Augmented particles

The thermal conductivity of the nanofluid is mainly determined by the characteristics of the nanoparticles used to be added into the base fluid. The normal practice is to have the augmented particles to have higher thermal conductivity property than the base fluid [Yu et al, 2008] and the base fluids that are easily accessible are water and ethylene glycol while the nanoparticles are normally oxide and metals [Sinha et al, 2009].

2.7.3.2 Augmented particle’s size and shape

A common difficulty encountered in nanofluid manufacture is nanoparticles tendency to agglomerate into larger particles, which limits the benefits of the high surface are nanoparticles. To counter this tendency, particle dispersion additives are often added to the base fluid with the nanoparticles.

Unfortunately, this practice can change the surface properties of the particles, and nanofluids prepared in this way may contain unacceptable levels of impurities. With this, by increasing the surface area of the conducted material, heat transfer rate can be improved and the rule still applies to the particles.

Heat transfer rate of nanoparticle increases as the surface area of the particles increases [Das et al, 2006]. There is however a limitation on how big the particles can be, and as bigger the particles, it will have a higher tendency of clogging the line [Das et al, 2006].

According to Yu et al., the normal size of the nanoparticle shoue be within the range of 1 to 100 nm [Yu et al, 2008] and with the nano size of the particles, the possibility of having the line clogged is very minimal. There is also a study conducted saying that as the size o the particles decreases, the heat transfer capability increases due to the more effective heat distribution by the nano atom [Tzeng et al, 2005]. This result appears to be contrary to what was highlighted by Yu et al. as based on the experiment performed using particles with the sizes of 28nm, 38nm and 60nm in which the smallest size particle that was expected to be the least effective appears to be in between 38 nm and 60nm [Kasaee et al, 2010].

The particle's shape also is believed to have an impact on the thermal conductivity of the fluid. According to the article published by Yu et al. the cylindrical shape particle exhibits increase thermal conductivity compared to spherical shape particle [Yu et al, 2008]. The diagram below shows how much difference the shape of the particle will have an impact on the thermal conductivity of the fluid.

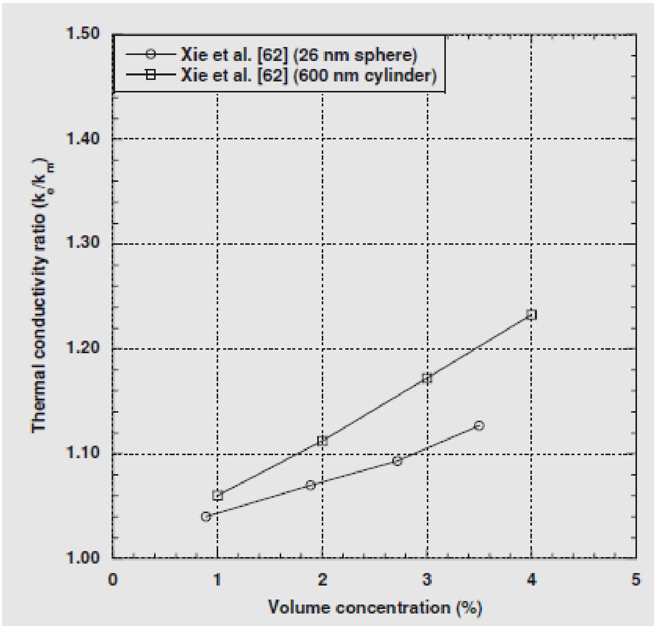


Figure 2.9 : Effect of paricle shape on thermal conductivity (Yu et al, 2008)

2.7.3.3 Augmented particle's materials

The type of material used to prepare the augmented particles also play a vital role in determining the effectiveness of nanofluid especially on the heat transfer capability. It was mentioned earlier that the particles added into the base fluid should have higher thermal conductivity than the base fluid [Yu et al, 2008] and the widely used materials are made mostly of oxides and metals [Sinha et al, 2009].

In one of the experiment conducted to determine the effect of the materials type on the heat transfer capability of nanofluid conducted by Sinha et al. it was observed that copper nanoparticles exhibit better thermal conductivity compared to iron nanoparticles with the increase in thermal conductivity recorded was 25% to 70% and 11% to 33% respectively [Sinha et al, 2009].

Both nanoparticles used in their experiment were prepared in such a way that both particles had similar properties geometrically in term of crystallize size, particle size and morphology [Sinha et al, 2009].

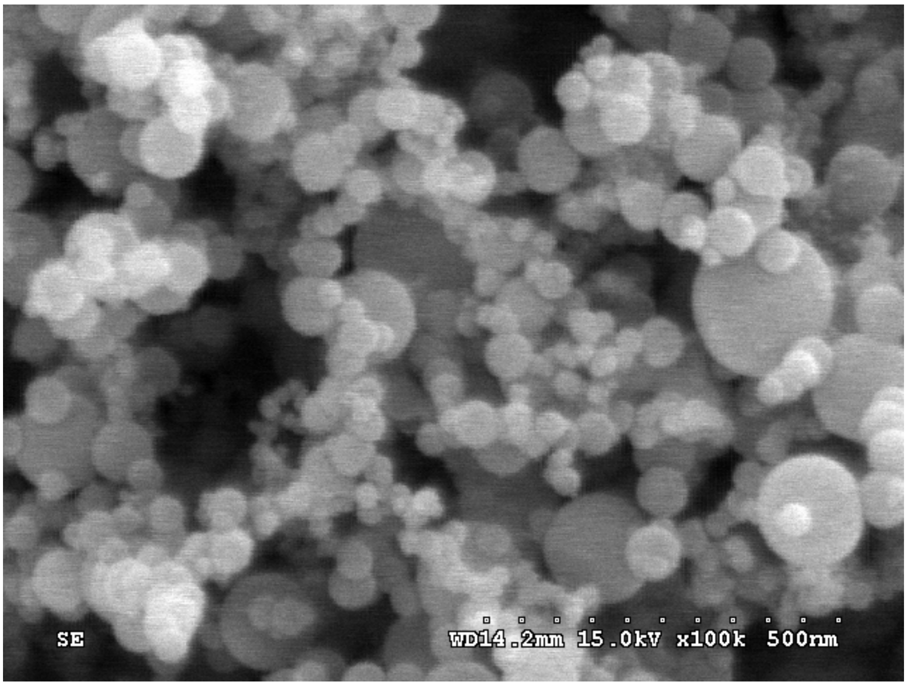


Figure 2.10 : Micro-scale size of Nanofluid particles

Another study done by Das, Choi and Patel on the type of particles used in nanofluid also shows that different particles have different effect on the thermal conductivity of the fluid [Das et al, 2006]. In their experiment, they tested (3) types of particles which are metallic, ceramic and carbon polymer and the results show that the greatest enhancement was observed by carbon and polymer nanoparticles [Das et al, 2006].

The other experiment conducted by Yu el al. also produced similar results that agreed with other studies on the effect of nanoparticles materials to the thermal conductivity of the fluid. In their experiment, Yu el al used (3) different types of particle, $Al_2O_{3,}$ Cu and Fe [Yu et al, 2008]. They found out that the metal particles produced better heat transfer enhancement compared to oxide particles at lower concentration [Yu et al, 2008].

All these studies show that different types of particle exhibit different performance in term of thermal conductivity when they are used to create the nanofluids.

2.8 Heat transfer Properties and characteristics of Nanofluid

Compared to conventional solid-liquid suspensions of heat transfer intensifications, engineered nanofluids has the following added advantages:- [Mohammeda et al, 2011]

i. Reduced pumping power compared to pure liquid to achieve equivalent heat transfer intensification
ii. High specific surface area and more heat transfer surface between particles and fluids.
iii. Adjustable properties inclusive of thermal conductivity and surface wettability
iv. High dispersion stability with predominant Brownian motion of particles
v. Reduced particle clogging as compared to conventional slurries

2.9 Enhancement of heat transfer using nanofluid

Based on Xuan and Roetzel, they have mentioned on the experimental studies that two phase enhancement of thermal dispersion model with assumption convective heat transfer enhancement in nanofluid comes from two factor: [Godson et al, 2010]

i. higher thermal conductivity
ii. thermal dispersion of the nanoparticles & its coefficient

Hence, the convective heat transfer enhancement was obtained with a decrease in the viscosity and consequent thinning of the laminar sub-layer.

2.10 Mechanism of thermal conductivity enhancement of nanofluids

Kelblinski and Eastman from experimental studies mentioned that four possible explanations for thermal conductivity enhancement of nanofluids depends on Brownian motion of nanoparticles, molecular-level layring of the liquid at the liquid/particle interface, nature of heat transport in the nanoparticles, and the effects of nanoparticles clustering, which is shown in Figure 2.11 [Xiang, 2007],[Keblinski et al, 2005].

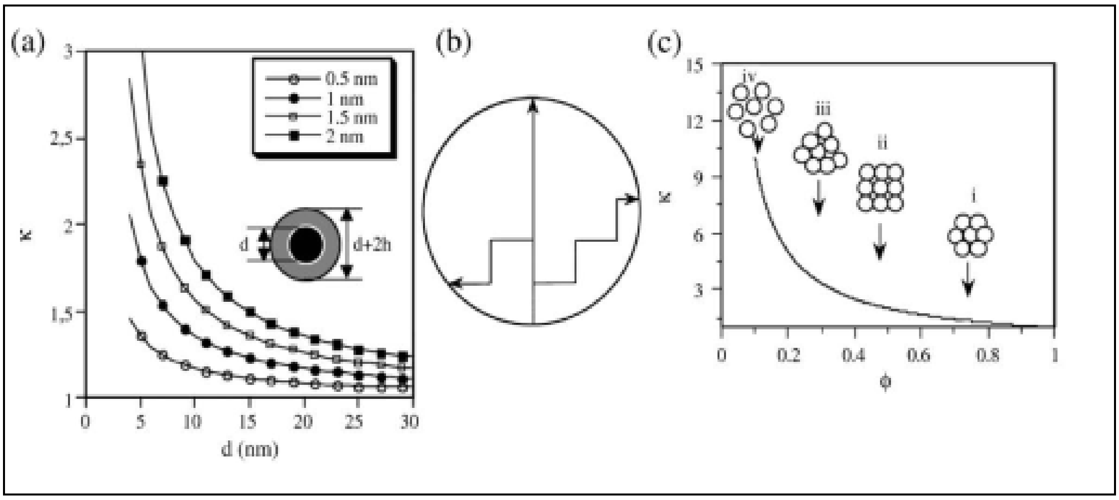


Figure 2.11 : Schematic diagram of several possible mechanisms; (a) Enhancement of k due to formation of highly conductive layer-liquid structure at the liquid/particle interface; (b) Ballistic and diffusive phonon transport in a solid particle; (c) Enhancement of k due to increased effective φ of highly conducting clusters.

Xuan and Li also mentioned based on experimental studies that four possible reasons for the improved effective thermal conductivity of nanofluids which is :

i. increased thermal conductivity of the fluid
ii. increased surface area due to suspended nanoparticles
iii. intensified mixing fluctuation and turbulence of the fluid
iv. interaction and collision among particles

Based on **Xie et al** studies, they proposed another four factor that influence thermal conductivity enhancement of nanofluids which is :-

i. micro convection caused by Brownian movement of nanoparticles
ii. the effect of nonlinear heat transfer in nanopaticles
iii. base fluid
iv. congregation of nanoparticles and orderly array of liquid molecules at the interface between the nanoparticles surface

From all three (3) different studies, we can clearly see that there are no any commonly accepted conclusion was obtained to explain the thermal behavior of nanofluids. More theoretical and experimental work need to be done as controversy still exits.

2.11 Challenges of Nanofluid

At current stage, research and development for nanofluid, it shown much of the nanofluid researches more concerned on thermal conductivity rather than its behavior during heat transfer. Most of the experiments carry out on single phase flow instead of two phases flow. Less paper are available for two phase flow and its thermal physics (pool boiling, flow boiling and condensation) [Cheng, 2009]. *This has also been discussed in Section 2.6*

2.12 Future Development

There are many challenges in the study of nanofluid two-phase flow and themal physics as mentioned aforegoing. Explanations and new theories are also needed to be taken into account all the important characteristics of nanofluid.

So far, no systematic knowledge of their effect is available. Therefore, it is recommended that two-phase flow and thermal physics (pool boiling, flow boiling and condensation with nanofluids) should also be investigated in the future. In future too, the nanofluid should not only be a limited role as water chiller coolant only.

2.13 Chillers

Chillers are a key component of air conditioning systems for large buildings. A typical chiller is rated between 15 to 1000 tons (180,000 to 12,000,000 BTU/h or 53 to 3,500 kW) in cooling power [Chein et al, 2005].

They produce cold water to remove heat from the air in the building. They also provide cooling for process loads such as file-server rooms and large medical imaging equipment. As with other types of air conditioning systems, most chillers extract heat from water by mechanically compressing a refrigerant.

Chillers are complex machines that are expensive to purchase and operate. Different types of chillers are typically distinguished from one another based on the compressor technology they employ. Choosing the right type of chillers are very vital to maximize energy efficiency, balance cooling costs, and stay cool on hot summer days.

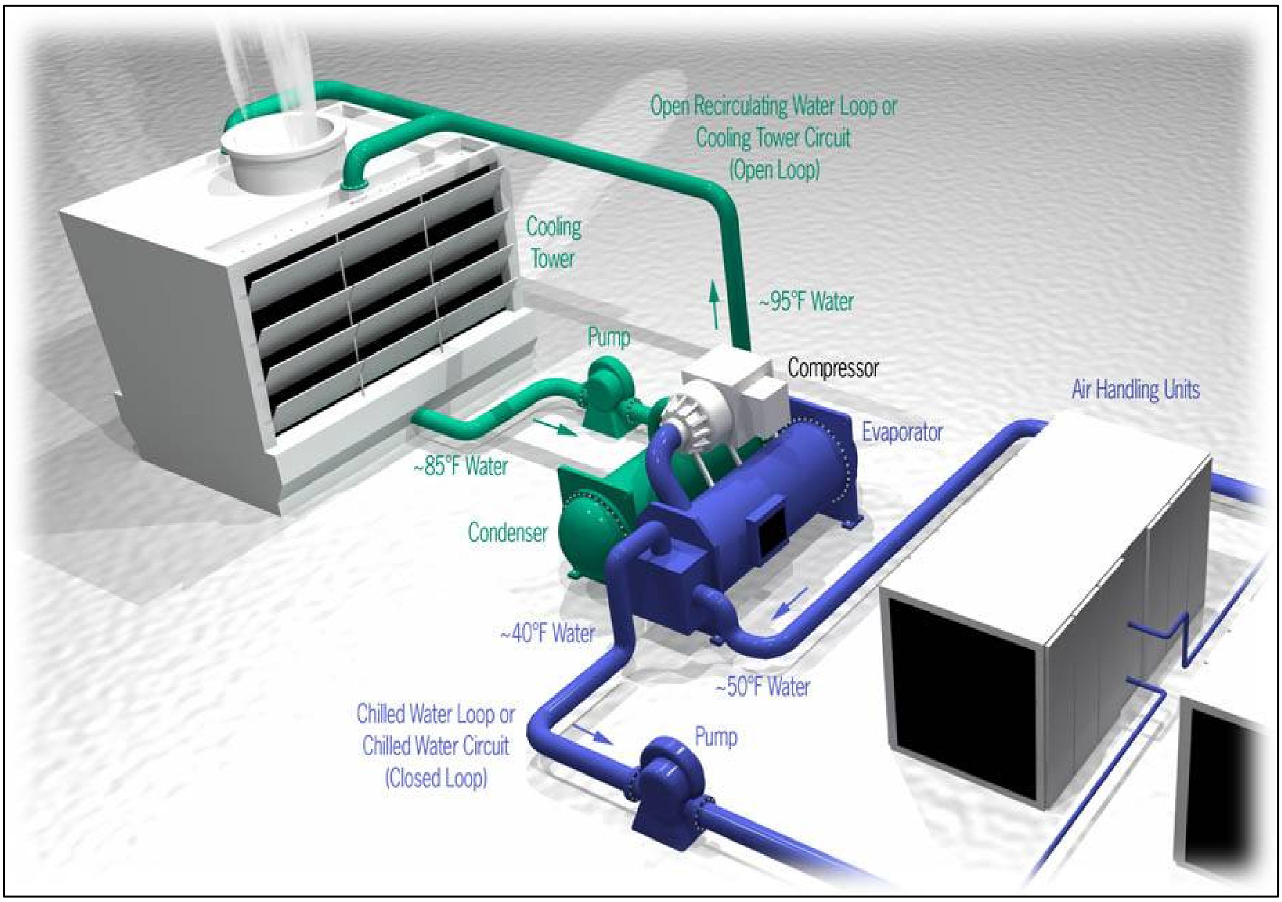


Figure 2.12 : Chiller and associated HVAC systems

2.14 Types of Chillers

The classification of chillers can be done based on various factors like portability, working, etc. Here we have classified chillers based on the basis of their functioning. However, in this study, water chiller will be further studied on heat transfer effect using nanofluid [Adnot et al, 2003].

2.14.11 Mechanical compression

During the compression cycle, the refrigerant passes through four major components within the chiller which is evaporator, the compressor, the condenser, and a flow-metering device such as an expansion valve. The evaporator is the low-temperature (cooling) side of the system and the condenser is the high temperature (heat-rejection) side of the system.

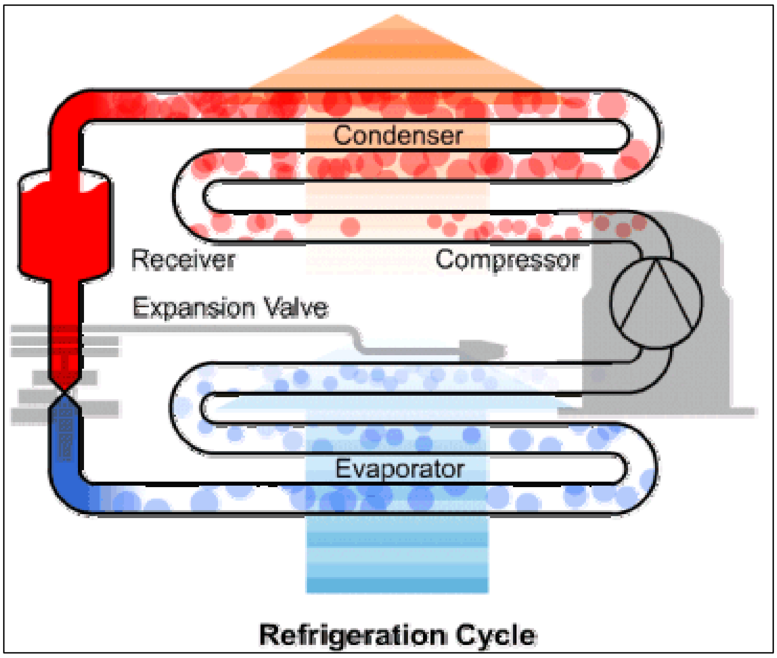


Figure 2.13 : The refrigeration cycle

2.14.12 Mechanical compressor chillers

Mechanical compression chillers are classified by compressor type which is either reciprocating, rotary screw, centrifugal and frictionless centrifugal.

2.14.13 Reciprocating Chiller

Reciprocating chillers utilizes an internal piston contained within a cylindrical compartment. As gaseous refrigerant enters the compressor, the piston compresses the refrigerant to increase the pressure. Once the pressure levels have risen to a high enough point, an exhaust valve releases the compressed refrigerant so it can re-enter the cooling system and claim more heat energy from the building.

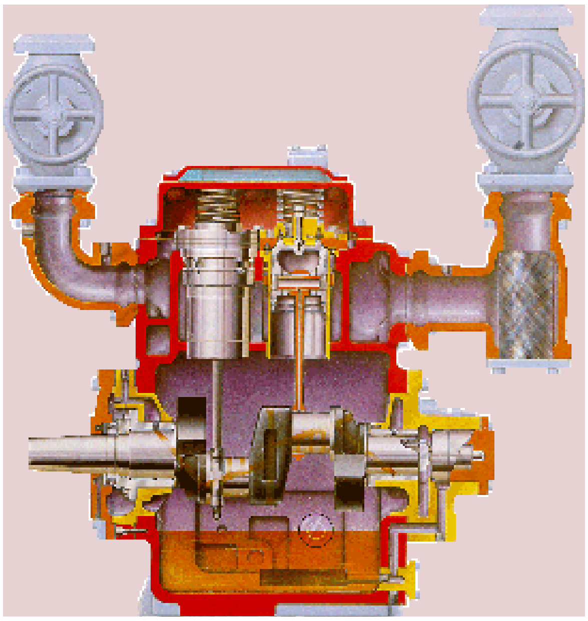


Figure 2.14 : Reciprocating compressor

2.14.14 Scroll Chiller

Scroll compressors feature the smallest capacity of all chiller models, and can handle loads between 30 and 60 tons. They use two interlocking coils, with one stationary and one rotating. As refrigerant enter the compressor, it gets caught between the walls of the coils and compressed down into the center of the two coils, where it exits through an exhaust port. It is mainly used in automobile air conditioners as well as small industrial cooling systems.

2.14.15 Rotary Chiller

Rotary chiller can handle loads as high as 300 tons, making them appropriate for large residential and most commercial applications. These units feature an internal roller that rotates within a steel cylinder. As refrigerant enters the cylinder through an intake valve, the rotating roller compresses it between the roller and the wall of the cylinder. As the roller continues to rotate, it forces the compressed refrigerant out through an exhaust valve to complete the cooling cycle.

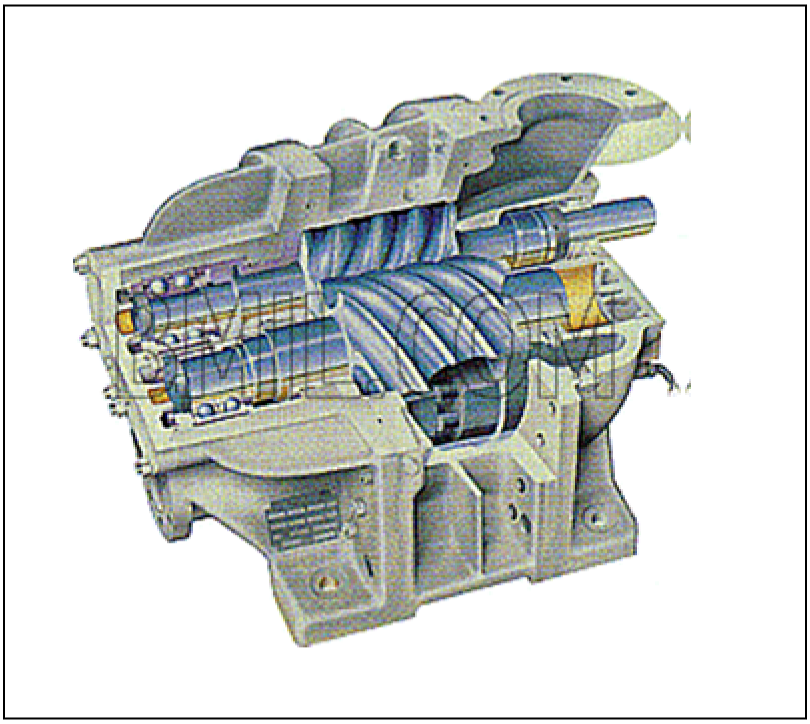


Figure 2.15 : Rotary screw compressor

2.14.16 Absorption chillers

Absorption chillers are used as a heat source such as natural gas or district steam to create a refrigerant cycle that does not used mechanical compression.

2.14.17 Centrifugal Chiller

Centrifugal chillers use an impeller to rapidly accelerate refrigerant from an intake port to the walls of a cylinder. The centrifugal force causes the gas to collect along the walls, then directs it to an exhaust port to continue to the cycle. Many commercial systems use multiple impellers to compress large quantities of refrigerant simultaneously. These systems have the largest capacity of all chillers, and are often used on applications requiring 300 tons of cooling capacity or greater.

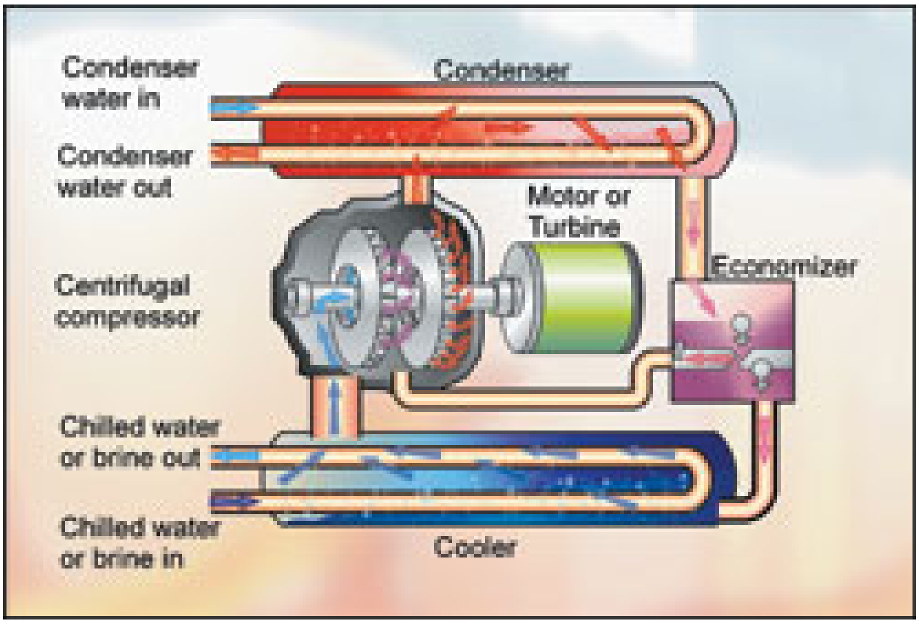


Figure 2.16 : Centrifugal compressor

2.14.18 Air-cooled chillers

An air-cooled chiller absorbs heat from process water and is transferred to the ambient air. They are mostly used in applications where the heat discharged is not a factor. They don’t need a cooling tower and condense water pump. The maintenance of air cooled chillers are less than water cooled units. However they consume 10% more power.

2.14.19Water chillers

Water chillers whereby absorb the heat from process water and is transferred to a separate water source like a river, pond, cooling tower, etc. It is mainly used at the places where the heat generated by air cooled chillers pose a problem. Due to their less consumption of power they are usually preferred by those seeking optimum efficiency of power consumption.

Water Chillers are used in many applications to cool or chill fluid. These applications include, but not limited to, manufacturing processes, comfort cooling and rental cooling system.

Figure 2.17 : Hydro Thrift - Water Chiller

2.14.20 Frictionless Centrifugal Chiller

This highly energy-efficient design employs magnetic bearing technology. The compressor requires no lubricant and has a variable-speed DC motor with direct-drive for the centrifugal compressor. Capacities range from 60 to 300 tons.

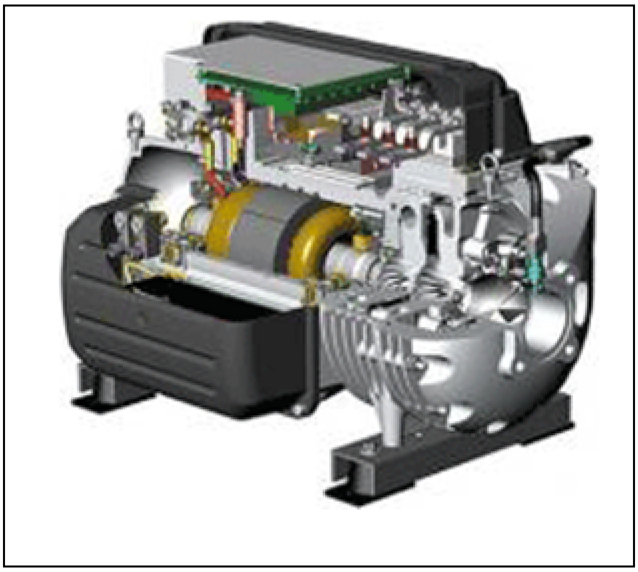


Figure 2.18 : Frictionless Turbocor centrifugal compressor

2.15 Water Chiller Efficiency

Chillers represent a substantial capital investment and are a major contributor to operating costs in institutional and commercial facilities. For many organizations, chillers are the largest single energy users, and comprehensive maintenance is critical to ensure their reliability and efficient operation [Nadeem Ener, 2001]

This is the reason chiller efficiencies are highly important and have improved steadily over the past decades due to advances in controls, refrigerants and equipment design. As a result, chillers now have tighter operational tolerances, and regular services and maintenance are more crucial than ever.

Below are 5 steps for water chiller efficiency

Step 1 : Maintaining a daily operating log

Chiller performance, which includes operating conditions are documented and analyzed on daily basis with an accurate and detailed log. Today's chillers are controlled via microprocessor controls, so operators can automate this process using microprocessor-controlled building automatic systems

Step 2 : Keep tubes Clean

One large potential hindrance to desire chiller performance is heat-transfer efficiency. Chiller performance and efficiency relate directly to its ability to transfer heat, which begins with clean evaporator and condenser tubes. Keeping large surfaces clean is vital for maintaining high-efficiency performance.

Most chiller manufacturer recommend cleaning condenser tubes annually, and recommend cleaning evaporator tubes once every three years for closed system.

Step 3 : Ensure a Leak-free unit

Manufacturers recommend quarterly tests of compressors for leaks. Although these chillers are the most common in today's facilities, it is difficult to create a perfectly sealed machine, and leaks allow air and moisture to enter the unit.

Moisture in a chiller also can create acids that corrode motor windings and bearing s and create rust inside the shell. Fines on tubes will result in decrease in the units heat transfer effectiveness and overall efficiency. This could even result in costly tube repairs. The best way to monitor leaks is to track purge-unit runtime and the amount of moisture accumulation at the purge unit.

Step 4 : Sustain Proper Water Treatment

Most chillers uses water for heat transfer, so the water must be properly treated to prevent scale, corrosion and biological growth. A one-time chemical treatment is required for closed-water systems.

Poor chemical treatment of the evaporator and condenser-water system could result in scaling. The quality of the water had to be tested every three months and correct water treatment program is highly important.

Step 5 : Analyze oil and Refrigerant

Annual chemical analysis of oil and refrigerant can aid in detecting chiller contamination problems before they become serious.

Oil analysis can help is detecting other chiller problems, for example, high moisture content in the oil can signal problem with the purge unit, and changes in oil characteristics can signal problems with the purge unit, and changes in oil characteristics can signal the development of unacceptable compressor wear.

As for refrigerant testing, it is done to determine contaminations that might lead to reliability and efficiency problems. One main contaminant is oil that migrates into the refrigerant.

2.16 Water Chiller & it's Working Principle

The main function of a water chiller is to remove heat from one substance and pass it to other sources like ambient water or air. A chilled-water applied system uses chilled water to transport heat energy between the airside, chillers and outdoors. These systems are more commonly found in large HVAC installations, given their efficiency advantages [Raghu et al, 2005].

A chiller consists of a few major components. Water chiller is compressor based equipment that cools and controls the temperature of a liquid. Besides compressor other components of a water chiller are, an evaporator heat exchanger, a condenser heat exchanger, an expansion valve or two and some piping and controls are the basics.

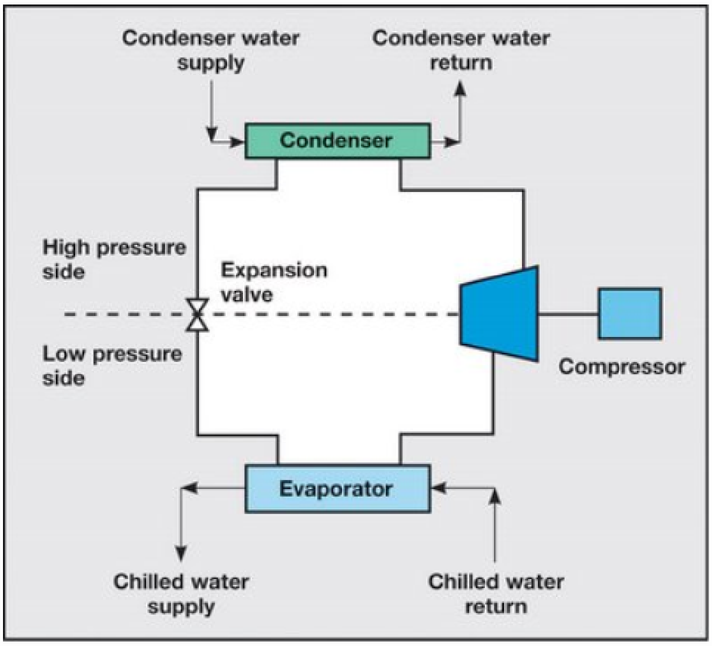


Figure 2.19: Chilled Water applied system

Compressors are usually reciprocating, scroll, centrifugal, or rotary screw types. The evaporator heat exchanger is usually of shell and tube constructions and is the exchanger where chilled water would be produced [Raghu et al, 2005].

The condenser heat exchanger can be either air-cooled, a coil or coils and a fan or fans, or water cooled, another shell and tube heat exchanger cooled by cooling tower or other water.

2.17 How does the water chiller functions?

Below are the working principles of a typical water chiller

i. The cycle begins in the evaporator where a liquid refrigerant flows over the evaporator tube bundle and evaporates
ii. The heat from the chilled water circulating is then absorbed through the bundle.
iii. The refrigerant vapor is drawn out of the evaporator by the compressor
iv. The compressor then pumps the refrigerant vapor to the condenser raising its pressure and temperature
v. Then the refrigerant condenses on or in the condenser tubes, giving up its heat to the cooling water.
vi. High pressure liquid refrigerant from the condenser then passes through the expansion device that eventually reduces the refrigerant pressure and temperature as it enters the evaporator.
vii. Refrigerant will flow again over the chilled water coils, absorbing more heat and completing the cycle.
viii. As a result, the indoor is thus cooled.

Benefit of water chiller applied system is the refrigerant containment. Having the refrigeration equipment installed in a central location minimizes the potential for refrigerant leaks, simplifies refrigerant handling practices, and typically makes it easier to contain a leak if one does occur.

Factors affecting the decision to selecting a Water Chiller system includes :-

- installation cost
- energy consumption
- space requirements
- system cooling and heating capacity
- centralized maintenance

When selecting the right water chiller, there are some key specifications need to be taken into consideration, which is:-

- Total life cycle cost
- Power source
- Cooling capacity
- Evaporator capacity, material and type
- Condenser material and capacity
- Ambient temperature
- Coolant requirements
- Number and type of compressors

2.18 Applications of Chillers

Cooling equipment's are used in a number of industries. Some of the most common application of chillers are [Singh et al, 2009],[Saidur et al, 2011],[Xiang et al, 2008],[Kaufui et al, 2010]:

- Chillers are used to cool the hot plastic in the plastic industry. It cools the plastic that is injected, blown extruded or stamped. They are also used to cool down the equipment used in the manufacturing process.
- In the printing industry, chillers are used to remove the heat generated by the printing rollers. They also help cooling the paper when it comes out of the ink drying ovens.
- Sophisticated chillers are used in the high powered electronics inside the machines like MRI and PET used in the latest diagnostic tools.
- Chillers cool down the lasers and the source of power supply used to power them

Figure 2.20: Upright chiller used at convenience store

Figure 2.21: Chiller used in heavy industries

2.19 Liquid Cooling

Liquid cooling is essentially a radiator for the water cooling system. Just like a radiator for a car, a liquid cooling system circulates a liquid through a heat sink attached to the water cooling system. As the liquid passes through the heat sink, heat is transferred from the hot source to the cooler liquid.

The hot liquid then moves out to from the water chiller and transfer heat to the ambient air outside. The cooled liquid then travels back through the system to the water chiller to continue the process.

Liquid cooling is a much more efficient system at removing heat away from the water chiller and outside of the system. This is the prime reason why nanofluids are used to enhance the heat transfer inorder to release more heat and keeping the system cool.

2.20 Coolant / Refrigeration used in Water Chiller for cooling purpose

There are many refrigerants options are available when selecting a chiller, the application cooling temperature requirements and refrigerant's cooling characteristics need to be matched. Important parameters to be considered are the operating temperatures and operating pressures. There are also several environmental factors that concerns refrigerants, and also affect the future availability for chiller applications [Adnot et al, 2003].

A coolant is a fluid which flows through a device to prevent its overheating, transferring the heat produced by the device to other devices that use to dissipate it. An ideal coolant has high thermal capacity, low viscosity, it low-cost, non-toxic, and chemically inert, neither causing not promoting corrosion of the cooling system. Some applications also require the coolant to be an electrical insulator.

While the term coolant is commonly used in automotive, residential and commercial temperature-control applications, in industrial processing, heat transfer fluid is one technical term more often used, in high temperature as well as low temperature manufacturing applications [Adnot et al, 2003].

Emerging and new classes of coolants are nanofluids. As discussed in *Section 2.1*, nanofluid are engineered colloids made of a base fluid and nanoparticles (1-100nm) [Tillman et al, 2005]. Common base fluid includes water, organic liquid (e.g ethylene, tri-glycol, refrigerants, etc), oil and lubricants, bio-fluids, polymeric solutions and other common liquids.

It consists of a carrier liquid, such as water, dispersed with tiny nano-scale particles known as nanoparticles. Purpose designed nanoparticles of e.g CuO, Alumina, Titanium Dioxide, Carbon nanotubes, Silica or metals (e.g. copper, or silver nano-rods) dispersed into the carrier liquid the enhances the heat transfer capabilities of the resulting coolant compared to the carrier liquid alone [Chein et al, 2005].

Types of coolants that are used for water chillers are mostly water (R718) since it is a natural refrigerant, ethylene glycol mixture – water based, R134a or R12, R502, R404 and many more [Yunus et al, 2006].

- **R11** – used in large-capacity water chillers serving air conditioning systems in buildings
- **R22** – used in window air conditioning, heat pumps, air conditioning of commercial buildings, etc
- **R134a** – (replaced R-12, which damages ozone layer) is used in domestic refrigerators and freezers, as well as automotive air conditioners.
- **R502** – (a blend of R115 and R22) is the dominant refrigerant used in commercial refrigerant system such as those in supermarkets.

2.21 Selecting the right refrigerant for water chiller

Selections of the right refrigerant are very important, for water chiller. Two important parameters that need to be considered in the selection a refrigerant are the temperatures of the two media (the refrigerant space and the environment) with which the refrigerant exchanges heat [Yunus et al, 2006].

Among other characteristics that have to be considered is vapor pressure, transport properties, lubricant and material compatibility, thermodynamic performance, cost, flammability, toxicity, stability and environmental properties.

CHAPTER III

METHODOLOGY

3.1 Nanofluid side calculation

In this study, two different types of nanofluid, which are TiO_2 & Al_2O_3 particles used along with water which is used as base fluid were used to calculate and compare the heat transfer performance of the water chiller. The comparisons are done by comparing the nanofluid with pure water.

The thermophysical property which comprises the density, viscosity, specific heat and thermal conductivity of TiO_2, Al_2O_3 and water at 25ºC are presented in Table 3.1 and will be further used in the subsequent calculatations. The volume fractions, Ø of 0.5%, 0.8%, 1.5%, 2.0% and 4% are used for thermophysical calculations from the following Equations (3.1) to (3.4). The calculation workings are presented in Appendix A.

Density of nanofluid:

$$\rho_{nf} = (1 - Ø)\rho_f + Ø\rho_p \tag{3.1}$$

Viscosity of nanofluid:

$$\mu_{nf} = \mu_{bf}\,(1 + 2.5Ø) \tag{3.2}$$

Specific heat of nanofluid:

$$(\rho C_p)_{nf} = (1 - Ø)\,(\rho C_p)_f + Ø(\rho C_p)_p \tag{3.3}$$

Thermal conductivity of nanofluid: (3.4)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)\O(k_f - k_p)}{k_p + (n-1)\,k_f + \O(k_f - k_p)}\;k_f$$

The spherical particles are assumed with n=2 for the nanoparticles.

Table 3.1 : Thermophysical properties of water and nanoparticles at T=25ºC [Mohammad et al, 2010]

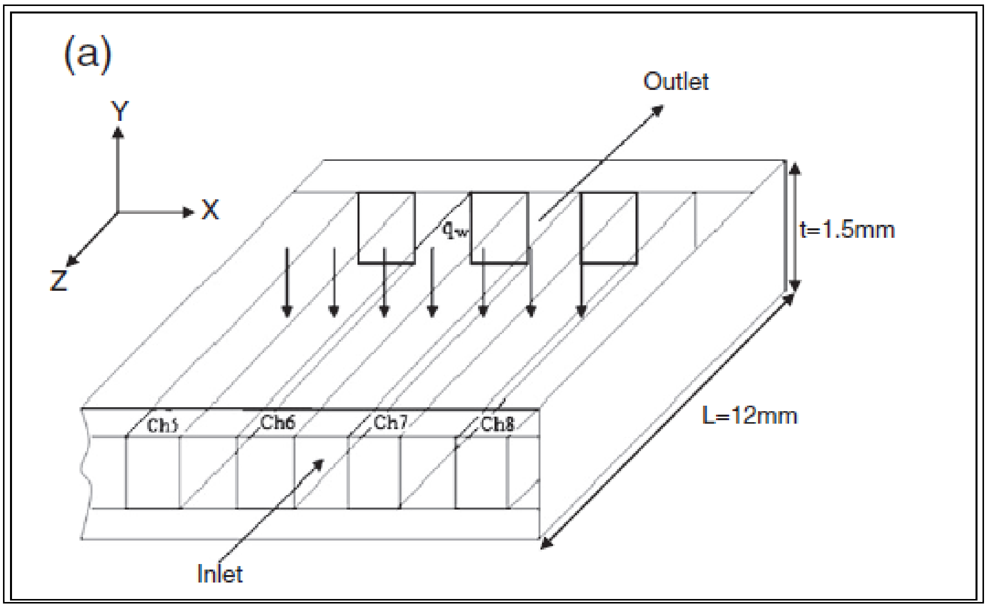
Properties	Nanoparticle Al_2O_3	Nanoparticle TiO_2	Base Fluid (Water)
ρ (kg/m^3)	3970	4197	997.1
Cp (J/kg K)	765	710	4179
k (W/m K)	40	8.4	0.613
μ (Ns/m^2)			0.001003

The parameters which are required to be calculated and compared on the heat transfer performance of the water chillers are nanofluid hydraulic diameter (D_h), Reynolds number (Re), Prandtl number (Pr), Nusselt number (Nu), heat transfer coefficient (h), pressure drop (ΔP), pumping power (P), and total heat transfer rate (Q).

3.2 Minichannel Heat Sink (Heat Exchanger)

In this study, the concept of minichannel heat sink is used to drive the development of efficient heat distribution (heat exchanger) in order to maintain high performance of the cooling devices. With having minichannel in the heat sink (heat exchanger) for liquid cooling, it will lead to the increase in heat transfer rate [Mohammad et al, 2010].

As such, heat is supplied to rectangular minichannel heat sink aluminum substrate by flowing nanofluid through a number of minichannels is studied [Mohammad et al, 2010]. The dimensions of the rectangular minichannel heat sink were taken from the H.A Mohammaed et al. [Mohammad et al, 2010] and shown in Table 3.2.



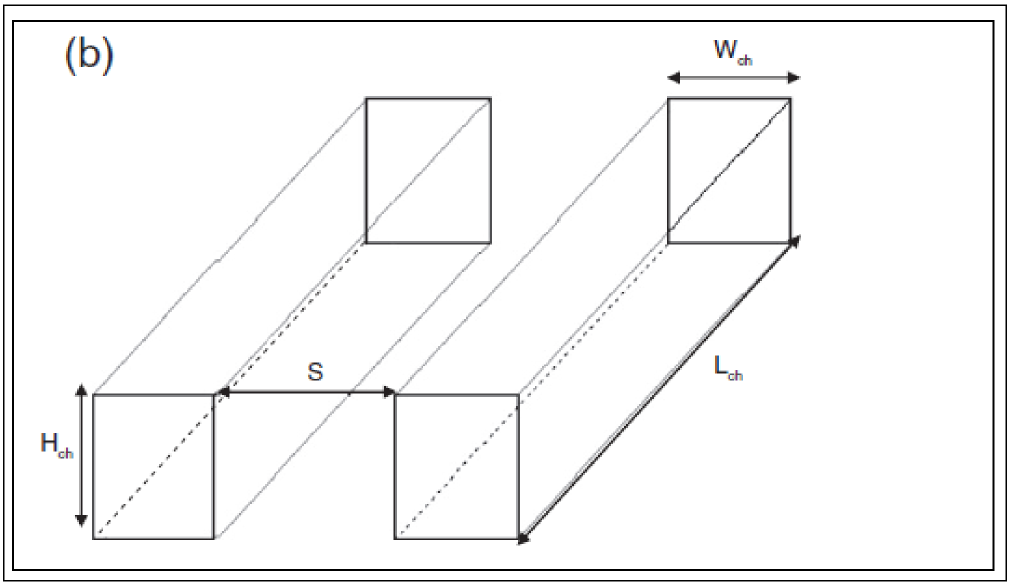


Figure 3.1 : (a) Schematic diagram of the computational domain

(b) Cross section of the rectangular shaped minichannel

Table 3.2 : Dimensions of the rectangular minichannel heat sink [Mohammad et al, 2010]

D_h (μm)	H_{ch} (μm)	W_{ch} (μm)	L_{ch} (μm)	S (μm)
339.15	430	280	10,000	500

At the minichannel sections, the hydraulic diameter, D_h is calculated based on Equation (3.5). The calculation workings are presented in Appendix A.

Hydraulic diameter, D_h (3.5)

$$D_h = \frac{4A}{P} = \frac{2H_{ch} W_{ch}}{H_{ch} + W_{ch}}$$

By utilizing the hydraulic diameter $D_{h,}$ the Reynolds number, Re can be calculated from the Equation (3.6). In this case, Reynolds number is measured using two different inlet velocity (u_m), which is 1.5 m/s and 5.0 m/s. The calculation workings are presented in Appendix A.

Reynolds number, Re (3.6)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Prandtl number, Pr is calculated using Equation (3.7). The calculation workings are presented in Appendix A.

Prandtl number, Pr (3.7)

$$Pr_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}}$$

Nusselt number, Nu is calculated using Equation (3.8). In this case, Nusselt number is measured using two different inlet velocity (u_m), which is 1.5 m/s and 5.0 m/s. The calculation workings are presented in Appendix A.

Nusselt number, Nu (3.8)

$$Nu_{nf} = 0.021 Re^{0.8}_{nf} \, Pr^{0.5}_{nf}$$

With the calculated Nusselt number above, the heat transfer coefficient, h can be calculated using Equation (3.9). The heat transfer coefficient is measured using two different inlet velocity (u_m), which is 1.5 m/s and 5.0 m/s. The calculation workings are presented in Appendix A.

Heat transfer coefficient, h (3.9)

$$\mathbf{h} = \frac{\mathbf{Nuk}_{nf}}{\mathbf{D}_h}$$

For the Pressure drop, ΔP can be calculated using Equation (3.10). The Pressure drop is measured using two different inlet velocity (u_m), which is 1.5 m/s and 5.0 m/s. The calculation workings are presented in Appendix A.

Pressure drop, ΔP (3.10)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

Where indicates

$$f = (1.82\log Re - 1.64)^{-2}$$

$V_m = U_m$

The Pumping power, P can be calculated using Equation (3.11). The Pumping power is measured using two different inlet velocity (u_m), which is 1.5 m/s and 5.0 m/s, causing two different volumetric flow rates used in the measurement. The calculation workings are presented in Appendix A.

Pumping power, P (3.11)

$$P = \dot{V}\,\Delta P$$

Where indicates

$$\dot{V} = N\,W_{ch}\,L_{ch}\,u_{nf}$$

For the overall heat transfer rate, Q can be calculated using Equation (3.12). The heat transfer rate is measured using two different inlet velocity (u_m), which is 1.5 m/s and 5.0 m/s. The calculation workings are presented in Appendix A.

Overall heat transfer rate, Q (3.12)

$$Q_{nf} = \dot{m}_{nf}\,Cp_{nf}\,(T_{out} - T_{in})_{nf}$$

The temperate difference is measure at 20ºC

Where indicates

$$\dot{m}_{nf} = P_{nf}\,\dot{V}$$

$$\dot{V} = N\,W_{ch}\,L_{ch}\,u_{nf}$$

3.3 Water side calculation

From Table 3.1, heat transfer rate for water can be computed from Equation (3.13) below:

$$Q_w = \dot{m}_w Cp_w (T_{in} - T_{out})_w \qquad (3.13)$$

The temperate difference is measure at 20ºC

Where indicates

$$\dot{m}_w = P_w\,\dot{V}$$

$$\dot{V} = N\,W_{ch}\,L_{ch}\,u_{nf}$$

The calculation workings are presented in Appendix A.

CHAPTER IV

RESULTS & DISCUSSION

4.1 Heat Transfer of water chiller using nanofluid

Based on the calculation done for Al_2O_3 & TiO_2 nanofluid using Equation (3.1) to Equation (3.4), we can notice that the thermophysical properties calculated, will increase with the increase of particle volume fraction, Ø. This has been shown in Table 4.1 and Table 4.2 below:

Table 4.1 : Thermophysical properties of (Al_2O_3) Nanofluid

Properties	**Nanoparticle (Al_2O_3)**				
	Ø = 0.5 %	**Ø = 0.8 %**	**Ø = 1.5 %**	**Ø = 2.0 %**	**Ø = 4.0 %**
ρ (kg/m^3)	1,011.96	1,020.88	1,041.69	1,056.56	1,116.02
Cp (J/kg K)	4,112.05	4,072.80	3,983.85	3,922.44	3,693.22
k (W/m K)	0.6190	0.6226	0.6311	0.6373	0.6625
μ (Ns/m^2)	1.0155×10^{-3}	1.0231×10^{-3}	1.0406×10^{-3}	1.0532×10^{-3}	1.1033×10^{-3}

Table 4.2 : Thermophysical properties of (TiO_2) Nanofluid

Properties	**Nanoparticle (TiO_2)**				
	Ø = 0.5 %	**Ø = 0.8 %**	**Ø = 1.5 %**	**Ø = 2.0 %**	**Ø = 4.0 %**
ρ (kg/m^3)	1,013.10	1,022.70	1,045.10	1,061.10	1,125.10
Cp (J/kg K)	4,107.14	4065.11	3970.04	3904.58	3661.38
k (W/m K)	0.6183	0.6215	0.6291	0.6459	0.6569
μ (Ns/m^2)	1.0155×10^{-3}	1.0231×10^{-3}	1.0406×10^{-3}	1.0532×10^{-3}	1.1033×10^{-3}

Heat transfer coefficient, (h) for both the nanofluids increases with the increase of particle volume fraction, Ø. **Figure 4.1** below shows at 1.5m/s inlet velocity for Al_2O_3 nanofluid with particle volume fraction of 4% has the highest heat transfer coefficient of 15,018.82 W/m2 K and 14987.55 W/m2 K for TiO_2 at 4% particle volume fraction. From **Figure 4.2** at 5.0 m/s inlet velocity for Al_2O_3 nanofluid with particle volume fraction of 4% has heat transfer coefficient of 39,349.75 W/m2 K followed by 39267.57 W/m2 K for TiO_2 at 4% particle volume fraction. This shows that for higher particle volume fraction and higher inlet velocity, it has the higher value of heat transfer coefficient. From above statement, heat transfer enhancement is increasing as the concentration of nanoparticle increases.

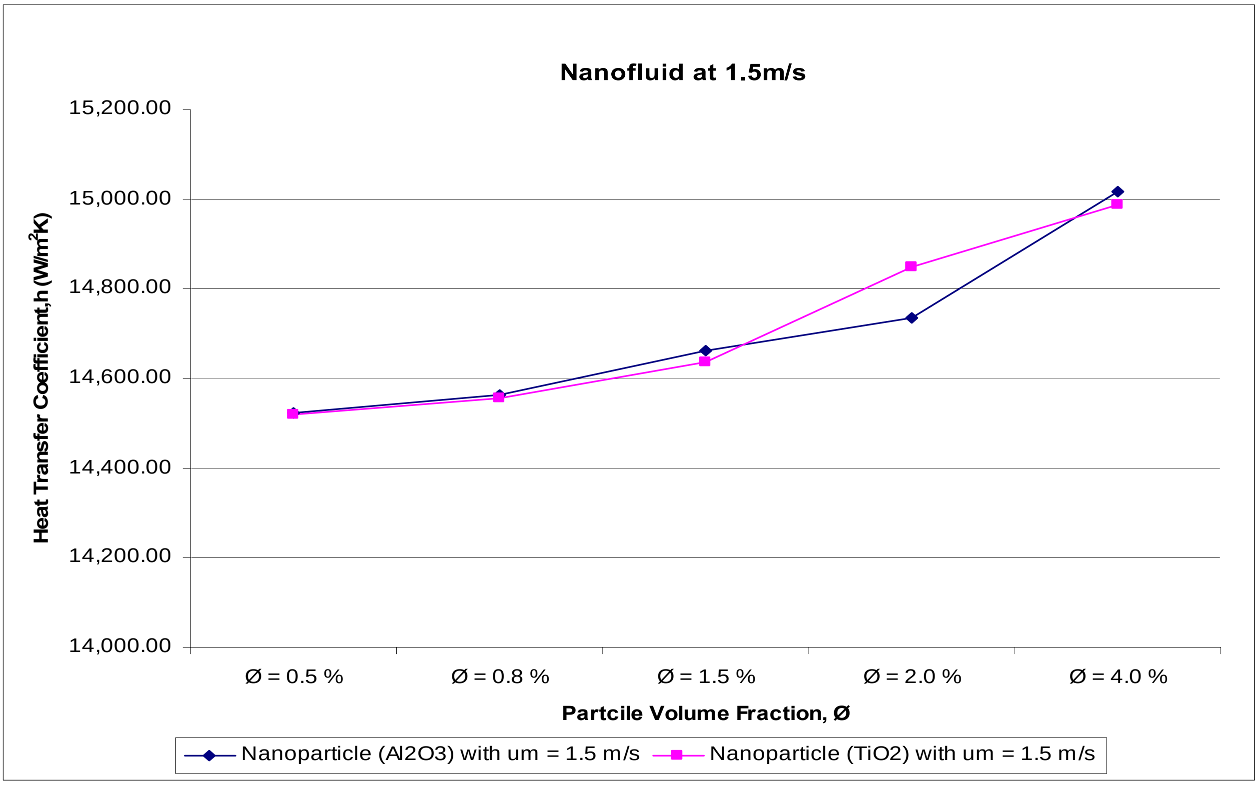


Figure 4.1 : Heat transfer coefficient at various particle volume fraction with 1.5m/s inlet velocity

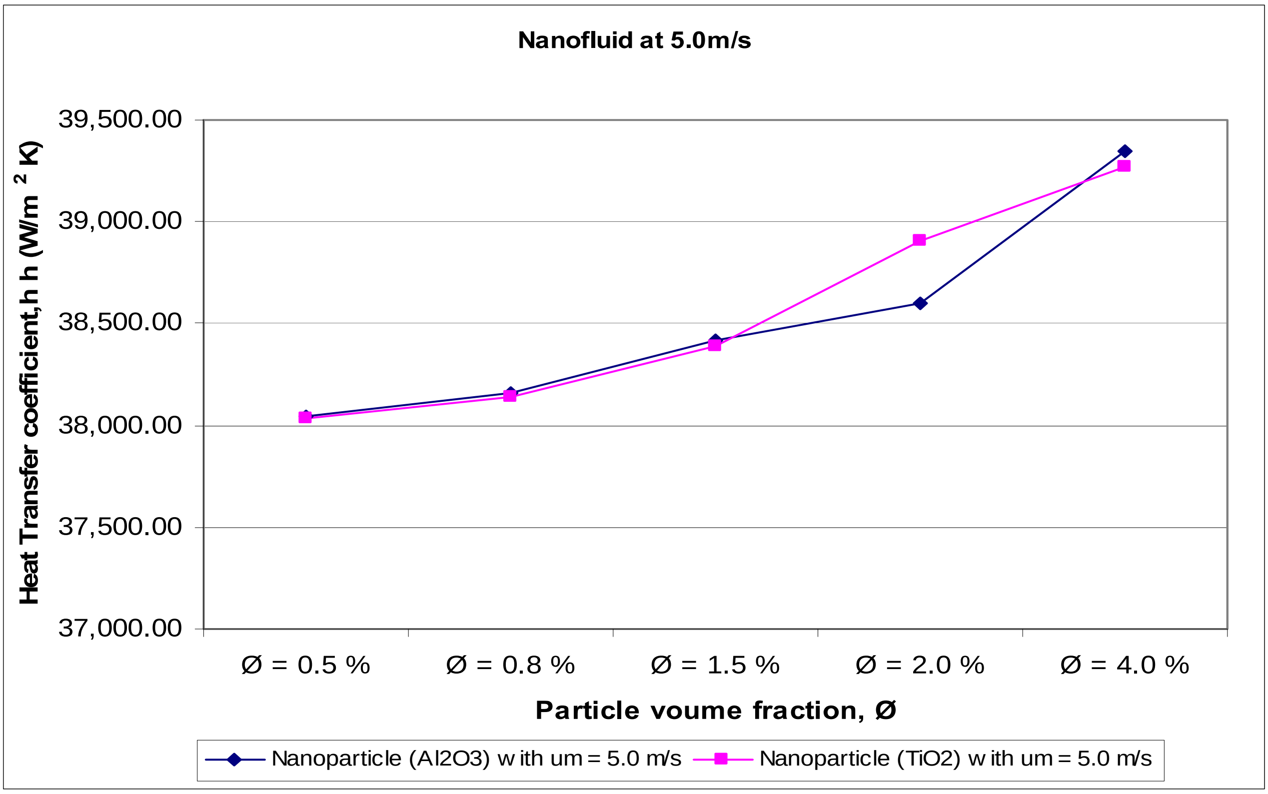


Figure 4.2 : Heat transfer coefficient at various particle volume fraction with 5.0 m/s inlet velocity

By having higher heat transfer coefficient, the thermal conductivity of the nanofluid also increases. Thermal conductivity for both the nanofluid increases with increasing the particle volume fraction. This can be seen from **Figure 4.3** whereby the thermal conductivity for Al_2O_3 nanofluid with 4% particle volume fraction has the highest value which is 0.6625 W/m K and for TiO_2 with 4% particle volume fraction has the highest value which is 0.6569 W/m K.

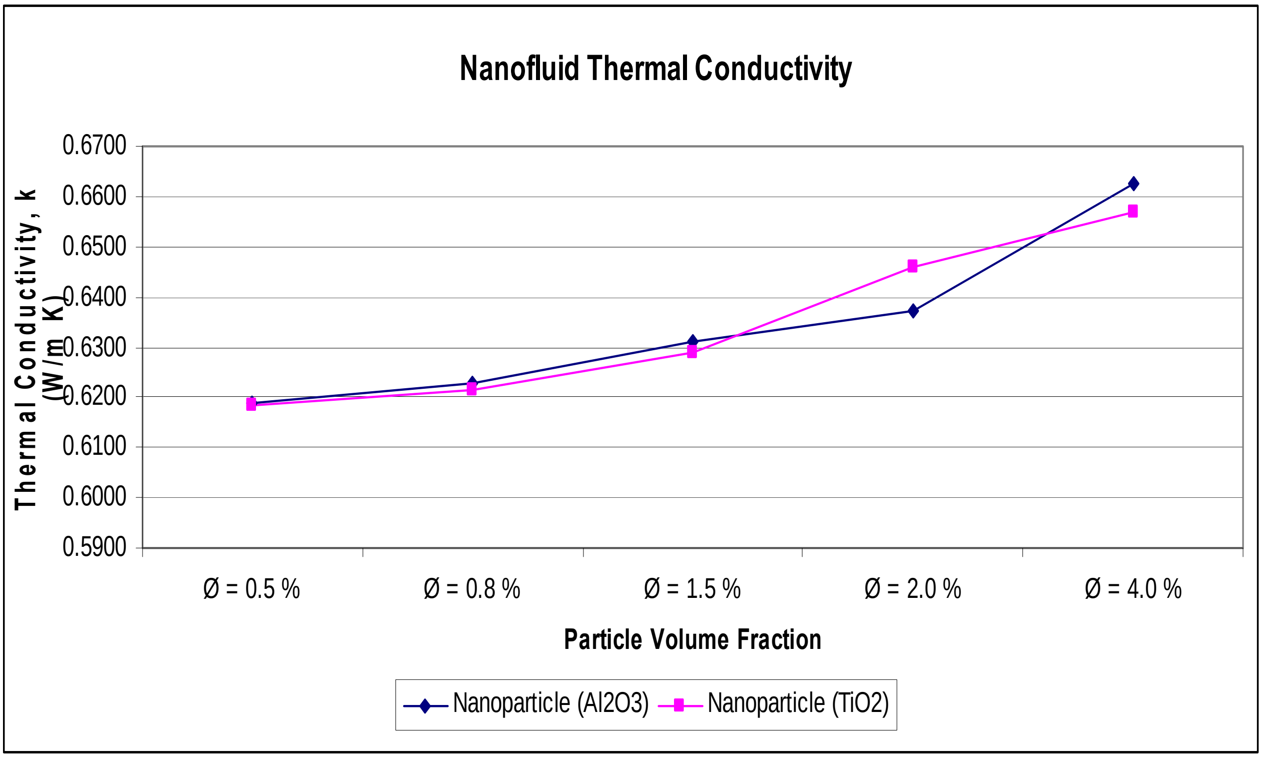


Figure 4.3 : Thermal conductivity of nanofluid at various particle volume fraction

With the presence of higher thermal conductivity of the nanofluid, it will have higher Reynolds number. This is shown in **Figure 4.4** and **Figure 4.5** , whereby the highest Reynolds Number with 1.5m/s inlet velocity is 514.59 for Al_2O_3 nanofluid with 0.6625 W/m K thermal conductivity and highest Reynolds Number is 518.78 for TiO_2 nanofluid with 0.6569W/m K thermal conductivity. For Reynolds Number with 5.0m/s inlet velocity has highest value of 1715.31 for Al_2O_3 nanofluid with 0.6625 W/m K thermal conductivity and highest Reynolds Number is 1729.26 for TiO_2 nanofluid with 0.6569W/m K thermal conductivity

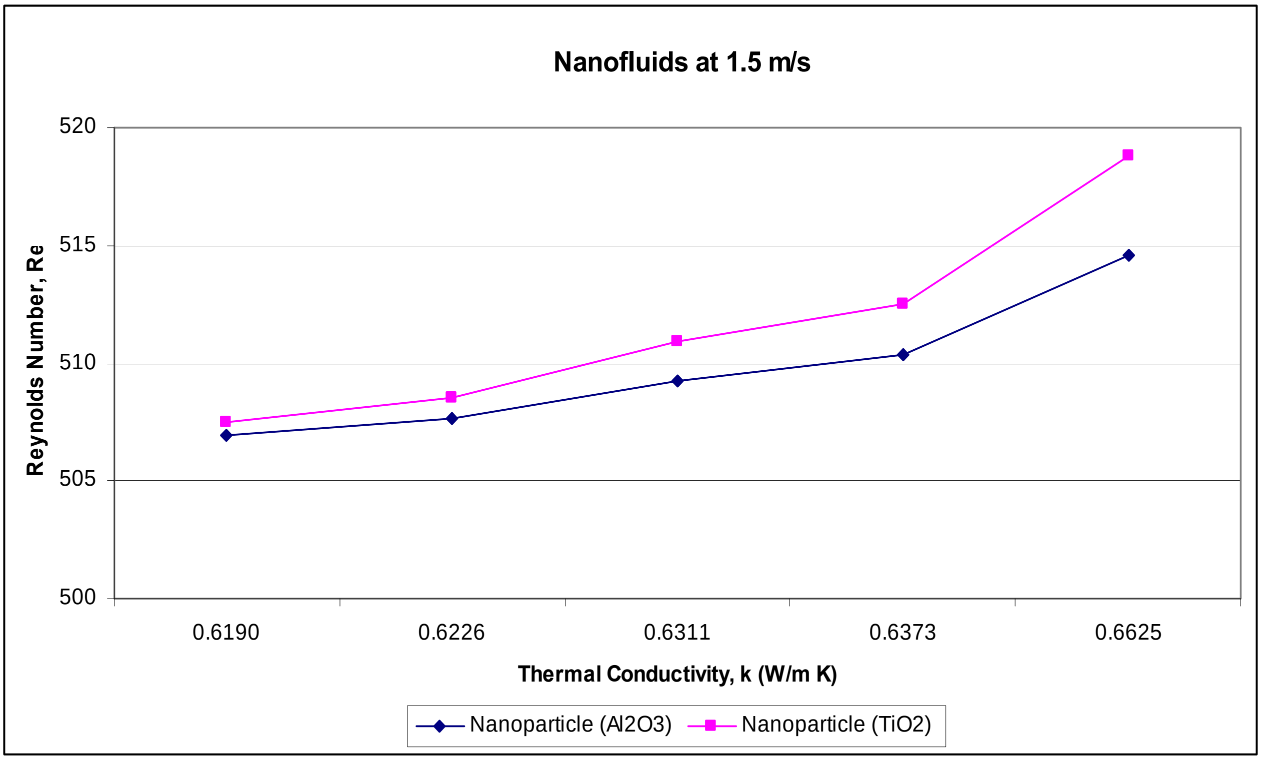


Figure 4.4 : Effect of thermal conductivity on Reynolds Number at 1.5 m/s inlet velocity

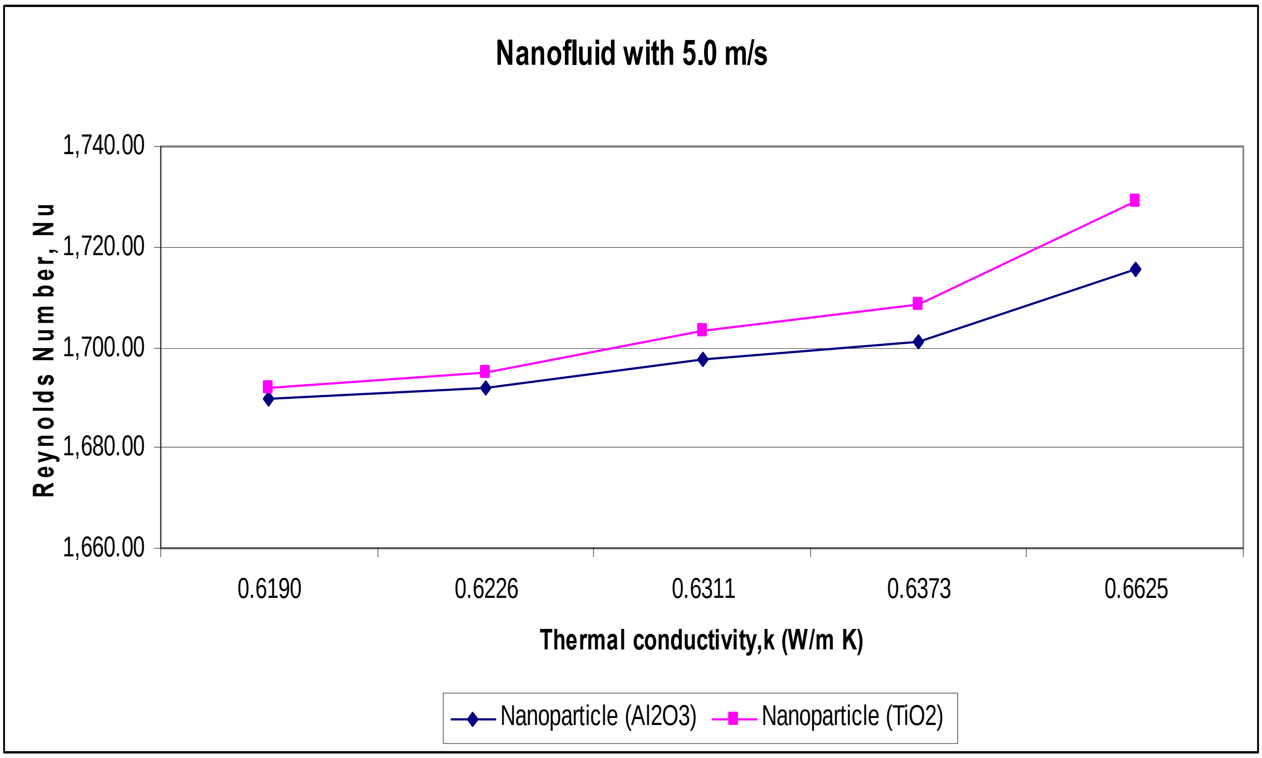


Figure 4.5 : Effect of thermal conductivity on Reynolds Number at 5.0 m/s inlet velocity

In this study, it was noticed that from calculations conducted, the value obtained for Prandtl number for both the nanofluid, decreases with the increase of particle volume fraction, as shown in **Figure 4.6**. It can be seen that the highest Prandtl number for Al_2O_3 nanofluid is 6.7460 at 0.5% particle volume fraction, whereby TiO_2 nanofluid is 6.7456 at 0.5% particle volume fraction. The reason of this phenomenon is due to the higher thermal conductivity of the nanofluid, caused by increasing of the particle volume fraction and due to the formula correlations used to compute Prandtl number. Having lower value of Prandtl number with the increase in the particle volume fraction, it will also cause the Nusselt number to be decreasing, based on calculation done and shown in **Figure 4.7**.

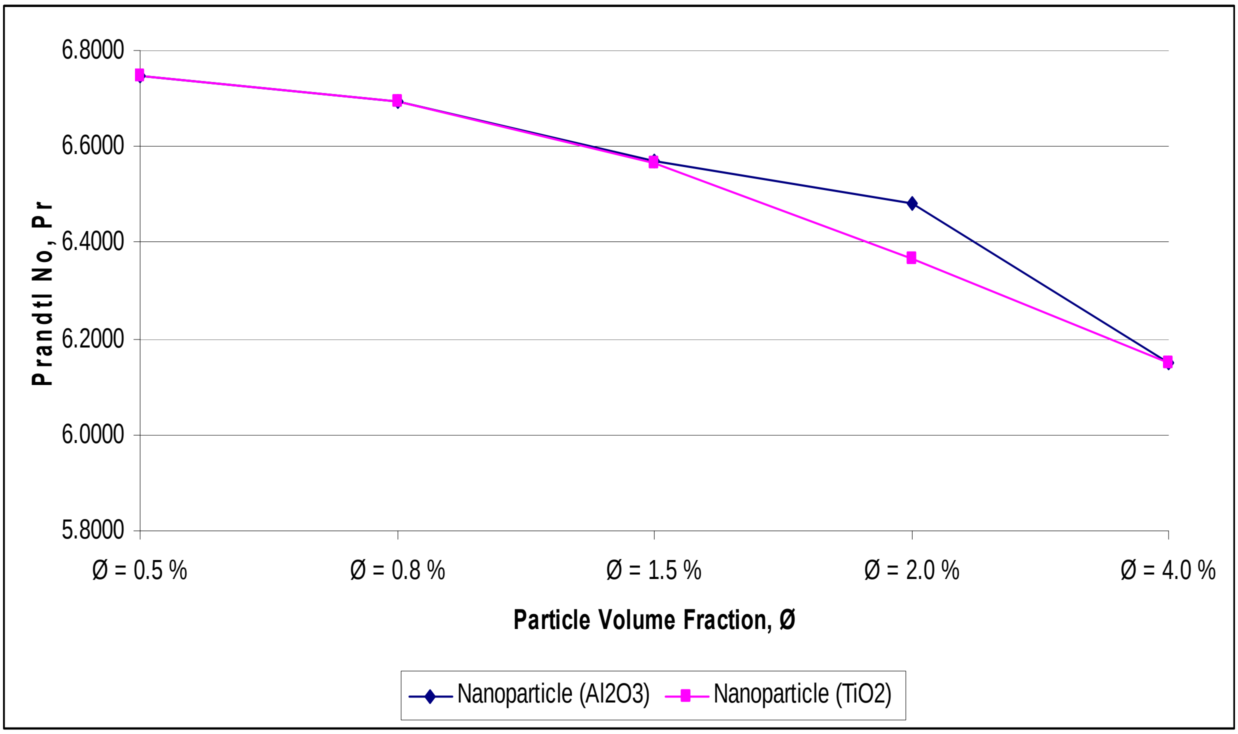


Figure 4.6 : Effect of various particle volume fraction to Prandtl number.

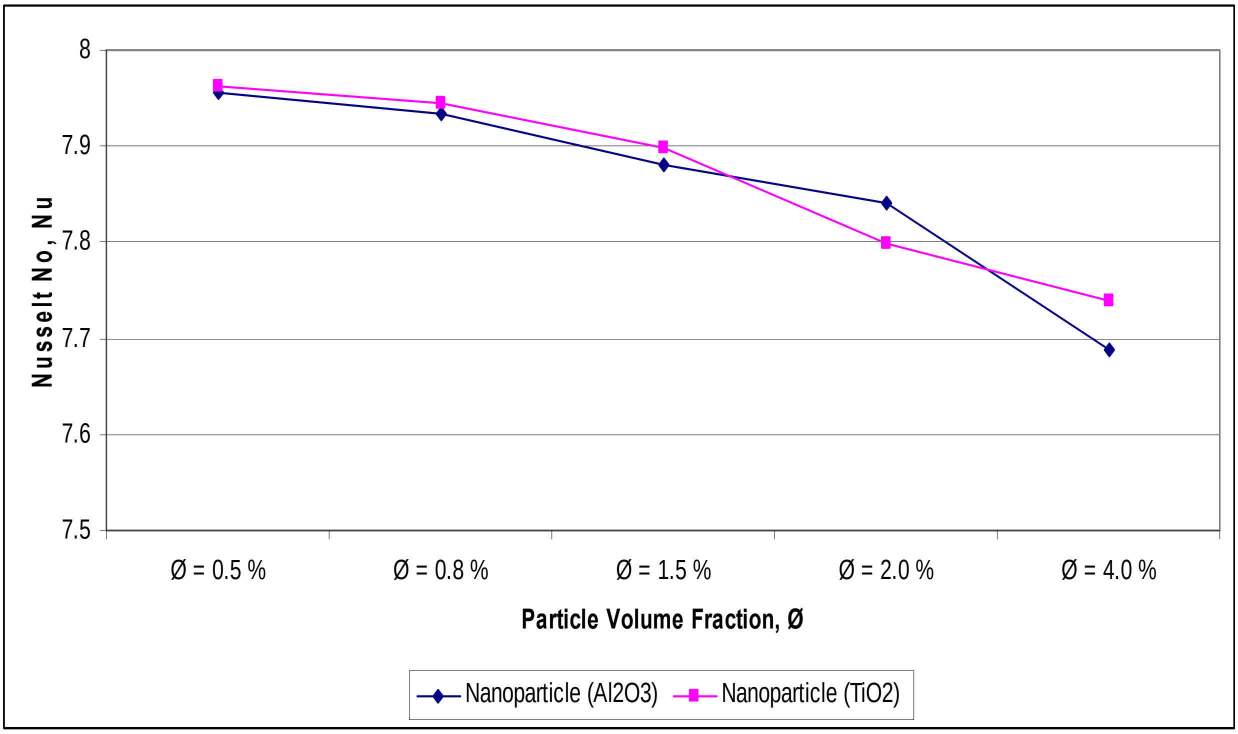


Figure 4.7 : Effect of various particle volume fraction to Nusselt number at 1.5 m/s inlet velocity.

4.2 Pressure Drop and Pumping Pressure

From calculation done in using Equation (3.9) and Equation (3.10) it is noticed that both the pressure drop and pumping power for the nanofluid increases with the increasing of the particle volume fraction, and it also increases along with the mass flow rate. The density and inlet velocity are the dependent variables for the increase in values of the pressure drop and eventually causing the increase in pumping power. This is due to the formula correlations used to compute Prandtl number as computed in Equation (3.7).

Based on **Figure 4.8**, we can notice that the highest pressure drop for Al_2O_3 nanofluid with 1.5 m/s inlet velocity is 4,092.02 Pa at 4.0% particle volume fraction and highest pressure drop for TiO_2 nanofluid with 1.5 m/s inlet velocity is 4,109.28 Pa at 4.0% particle volume fraction.

Referring to **Figure 4.9**, we can notice that the highest pressure drop for Al_2O_3 nanofluid with 5.0 m/s inlet velocity is 2,162.27 Pa at 4.0% particle volume fraction and highest pressure drop for TiO_2 nanofluid with 5.0 m/s inlet velocity is 2,176.01 Pa at 4.0% particle volume fraction. The reason for the increase in pressure drop as the particle volume fraction increase is due to particle deposition that increasing the wall roughness.

As for the highest pumping power seen from **Figure 4.8**, for Al_2O_3 nanofluid with 1.5 m/s inlet velocity is 0.4297 W at 4.0% particle volume fraction and highest pumping pressure for TiO_2 nanofluid with 1.5 m/s inlet velocity is 0.4315 W at 4.0% particle volume fraction.

As for the highest pumping power seen **Figure 4.9**, for Al_2O_3 nanofluid with 5.0 m/s inlet velocity is 0.7568 W at 4.0% particle volume fraction and highest pumping pressure for TiO_2 nanofluid with 1.5 m/s inlet velocity is 0.7616 W at 4.0% particle volume fraction. The reason for the increase in the pumping power is due to the increase in the particle volume fraction and heat transfer coefficient which in return will also increase thermal conductivity of the nanofluid.

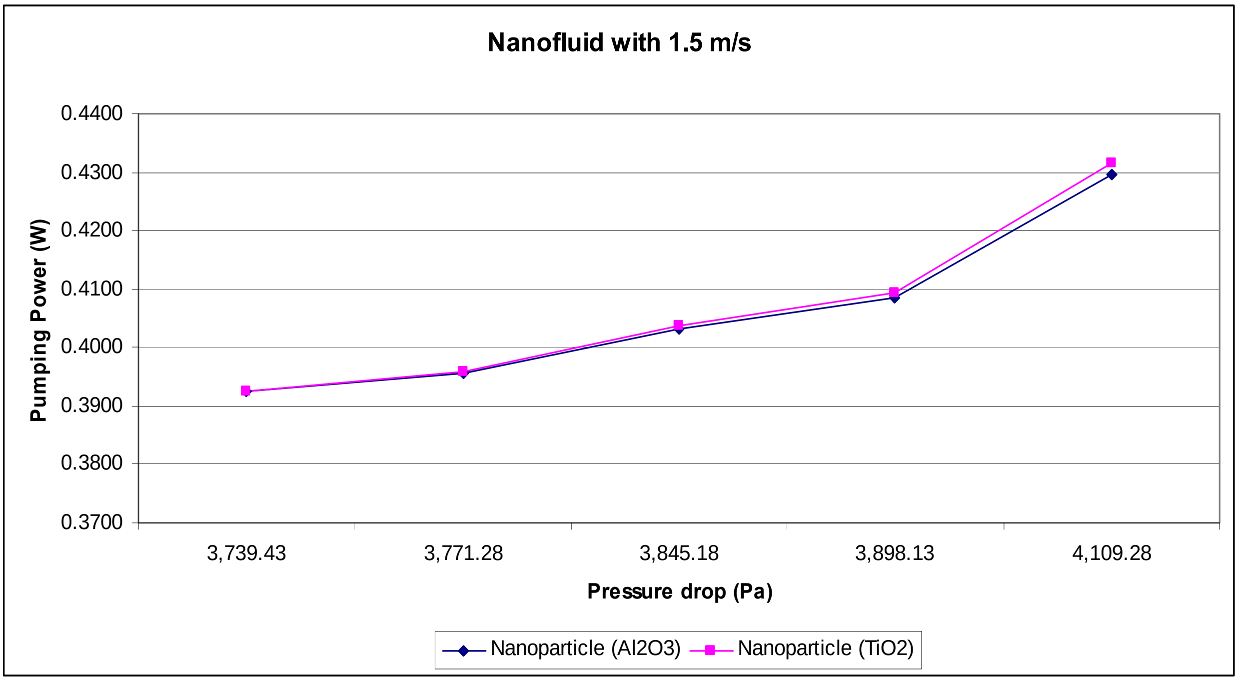


Figure 4.8 : Effect of pressure drop and Pumping power to Particle Volume Fraction at 1.5 m/s inlet velocity

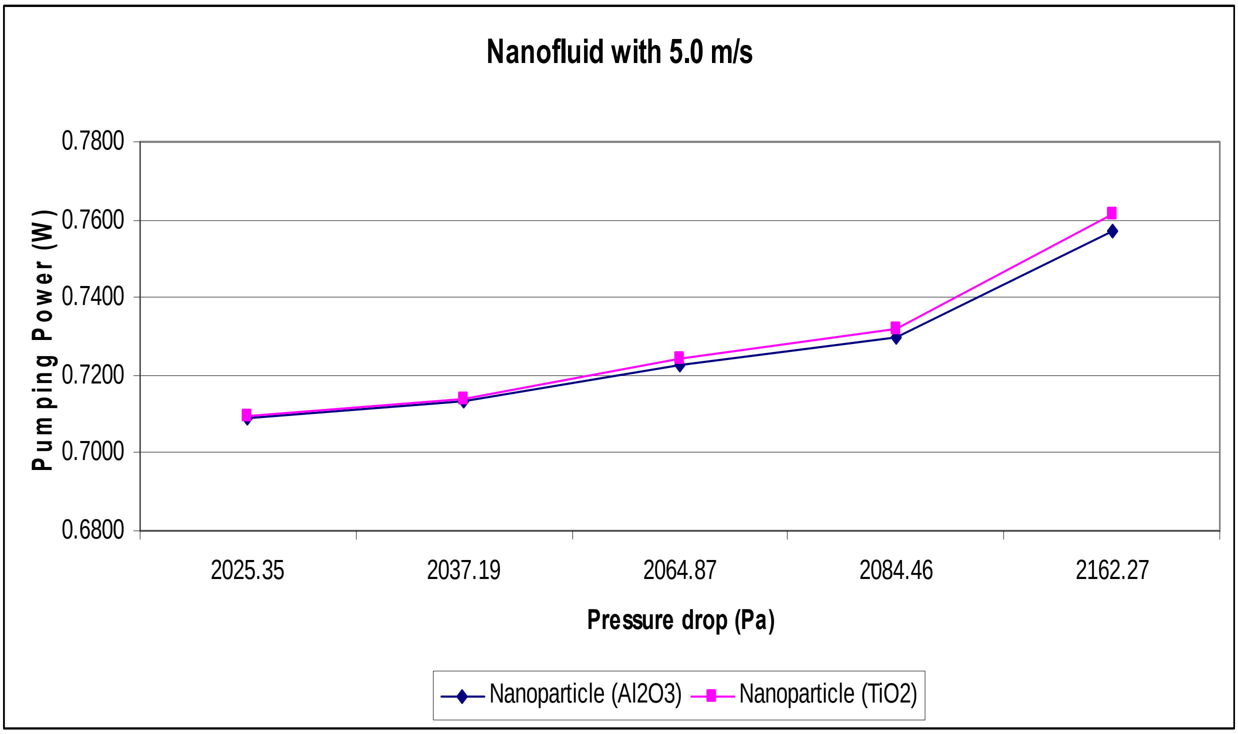


Figure 4.9 : Effect of pressure drop and Pumping power to Particle Volume Fraction at 5.0 m/s inlet velocity

4.3 Heat Transfer rate using Water in Water Chiller

From water side calculation in, heat transfer rate for water with inlet velocity of 5m/s has higher value compared to 1.5m/s. The **Figure 4.10** below shows the comparison at different inlet velocity. This due to it's higher mass flow rate for water inlet velocity of 5m/s compared to 1.5m/s.

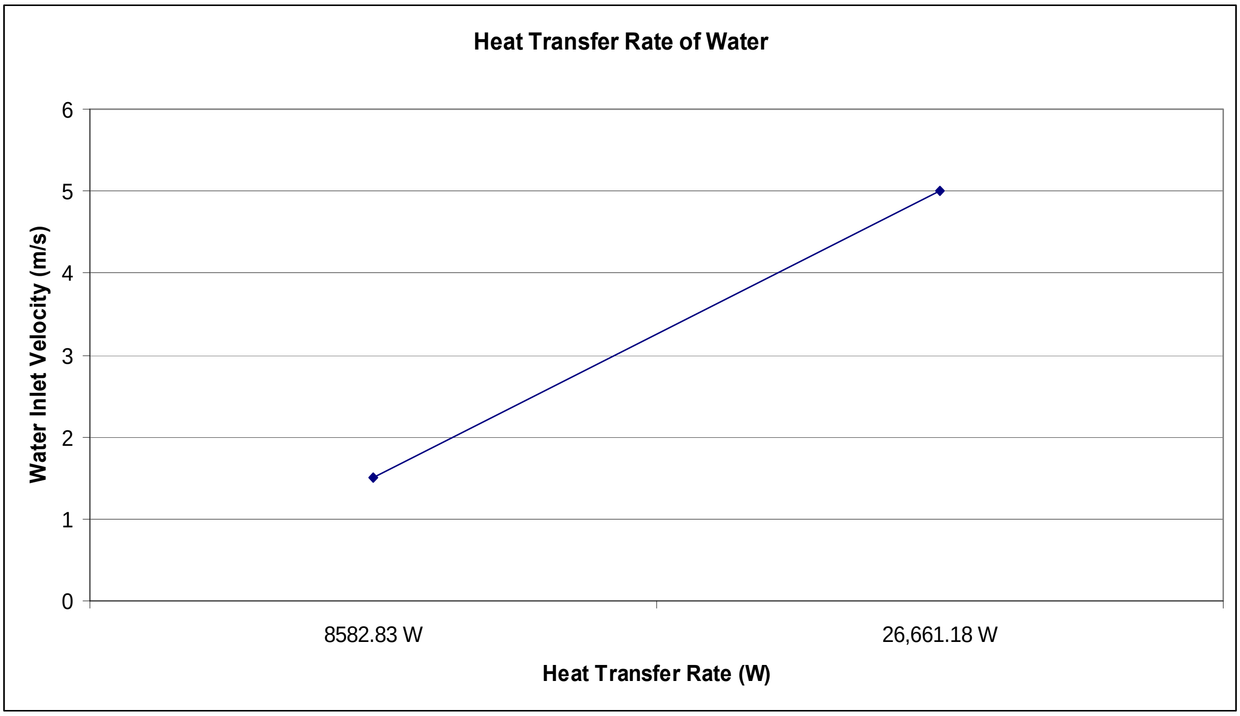


Figure 4.10 : Heat Transfer of Water with 1.5 m/s and 5.0 m/s inlet velocity

4.4 Overall Heat Transfer Rate

The overall heat transfer rate is calculated from Equation (3.13) for water and Equation (3.12) for nanofluid. By comparison, it is noted that the highest heat transfer rate is achieved using Al_2O_3 nanofluid which is 29,128.62 W with 5.0 m/s inlet velocity by 0.5% particle volume fraction, followed by TiO_2 nanofluid 29,126.19 W with 0.5% particle volume fraction at 5m/s inlet velocity, and finally using pure water in water chiller with 26,661.18 W at 5.0m/s inlet velocity.

CHAPTER V

CONCLUSION

This study on heat transfer performance investigation of water chiller using nanofluids is done by comparing water chiller using pure water as coolant with nanofluids with regards to thermophysical properties, heat transfer coefficient, thermal conductivity, heat transfer rate, pumping power and pressure drop.

Based on the calculations done, the thermophysical properties will increase with the increase of particle volume fraction. Moreover, heat transfer coefficient also increases with the increase of particle volume fraction, causing the thermal conductivity of the nanofluid to increase. At 4% of particle volume fraction, thermal conductivity of nanofluid had increased 7.47% for Al_2O_3 nanofluid and 6.68% for TiO_2 nanofluid.

For Al_2O_3 nanofluid, the maximum pumping power is 0.4297 W for 4% particle volume fraction with 1.5m/s inlet velocity and 4,092.02 Pa of Pressure drop is achieved. For inlet velocity of 5.0m/s, the pumping power found to be 0.7568 Pa. As for TiO_2 nanofluid, maximum pumping power is 0.4315 W for 4% particle volume fraction with 1.5m/s inlet velocity and 4,109.28 Pa of Pressure drop is achieved. For inlet velocity of 5.0m/s, the pumping power found to be 0.7616 Pa

As for the overall heat transfer rate, based on calculation it can be mentioned that heat transfer rate is much higher using Al_2O_3 nanofluid, followed by TiO_2 nanofluid and finally using pure water.

Finally, it can be mentioned that from the calculation done above, the heat transfer of water chiller using nanofluid is much more higher compared to water. This is with regards to the characteristics, properties and capability of nanofluid to disperse more heat compared to pure water.

With all the studies, literature reviews and calculations conducted, as a conclusion, all three (3) objectives had been achieved.

APPENDIX

Appendix A : <u>Calculation workings from Equation 3.1 to Equation 3.13</u>

<u>From Equation (3.1)</u>

Density of Al_2O_3 (with Ø = 0.5%)

$\rho_{nf} = (1 - \text{Ø})\rho_f + \text{Ø}\rho_p$

ρ = (1-0.5%) 997.1 + 0.5% (3970)

= **1,011.96 kg/m^3**

Density of Al_2O_3 (with Ø = 0.8 %)

$\rho_{nf} = (1 - \text{Ø})\rho_f + \text{Ø}\rho_p$

ρ = (1-0.8%) 997.1 + 0.8% (3970)

= **1,020.88 kg/m^3**

Density of Al_2O_3 (with Ø = 1.5%)

$\rho_{nf} = (1 - \text{Ø})\rho_f + \text{Ø}\rho_p$

ρ = (1-1.5%) 997.1 + 1.5% (3970)

= **1,041.69 kg/m^3**

Density of Al_2O_3 (with Ø = 2.0%)

$\rho_{nf} = (1 - \text{Ø})\rho_f + \text{Ø}\rho_p$

ρ = (1-2.0%)997.1 + 2.0%(3970)

= **1,056.56 kg/m^3**

Density of Al_2O_3 (with Ø = 4.0%)

$\rho_{nf} = (1 - \text{Ø})\rho_f + \text{Ø}\rho_p$

ρ = (1-4.0%)997.1 + 4.0%(3970)

= **1,116.02 kg/m^3**

Density of TiO_2 (with Ø = 0.5%)

$\rho_{nf} = (1 - Ø)\rho_f + Ø\rho_p$

ρ = (1-0.5%)997.1+0.5%(4197)

= **1,013.10 kg/m^3**

Density of TiO_2 (with Ø = 0.8%)

$\rho_{nf} = (1 - Ø)\rho_f + Ø\rho_p$

ρ = (1-0.8%)997.1+0.8%(4197)

= **1,022.70 kg/m^3**

Density of TiO_2 (with Ø = 1.5%)

$\rho_{nf} = (1 - Ø)\rho_f + Ø\rho_p$

ρ = (1-1.5%)997.1+1.5%(4197)

= **1,045.10 kg/m^3**

Density of TiO_2 (with Ø = 2.0%)

$\rho_{nf} = (1 - Ø)\rho_f + Ø\rho_p$

ρ = (1-2.0%)997.1+2.0%(4197)

= **1,061.10 kg/m^3**

Density of TiO_2 (with Ø = 4.0%)

$\rho_{nf} = (1 - Ø)\rho_f + Ø\rho_p$

ρ = (1-4.0%)997.1+4.0%(4197)

= **1,125.10 kg/m^3**

From Equation (3.2)

Viscosity of Al_2O_3 (with Ø = 0.5 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x0.5\%)$

= **1.0155×10^{-3} Ns/m^2**

Viscosity of Al_2O_3 (with Ø = 0.8 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x0.8\%)$

= **1.0231×10^{-3} Ns/m^2**

Viscosity of Al_2O_3 (with Ø = 1.5 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x1.5\%)$

= **1.0406×10^{-3} Ns/m^2**

Viscosity of Al_2O_3 (with Ø = 2.0 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x2.0\%)$

= **1.0532×10^{-3} Ns/m^2**

Viscosity of Al_2O_3 (with Ø = 4.0 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x4.0\%)$

= **1.1033×10^{-3} Ns/m^2**

Viscosity of TiO_2 (with Ø = 0.5 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x0.5\%)$

= **1.0155×10^{-3} Ns/m^2**

Viscosity of TiO_2 (with Ø = 0.8 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x0.8\%)$

$= \underline{\underline{\mathbf{1.0231 \times 10^{-3}\ Ns/m^2}}}$

Viscosity of TiO_2 (with Ø = 1.5 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x1.5\%)$

$= \underline{\underline{\mathbf{1.0406 \times 10^{-3}\ Ns/m^2}}}$

Viscosity of TiO_2 (with Ø = 2.0 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x2.0\%)$

$= \underline{\underline{\mathbf{1.0532 \times 10^{-3}\ Ns/m^2}}}$

Viscosity of TiO_2 (with Ø = 4.0 %)

$\mu_{nf} = \mu_{bf}(1 + 2.5Ø)$

$\mu = 0.001003(1+2.5x4.0\%)$

$= \underline{\underline{\mathbf{1.1033 \times 10^{-3}\ Ns/m^2}}}$

From Equation (3.3)

Specific heat of Al_2O_3 (with Ø = 0.5 %)

$(\rho C_p)_{nf} = (1- Ø)(\rho C_p)_f + Ø(\rho C_p)_p$

$= (1\text{-}0.5\%)(997.1x4179)+0.5\%(3970x765)/\ 1011.96$

$= \underline{\underline{\mathbf{4{,}112.05\ J/kg\ K}}}$

Specific heat of Al_2O_3 (with Ø = 0.8 %)

$(\rho C_p)_{nf} = (1- Ø)(\rho C_p)_f + Ø(\rho C_p)_p$

$= (1\text{-}0.8\%)(997.1x4179)+0.8\%(3970x765)/\ 1020.88$

$= \underline{\underline{\mathbf{4{,}072.80\ J/kg\ K}}}$

Specific heat of Al_2O_3 (with Ø = 1.5 %)

$(\rho C_p)_{nf} = (1 - Ø)\ (\rho C_p)_f + Ø(\rho C_p)_p$

= (1-1.5%)(997.1x4179)+1.5%(3970x765)/ 1041.69

= **3,983.85 J/kg K**

Specific heat of Al_2O_3 (with Ø = 2.0 %)

$(\rho C_p)_{nf} = (1 - Ø)\ (\rho C_p)_f + Ø(\rho C_p)_p$

= (1-2.0%)(997.1x4179)+2.0%(3970x765)/ 1056.56

= **3,922.44 J/kg K**

Specific heat of Al_2O_3 (with Ø = 4.0 %)

$(\rho C_p)_{nf} = (1 - Ø)\ (\rho C_p)_f + Ø(\rho C_p)_p$

= (1-4.0%)(997.1x4179)+4.0%(3970x765)/ 1116.02

= **3,693.22 J/kg K**

Specific heat of TiO_2 (with Ø = 0.5 %)

$(\rho C_p)_{nf} = (1 - Ø)\ (\rho C_p)_f + Ø(\rho C_p)_p$

= (1-0.5%)(997.1x4179)+0.5%(4197x710)/ 1013.10

= **4,107.14 J/kg K**

Specific heat of TiO_2 (with Ø = 0.8 %)

$(\rho C_p)_{nf} = (1 - Ø)\ (\rho C_p)_f + Ø(\rho C_p)_p$

= (1-0.8%)(997.1x4179)+0.8%(4197x710)/ 1022.70

= **4,065.11 J/kg K**

Specific heat of TiO_2 (with Ø = 1.5 %)

$(\rho C_p)_{nf} = (1 - Ø)\ (\rho C_p)_f + Ø(\rho C_p)_p$

= (1-1.5%)(997.1x4179)+1.5%(4197x710)/ 1045.10

= **3,970.04 J/kg K**

Specific heat of TiO_2 (with Ø = 2.0 %)

$(\rho C_p)_{nf} = (1-Ø)\,(\rho C_p)_f + Ø(\rho C_p)_p$

= (1-2.0%)(997.1x4179)+2.0%(4197x710)/ 1061.10

= **<u>3,904.58 J/kg K</u>**

Specific heat of TiO_2 (with Ø = 4.0 %)

$(\rho C_p)_{nf} = (1-Ø)\,(\rho C_p)_f + Ø(\rho C_p)_p$

= (1-4.0%)(997.1x4179)+4.0%(4197x710)/ 1125.10

= **<u>3,661.38 J/kg K</u>**

<u>From Equation (3.4)</u>

Thermal conductivity of Al_2O_3 (with Ø = 0.5 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\,k_f$$

= **<u>0.6190 W/m K</u>**

Thermal conductivity of Al_2O_3 (with Ø = 0.8 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\,k_f$$

= **<u>0.6226 W/m K</u>**

Thermal conductivity of Al_2O_3 (with Ø = 1.5 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\,k_f$$

= **<u>0.6311 W/m K</u>**

Thermal conductivity of Al_2O_3 (with Ø = 2.0 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\;k_f$$

= **<u>0.6373 W/m K</u>**

Thermal conductivity of Al_2O_3 (with Ø = 4.0 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\;k_f$$

= **<u>0.6625 W/m K</u>**

Thermal conductivity of TiO_2 (with Ø = 0.5 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\;k_f$$

= **<u>0.6183 W/m K</u>**

Thermal conductivity of TiO_2 (with Ø = 0.8 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\;k_f$$

= **<u>0.6215 W/m K</u>**

Thermal conductivity of TiO_2 (with Ø = 1.5 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\;k_f$$

= **<u>0.6291 W/m K</u>**

Thermal conductivity of TiO_2 (with Ø = 2.0 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\; k_f$$

= **0.6459 W/m K**

Thermal conductivity of TiO_2 (with Ø = 4.0 %)

$$k_{nf} = \frac{k_p + (n-1)\,k_f - (n-1)Ø(k_f - k_p)}{k_p + (n-1)\,k_f + Ø(k_f - k_p)}\; k_f$$

= **0.6569 W/m K**

From Equation (3.5):

The hydraulic diameter, D_h of the microchannel

$$D_h = \frac{4A}{P} = \frac{2H_{ch}\,W_{ch}}{H_{ch} + W_{ch}}$$

$D_h = 2\,(430\text{x}10^{-6} \text{ x } 280\text{x}10^{-6}) / 430\text{x}10^{-6} + 280\text{x}10^{-6}$

= **$3.3915 \text{ x } 10^{-4}$ m**

From Equation (3.6) :

The Reynolds number of Al_2O_3 (with Ø = 0.5 % & u_m = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf}\,u_m D}{\mu_{nf}}$$

$Re = (1011.96)(1.5)(3.3915 \text{ x } 10^{-4}) / 1.0155 \text{ x } 10^{-3}$

= **506.95**

The Reynolds number of Al_2O_3 (with Ø = 0.8 % & u_{m} = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1020.88)(1.5)(3.3915 x 10^{-4}) / 1.0231 x 10^{-3}

= **507.62**

The Reynolds number of Al_2O_3 (with Ø = 1.5 % & u_{m} = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1041.69)(1.5)(3.3915 x 10^{-4}) / 1.0406 x 10^{-3}

= **509.26**

The Reynolds number of Al_2O_3 (with Ø = 2.0 % & u_{m} = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1056.56)(1.5)(3.3915 x 10^{-4}) / 1.0532 x 10^{-3}

= **510.35**

The Reynolds number of Al_2O_3 (with Ø = 4.0 % & u_{m} = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1116.02)(1.5)(3.3915 x 10^{-4}) / 1.1033 x 10^{-3}

= **514.59**

The Reynolds number of Al_2O_3 (with Ø = 0.5 % & u_{m} = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1011.96)(5.0)(3.3915 x 10^{-4}) / 1.0155 x 10^{-3}

= **1,689.83**

The Reynolds number of Al_2O_3 (with Ø = 0.8 % & u_{m} = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1020.88)(5.0)(3.3915 x 10^{-4}) / 1.0231 x 10^{-3}

= **1,692.07**

The Reynolds number of Al_2O_3 (with Ø = 1.5 % & u_{m} = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1041.69)(5.0)(3.3915 x 10^{-4}) / 1.0406 x 10^{-3}

= **1,697.53**

The Reynolds number of Al_2O_3 (with Ø = 2.0 % & u_{m} = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1056.56)(5.0)(3.3915 x 10^{-4}) / 1.0532 x 10^{-3}

= **1,701.16**

The Reynolds number of Al_2O_3 (with Ø = 4.0 % & u_m = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1116.02)(5.0)(3.3915 x 10^{-4}) / 1.1033 x 10^{-3}

= **1,715.31**

The Reynolds number of TiO_2 (with Ø = 0.5 % &u_m = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1013.10)(1.5)(3.3915 x 10^{-4}) / 1.0155 x 10^{-3}

= **507.52**

The Reynolds number of TiO_2 (with Ø = 0.8 % &u_m = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1022.70)(1.5)(3.3915 x 10^{-4}) / 1.0231 x 10^{-3}

= **508.53**

The Reynolds number of TiO_2 (with Ø = 1.5 % &u_m = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1045.10)(1.5)(3.3915 x 10^{-4}) / 1.0406 x 10^{-3}

= **510.92**

The Reynolds number of TiO_2 (with Ø = 2.0 % &u_{m} = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1061.10)(1.5)(3.3915 x 10^{-4}) / 1.0532 x 10^{-3}

= **512.54**

The Reynolds number of TiO_2 (with Ø = 4.0 % &u_{m} = 1.5 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1125.10)(1.5)(3.3915 x 10^{-4}) / 1.1033 x 10^{-3}

= **518.78**

The Reynolds number of TiO_2 (with Ø = 0.5 % & u_{m} = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1013.10)(5.0)(3.3915 x 10^{-4}) / 1.0155 x 10^{-3}

= **1,691.74**

The Reynolds number of TiO_2 (with Ø = 0.8 % & u_{m} = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1022.70)(5.0)(3.3915 x 10^{-4}) / 1.0231 x 10^{-3}

= **1,695.09**

The Reynolds number of TiO_2 (with Ø = 1.5 % & u_m = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1045.10)(5.0)(3.3915 x 10^{-4}) / 1.0406 x 10^{-3}

= **1,703.08**

The Reynolds number of TiO_2 (with Ø = 2.0 % & u_m = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1061.10)(5.0)(3.3915 x 10^{-4}) / 1.0532 x 10^{-3}

= **1,708.47**

The Reynolds number of TiO_2 (with Ø = 4.0 % & u_m = 5.0 m/s)

$$Re_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}}$$

Re = (1125.10)(5.0)(3.3915 x 10^{-4}) / 1.1033 x 10^{-3}

= **1,729.26**

From Equation (3.7)

Prandtl number of Al_2O_3 (with Ø = 0.5 %)

$$Pr_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}}$$

= **6.7460**

Prandtl number of Al_2O_3 (with Ø = 0.8 %)

$$Pr_{nf} = \frac{\mu_{nf}\, Cp_{nf}}{k_{nf}}$$

$$= \underline{\underline{\mathbf{6.6927}}}$$

Prandtl number of Al_2O_3 (with Ø = 1.5 %)

$$Pr_{nf} = \frac{\mu_{nf}\, Cp_{nf}}{k_{nf}}$$

$$= \underline{\underline{\mathbf{6.5688}}}$$

Prandtl number of Al_2O_3 (with Ø = 2.0 %)

$$Pr_{nf} = \frac{\mu_{nf}\, Cp_{nf}}{k_{nf}}$$

$$= \underline{\underline{\mathbf{6.4822}}}$$

Prandtl number of Al_2O_3 (with Ø = 4.0 %)

$$Pr_{nf} = \frac{\mu_{nf}\, Cp_{nf}}{k_{nf}}$$

$$= \underline{\underline{\mathbf{6.1505}}}$$

Prandtl number of TiO_2 (with Ø = 0.5 %)

$$Pr_{nf} = \frac{\mu_{nf}\, Cp_{nf}}{k_{nf}}$$

$$= \underline{\underline{\mathbf{6.7456}}}$$

Prandtl number of TiO_2 (with Ø = 0.8 %)

$$Pr_{nf} = \frac{\mu_{nf}\, Cp_{nf}}{k_{nf}}$$

$$= \underline{\underline{\mathbf{6.6919}}}$$

Prandtl number of TiO_2 (with Ø = 1.5 %)

$$Pr_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}}$$

$= \underline{\underline{6.5669}}$

Prandtl number of TiO_2 (with Ø = 2.0 %)

$$Pr_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}}$$

$= \underline{\underline{6.3668}}$

Prandtl number of TiO_2 (with Ø = 4.0 %)

$$Pr_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}}$$

$= \underline{\underline{6.1495}}$

From Equation (3.8)

Nusselt number for Al_2O_3 (with Ø = 0.5 % & u_m = 1.5 m/s)

$Nu_{nf} = 0.021 Re^{0.8}_{nf} Pr^{0.5}_{nf}$

$= \underline{\underline{7.9564}}$

Nusselt number for Al_2O_3 (with Ø = 0.8 % & u_m = 1.5 m/s)

$Nu_{nf} = 0.021 Re^{0.8}_{nf} Pr^{0.5}_{nf}$

$= \underline{\underline{7.9332}}$

Nusselt number for Al_2O_3 (with Ø = 1.5 % & u_m = 1.5 m/s)

$Nu_{nf} = 0.021 Re^{0.8}_{nf} Pr^{0.5}_{nf}$

$= \underline{\underline{7.8798}}$

Nusselt number for Al_2O_3 (with Ø = 2.0 % & u_{m} = 1.5 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **7.8411**

Nusselt number for Al_2O_3 (with Ø = 4.0 % & u_{m} = 1.5 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **7.6885**

Nusselt number for Al_2O_3 (with Ø = 0.5 % & u_{m} = 5.0 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **20.8457**

Nusselt number for Al_2O_3 (with Ø = 0.8 % & u_{m} = 5.0 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **20.7852**

Nusselt number for Al_2O_3 (with Ø = 1.5 % & u_{m} = 5.0 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **20.6451**

Nusselt number for Al_2O_3 (with Ø = 2.0 % & u_{m} = 5.0 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **20.5436**

Nusselt number for Al_2O_3 (with Ø = 4.0 % & u_{m} = 5.0 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **20.1441**

Nusselt number for TiO_2 (with Ø = 0.5 % & u_m = 1.5 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **7.9633**

Nusselt number for TiO_2 (with Ø = 0.8 % & u_m = 1.5 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **7.9441**

Nusselt number for TiO_2 (with Ø = 1.5 % & u_m = 1.5 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **7.8992**

Nusselt number for TiO_2 (with Ø = 2.0 % & u_m = 1.5 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **7.7976**

Nusselt number for TiO_2 (with Ø = 4.0 % & u_m = 1.5 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **7.7379**

Nusselt number for TiO_2 (with Ø = 0.5 % & u_m = 5.0 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **20.8639**

Nusselt number for TiO_2 (with Ø = 0.8 % & u_m = 5.0 m/s)

$Nu_{nf} = 0.021Re^{0.8}_{nf}\ Pr^{0.5}_{nf}$

= **20.8136**

Nusselt number for TiO_2 (with Ø = 1.5 % & u_{m} = 5.0 m/s)

$$Nu_{nf} = 0.021 Re^{0.8}_{nf}\, Pr^{0.5}_{nf}$$

$$= \underline{\underline{\mathbf{20.6961}}}$$

Nusselt number for TiO_2 (with Ø = 2.0 % & u_{m} = 5.0 m/s)

$$Nu_{nf} = 0.021 Re^{0.8}_{nf}\, Pr^{0.5}_{nf}$$

$$= \underline{\underline{\mathbf{20.4299}}}$$

Nusselt number for TiO_2 (with Ø = 4.0 % & u_{m} = 5.0 m/s)

$$Nu_{nf} = 0.021 Re^{0.8}_{nf}\, Pr^{0.5}_{nf}$$

$$= \underline{\underline{\mathbf{20.2734}}}$$

<u>From Equation (3.9)</u>

Heat Transfer Coefficient for Al_2O_3 (with Ø = 0.5 % & u_{m} = 1.5 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

$$= \underline{\underline{\mathbf{14{,}521.63\ W/m^2\ K}}}$$

Heat Transfer Coefficient for Al_2O_3 (with Ø = 0.8 % & u_{m} = 1.5 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

$$= \underline{\underline{\mathbf{14{,}563.50\ W/m^2\ K}}}$$

Heat Transfer Coefficient for Al_2O_3 (with Ø = 1.5 % & u_{m} = 1.5 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

$$= \underline{\underline{\mathbf{14{,}662.96\ W/m^2\ K}}}$$

Heat Transfer Coefficient for Al_2O_3 (with Ø = 2.0 % & u_m = 1.5 m/s)

$$h = \frac{Nuk_{nf}}{D_h}$$

= **14,734.29 W/m² K**

Heat Transfer Coefficient for Al_2O_3 (with Ø = 4.0 % & u_m = 1.5 m/s)

$$h = \frac{Nuk_{nf}}{D_h}$$

= **15,018.82 W/m² K**

Heat Transfer Coefficient for Al_2O_3 (with Ø = 0.5 % & u_m = 5.0 m/s)

$$h = \frac{Nuk_{nf}}{D_h}$$

= **38,046.55 W/m² K**

Heat Transfer Coefficient for Al_2O_3 (with Ø = 0.8 % & u_m = 5.0 m/s)

$$h = \frac{Nuk_{nf}}{D_h}$$

= **38,156.76 W/m² K**

Heat Transfer Coefficient for Al_2O_3 (with Ø = 1.5 % & u_m = 5.0 m/s)

$$h = \frac{Nuk_{nf}}{D_h}$$

= **38,416.99 W/m² K**

Heat Transfer Coefficient for Al_2O_3 (with Ø = 2.0 % & u_m = 5.0 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

$$= \underline{\underline{38{,}603.67 \text{ W/m}^2 \text{ K}}}$$

Heat Transfer Coefficient for Al_2O_3 (with Ø = 4.0 % & u_m = 5.0 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

$$= \underline{\underline{39{,}349.75 \text{ W/m}^2 \text{ K}}}$$

Heat Transfer Coefficient for TiO_2 (with Ø = 0.5 % & u_m = 1.5 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

$$= \underline{\underline{14{,}517.79 \text{ W/m}^2 \text{ K}}}$$

Heat Transfer Coefficient for TiO_2 (with Ø = 0.8 % & u_m = 1.5 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

$$= \underline{\underline{14{,}557.74 \text{ W/m}^2 \text{ K}}}$$

Heat Transfer Coefficient for TiO_2 (with Ø = 1.5 % & u_m = 1.5 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

$$= \underline{\underline{14{,}636.94 \text{ W/m}^2 \text{ K}}}$$

Heat Transfer Coefficient for TiO_2 (with Ø = 2.0 % & u_m = 1.5 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

= **14,850.27 W/m^2 K**

Heat Transfer Coefficient for TiO_2 (with Ø = 4.0 % & u_m = 1.5 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

= **14,987.55 W/m^2 K**

Heat Transfer Coefficient for TiO_2 (with Ø = 0.5 % & u_m = 5.0 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

= **38,036.71 W/m^2 K**

Heat Transfer Coefficient for TiO_2 (with Ø = 0.8 % & u_m = 5.0 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

= **38,141.39 W/m^2 K**

Heat Transfer Coefficient for TiO_2 (with Ø = 1.5 % & u_m = 5.0 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

= **38,389.85 W/m^2 K**

Heat Transfer Coefficient for TiO_2 (with Ø = 2.0 % & u_{m} = 5.0 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

= **38,908.07 W/m² K**

Heat Transfer Coefficient for TiO_2 (with Ø = 4.0 % & u_{m} = 5.0 m/s)

$$h = \frac{Nu k_{nf}}{D_h}$$

= **39,267.57 W/m² K**

From Equation 3.10

Pressure drop for Al_2O_3 (with Ø = 0.5 % & u_{m} = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **3,737.23 Pa**

Pressure drop for Al_2O_3 (with Ø = 0.8 % & u_{m} = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **3,767.78 Pa**

Pressure drop for Al_2O_3 (with Ø = 1.5 % & u_{m} = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **3,838.65 Pa**

Pressure drop for Al_2O_3 (with Ø = 2.0 % & u_{m} = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>3,889.44 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 4.0 % & u_{m} = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>4,092.02 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 0.5 % & u_{m} = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>2,025.35 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 0.8 % & u_{m} = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>2,037.19 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 1.5 % & u_{m} = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>2,064.87 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 2.0 % & u_m = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>2,084.46 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 4.0 % & u_m = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>2,162.27 Pa</u>**

Pressure drop for TiO_2 (with Ø = 0.5 % & u_m = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>3,739.43 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 0.8 % & u_m = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>3,771.28 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 1.5 % & u_m = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **<u>3,845.18 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 2.0 % & u_{m} = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2{}_m}{2}$$

= **<u>3,898.13 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 4.0 % & u_{m} = 1.5 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2{}_m}{2}$$

= **<u>4,109.28 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 0.5 % & u_{m} = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2{}_m}{2}$$

= **<u>2,027.11 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 0.8 % & u_{m} = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2{}_m}{2}$$

= **<u>2,040.05 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 1.5 % & u_{m} = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2{}_m}{2}$$

= **<u>2,070.13 Pa</u>**

Pressure drop for Al_2O_3 (with Ø = 2.0 % & u_{m} = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **2,091.48 Pa**

Pressure drop for Al_2O_3 (with Ø = 4.0 % & u_{m} = 5.0 m/s)

$$\Delta P = f \frac{L}{D_h} \times \frac{\rho V^2_m}{2}$$

= **2,176.01Pa**

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

= 1.05×10^{-4} m^3

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 5.0 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= 3.5×10^{-4} m^3

From Equation 3.11

Pumping power for Al_2O_3 (with Ø =0.5 % & u_{m} = 1.5 m/s)

$P = \dot{V}\, \Delta P$

P = 0.3924 W

Pumping power for Al_2O_3 (with Ø =0.8 % & u_{m} = 1.5 m/s)

$P = \dot{V}\, \Delta P$

P = 0.3956 W

Pumping power for Al_2O_3 (with Ø =1.5 % & $u_{m\,=}$ 1.5 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.4031 W</u>

Pumping power for Al_2O_3 (with Ø =2.0 % & $u_{m\,=}$ 1.5 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.4084 W</u>

Pumping power for Al_2O_3 (with Ø =4.0 % & $u_{m\,=}$ 1.5 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.4297 W</u>

Pumping power for Al_2O_3 (with Ø =0.5 % & $u_{m\,=}$ 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.7089 W</u>

Pumping power for Al_2O_3 (with Ø =0.8 % & $u_{m\,=}$ 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.7131 W</u>

Pumping power for Al_2O_3 (with Ø =1.5 % & $u_{m\,=}$ 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.7227 W</u>

Pumping power for Al_2O_3 (with Ø =2.0 % & $u_{m\,=}$ 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.7296 W</u>

Pumping power for Al_2O_3 (with Ø =4.0 % & $u_{m\,=}$ 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.7568 W</u>

Pumping power for TiO_2 (with Ø =0.5 % & $u_{m\,=}$ 1.5 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.3926 W</u>

Pumping power for TiO_2 (with Ø =0.8 % & $u_{m\,=}$ 1.5 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.3960 W</u>

Pumping power for TiO_2 (with Ø =1.5 % & $u_{m\,=}$ 1.5 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.4037 W</u>

Pumping power for TiO_2 (with Ø =2.0 % & $u_{m\,=}$ 1.5 m/s)

$P = \dot{V}\,\Delta P$

P = <u>0.4093 W</u>

Pumping power for TiO_2 (with Ø =4.0 % & u_{m} = 1.5 m/s)

$P = \dot{V}\,\Delta P$

P = 0.4315 W

Pumping power for TiO_2 (with Ø =0.5 % & u_{m} = 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = 0.7095 W

Pumping power for TiO_2 (with Ø =0.8 % & u_{m} = 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = 0.7140 W

Pumping power for TiO_2 (with Ø =1.5 % & u_{m} = 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = 0.7245 W

Pumping power for TiO_2 (with Ø =2.0 % & u_{m} = 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = 0.7320 W

Pumping power for TiO_2 (with Ø =4.0 % & u_{m} = 5.0 m/s)

$P = \dot{V}\,\Delta P$

P = 0.7616 W

From Equation 3.12

Heat Transfer rate for Al_2O_3 (with Ø =0.5 % & u_m = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5
= $1.05 \times 10^{-4}\ m^3$

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

=0.10626 kg/s

Q = 8,738.93 W

Heat Transfer rate for Al_2O_3 (with Ø =0.8 % & u_m = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5
= $1.05 \times 10^{-4}\ m^3$

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= 0.10719 kg/s

Q = 8,731.27 W

Heat Transfer rate for Al_2O_3 (with Ø =1.5 % & u_m = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

= $1.05 \times 10^{-4}\ m^3$

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= <u>0.10938 kg/s</u>

Q = <u>8,715.07 W</u>

Heat Transfer rate for Al_2O_3 (with Ø =2.0 % & u_m = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

= <u>1.05 x 10^{-4} m^3</u>

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= <u>0.11094 kg/s</u>

Q = <u>8,703.11 W</u>

Heat Transfer rate for Al_2O_3 (with Ø =4.0 % & u_m = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

= <u>1.05 x 10^{-4} m^3</u>

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

=<u>0.11718 kg/s</u>

Q = <u>8,655.43 W</u>

Heat Transfer rate for Al_2O_3 (with Ø =0.5 % & u_{m} = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= 3.5×10^{-4} m^3

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= 0.354186 kg/s

Q = 29,128.62 W

Heat Transfer rate for Al_2O_3 (with Ø =0.8 % & u_{m} = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= 3.5×10^{-4} m^3

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= 0.357308 kg/s

Q = 29,104.88 W

Heat Transfer rate for Al_2O_3 (with Ø =1.5 % & u_{m} = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= 3.5×10^{-4} m^3

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= <u>0.36459 kg/s</u>

Q = <u>29,049.44 W</u>

Heat Transfer rate for Al_2O_3 (with Ø =2.0 % & u_m = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= <u>3.5 x 10^{-4} m^3</u>

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= <u>0.3698 kg/s</u>

Q = <u>29,010.37 W</u>

Heat Transfer rate for Al_2O_3 (with Ø =4.0 % & u_m = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= <u>3.5 x 10^{-4} m^3</u>

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= <u>0.39061 kg/s</u>

Q = <u>28,852.17 W</u>

Heat Transfer rate for TiO_2 (with Ø =0.5 % & u_{m} = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

= 1.05×10^{-4} m^3

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

=0.10638 **kg/s**

Q = 8,738.35 W

Heat Transfer rate for TiO_2 (with Ø =0.8 % & u_{m} = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

= 1.05×10^{-4} m^3

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

=0.10738 kg/s

Q = 8,730.23 W

Heat Transfer rate for TiO_2 (with Ø =1.5 % & u_{m} = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

= 1.05×10^{-4} m^3

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

$= \underline{0.10974 \text{ kg/s}}$

Q = $\underline{\mathbf{8{,}713.44\ W}}$

Heat Transfer rate for TiO_2 (with Ø =2.0 % & u_m = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

$= \underline{1.05 \times 10^{-4}\ m^3}$

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

$= \underline{0.11142 \text{ kg/s}}$

Q = $\underline{\mathbf{8{,}700.97\ W}}$

Heat Transfer rate for TiO_2 (with Ø =4.0 % & u_m = 1.5 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the nanofluid used (**for u_m = 1.5 m/s** with N = 25)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

$= \underline{1.05 \times 10^{-4}\ m^3}$

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

$= \underline{0.11814 \text{ kg/s}}$

Q = $\underline{\mathbf{8{,}651.11\ W}}$

Heat Transfer rate for TiO_2 (with Ø =0.5 % & u_{m} = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= $\underline{3.5 \times 10^{-4}\ m^3}$

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= 0.35458 kg/s

Q = 29,126.19 W

Heat Transfer rate for TiO_2 (with Ø =0.8 % & u_{m} = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= $\underline{3.5 \times 10^{-4}\ m^3}$

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= 0.35794 kg/s

Q = 29,101.31 W

Heat Transfer rate for TiO_2 (with Ø =1.5 % & u_{m} = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= $\underline{3.5 \times 10^{-4}\ m^3}$

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= <u>0.36578 kg/s</u>

Q = 29,043.22 W

Heat Transfer rate for TiO_2 (with Ø =2.0 % & u_m = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= 3.5×10^{-4} m^3

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= 0.37138 kg/s

Q = 29,001.66 W

Heat Transfer rate for TiO_2 (with Ø =4.0 % & u_m = 5.0 m/s)

$Q_{nf} = \dot{m}_{nf} Cp_{nf} (T_{out} - T_{in})_{nf}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= 3.5×10^{-4} m^3

$\dot{m}_{nf} = \rho_{nf} \dot{V}$

= 0.39378 kg/s

Q = 28,835.56 W

From Equation 3.13

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 1.5 m/s with N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x1.5

= $\underline{1.05 \times 10^{-4}\ m^3}$

$\dot{V}$ is the volumetric flow rate of the water used (**for u_m = 5.0 m/s N = 25**)

$\dot{V} = N\, W_{ch}\, L_{ch}\, u_{nf}$ = 25 x 0.00028 x 0.01x5.0

= $\underline{3.5 \times 10^{-4}\ m^3}$

$\dot{m}_{w} = \rho_{nf}\, \dot{V}$

$\dot{m}_w$ = **0.10269 kg/s** **(for u_m = 1.5 m/s)**

$\dot{m}_{w} = \rho_{nf}\, \dot{V}$

$\dot{m}_w$ = **0.31899 kg/s** **(for u_m = 5.0 m/s)**

So, Heat transfer rate for water with **(u_m = 1.5 m/s),** Q = 0.10269 x 4179 x 20

= **8,582.83 W**

So, Heat transfer rate for water with **(u_m = 5.0 m/s),** Q = **0.31899** x 4179 x 20

= **26,661.18 W**

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