HEAT TRANSFER PROPERTIES OF NANOPARTICLES AND THE ENHANCED PERFORMANCE OF A MULTIPHASE FLUID.

This thesis is submitted to the department of Mechanical and Chemical Engineering (MCE), Islamic University of Technology (IUT), in the partial fulfillment of the requirement for the degree of Bachelor in Science in Mechanical Engineering.

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CERTIFICATE OF RESEARCH

This thesis titled **'HEAT TRANSFER PROPERTIES OF NANOPARTICLES AND THE ENHANCED PERFORMANCE OF A MULTIPHASE FLUID FLOW'** submitted by **Sami Ahmad Shabah (091402) and Syed Faiyaz Ahsan (091401)** has been accepted as satisfactory in fulfillment of the requirement for the Degree of Bachelor of Science in Mechanical and Chemical Engineering Department, Islamic University of Technology, Boardbazar, Gazipur.

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DECLARATION

This is to certify that the work presented in this thesis is an outcome of research carried out by the authors under the supervision of **Dr. A. K. M. Sadrul Islam**.

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Acknowledgement

We state our heartiest gratefulness to almighty Allah for His kindness so that we are able to finish our project on '**HEAT TRANSFER PROPERTIES OF NANOPARTICLES AND THE ENHANCED PERFORMANCE OF A MULTIPHASE FLUID FLOW**' successfully and on time.

It is our pleasure to express our sincere gratitude to the project supervisor **Dr. A. K. M. Sadrul Islam** for his support, helpful suggestions and supervision at all stages on the progress of this thesis work. His guidance, encouragement & enthusiasm influenced us to carry out the thesis up to this point.

We are also grateful to **Mr. Hamidur Rahman**, for lending us his valuable time and vast practical experience in this field and for providing us necessary support.

We are highly indebted to the above mentioned teachers. Without their association it would have been impossible to bring out this report. We seek excuse for any error that might have in the report involuntarily despite trying our best.

We appreciate your kind considerations and prayers.

Abstract

Heat transfer is one of the most important fields in modern day engineering. In the last few decades, the field of heat transfer has gained a major research topic in the form of nanofluid. Traditional heat exchanger fluids have poor thermal conductivity whereas some solid particles have high thermal conductivity. Therefore the prospect of formulating a mixture of two materials in different phases has been in motion for some time. These fluids carrying nanoparticles are called nanofluids. They enhance the heat transfer rate significantly due to the higher specific surface area created by the nanometer sized particles. In this study, we simulate the heat transfer characteristics of Al_2O_3/water nanofluids in a simple heat exchanger under laminar flow condition. In our case, we varied the concentration of nanoparticles in the base fluid to observe the change of several properties of the multiphase fluid simultaneously. The effects of Nusselt number, thermal conductivity, viscosity and particle type on the heat transfer characteristics were investigated. Based on the results, further nanoparticles were added to the base fluid to significantly enhance the heat transfer characteristics. The data accumulated by this process helps us to predict the behavior of a multiphase fluid with known concentration of nanoparticles. It also creates an opportunity for us to modify the fluid properties accordingly by varying necessary variables like particle concentration, particle size etc.

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Chapter 1

Introduction & Objectives

1.1 Introduction

The rapid growth of nanofluids research in recent years including US, EU, and China, and more recently, India and South Korea has seen the potential market for nanofluids for heat transfer applications grow over 2 billion dollars per year worldwide (CEA, 2007), with the prospect of further growth in the next 5–10 years. A critical review of state-of-the-art nanofluids work for heat transfer intensification is both necessary and timely.

Heat transfer fluids have inherently low thermal conductivity that greatly limits the heat exchange efficiency. While the effectiveness of extending surfaces and redesigning heat exchange equipments to increase the heat transfer rate has reached a limit, many research activities have been carried out attempting to improve the thermal transport properties of the fluids by adding more thermally conductive solids into liquids. Liquid dispersions of nanoparticles, which have been termed “nanofluids”, exhibit substantially higher thermal conductivities than those of the corresponding base fluids.

The enhanced thermal behaviour of nanofluids could provide a basis for an enormous innovation for heat transfer intensification, which is of major importance to a number of industrial sectors including transportation, power generation, micro-manufacturing, thermal therapy for cancer treatment, chemical and metallurgical sectors, as well as heating, cooling, ventilation and air-conditioning. Nanofluids are also important for the production of nanostructured materials (Kinloch et al. 2002), for the engineering of complex fluids (Tohver et al. 2001), as well as for cleaning oil from surfaces due to their excellent wetting and spreading behaviour (Wasan & Nikolov 2003).

Despite considerable research effort and significant progress in the past decade, our fundamental understanding of nanofluids is limited. This is indeed reflected in the significant scattering/disagreement of published data and less convincing arguments in interpreting the data. It is fair to say that there is a long way to go before we can actually tailor-make nanofluids for targeted applications.

This paper aims to provide a brief overview of the thermal properties and behaviour of nanofluids. The focus will be on our own work on conduction, convection and change of properties of the multiphase flow due to introduction of nanofluids. A brief review of the literature is also carried out where it is deemed appropriate. Discussions will be made on possible mechanisms of heat transfer enhancement.

Formulation of nanofluids and the flow behaviour of nanofluids will not be included. Interested parties are referred to recent publications by, for example, Kwak and Kim (2005), Prasher et al. (2006a) and Ding et al.(2007).

1.2 Research Objectives

General Objectives:

- To learn the formation, properties, advantages and usage of nanofluids.
- Using commercially developed software to analyze a nanofluid flow.
- Application of CFD in the research of nanofluid.
- Nanofluid flow inside a circular shaped pipe with velocity & pressure distribution.
- Solving real world problems involving nanofluid.

Specific Objectives:

- To determine the relationship between Nusselt number and particle concentration.
- To determine the relationship between overall heat transfer co-efficient and particle concentration.
- To determine how any specific property of the multiphase fluid changes with the change of controlling variables like particle diameter, particle concentration.

1.3 Hypothesis

Single phase fluid in room temperature will exchange heat with pipe body which is at a higher temperature while passing through the length of the pipe. By injecting nanoparticles to the base fluid to form a multiphase fluid, the heat transfer rate can be significantly enhanced**.**

Chapter 2

Literature Review

The thermal conductivity of nanometer sized particles is typically in the order of magnitude higher than those of the base fluids. The addition of nanoparticles to the base fluid even at low volume concentrations, results in significant increases in thermal performance. Choi was the first person used the term “nanofluid”. In his study it was shown that the addition of small nanoparticles less than 1% by volume led to increase in the thermal conductivity of the fluid by approximately two times. Masuda et al. measured the thermal conductivity of nanofluids which include Al2O3 (13nm), SiO2 (12 nm), and TiO2 (27 nm) nanoparticles suspended in water based fluids. This was the first experimental study on the thermal conductivity of nanofluids. The enhancement was around 32.4% in thermal conductivity with 4.3 vol. % of Al2O3 at 31.85 C.

Thermal conductivity is the intrinsic property of nanofluids that has motivated the most research articles - we see more work on this in the publications of Keblinski, R. Prasher, & Eapen, 2008; Kleinstreuer & Feng, 2011; Trisaksri & Wongwises, 2007. This seems to be mostly due to the fact that some early experimental works demonstrated anomalous increases in thermal conductivity. That is, the first few experimental works indicated that the effective thermal conductivity of common base fluids (chiefly water) can be increased by up to 30% with volume fractions of <5%.(Hong, H.-S. Yang, & C. J. Choi, 2005; Kleinstreuer & Feng, 2011; S. Lee, S. U.-S. Choi, S. Li, & Eastman, 1999; Volz, 2010)

There has also been a lot of recent research into convective heat transfer (Eapen et al., 2007; Lai, 2010; J. Lee, Gharagozloo, Kolade, Eaton, & Goodson, 2010; Putra, Roetzel, & Sarit K. Das, 2003; Zeinaliheris, Etemad, & Nasresfahany, 2006). This is logical because if heat transfer fluids are ever going to be used in heat transfer applications they will undoubtedly be in flowing systems. To truly push the boundaries of heat transfer much of this research is done in micro-channels.

In the field of nanofluid convective heat transfer research there is a similar debate over the magnitude (if any) of enhancement. There is also disagreement about the source of enhancement as several ideas have been proposed to explain how nanoparticles interact in the fluid. The idea is that energy exchange is improved because particles move randomly via Brownian motion and pull / mix fluid with them. Some researchers - (Duangthongsuk & Wongwises, 2009) for example, have noted that in turbulent flow nanofluid convection increases with Reynolds number and with volume fraction. Others, like (Pak & Cho, 1998), found that for water-based γ-Al2O3 and titania (TiO2) nanofluids, convective heat transfer is actually decreased by up to 12% due to increased viscosity. Others, like (W. Williams, Jacopo Buongiorno, & L.-W. Hu, 2008), have shown no change from the base fluid for a large range of flow rates (9,000<Re<63,000) in zirconia ZrO2) nanofluids. Overall, it seems that here again classical models are the best approximation of the enhancement. In selecting nanofluids for convective heat transfer, one must also be very careful not to increase the viscosity as this can cause decreased overall performance.

One of the most promising factors of nano-sized particles is that, as opposed to larger-sized particles, they can be put into conventional liquid pumping and plumbing with little adverse affects (i.e. without abrasion or clogging) (R. Prasher, Song, J. Wang, & P. Phelan, 2006) and (Sarit Kumar Das, Stephen U S

Choi, & Patel, 2006). Also, ideal nanoparticle volume fractions end up being < 0.001 %v for sizable solar collector fluid depths. That is, any improvements in other heat transfer properties cannot be offset by added pumping costs or particle clogging.

Studies on natural convection using nanofluids are very limited and they are related with differentially heated enclosures. Hwang et al. (2007) investigated the buoyancy-driven heat transfer of water-based Al2O3 nanofluids in a rectangular cavity. They showed that the ratio of heat transfer coefficient of nanofluids to that of base fluid is decreased as the size of nanoparticles increases, or the average temperature of nanofluids is decreased. Khanafer et al. (2003) investigated the heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids for various pertinent parameters. They tested different models for nanofluid density, viscosity, and thermal expansion coefficients. It was found that the suspended nanoparticles substantially increase the heat transfer rate any given Grashof number. Jou and Tzeng (2006) used nanofluids to enhance natural convection heat transfer in a rectangular enclosure. They conducted a numerical study using Khanafer's model. They indicated that volume fraction of nanofluids cause an increase in the average heat transfer coefficient. Jang and Choi (2004) investigated the Benard regime in nanofluid filled rectangular enclosures. Wang et al. (2006) conducted a study on natural convection in nanofluid filled vertical and horizontal enclosures. Also, a recent study by Polidori et al. (2007) analyzed the heat transfer enhancement in natural convection using nanofluids.

Nanofluids are also important for the production of nanostructured materials (Kinloch et al. 2002), for the engineering of complex fluids (Tohver et al. 2001), as well as for cleaning oil from surfaces due to their excellent wetting and spreading behaviour (Wasan & Nikolov 2003).

Compared with the experimental studies on thermal conductivity of nanofluids, there are limited rheological studies reported in the literature. In one study, the Al_2O_3-water mixture showed a viscosity increase between 20% and 30% for 3 vol.% Al_2O_3 solution compared to that of water alone. The results by Das *et al*. on the viscosity of alumina-water nanofluids against shear rate demonstrated an increase of viscosity with increased particle concentrations indicating strong possibility that nanofluid may be non-Newtonian. Further investigations are, however, required to define the viscosity models of nanofluids.

In another study, a two-step method was used to produce Al_2O_3-water nanofluids with low concentrations of Al_2O_3 nanoparticles from 0.01 to 0.3 vol.% without any surfactant and measured viscosity at the temperature range from 21°C to 39°C. Experimental results showed that the effective viscosities of the dilute Al_2O_3-water nanofluids significantly decreases with increasing temperature and slightly increases with increasing volume fraction. The measured viscosity of the Al_2O_3-water nanofluids is nonlinear with the Al_2O_3 nanoparticle volume concentration. The nonlinear viscosity behavior occurs at very low particle concentrations far below 2 vol.%. Nonlinear behavior implies that there is particle-particle interactions which invalidate the Einstein equation developed for dilute suspensions. The result is similar in another experiment, wherein, the viscosity increased by 83.4% at a volume fraction of 0.05 (5 vol.%).

Chapter 3

Multiphase Flow & Nanofluids

3.1 Multiphase Flow

The term multiphase flow is used to refer to any fluid flow consisting of more than one phase or component. In fluid mechanics, multiphase flow is a generalization of the modeling used in two-phase flow to cases where the two phases are not chemically related (e.g. dusty gases) or where more than two phases are present (e.g. in modeling of propagating steam explosions).

Each of the phases is considered to have a separately defined volume fraction (the sum of which is unity), and velocity field. Conservation equations for the flow of each species (perhaps with terms for interchange between the phases), can then be written down.

The momentum equation for each phase is less straightforward. It can be shown that a common pressure field can be defined and that each phase is subject to the gradient of this field, weighted by its volume fraction. Transfer of momentum between the phases is sometimes less straightforward to determine and in addition, a very light phase in bubble form has a virtual mass associated with its acceleration. (The virtual mass of a single bubble is about half its displaced mass).

These terms, often called constitutive relations, are often strongly dependent on flow regime.

Multiphase flow could be classified according to the state of the different phases or components and therefore refer to gas/solids flows or liquid/solids flows or gas/particle flows or bubbly flows and so on; many texts exist that limit their attention in this way. Some treatises are defined in terms of a specific type of fluid flow and deal with low Reynolds number suspension flows, dusty gas dynamics and so on. Others focus attention on a specific application such as slurry flows, cavitating flows, aerosols, debris flows, fluidized beds and so on.

In our case, we considered a simple heat exchange process involving a base fluid (water) and solid Aluminium oxide nanoparticles to compare the performance of heat transfer between a single phase flow and a multiphase flow.

3.2 Nanofluids

Nanofluids are dilute suspensions of functionalized nanoparticles smaller than 100 nm, which belong to a new type of functional composite materials developed about a decade ago with the specific aim of increasing the thermal conductivity of heat transfer fluids, which have now evolved into a promising nanotechnological area. Such thermal nanofluids for heat transfer applications represent a class of its own different from conventional colloids for other applications. Compared to conventional solid-liquid suspensions for heat transfer intensifications, properly engineered thermal nanofluids possess the following advantages:

• High specific surface area and therefore more heat transfer surface between particles and fluids.

• High dispersion stability with predominant Brownian motion of particles.

• Reduced pumping power as compared to pure liquid to achieve equivalent heat transfer intensification.

• Reduced particle clogging as compared to convention slurries, thus promoting system miniaturization.

• Adjustable properties, including thermal conductivity and surface wet ability, by varying particle concentrations to suit different applications.

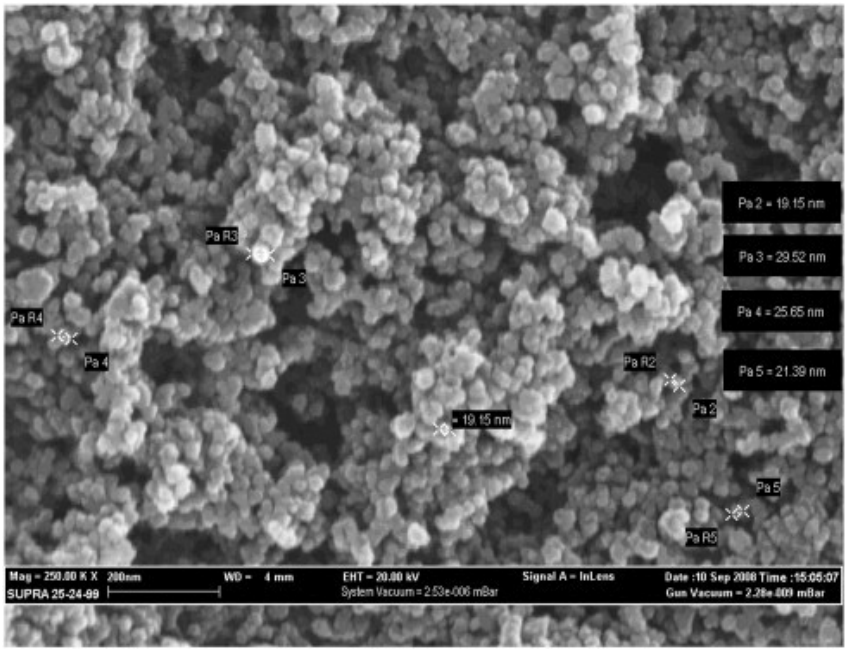


Figure 1: Aluminuim Oxide nanoparticles

3.3 Rationale behind Nanofluid Research

Since solid materials have much higher thermal conductivities than fluids, it is then a straightforward logic to increase the thermal conductivity of fluids by adding solids. However, if solid particles of micrometer, even millimeter magnitudes are added into the base fluids to make slurries, the increase in thermal conductivity of the slurries is insignificant even at high particle loading. Meanwhile, large particles cause many troublesome problems:

a) Large particles are easy to settle out from the base fluids, especially in low speed circulation, not only losing the enhancement in thermal conductivity, but forming a sediment layer at the surface, increasing the thermal resistance and impairing the heat transfer capacity of the fluids;

b) The large size of the particles or the agglomerates of these particles causes severe clogging problems, especially at low circulation rate of fluids or in micro channels;

c) Large particles and the agglomerates in fluid flows carry too much momentum and kinetic energy, which may cause damage to the surface;

d) The erosion of the pipelines by the coarse and hard particles increases rapidly when the speed the circulation increases;

e) Noticeable conductivity enhancement is based on high particle concentration, which leads to apparent increase in viscosity. The pressure drop in fluids (slurries) goes up considerably due to the increase of viscosity.

To avoid these issues, nanoparticles are added to base fluids within a limited range to form multiphase fluid of high thermal conductivity

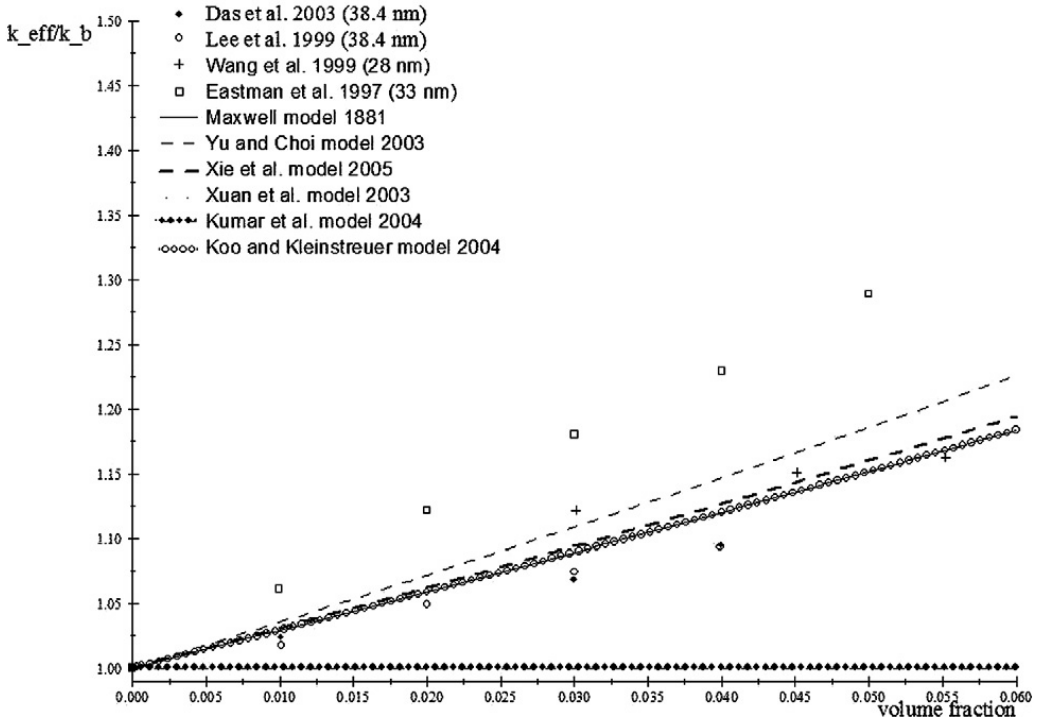


Figure 2: Recent works involving Aluminium Oxide nanoparticle. A clear pattern has been established that thermal conductivity increases with the increase in particle concentration.

In simple words, the rationale behind nanoparticle research is to find new and improved way of heat transfer. The efficiency of the heat transfer increases significantly due to the addition of nanoparticles. Researchers have found that by introducing nanometer sized particles within a base fluid the thermal conductivity can be increased by up to 30%. This requires very close attention since the heat transfer enhancement is only effective within a certain range of concentration of the solid particle of a definite size within the base particle.

Chapter 4

Relevant Factors in Enhancement of Heat Transfer Property

4.1 Thermal Conductivity (k)

Nanofluids are composite materials and, therefore, any discussion of nanofluid's thermal conductivity must begin with effective medium theories. Effective medium theories were introduced by Mossotti, Clausius, Maxwell, and Lorenz in the late 19th century, firmly established with the work of Bruggeman, and thoroughly investigated and applied in many fields of science and engineering since then.

Effective medium approximations or effective medium theory (sometimes abbreviated as EMA or EMT) pertains to analytical or theoretical modeling that describes macroscopic properties of composite materials. EMAs or EMTs are developed from averaging the multiple values of the constituents that directly make up the composite material. At the constituent level, the values of the materials vary and are inhomogenous. Precise calculation of the many constituent values is nearly impossible. However, theories have been developed that can produce acceptable approximations which in turn describe useful parameters and properties of the composite material as a whole. In this sense, effective medium approximations are descriptions of a medium (composite material) based on the properties and the relative fractions of its components and are derived from calculations.

Nanofluids containing less than 10 nm diameter nanoparticles show much higher Thermal Conductivity enhancements than nanofluids containing particles of over diameter 35 nm. This phenomenon can be explained by the increase of specific surface area of the particle. If we consider the equal volume of nanoparticles in two separate cases, the thermal conductivity will be higher in that case where the smaller particle size unmasks new surfaces to take part in heat exchange process. Thus the enhanced thermal conductivity ensures more heat transfer compared to a single phase flow.

Since nanofluid behavior is yet to be defined as a pattern under changing conditions, there is no reliable theory to predict the thermal conductivity of nanofluids. From the experimental results of many researchers, it is known that the thermal conductivity of nanofluids depends on parameters including the thermal conductivities of the base fluid and the nanoparticles, the volume fraction, the surface area, and the shape of the nanoparticles, and the temperature. There are no theoretical formulas currently available to predict the thermal conductivity of nanofluids satisfactorily.

However, there exist several semi-empirical correlations to calculate the apparent conductivity of two-phase mixtures. They are mainly based on the following definition of the effectivethermal conductivity of a two-component mixture:

$$k_{eff} = \frac{k_p \emptyset_{\mathrm{p}} (\mathrm{d}T/\mathrm{d}x)\mathrm{p} + k_b \emptyset_b (\mathrm{d}T/\mathrm{d}x)\mathrm{b}}{\emptyset_p (\mathrm{d}T/\mathrm{d}x)\mathrm{p} + \emptyset_b (\mathrm{d}T/\mathrm{d}x)\mathrm{b}}$$

For particle–fluid mixtures, numerous theoretical studies have been conducted dating back to the classical work of Maxwell. The Maxwell model for thermal conductivity for solid–liquid mixtures of relatively large particles (micro/mini-size) is good for low solid concentrations.

The effective thermal conductivity, k_{eff}, is given by:

$$k_{eff} = \frac{k_p + 2k_b + 2(\mathrm{k_p} - k_b)\emptyset}{k_p + 2k_b - (\mathrm{k_p} - k_b)\emptyset} k_b$$

Bruggeman proposed a model to analyze the interactions among randomly distributed particles. For a binary mixture of homogeneous spherical inclusions, the Bruggeman model gives,

$$\emptyset\left(\frac{k_p - k_{eff}}{k_p + 2k_{eff}}\right) + (1 - \emptyset)\left(\frac{k_p - k_{eff}}{k_p + 2k_{eff}}\right) = 0$$

This model can be applied to spherical particles with no limitations on the concentration of inclusions. For low solid concentrations, the Bruggeman model results in almost the same results as the Maxwell model provides. When the particle concentration is sufficiently high, the Maxwell model fails to provide a good match with the experimental results. However, the Bruggeman model agrees quite well with the experimental data.

Hamilton and Crosser proposed a model for liquid–solid mixtures for non-spherical particles. They introduced a shape factor, *n*, to account for the effect of the shape of the particles. The thermal conductivity, in which the ratio of conductivity of the solid and fluid phases is larger than 100 (k_p/k_b> 100), can be expressed as follows:

$$k_{eff} = \frac{k_p + (n-1)k_b - (n-1)(k_b - k_p)\emptyset}{k_p + (n-1)k_b + (k_b - k_p)\emptyset} k_b$$

where n is the particle shape factor, $n = \frac{3}{\psi}$. Here *ψ=particle spherity,* defined as the ratio of the surface area of a sphere with volume equal to that of the particle, to the surface area of the particle.

4.2 Particle Type (Material)

Particle material is an important parameter that affects the thermal conductivity of nanofluids. Simple deduction reasoning can lead to the thought that the difference in the thermal conductivities of particle materials is the main reason of this effect. However, studies show that particle type may affect the thermal conductivity of nanofluids in other ways. For example, Lee et al. considered the thermal conductivity of nanofluids with Aluminium Oxide and CuO nanoparticles and they found that nanofluids with CuO nanoparticles showed better enhancement when compared to the nanofluids prepared using Aluminium Oxide nanoparticles despite the fact that Aluminium Oxide, as a material, has higher thermal conductivity than CuO. Therefore there other factors come into play in multiphase condition irrespective of the solid material's individual thermal properties.

Commonly used nanoparticle materials include:

- ✓ Oxide ceramics – Al_2O_3, CuO
- ✓ Metal carbides – SiC
- ✓ Nitrides – AlN, SiN
- ✓ Metals – Al, Cu
- ✓ Nonmetals – Graphite, carbon nanotubes
- ✓ Layered – Al + Al_2O_3, Cu + C
- ✓ PCM – S/S
- ✓ Functionalized nanoparticles

Effect of particle material is much more pronounced when carbon nanotubes are used for the preparation of nanofluids. Some authors noted that such an anomalous enhancement might be due to the liquid nanolayers forming around the nanotubes. On the other hand, the fact that heat is transported ballistically inside the nanotubes improves the conduction of heat in the tubes, but the effect of this factor is not dominant according to the most authors.

Base fluids mostly used in the preparation of nanofluids are the common working fluids of heat transfer applications; such as, water, ethylene glycol and engine oil. According to the conventional thermal conductivity models such as the Maxwell model, as the base fluid thermal conductivity of a mixture decreases, the thermal conductivity ratio (thermal conductivity of nanofluid divided by the thermal conductivity of base fluid increases. It is seen that poor conductive fluid serve best then highly conductive ones. Hence water is generally is avoided. When it comes to nanofluids, the situation is more complicated due to the fact that the viscosity of the base fluid affects the Brownian motion of nanoparticles and that in turn affects the thermal conductivity of the nanofluid.

4.3 Particle Size

This is perhaps the most important factor to enhance the heat transfer rate in multiphase flow. The smaller the particle size, the greater is the specific surface area to engage in thermodynamic process. It is possible to produce nanoparticles of various sizes, generally ranging between 5 and 100 nm. Eastman et al. concluded that the size of the nanoparticles is an important factor that affects the thermal conductivity enhancement, which is contrary to the predictions of conventional models such as Hamilton and Crosser model, which does not take the effect of particle size on thermal conductivity into account.

The general trend in the experimental data is that the thermal conductivity of nanofluids increases with decreasing particle size. This trend is theoretically supported by two mechanisms of thermal conductivity enhancement; Brownian motion of nanoparticles and liquid layering around nanoparticles. However, there is also a significant amount of contradictory data in research work today that indicate decreasing thermal conductivity with decreasing particle size.

4.4 Temperature Gradient:

Heat transfer rate is dependent on temperature gradient as established by Fourier's Law of heat conduction. Any two bodies with a higher temperature gradient will exchange heat at a higher rate than two bodies with a lower temperature gradient. Therefore any comparison study between a single phase and a multiphase flow must be done with similar temperature difference between the bodies. However the heat transfer rate may yet differ due to the change of chemical composition of the medium (by introducing nanoparticles).

Fourier's Law suggests,

$$\frac{\partial Q}{\partial t} = -k \oint_S \vec{\nabla} T \cdot \overrightarrow{dA}$$

Where $\underset{\nabla}{\rightarrow} T$ is the temperature gradient.

4.5 Nusselt Number

In heat transfer, **Nusselt number** is the ratio of convective to conductive heat transfer across (normal to) the boundary. Named after Wilhelm Nusselt, it is a dimensionless number. The conductive component is measured under the same conditions as the heat convection but with a (hypothetically) stagnant (or motionless) fluid.

$$Nu = \frac{Convective\ heat\ transfer}{Conductive\ heat\ transfer} = \frac{hL}{k_f}$$

A Nusselt number close to unity, namely convection and conduction of similar magnitude, is characteristic of "slug flow" or laminar flow. A larger Nusselt number corresponds to more active convection, with turbulent flow typically in the 100-1000 range.

The convection and conduction heat flows are parallel to each other and to the surface normal of the boundary surface, and are all perpendicular to the mean fluid flow in the simple case.

Selection of the characteristic length should be in the direction of growth (or thickness) of the boundary layer. Some examples of characteristic length are: the outer diameter of a cylinder in (external) cross flow (perpendicular to the cylinder axis), the length of a vertical plate undergoing natural convection, or the diameter of a sphere. For complex shapes, the length may be defined as the volume of the fluid body divided by the surface area. The thermal conductivity of the fluid is typically (but not always) evaluated at the film temperature, which for engineering purposes may be calculated as the mean-average of the bulk fluid temperature and wall surface temperature. For relations defined as a local Nusselt number, one should take the characteristic length to be the distance from the surface boundary to the local point of interest. However, to obtain an average Nusselt number, one must integrate said relation over the entire characteristic length.

Typically, for free convection, the average Nusselt number is expressed as a function of the Rayleigh number and the Prandtl number, written as: Nu = f {Ra, Pr}. Else, for forced convection, the Nusselt number is generally a function of the Reynolds number and the Prandtl number, or Nu=f{Re, Pr}. Empirical correlations for a wide variety of geometries are available that express the Nusselt number in the aforementioned forms.

For free convection at vertical walls:

$$Nu_L = 0.68 + \frac{0.67Ra_L^{0.25}}{[1 + (0.492/\Pr)^{9/16}]^{4/9}}$$

For Laminar Flow over a Flat Plate:

$$Nu_x = 0.332Re_x^{0.5}Pr^{0.33}; Pr < 0.6$$

For Turbulent Flow over a Flat Plate:

$$Nu_x = 0.0296 Re_x^{4/5} Pr^{0.33}; 0.6 < Pr < 60$$

For Turbulent Flow in Tubes: Gnielinski correlation:

$$Nu_D = \frac{(f/8)\,(Re_D - 1000)Pr}{1 + 12.7\,(\frac{f}{8})^{0.5}(Pr^{2/3} - 1)}$$

$$\text{Where, } \mathrm{f} = (0.79\ln(\mathrm{Re_D} — 1.64)^{-2}$$

This is only valid for $0.5 \leq Pr \leq 2000\ and\ 3000 \leq Re_D \leq 5 \times 10^6$

For turbulent Flow through smooth tubes, the Dittus-Boelter Equation is used:

$$Nu_x = 0.023 Re_D^{0.8} Pr^n; when\ 0.6 \leq Pr \leq 160\ and\ Re_D > 10{,}000$$

4.6 Heat Capacity

Researchers have also noted that the specific heat of a fluid can be changed by adding nanoparticles (Shin & Banerjee, 2011a; 2011b; S.-Q. Zhou & Ni, 2008). One relatively easy approach to modeling this change is through the following equation (S.-Q. Zhou & Ni, 2008):

$$\boldsymbol{c_{p,t} = \frac{f_p \rho_p c_{p,p} + f_b \rho_b c_{p,b}}{f_p \rho_p + f_b \rho_b}}$$

where $c_{p,t}$ is the effective specific heat capacity of the mixture, $c_{p,b}$ the specific heat capacity of the fluid, $c_{p,p}$ the specific heat capacity of the particles, f_p the volume fraction of the particles, f_f the volume fraction of the fluid, ρ_p the particle density, and ρ_b the fluid density.
Assume a nanofluid is composed of copper nanoparticles (ρ_p = 8,000 kg/m^3, $c_{p,p}$ = 0.39 kJ kg^{-1} K^{-1}) in water (ρ_f =1,000 kg/m^3, $c_{p,b}$ =4.2 kJ kg^{-1} K^{-1}). For this situation, we expect a significant decrease in the specific heat of the mixture - depending on the volume fraction. As a matter of fact, by using this equation, one would be hard pressed to find a nanofluid with an effective specific heat higher than the base fluid. This is because almost all liquids (organic and inorganic - except liquid metals) have a rather high specific heat, greater than 1.5 kJ kg^{-1} K^{-1}. Thus, the specific heat of the base fluid is lowered when solid particles - most of which have specific heats lower than 0.8 kJ kg^{-1} K^{-1} - are added.

Chapter 5

Simulation Process (Methodology)

5.1 Problem Description

A laminar flow is flowing through a pipe of 20 mm diameter. The pipe is 1 m long. Fluid entering the inlet boundary has a temperature of 298 K and it exchanges heat with the wall which is at a constant temperature of 373 K. In initial condition only pure water is allowed to go through the pipe. However to increase heat transfer rate between the water and the pipe wall, nanaoparticles are added to the base fluid (water) at a varying concentration. The particle diameter at initial condition is 10 nm. The concentration of nanoparticle in the base fluid varies from 0.5% to 5%.

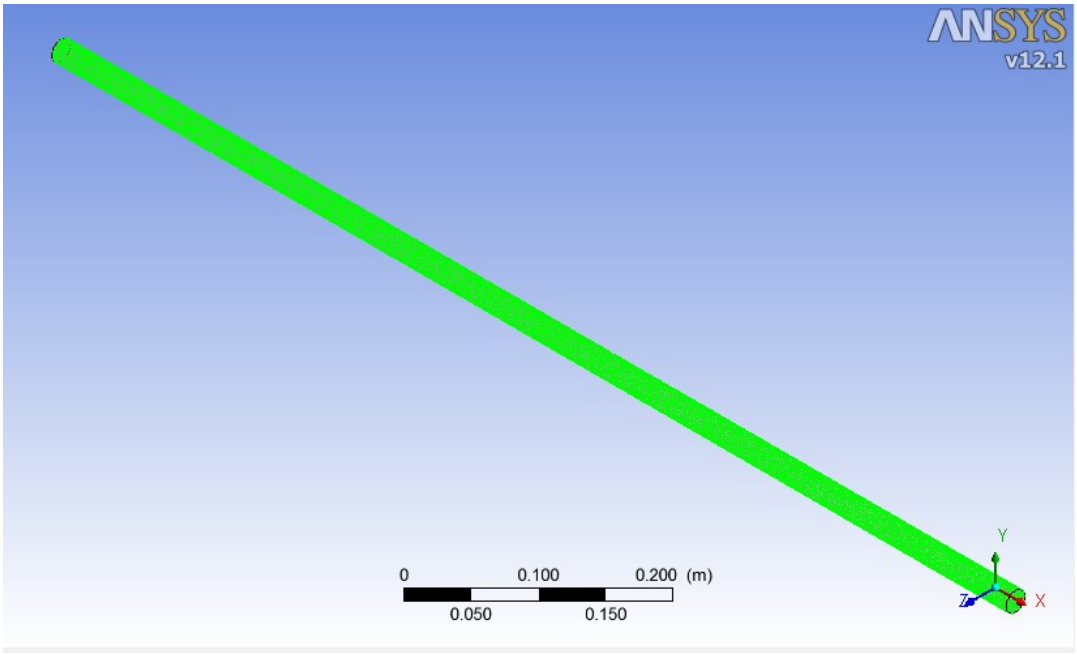


Figure 3: Pipe Geometry

The flow is laminar
Pipe Diameter, D = 20 mm
Nanoparticle Diameter, d = 10 nm
Water Density (liquid pure state) ρ = 1000 kg/m^3
Specific heat capacity of water (liquid pure state) c_{pw} = 4181 kJ$Kg^{-1}K^{-1}$
Dynamic viscosity of water, v = $8.94 \times 10^{-4}\ Pa.s$
Continuous particle injection
No heat generation within the system
Pipe Length, L = 1 m
Fluid Temperature = 298 K
Wall Temperature = 373 K
Flow rate at inlet,Q = 0.02 kg/s
Smooth Wall Pipe, No slip condition

5.2 Geometry & Mesh Generation

To run the simulation, the geometry has to be designed in the first place. For our purpose, we designed the geometry using ANSYS CFD. The pipe was drawn to specific dimensions before meshing the boundaries. A standard tetrahedral meshing system was used. Once the meshing was done, we used ANSYS Fluent to set up the boundary conditions and material properties. A simple process of the simulation goes:

Geometry Modeling:

Modeling

1) Create>Primitives>Cylinder
2) Set up the details
3) Generate the geometry
4) How to see the geometry model

Meshing:

1) Specify regions
2) Set spacing for each region
3) Inflation mesh
4) Generate the surface mesh
5) Generate the volume mesh
6) Save and create CFD simulation with mesh

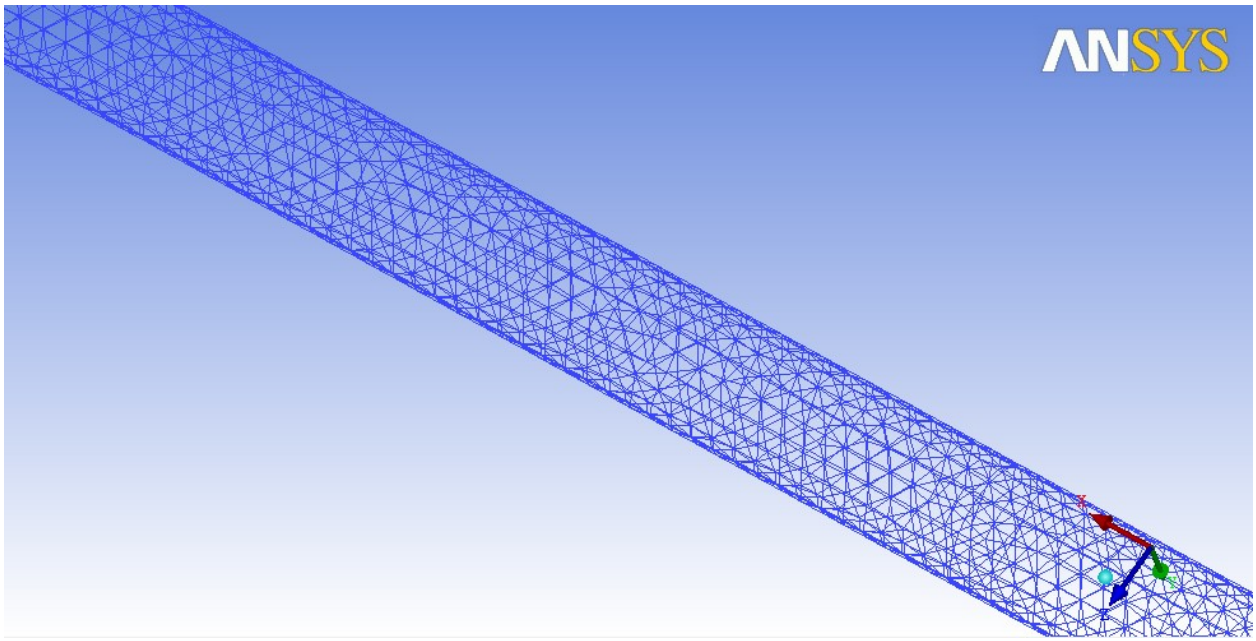


Figure 4: Tetrahedral Mesh of the pipe body

5.3 Simulation using ANSYS CFD

The simulation can be run using both ANSYS CFD and ANSYS Fluent. But it is highly recommended to use ANSYS fluent to obtain better precision and outcome.
In case of ANSYS CFD simulation, the process is divided into three stages. They are:

(FOR ANSYS CFD only)

CFX-PRE

- Create a domain
- Set up boundary conditions like inlet, outlet and solid wall
- Set solver control
- Set material properties

CFX-SOLVER

- Save and write solver file (.def)
- Special initial file if needed
- Start run

CFX-POST

- Create locations point, line, plane to study the result
- Create contour, vector, stream line to study the result
- Create chart, table to express the findings.

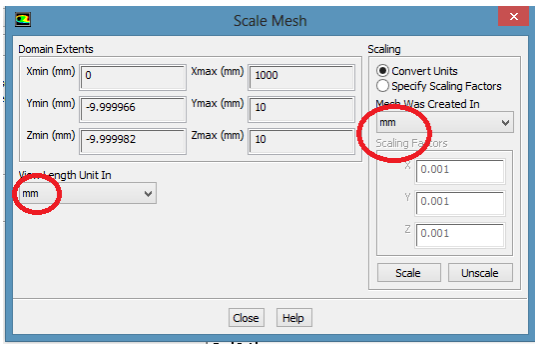
5.4 Simulation using ANSYS FLUENT

For our simulation purpose we used ANSYS Fluent to obtain more accurate results. To increase our efficiency, we used the DOUBLE PRECISION method. Fluent software is more user friendly than ANSYS CFD for multiphase simulation. It carries more equations for mixed flow than CFD software. Therefore any data obtained by Fluent software will be more accurate than CFD software.

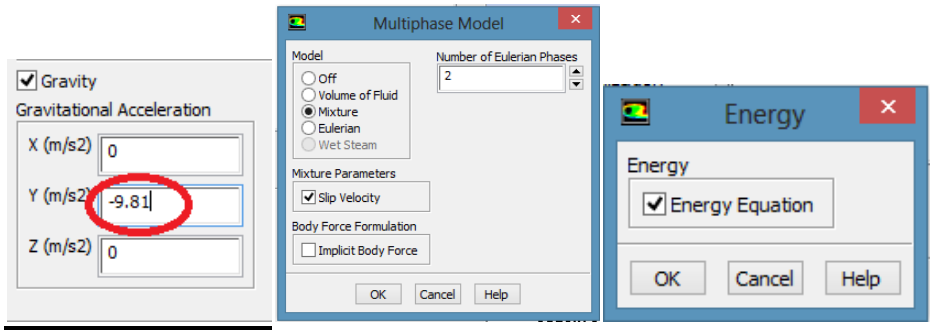
However to use ANSYS fluent, geometry and mesh files are required which can be generated using ANSYS CFD. They were routinely simulated in the aforementioned procedure.

At first, the mesh file is read from the following directory:
File>Read>Mesh

Then **mesh scaling** is performed as showed:

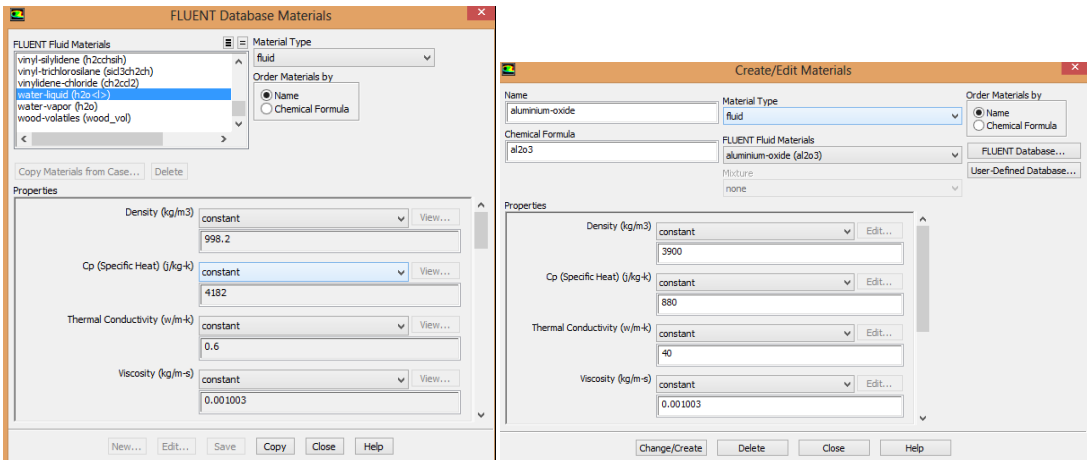


Afterwards the **gravitational acceleration** is included to ensure the pipe flow is influenced by gravitational force:

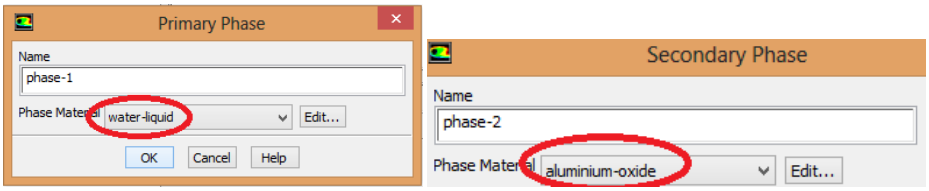


Then the **multiphase option** is selected. This creates a flow of two different phases. Then the **energy equation box** is selected to include energy calculation during the simulation.

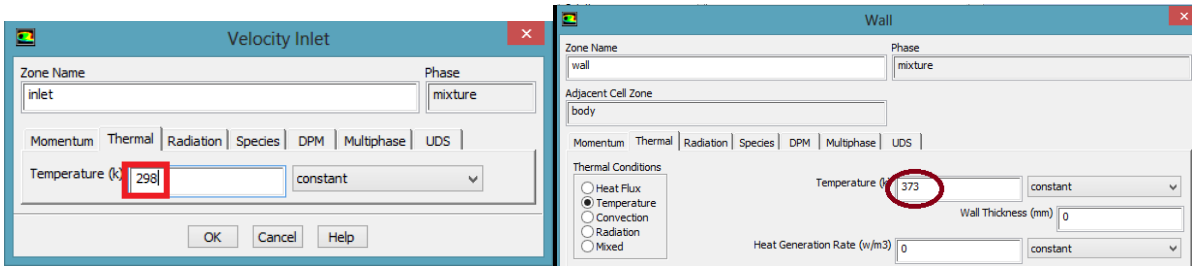
The **material properties** are not always stored in the ANSYS fluent directory. In these cases, the user needs to define the necessary properties to advance. For our purpose, we had to manually create the aluminium oxide particle.



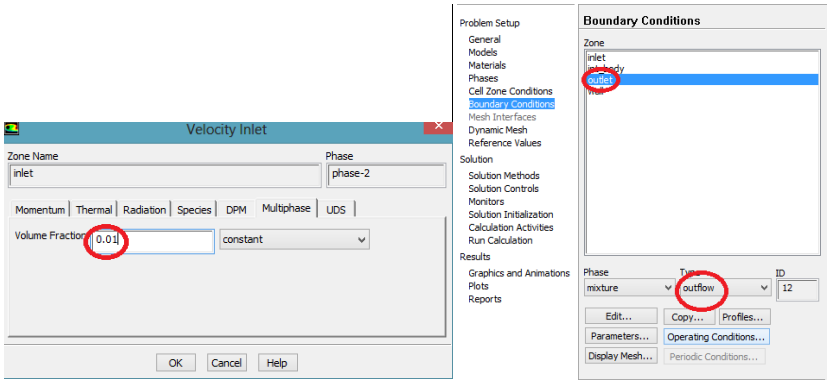
Now the phase selection is required. Since a two phase flow was selected earlier, **primary and secondary phases** must be specified clearly.



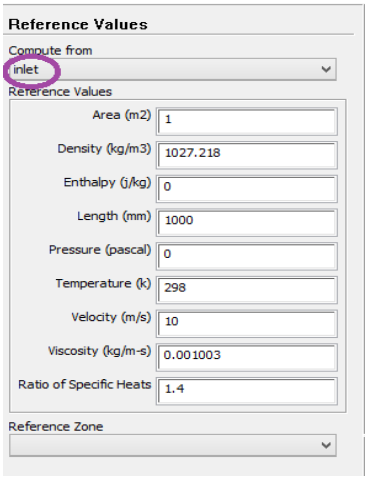
Boundary Conditions: After the materials and the phases have been selected, the boundary conditions have to be selected. For our purpose, we considered the **flow rate** at inlet is 0.02 kg/s. The water at room temperature is entering at inlet and exchanging heat with the **pipe wall** which is at a constant temperature of **373 K**. Here we assumed despite the heat loss, there is no change in temperature of the pipe wall. User is also provided with the option of selecting heat flux, convection or radiation coefficients if necessary.



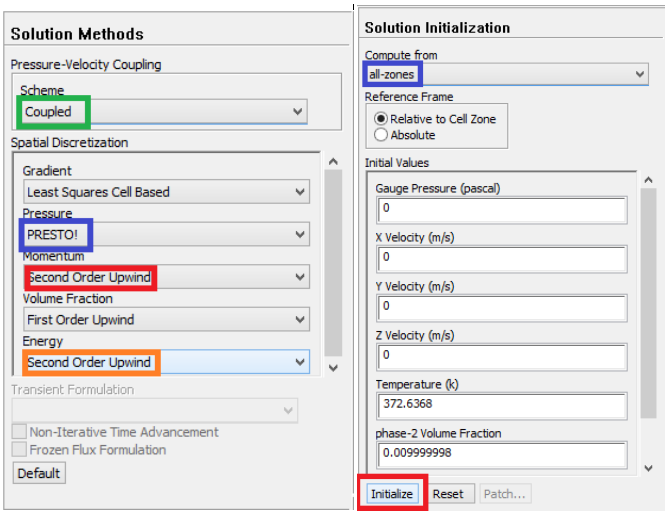
For phase-2, at inlet conditions, the **volume fraction** of the secondary phase must be selected. This has been varied to generate many simulations. The concentration of nanoparticles has been varied from 0.2% to 5.0%. For only water flow through the pipe, the volume fraction of phase-2 should be zero.



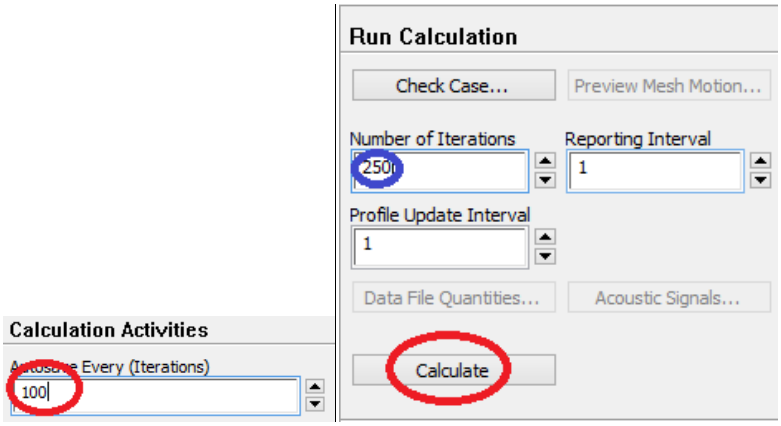
For the outlet section, the **outflow** option must be selected. Afterwards the **reference values** are selected. It must be noted that all reference values should taken from **inlet**.



Once reference value selection process is completed, the solution is ready to be initialized. The **solution methods** are then chosen. The **phases are coupled** and **second degree upwind momentum and energy equations** are summoned. Then the **solution is initialized**.



After the solution is initialized, the **number of iterations** must be saved. Here the user is presented with the opportunity to save a data file after a certain number of iterations are completed. This allows the user to justify the data variation in every step and analyze it. However a total number of iteration must be set for the simulation. Once this number is reached, the simulation will stop and prepare a data and a case file for the user to analyze. However fluent allows the user to create a combined **data and case file**. This process is more convenient for the user.



Once the simulation is finished, the user can use fluent to analyze the result or export it to CFD post. For our case, we exported the data file to **CFD post**.

5.5 Accumulation of Data

After exporting the data files, to CFD post, we used the **Plane Tool** to draw a plane parallel to the ZX plane. This showed a cross-section view of the pipe along its length. Now we used the **"areaave"** function to calculate the temperature at inlet, outlet and wall by the **function calculator**. The data were satisfactory compared to the input boundary conditions.

Sample Data Profiles are shown below:

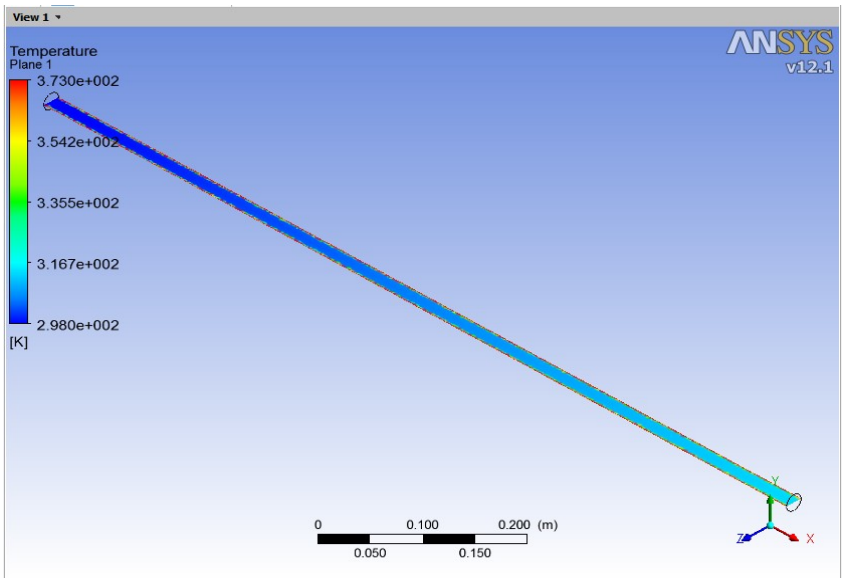


Figure 5: Temperature Profile of Water flow (Outlet Temperature = 334.6 K)

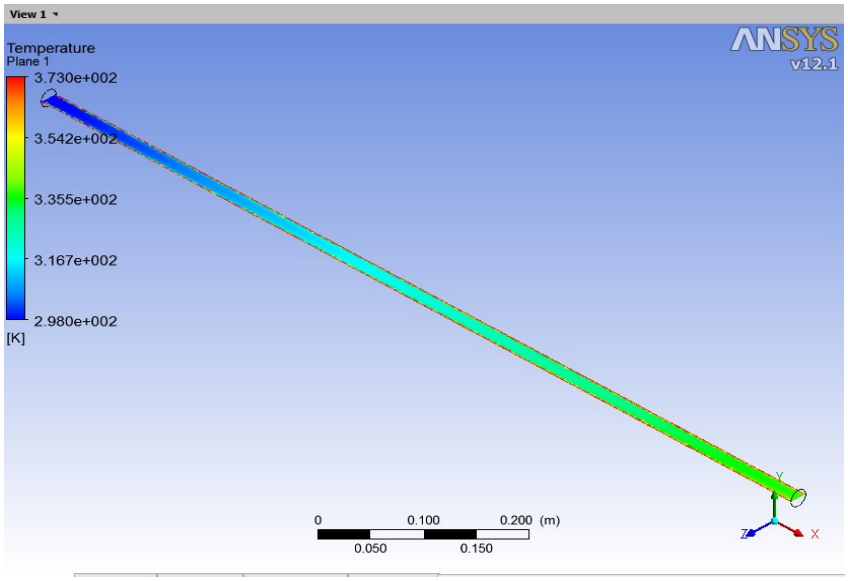


Figure 6: Temperature Profile of Nanofluid (0.5% volume concentration) flow (Outlet Temperature = 350.368 K)

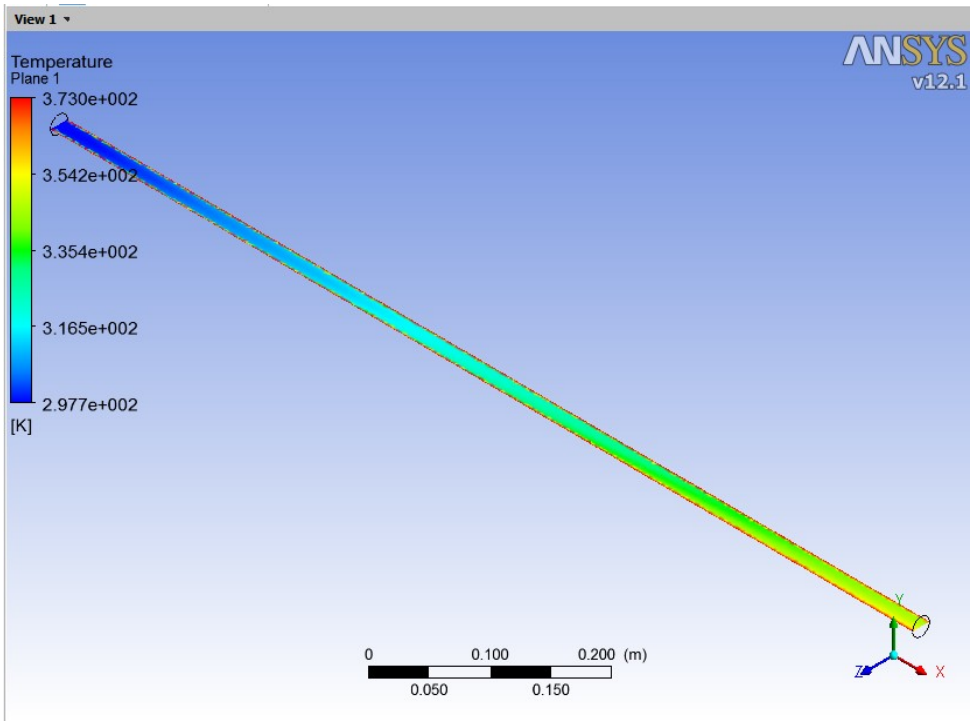


Figure 7: Temperature Profile of Nanofluid (2.5% volume concentration) flow (Outlet Temperature = 357.45 K)

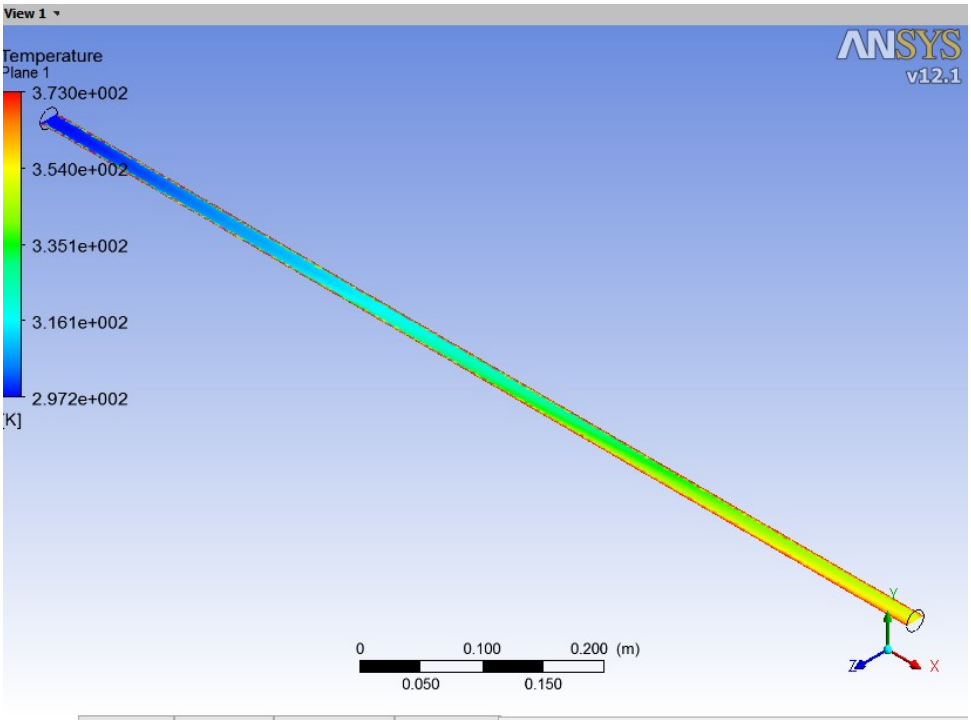


Figure 8: Temperature Profile of Nanofluid (4.0% volume concentration) flow (Outlet Temperature = 360.51 K)

Chapter 6

Results & Data Analysis

6.1 Equations Required for Necessary Calculation

Nanofluid's density may be calculated from the equation below:

$$\rho_{nb} = (1-\phi)\rho_f + \phi\rho_p$$

Nanofluid's heat capacity may be calculated from the equation below:

$$c_{p,t} = \frac{f_p \rho_p c_{p,p} + f_b \rho_b c_{p,b}}{f_p \rho_p + f_b \rho_b}$$

The effective thermal conductivity, k_{eff}, is given by:

$$k_{eff} = \frac{k_p + 2k_b + 2(k_p - k_b)\emptyset}{k_p + 2k_b - (k_p - k_b)\emptyset} k_b$$

Nanofluid's viscosity may be calculated from the equation below:

$$\frac{\mu_{nb}}{\mu_b} = \frac{1}{(1-\phi)^{2.5}}$$

Nanoparticle's Prandtl number may be calculated in the following manner:

$$\mathrm{Pr}_{nb} = \frac{c_{p,nb}\mu_{nb}}{k_{nb}}$$

Nanofluid's Reynold's number may be calculated from the equation below:

$$\mathrm{Re}_{nb} = \frac{m_{nb} d_i}{A_{o,t}\mu_{nb}}$$

Heat Transfer coefficient for the flow may be calculated from the equation:

$$h_{nb} = \frac{Nu_{nb} k_{nb}}{d_i}$$

Friction factor may be calculated from the equation:

$$f = \frac{64}{\mathrm{Re}_{nb}}$$; for Laminar Flow

$$\mathrm{f} = (0.79\ln(\mathrm{Re_{nb}} - 1.64)^{-2}$$; for Turbulent Flow

Nusselt Number calculation may be done from the following equation:

$$Nu = \frac{hD}{k_f}$$

For the nanofluid we use k_{nf} instead of k_f in the above equation.

6.2 Data Table

✓ **Property Table:**

Material Properties	Water	Aluminium Oxide ($Al_2O_{3)}$
Density, ρ	1000 kg/m^3	3900 kg/m^3
Specific Heat, c_p	4200 J/kg K	880 J/kg K
Molecular Mass, M	18 g	102 g
Thermal Conductivity, k	0.58 W/(m.K)	30 W/(m.K)

✓ **Simulation Data Table 1:**

Volume Fraction (%)	Outlet Temperature T_2 (K)	Specific Heat Capacity, c_p (J.kg^{-1}.K^{-1})	Heat Transferred Q,(W)	Thermal Conductivity, k (W.$m^{-1}.K^{-1}$)	Heat Transfer Co-efficient h (W.$m^{-2}.K^{-1}$)	Nusselt Number Nu
0	334.57	4200	752.75	0.565	163.8	5.8
0.001	350.11	4182.62	1080.48	0.568	165	5.81
0.002	350.17	4174.25	1092.87	0.572	166.7	5.83
0.004	350.25	4148.80	1117.52	0.579	170.2	5.88
0.005	350.37	4136.19	1143.12	0.582	173.7	5.97
0.007	350.80	4111.17	1178.38	0.587	177.6	6.05
0.009	351.48	4089.24	1221.79	0.592	181.8	6.14
0.01	351.76	4074.17	1249.80	0.594	185	6.23
0.015	353.91	4013.88	1409.39	0.605	200.6	6.63
0.02	355.87	3955.24	1651.51	0.618	227.1	7.35
0.025	357.45	3898.18	2046.97	0.632	274	8.67
0.03	358.73	3842.65	2567.56	0.647	336.44	10.4
0.035	359.71	3788.58	3070.86	0.66	396	12
0.04	360.51	3735.90	3425.67	0.674	436.1	12.94
0.05	361.71	3634.60	3789.26	0.696	473.3	13.6

✓ **Simulation Data Table 2:**

Volume Concentration	k_{nf}/k_f	Increase in k (%)	Dynamic Viscosity, μ , Pas.s
0	1	0	.000894
0.001	1.005	0.5	.00085
0.002	1.012	1.2	0.00086
0.004	1.025	2.5	0.00088
0.005	1.030	3.0	0.00089
0.007	1.039	3.9	0.00091
0.009	1.048	4.8	0.00092
0.01	1.051	5.1	0.00093
0.015	1.071	7.1	0.00096
0.02	1.094	9.4	0.00098
0.025	1.119	11.9	0.001
0.03	1.145	14.5	0.00101
0.035	1.168	16.8	0.00102
0.04	1.193	19.3	0.00103
0.05	1.232	23.2	0.00104

6.3 Effect of Volume Fraction on Thermal Conductivity

Change of thermal conductivity with the change of volume fraction or particle concentration is the most important effect of nanoparticles known to date. Using various types of materials as nanoparticles, researchers have proved that it is possible to enhance the thermal conductivity of nanofluids by over 40% than the conventional base fluid. Some research works suggest using various mixtures like aluminium oxide, copper oxide and Titanium oxide, the thermal conductivity can improved as much as 60%. In our case, we used a simple Aluminium Oxide/water combination at a definite mixing range to form nanofluid. Recent research works on this material suggest, aluminium oxide particles can improve the thermal conductivity of a base fluid (water) by up to 30%.

Selecting the correct concentration of solid particles is extremely necessary to get the desired effect on thermal conductivity or any other properties. Most researchers suggest nanoparticle concentration must not be over 4% of the total volume of the fluid in order to obtain enhanced performance from the multiphase flow. But there is a significant number of data available that suggests nanoparticle concentration can go up to 10% of the total fluid volume and yet provide significantly improved performance. However this only applies for a few materials including the base fluid. For our research, we considered a variety of particle concentrations starting from 0.1% to 5%. A total of 15 different concentrations were noted and any relevant data has been recorded.

The following graph denotes the relationship between the volume fractions of Al_2O_3 particles and their effect on thermal conductivity.

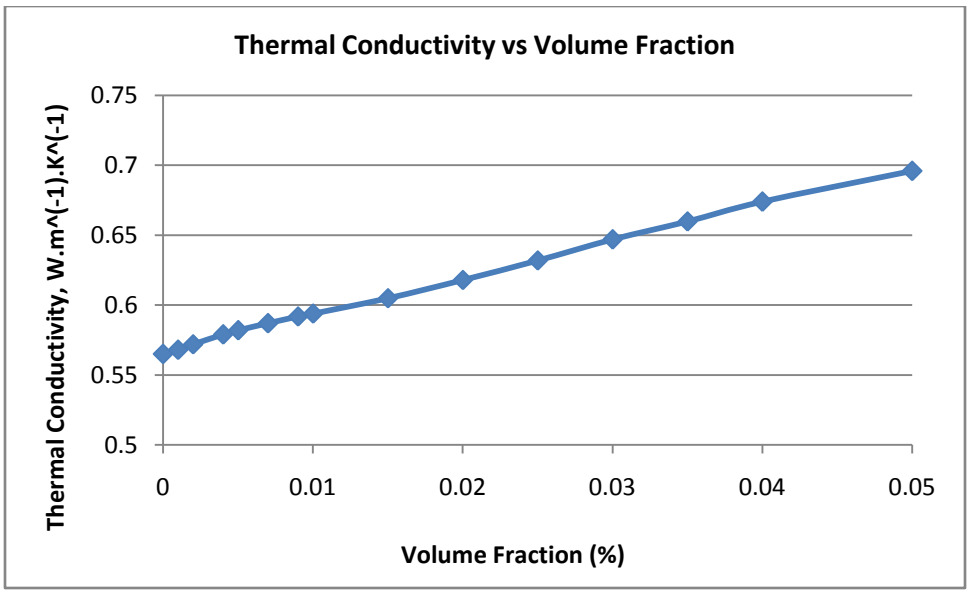


Figure 9: Thermal Conductivity vs Volume Fraction

Here it has clearly established that the thermal conductivity of nanofluid has increased dramatically due to the addition of nanoparticles. The actual rate of increment of thermal conductivity can be better understood from the following plot:

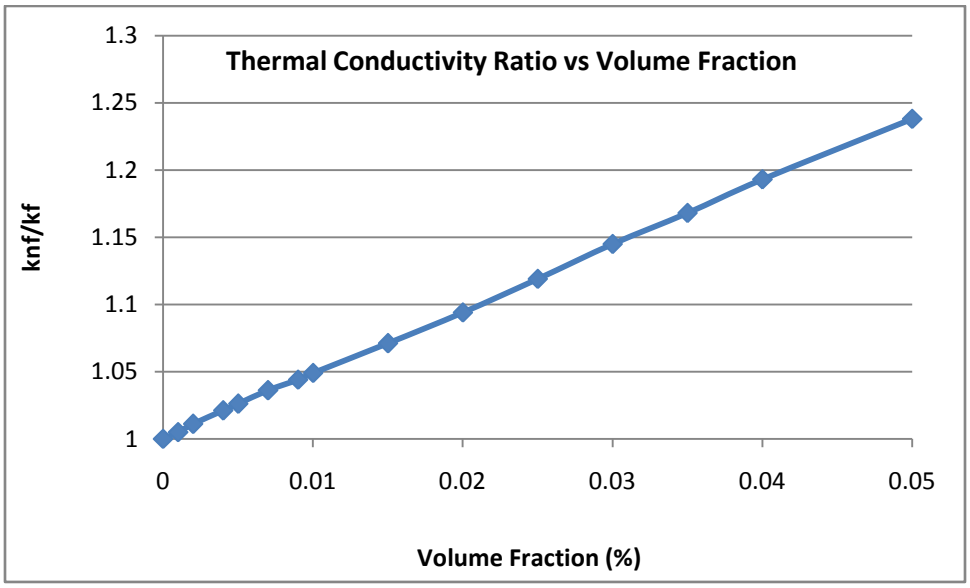


Figure 10: Thermal Conductivity Ratio vs Volume Fraction

The above figure illustrates that the thermal conductivity of the fluid has gone up by nearly 24% by introducing only 5% Aluminium Oxide to the base particle. It is possible to enhance its thermal properties further up to 30%.

Most fluids used as a heat transfer medium have poor thermal conductivity. But solid materials especially metals and metallic oxides have noticeably higher thermal conductivity than the common medium. Solid Aluminium Oxide has thermal conductivity of 30 W/m K compared to water's thermal conductivity of 0.565 W/m K. Therefore it has been an obvious solution to mix in two separate phases. The loose electrons in outer shells of metals are responsible for good thermal conductivity. When mixed with fluid particles, the presence of these electrons adds more conduction ability to the material. Since the solid particle is mixed at a small fraction compared to the fluid, it is actually the fluid's thermal conductivity that improves.

6.4 Effect of Volume Fraction on Heat Transfer Coefficient

Along with thermal conductivity, the heat transfer coefficient is one of the defining properties of a material's thermodynamic behavior. Heat transfer coefficient usually indicates the heat transfer coefficient of convection. The effect of overall heat transfer coefficient (U) has not been discussed here. In our plotting of the heat transfer coefficient against the volume friction, the value increased by nearly three times. This suggests a significant change in convective activity. This explains the sudden jump in heat energy transfer and the Nusselt number of the flow. The change of heat transfer coefficient with respect to volume fraction of nanoparticles is shown below:

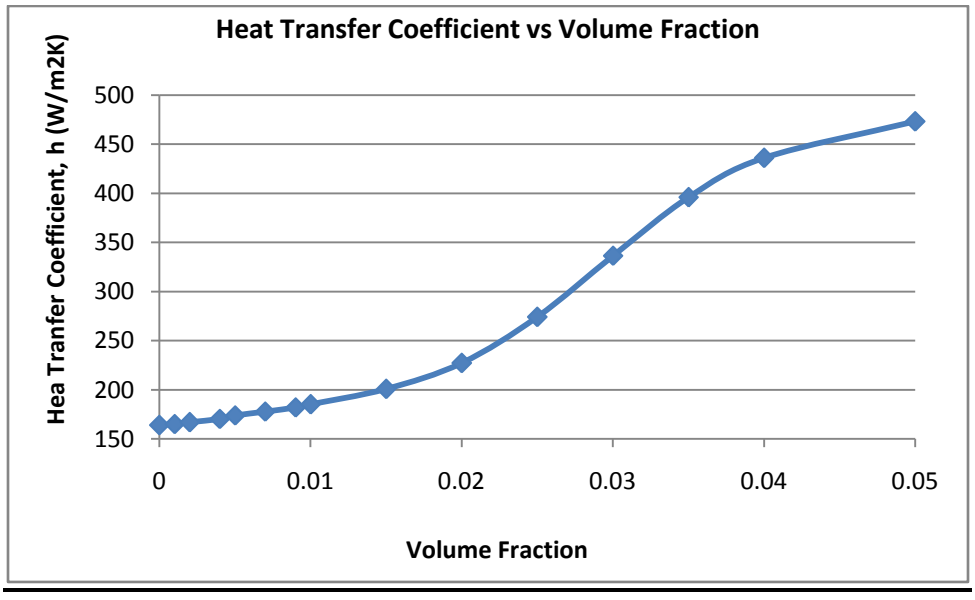


Figure 11: Heat Transfer Coefficient vs Volume Fraction

Due to the different temperatures of the fluid and the pipe wall, a thermal boundary layer is developed, though its thickness and the entrance length can be different. Macroscopically, the forced convective heat transfer coefficient, *h*, is given by $h = k_f / \delta_t$, with δ_t representing the local thickness of thermal boundary layer and be k_f the local effective thermal conductivity of nanofluids adjacent to the wall surface. This simple expression indicates that either an increase in k_f and a decrease in δ_t, or both can result in an increase of the convective heat transfer coefficient. This explains why the entrance region gives a higher convective heat transfer coefficient. As nanofluids have a higher thermal conductivity in comparison with the base liquid, the simple expression also partially explains the enhanced convective heat transfer coefficient. The expression, however, cannot provide an adequate explanation of the experimental observations that, in some cases, the convective heat transfer coefficient enhancement is much higher than the thermal conduction enhancement, while in other cases, there is no convective heat transfer enhancement despite considerable thermal conduction enhancement, e.g. aqueous-based nano-diamond and ethylene-glycol-based titania nanofluids (Ding et al. 2007). This may be explained from the microscopic point of view; see below.

Microscopically, nanofluids are inhomogeneous. There are at least two possible reasons for the inhomogeneity (Ding et al. 2006, Ding et al. 2007). One is the presence of agglomerates in nanofluids, which can be associated with either sintering during nanoparticle manufacturing or solution chemistry during nanofluids formulation. The former is often seen in processes involving elevated temperatures, e.g. aerosol reactors. The resulting agglomerates are very strong and are difficult to break down to primary nanoparticles even with prolonged high-shear processing and ultrasonication. The latter is due to the attraction between nanoparticles, e.g. van der Waals' attractive force and depletion phenomena.

The agglomerates (aggregates) can be controlled by adjusting the solution chemistry and applying shear. The second reason is particle migration due to viscosity and velocity gradients. Experimental evidence of particle migration is the longer entrance length of nanofluids as discussed in a recent experimental study by Merhi et al. (2005). There are also plenty of theoretical studies on particle migration; see, for example Phillips et al. (1992), Frank et al. (2003) and Ding and Wen (2005). If particles are very small, Brownian motion is strong and the effect of the above-mentioned particle migration is negligible. If particles are large, e.g. aggregates of hundreds of nanometres, the contribution of the Brownian motion is small, and a particle depletion region may exist at the wall region, which gives non-uniform distributions of particle concentration, viscosity and thermal conductivity. The direct results of particle migration are lower particle concentration at the wall region and a thinner boundary thickness due to disturbance by the moving particles. This, according to $h = k_f / \delta_t$, can lead to three possible scenarios: (i) *h* is enhanced if the decrease in δ_t exceeds the decrease in k_f .; (ii) *h* does not change if the decrease in δ_t is equal to the decrease in k_f ; and (iii) *h* is reduced if the decrease in δ_t is lower than the decrease in k_f . This qualitatively explains the experimental results. However, quantitative explanation requires understanding of how nanoparticles behave under shear and how they interact with each other and with fluid in the boundary layer.

6.5 Effect of Volume Fraction on Heat Capacity

This is a rather interesting issue. We know water has relatively high specific heat capacity compared to commonly known materials of any phase or type. Solid particles like Aluminium Oxide have significantly lower specific heat capacity than water. But when the solid particles are mixed within the base fluid, the heat capacity drops substantially. This may lead to interpretations like conduction heat transfer should decrease since the specific heat capacity of the multiphase fluid drops below the heat capacity of base fluid. However the temperature gradient is the conduction equation has a significantly higher value than the decrease in heat capacity. Therefore overall the heat transfer increases.

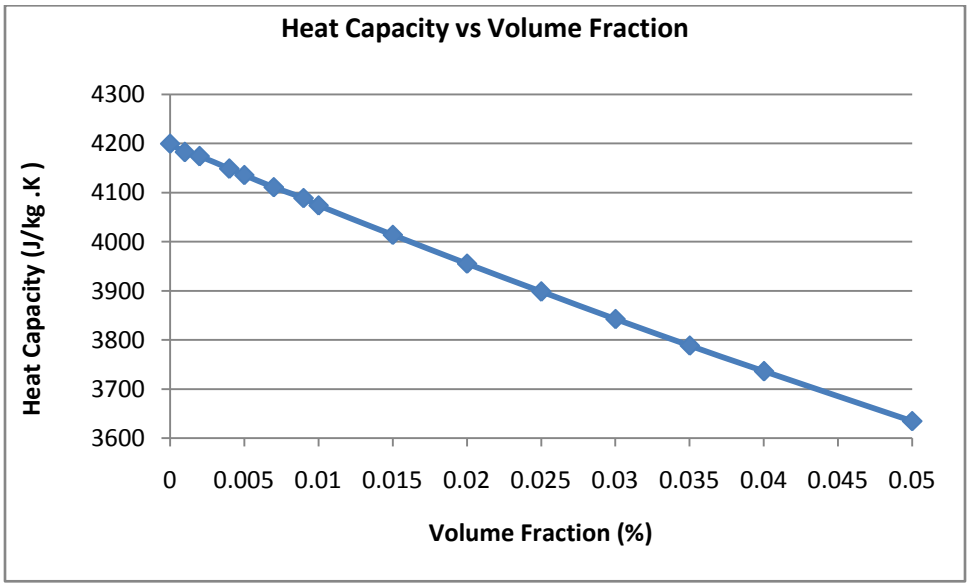


Figure 12: Heat Capacity vs Volume Fraction

The reason behind such a phenomenon is simple. The solid particle injected within the base liquid disrupts the fluid's ability to conduct heat from one molecule to another. Therefore the heat capacity of the multiphase fluid decreases due to the interruption in continuous conduction.

Our finding show that the heat capacity of the nanofluid dropped by a mere 13.5%. The final heat capacity for 5% particle concentration of Aluminium Oxide is about 3635 J/Kg.K which is still very high compared to most materials in pure state.

Although there was a 13.5% decrease in heat capacity, the temperature gradient showed an almost 23% increment in the output temperature. Therefore the overall heat energy transferred during the thermodynamic process actually increased despite the sudden decrease in specific heat capacity of the multiphase fluid

6.6 Effect of Volume Fraction on Nusselt Number

Nusselt number is a common parameter to evaluate heat transfer. This indicates the ratio between the convection and conduction heat transfer. For a laminar flow, the Nusselt Number is a function of thermal conductivity, convective heat transfer coefficient and characteristic length of the geometry. For a pipe, the characteristics length is the pipe diameter. For our purpose, we separately calculated the thermal conductivity and the heat transfer coefficient from the data gained from simulation process for various concentrations of nanoparticles in the base fluid. Afterwards a graph was plotted to show the change of Nusselt Number with respect to the nanoparticle concentration.

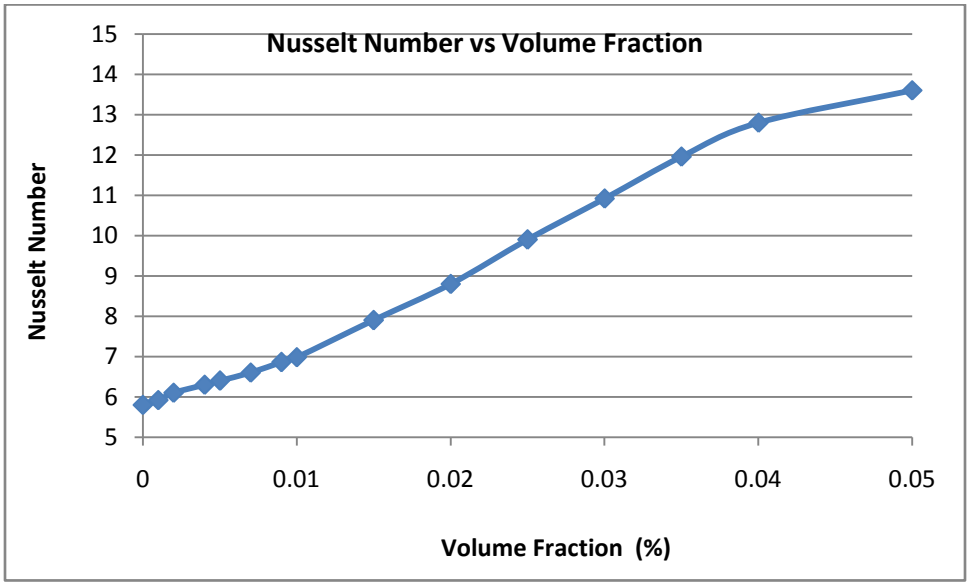


Figure 13: Nusselt Number vs Volume Fraction

The graph shows that the convective heat transfer improves by almost 2.5 times over the change of particle concentration from 0% (pure water) to 5%. Our findings show Nusselt number has increased gradually from 5.8 to 13.6 with respect to increased volume fraction of nanofluid.

As explained before, the different temperatures of the fluid and the pipe wall develops a thermal boundary layer. But its thickness and the entrance length can be different under altering conditions. The forced convective heat transfer coefficient, *h*, increases from the expression $h = k_f / \delta_t$, with δ_t representing the local thickness of thermal boundary layer and k_f be the local effective thermal conductivity of nanofluids adjacent to the wall surface. However the increase of h is noticeably higher than the increase of k_f . The thermal boundary layer thickness also decreases with the increase of k_f , Therefore Nusselt number (Nu=hD/ k_f) benefits from both the increase in k_f and the decrease in δ_t . As nanofluids have a higher thermal conductivity in comparison with the base liquid, the simple expression also partially explains the enhanced convective heat transfer coefficient.

6.7 Effect of Particle Diameter on Thermal Conductivity

In order to observe the effect of changing particle diameter on thermal conductivity of the nanofluids, we considered Aluminium Oxide particles of 10 nm, 20 nm, 25 nm, 30nm, 40 nm, 50 nm, 100 nm and 140 nm. Then using the k_{nf}/k_f ratio we obtained the following curve:

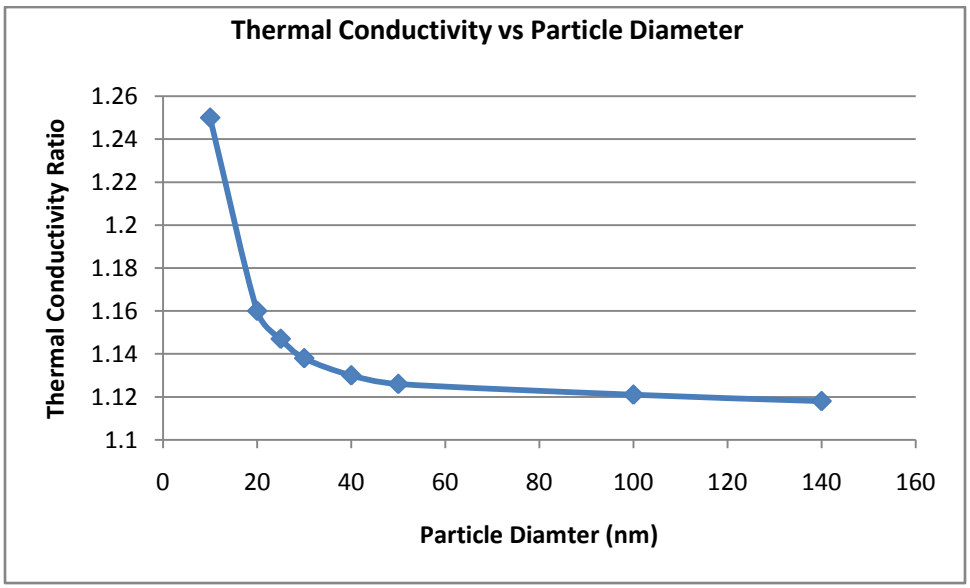


Figure 14: Thermal Conductivity Ratio vs Particle Diamter

As the particle size increases, the Brownian motion will decrease. With the decrease in Brownian motion the disturbance will only be reduced. Thus the decreased disturbance within the nanofluid will cause the thermal conductivity to decrease.

6.8 Effect of Volume Fraction on Heat Energy Transfer & Outlet Temperature

Nanofluids are mostly used for cooling purposes. The primary objective of such a setup is to transfer as much heat energy as possible so that the coolant will achieve the highest possible temperature at the outlet. A multiphase fluid can carry out any such process with remarkably high efficiency due to increased rate of heat absorption. Therefore the heat energy transferred by a multiphase fluid will be significantly higher than a single phase flow operating under similar conditions.

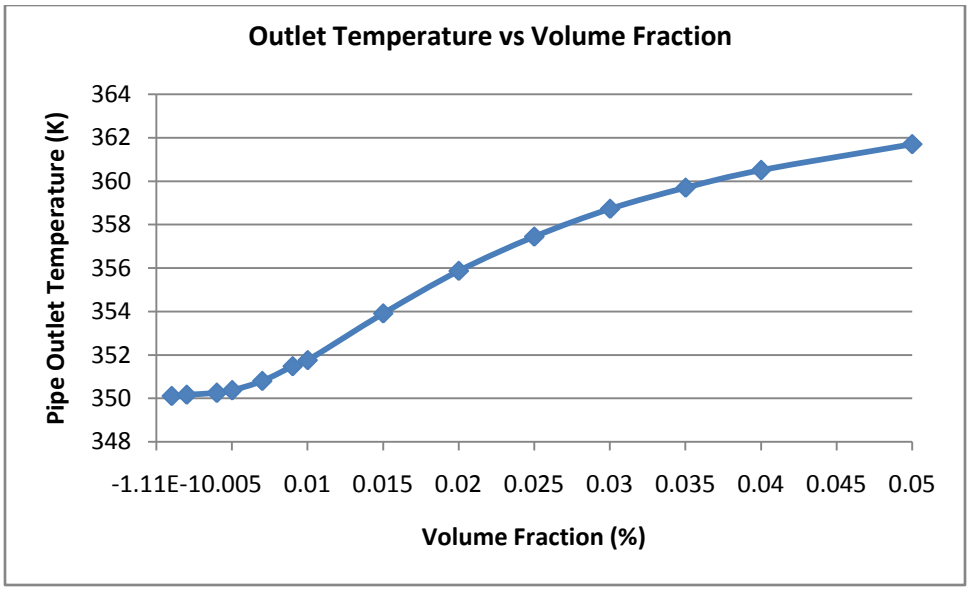


Figure 15: Outlet Temperature vs volume fraction

It is seen from our findings that the temperature at the outlet can vary by over 30 K over a very small temperature difference of 75 K between the pipe wall and the fluid temperature at inlet. As the nanoparticle concentration reaches 4%, the rate of increase in outlet temperature starts to approach the flat line. But the curve's steep rise between 0.5% to 4% concentrations has caused the recent upbringing in the field of nanoparticle research.

Our finding s show the pipe outlet temperature increase becomes very small if more particles are added after the particle concentration reaches 5%. Therefore the temperature gradient becomes nearly constant and the heat energy transfer also changes infinitesimally.

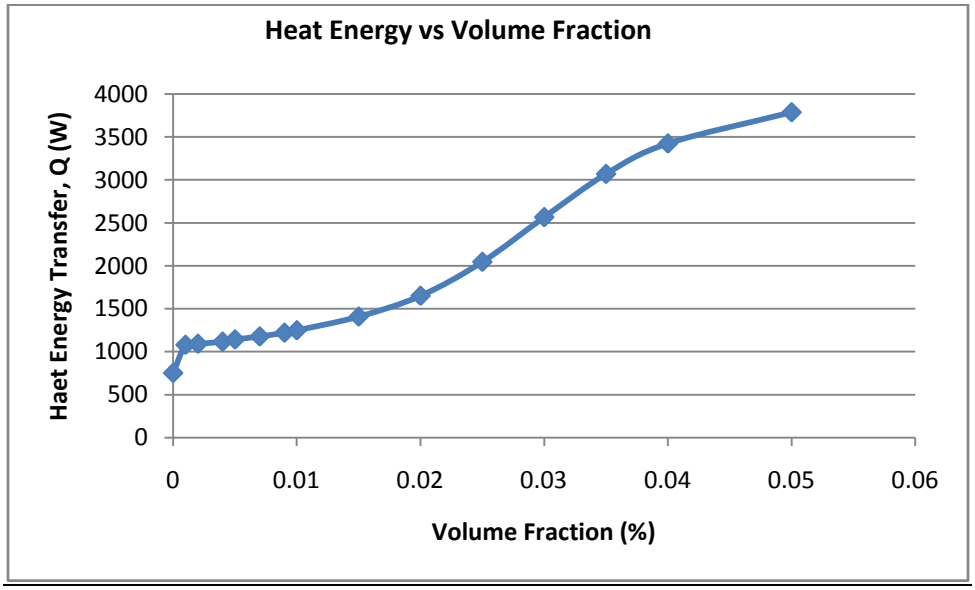


Figure 16: Heat Energy vs Volume Fraction

The figure illustrates how the total heat transfer increases with the increase of volume fraction. At the very beginning of the curve, the steep rise between the first and second point denotes the change in heat energy absorption by the introduction of a solid phase material. In our research, we found that the total heat energy exchanged during the thermodynamic process for a multiphase flow can be over four times as high as the single phase flow. The sudden jump in heat transfer coefficient is responsible for such an increase. The convective transfer occurs more noticeably than conduction as soon as the solid phase particles are added to the base fluid. We observe the same phenomenon over Nusselt number and volume fraction study. Therefore the nanoparticles are used more and more often to enhance the heat transfer process and increase efficiency by saving heat energy loss.

6.9 Effect of Volume Fraction on Dynamic Viscosity

Researchers have previously shown that the dynamic viscosity of the nanofluid decreases if more particles are injected to increase concentration. However the number of works published in this matter is remarkably low. Some researchers have even found out some controversial data that are yet to be explained.

In this experiment, we once again used the data generated through simulation to calculate the dynamic viscosity of the nanofluid. The particle injection started from 0% concentration and stopped at 5%.The graph illustrates a 25% increase of dynamic viscosity with respect to incremental volume fraction.

The simple explanation behind this phenomenon is the presence of solid particles and their effects on Brownian motion.

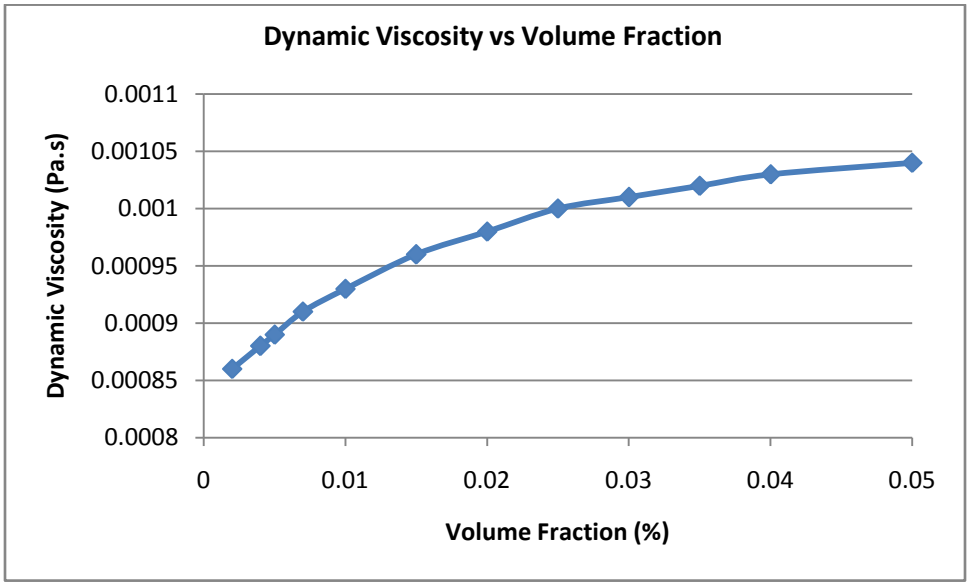


Figure 17: Dynamic Viscosity vs Volume Fraction

Particle migration takes place due to viscosity and velocity gradients. Experimental evidence of particle migration is the longer entrance length of nanofluids as discussed in a recent experimental study by Merhi et al. (2005). There are also plenty of theoretical studies on particle migration; see, for example Phillips et al. (1992), Frank et al. (2003) and Ding and Wen (2005). If particles are very small, Brownian motion is strong and the effect of the above-mentioned particle migration is negligible. If particle concentration is increased the contribution of the Brownian motion is influenced, and a particle depletion region may exist at the wall region, which gives non-uniform distributions of particle concentration, viscosity and thermal conductivity. The direct results of particle migration are lower particle concentration at the wall region and a thinner boundary thickness due to disturbance by the moving particles. This disturbance increases with particle concentration and causes the dynamic viscosity to increase.

Chapter 7

Conclusion

7.1 Conclusion

The convective heat transfer performance and flow characteristics of Aluminium oxide nanofluid flowing in a horizontal circular pipe has been investigated using CFD. The simulations have been carried out under laminar conditions. The nanoparticle concentration had a direct effect on thermal conductivity, heat transfer co-efficient and the Nusselt number. The use of nanoparticles significantly increased the thermal conductivity and heat transfer co-efficient and hence the Nusselt number. Additionally, the increase in particle concentration resulted in increases in the thermal conductivity, heat transfer co-efficient and the Nusselt number. This proved the hypothesis that the heat transfer rate can be increased by introducing nanometer sized solid particles in the base fluid. We also proved that by changing the volume fraction of nanoparticle within the base fluid, we can obtain desired properties and performances from the nanofluid.

7.2 Recommendations for Future Work

- To explore heat transfer characteristics for turbulent flow
- To explore heat transfer application in complex heat exchangers.
- To explore heat transfer properties with varying nanoparticle diameter and material.
- To compare existing heat transfer application between a single phase and a multiphase flow.
- To simulate practical conditions using CFD where wind resistance and other disturbances may come into play.

7.3 NOMENCLATURE

Common Notations:

A = Cross sectional area (m^2)
S = Surface area (m^2)
D = *Pipe Diameter* (m)
L = *Pipe* length (m)
P = Pressure
M = Mass flow rate (kg/s)

Re = Reynolds number,
Pr = Prandtl number,
cp = Specific heat (J/kg K)
f = Friction factor
h = Convective heat transfer coefficient (W/m^2K)
k = Thermal conductivity (W/m K)
Nu = Nusselt number, hD/k
T = Temperature (K)
v = Fluid velocity (m/s)
Q = Flow Rate (kg/ m^3)
u, v, w = Velocity components in x, y & z direction
υ = kinematic viscosity (m^2) /s

Greek Symbols

μ = Dynamic viscosity (kg/m^2 s)
υ = kinematic viscosity (m^2) /s

ρ = Density (kg · /m^3)

ψ = particle spherity

ϕ = Volume concentration (%).

Subscripts
f = fluid
p = nanoparticle
n = shape factor
nf = naofluid
b = base fluid
in = inlet
nf = nanofluid
out = outlet
s = solid phase

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