DETERMINATION OF HEAT TRANSFER COEFFICIENT USING EXPERIMENTAL VALUES OF PRESSURE DROP OF A SINGLE PHASE FLUID

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I certify that the project entitled "*Determination of Heat Transfer Coefficient Using Experimental Values of Pressure Drop of a Single Phase Fluid*" is written by *Muhammad Bishrul Hafi bin Ab. Jalil*. I have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering.

Professor Dr Shahrani Bin Anuar	....
Examiner	Signature

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SESI PENGAJIAN: 2010/2011

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I Muhammad Bishrul Hafi bin Ab Jalil hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Date : 6TH DECEMBER 2010

Dedicated to my dear parents

AB JALIL BIN HJ MD NOR
and
HASNAH BINTI HJ AHMAD

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ABSTRACT

Analogical procedure to obtain the heat transfer coefficient for fluid flowing inside tube in turbulent range with carbon nanotubes is carried out. A regression equation valid for both water and nanofluid is developed by making use of Colburn analogy to estimate the Nusselt number. Heat transfer coefficient and pressure drop with carbon nanotubes has been analogically determined with different Prandtl number and volume concentration. Based on the analysis, the regression equation showed considerable deviation with the Gnielinski correlation and considered reliable in turbulent flow for single-phase fluid. The results also showed that convective heat transfer flow in plain tube is enhanced significantly by the existence of carbon nanotubes when compared with water using the regression equation developed. It is also observed that heat transfer coefficient for carbon nanotubes having volume concentration of 0.1% is 48.16% higher compared with water at 20,000 Reynolds number. Heat transfer coefficient is also enhanced with the increase of Prandtl number and volume concentration with maximum value of 0.5%.

ABSTRAK

Prosedur berdasarkan analogi untuk menentukan pekali pemindahan haba untuk cecair yang bergerak di dalam tiub dalam lingkungan nilai turbulen telah dilaksanakan. Persamaan regresi yang sah untuk air dan cecair nano telah diterbitkan berdasarkan analogi Colburn untuk menentukan nombor Nusselt. Pekali pemindahan haba dan tekanan jatuh tiub nano karbon telah ditentukan secara analogi dengan penggunaan nombor Prandtl dan kepekatan yang berlainan. Berdasarkan analisis, persamaan regresi telah menunjukkan pensasaran nilai yang boleh diambil kira dengan persamaan Gnielinski dan boleh dianggap benar dalam aliran turbulen untuk cecair satu-fasa. Keputusan menunjukkan paksaan aliran pemindahan haba dalam tiub kosong telah ditingkatkan oleh kewujudan tiub nano karbon apabila dibandingkan dengan air menggunakan persamaan regresi yang telah diterbitkan. Selain itu diperhatikan juga bahawa pekali pemindahan haba untuk tiub nano karbon yang mempunyai kepekatan 0.1% adalah 48.16% lebih tinggi daripada air pada nombor Reynolds 20,000. Pekali pemindahan haba juga meningkat apabila nombor Prandtl dan kepekatan meningkat dengan nilai maksimum sebanyak 0.5%.

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LIST OF SYMBOLS

U	Local time averaged velocity
Θ	Temperature
u	Friction velocity
q	Rate of heat transfer flux
y	Normal distance from the wall
d	Diameter of tube
d_{np}	Diameter of nanoparticle
m	Mass
Π	Pi
$\emptyset$	Volume concentration
Re	Reynolds number
c_p	Specific heat
c_{bf}	Specific heat of base fluid
c_{nf}	Specific heat of nanofluid
c_p	Specific heat of nanoparticle
Pr	Prandtl number
Pr_w	Prandtl number of water
Pr_{nf}	Prandtl number of nanofluid
St	Stanton number
Nu	Nusselt number
f	Friction factor
$C_{\boldsymbol{d}}$	Drag coefficient
ρ	Density of fluid

ρ_{nf}	Density of nanoparticle
ρ_p	Density of nanoparticle
ρ_{bf}	Density of base fluid
k	Thermal conductivity
k_{nf}	Thermal conductivity of nanofluid
k_{bf}	Thermal conductivity of base fluid
T_{nf}	Temperature of nanofluid
μ	Dynamic viscosity
μ_{nf}	Dynamic viscosity of nanofluid
T_b	Bulk temperature
T_w	Temperature of water
h	Heat transfer coefficient

LIST OF ABBREVIATIONS

SWCNTs	Single-walled carbon nanotubes
MWCNTs	Multi-walled carbon nanotubes
VEROS	Vacuum Evaporation onto a Running Oil Substrate
SANSS	Submerged Arc Nanoparticle Synthesis System
CTAB	Oleic acid and cetyltrimethylammoniumbromide
CNTs	Carbon nanotubes
TCNT	Treated carbon nanotube
PCNT	Pristine carbon nanotube
FYP	Final year project

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Nanofluids are fluids 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. Water, oil and ethylene glycol are the conventional heat transfer fluids. Nanofluids are able to enhance the thermal properties in term of thermal conductivity and heat transfer coefficients compared to the conventional heat transfer fluids. Nanofluids have novel properties that make them potentially useful in many applications in heat transfer including microelectronics, fuel cells, pharmaceutical processes, and hybrid-powered engine. They exhibit enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid.

Carbon nanotube is one of the nanoparticles used to produce the nanofluids. Since the first discovery of carbon nanotube in 1991, there have been a lot of experimental, simulation and theoretical investigations on electronic, anisotropic mechanical and adsorptive properties of carbon nanotube. There are two types of carbon nanotube which are single-walled and multi-walled carbon nanotube depending on the synthesis conditions. Nanotubes can be single-walled (a single tubule of 1 nm) or multi-walled (2–50 tubules of 2–50 nm positioned concentrically).

Single-walled carbon nanotubes (SWCNTs) are often found in self-organized bundles. For example, a set of aligned tubes arranged in a two-dimensional triangular lattice in the plane perpendicular to their common axes is categorized as SWCNTs. One of the applications of SWCNTs bundles is field emission electron sources for flat panel display to which both mechanical and electrical properties are important and coupled. It has been predicted that radial deformation, resulting in polygonized cross-sections, alters the band gap, leading to changes in the electron transport characteristics of carbon nanotubes.

Meanwhile, multi-walled carbon nanotubes (MWCNTs) consist of many graphite layers concentrically nested like rings of a tree trunk. MWCNTs was reported to have lower mechanical performance than the SWCNTs, but can be produced in a much larger quantity and at a lower cost. MWCNTs have been investigated for a variety of applications based on its unique electrical, optical, and mechanical properties. While such properties are truly significant, the practical realization of reproducible performance in devices such as field effect transistors, high-strength composite materials, sensors, actuators, and catalyst supports will require material standardization, especially in terms of length and degree of distribution. Rational chemical functionalization of carbon nanotubes is important for predictive manipulation of these nanotubes. MWCNTs is also more rigid because their section is much larger compared to that of SWCNTs. MWCNTs have been proven to be very effective fillers especially in tailored polymeric materials suited to prescribed applications at very low loadings. This is because neat MWCNTs exhibit excellent mechanical, thermal, and electrical properties. One of the advantages of MWCNTs used as filler is their high aspect ratio, as high as 1000, which can induce better adhesion with the polymeric matrix, which is an important factor for effective enhancement of the nanocomposite's properties. This enables percolation of the fillers at very low concentrations and makes them attractive for use in a broad spectrum of applications, especially as reinforcing fibers in nanocomposites.

1.2 PROBLEM STATEMENTS

During the study on nanofluids, it was found out that the knowledge on nanofluids is very limited. Thus, the determination of heat transfer coefficient for nanofluids is much difficult. Further understanding is needed regarding impact of particle size, shape, concentration, temperature and pH. This problem however can be overcome by conducting the pressure drop experiment. However, due to the expensive cost of conducting experiment and involves a lot of time, an analogy is proposed instead of scientific experiment setup in order to estimate the heat transfer coefficient of nanofluids.

1.3 PROJECT OBJECTIVE

The objectives of this project are:

1. Propose an analogy to estimate the heat transfer coefficients of CNTs
2. Develop a regression equation in the similar manner as Colburn analogy to evaluate the heat transfer coefficient for internal flow
3. The equation should have the flexibility to estimate Nusselt number of single phase fluid in the absence of nanoparticles

1.4 PROJECT SCOPES

Heat transfer coefficient of pure fluids can be estimated by making use of Colburn analogy, thus similar approach is proposed to be undertaken for nanofluids also.

The scopes of this project are:

1. Compare the thermophysical experimental data of MWCNTs nanofluid with available property equations
2. Develop an equation for the estimation of nanofluid heat transfer coefficient using the concept of analogy for water based nanofluids
3. Estimate the Nusselt number and heat transfer coefficient for MWCNT nanofluid at different concentrations, Prandtl number and temperatures.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will discusses about the previous related study and researches on nanofluids. The sources of the review are extracted from journals, articles, reference books and internet. The purpose of this section is to provide additional information and relevant facts based on past researches which related to this project. This chapter will cover the corresponding terms such as the Colburn analogy, fundamentals of nanofluids, heat transfer and the enhancement of heat transfer caused by nanofluids which had been proved experimentally.

2.2 THE COLBURN ANALOGY

Colburn analogy is the most successful and widely used analogy on heat, momentum and mass transfer analogies for pure fluid. The basic mechanisms and mathematics of heat, mass and momentum transport are essentially the same. Among other analogies such as Reynolds analogy and Prandtl-Taylor analogy, Colburn analogy was developed to relate the heat transfer coefficients with the friction factors directly for flow inside tube. This analogy is proved to be the most accurate analogy in heat and mass transfer problem.

Pure fluid such as water flowing inside circular horizontal tube will results to the existence of friction between water and the internal part of the tube which is called the friction factor. By using the Colburn analogy, also knowing the Prandtl and Stanton number, the heat transfer coefficient for external flow can be determined using the expression below;

$$St.Pr^{2/3} = \frac{f}{2}$$

Since the project is focused on the internal turbulent flow, the equation is given by;

$$St.Pr^{2/3} = \frac{f}{8}$$

where;

St = Stanton number

Pr = Prandtl number

f = friction factor

2.2.1 The Derivation of Colburn Analogy

The velocity and temperature profiles can be expressed in terms of a log-law and a power law. The power law form is;

$$\frac{U}{U_\infty} = \left(\frac{y}{\delta_{m,t}}\right)^p \tag{1}$$

$$\frac{\Theta-\Theta_w}{\Theta_\infty-\Theta_w} = \left(\frac{y}{\delta_{h,t}}\right)^{p'} \tag{2}$$

where U and Θ are the local time averaged velocity and temperature and the suffices w, ∞ refer to values at the wall and at an infinite normal distance in fact at the edge of the boundary layer.

The logarithmic form is

$$U^+ = 2.5 \ln y^+ + B \tag{3}$$

$$\Theta^{+} = 2.5 \ln y^{+} + B' \tag{4}$$

where;

$U^{+} = \dfrac{U}{u}$

$y^{+} = yu\,\frac{\rho}{\mu} = \frac{yu}{v}$

$\Theta^{+} = \rho c_{p}(\Theta - \Theta_{w})u/q_{w}$

$u = \dfrac{\sqrt{t_{w}}}{\rho}$

In this analysis, we pass equation (1) through the Kolmogorov point which is the intersection of the log law with the equation;

$$U^{+} = y^{+} \tag{5}$$

The coordinates of this Kolmogoroff point are $y_{k}^{+} = U_{k}^{+} = 11.8$, substituting into equation (1) and rearranging we obtain;

$$\delta_{m,t} = 11.8(\frac{U_{\infty}^{+}}{11.8})^{1/p} \tag{6}$$

Now the intersection between equation (4) and the diffusive equation at the wall,

$$\Theta^{+} = y^{+}Pr \tag{7}$$

is 11.8 Pr^{-b}, 11.8 Pr^{1-b}. Substituting into equation (4) gives;

$$\delta_{h,t} = 11.8Pr^{-b}\left(\frac{\Theta_{\infty}^{+}}{11.8Pr^{1-b}}\right)^{1/p'} \tag{8}$$

Then the ratio between the turbulent thermal and momentum boundary layers $\delta^+_{h,t}, \delta^+_{m,t}$ becomes;

$$\sigma_t = \frac{\delta_{h,t}}{\delta_{m,t}} = \frac{\Theta_\infty^{+1/p'}}{U_\infty^{+1/p}} Pr^{-b-\frac{1-b}{p'}} 11.8^{\frac{1}{p}-\frac{1}{p'}} \tag{9}$$

We now apply Reynolds' analogy by stating;

$$p = p' \tag{10}$$

Then;

$$\sigma_{t=} \left(\frac{\Theta_\infty^+}{U_\infty^+}\right)^{1/p} Pr^{\frac{b-bp-1}{p}} \tag{11}$$

By definition, for a boundary layer;

$$\frac{\Theta_\infty^+}{U_\infty^+} = \frac{f/2}{St} \tag{12}$$

and

$$\sigma_{t=} \left(\frac{f/2}{St}\right)^{1/p} Pr^{\frac{b-bp-1}{p}} \tag{13}$$

The Stanton number is obtained from the integral energy equation (Knudsen & Katz, 1958)

$$St = \frac{\partial}{\partial x} \int_0^{\delta_{h,t}} \frac{U}{U_\infty} \left[1 - \left(\frac{\Theta - \Theta_w}{\Theta_\infty - \Theta_w}\right)\right] dy \tag{14}$$

Substituting for (1) and (2);

$$St = \frac{\partial}{\partial x}\int_0^{\delta_{h,t}} \left(\frac{y}{\delta_{m,t}}\right)^p \left[1 - \left(\frac{y}{\delta_{h,t}}\right)^{p'}\right] dy \tag{15}$$

$$St = \frac{\partial}{\partial x}\left[\frac{p\delta_{m,t}}{(1+p)(1+p+p')^{\sigma_t^{p+1}}}\right] = \left[\frac{p\sigma_t^{p+1}}{(2p+1)(p+1)}\right]\frac{\partial\delta_{m,t}}{\partial x} \tag{16}$$

Most experimental data show that the ratio $\frac{f/2}{St}$ is independent of x and equation (13) indicates then that we can take σ_t to be independent of x. Then;

$$St = \left(\frac{\delta_{m,t}}{x}\right)\left[\frac{p\sigma_t^{p+1}}{(2p+1)(p+1)}\right] \tag{17}$$

The friction factor can be expressed as $\delta_{m,t}$ can be estimated from the integral momentum equation by standard techniques. The friction factor can be expressed as;

$$f = \frac{\alpha}{Re_g^{\beta}} \tag{18}$$

Giving (Skelland and Sampson, 1973, Trinh, 2010)

$$p = \frac{\beta}{2-\beta} \tag{19}$$

And

$$\frac{\delta_{m,t}}{x} = \left[\frac{\alpha(\beta+1)(\beta+2)}{\beta(2-\beta)}\right]^{1/\beta+1}\left[\frac{v}{U_\infty x}\right]^{\beta/\beta+1} \tag{20}$$

$$\frac{\delta_{m,t}}{x} = \left[\frac{\alpha(1+3p)(1+2p)}{2p}\right]^{1+p/1+3p}\left[\frac{v}{U_\infty x}\right]^{2p/1+3p} \tag{21}$$

Combining (13), (17) and (21), and rearranging gives;

$$St = \frac{f}{2} Pr^{(b-bp-1)\frac{p+1}{p+2}} \tag{22}$$

Putting b=1/3 for high Schmidt numbers, (Trinh, 2010b) and p=1/7 (Blasius, 1913) gives;

$$St = \frac{f}{2} Pr^{-0.63} \tag{23}$$

The study of heat and mass transfer in turbulent flows has been heavily influenced by the formulation of an analogy with the better known law for momentum transfer by Colburn. Thus, analogy proposed in this project is developed in the similar manner as Colburn analogy.

2.3 CONVENTIONAL HEAT TRANSFER FLUIDS

Conventional heat transfer fluids such as water, oil and ethylene glycol were commonly used in heat and mass transfer experiments but their applications are limited due to the poor capabilities in term of thermal properties. They also exhibit poor heat transfer performance and therefore high compactness and effectiveness of heat transfer systems are necessary to achieve the required heat transfer. In the past years, many different techniques were utilized to improve the heat transfer rate for these conventional heat transfer fluids in order to reach a satisfactory level of thermal efficiency. However, the heat transfer rate can passively be enhanced by changing the flow geometry, boundary conditions or by improving the thermophysical properties of the heat transfer fluids to increase the fluid thermal conductivity. However, there is one way to enhance the thermal conductivity which is by adding small size solid particles in the fluid. According to the past research conducted by J.C. Maxwell, thermal conductivity of a solid-liquid mixture can be increased by using more volume fraction of solid particles. In the experiment, particles of micrometer or millimeter-sized dimensions were used. The results showed some enhancement but at the same time those particles were found out to be the cause of numerous problems, such as abrasion, clogging, high pressure drop and poor suspension stability. Therefore, a new advanced fluid is engineered to improve the thermal conductivity instead of avoiding adverse effects due to the presence of particles.

2.4 FUNDAMENTALS OF NANOFLUIDS

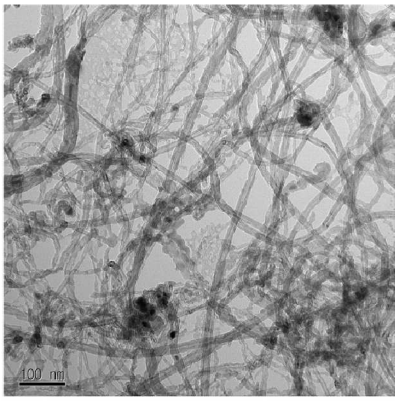
2.4.1 Introduction to Nanofluids

Heat transfer is one of the most important processes in many industrial and consumer products. However, due to the poor thermal conductivity of conventional heat transfer fluid such as water, oil and ethylene glycol, heat transfer process had achieved it limitation. Thus, scientists and engineers have worked very hard for more than a century and showed great efforts in order to break this fundamental limit. This has led to the founding of nanofluids, a brand new heat transfer fluid produced by dispersing nanometer-sized particle in liquids to enhance the heat transfer.

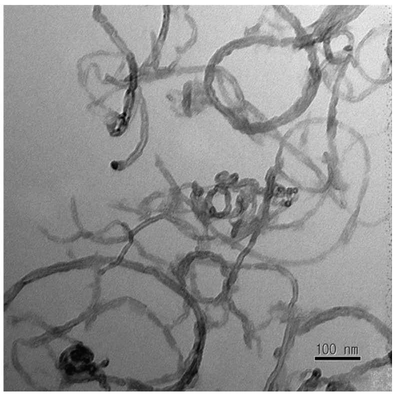
The development of nanofluids is the solution for changing the flow geometry or enhancing the thermal conductivity of the fluid. Previously, various techniques have been proposed to enhance the heat transfer performance of fluids. Based on the previous experiments, researchers have tried to increase the thermal conductivity of base fluids by suspending micro or larger-sized solid particles in fluids. This is because thermal conductivity of solid is typically higher than the liquid. Various theoretical and experimental studies of suspensions containing solid particles have been conducted since Maxwell's theoretical work was published more than 100 years ago but due to the large size and high density of the particles, there is no proper way to prevent the solid particles from settling out of suspension. However, this problem was solved when nanofluids was discovered.

Nanofluids can be considered to be the next-generation heat transfer fluids as they offer new possibilities in enhancing heat transfer performance compared to pure fluids. They are expected to have ultimate thermal properties compared to other conventional heat transfer fluids and fluids containing micro-sized metallic particles.

Larger surface area of nanoparticles will not only significantly improve the heat transfer capabilities but also increase the stability of the suspensions. Besides, nanofluids also improve the abrasion-related properties. Successful researches on nanofluids results in designing smaller and lighter heat exchanger systems. However, the development of nanofluids is still hindered by several factors such as the lack of agreement between results, poor characterization of suspensions and the lack of theoretical understanding of the mechanisms.



(a)



(b)

Figure 2.1: Microscopic images of CNTs sampled from a) PCNT nanofluids and b) TCNT nanofluids

Source: Ko *et al*, 2007

The employment of nanoparticles in base fluids can alter the fluid flow and heat transfer characteristics of the base fluids. Necessary studies need to be carried out before wide application can be found for nanofluids. Figure 2.1 shows microscopic images of CNTs at 50 ppm concentration.

2.4.2 Thermal Conductivity of Nanofluids

In order to develop the efficient heat transfer fluids, the thermal conductivity of heat transfer fluid plays a crucial role. However, conventional heat transfer fluids such as water, oil and ethylene glycol have inherently poor thermal conductivities which led to the discovery of nanofluids, an advanced heat transfer fluid with significantly higher thermal conductivity to replace presently available heat transfer fluids. Thermal conductivity of various materials is presented in Table 2.1.

Table 2.1: Thermal conductivity of various materials

	Material	**Thermal Conductivity (W/m. K)**
Metallic solids	Silver	429
	Copper	401
	Aluminum	237
Nonmetallic solids	Diamond	3300
	Carbon nanotubes	3000
	Silicone	148
	Alumina	40
	Sodium at 644K	72.3
Nonmetallic liquids	Water	0.613
	Ethylene glycol	0.253
	Engine oil	0.145

Source: Choi *et al*, 2008

2.4.3 Thermal Conductivity of Carbon Nanotubes

Carbon nanotubes are categorized as nonmetallic solid and their high thermal conductivities in heat transfer processes instead of their low densities compared to metals has made them an attractive material to produce nanofluids. Stephen U. S. Choi and his team were the first to disperse multi-walled carbon nanotubes (MWNTs) into a host material, synthetic poly (α-olefin) oil by the two-step method and measured the effective thermal conductivity of nanotubes-in-oil suspensions. From the experiment, they discovered that nanotubes produce an anomalously large increase in thermal conductivity (up to a 150% increase in the conductivity of oil at approximately 1 volume% nanotubes), which is by far the highest thermal conductivity enhancement ever achieved in a liquid. This measured increase in thermal conductivity of nanotube nanofluids is an order of magnitude higher than that predicted using existing theories.

However, the experimental results also showed another anomaly. The measured thermal conductivity is nonlinear with nanotube loadings, while all theoretical predictions clearly show a linear relationship. This nonlinear behavior as shown in Figure 2.2 is not expected in conventional fluid suspensions of micrometer-sized particles at such low concentrations. Interestingly, similar results have been reported for polymer–nanotube composites. Thus, there could be some common enhancement mechanism between these two dispersions of carbon nanotubes, one in liquids and the other in polymers.

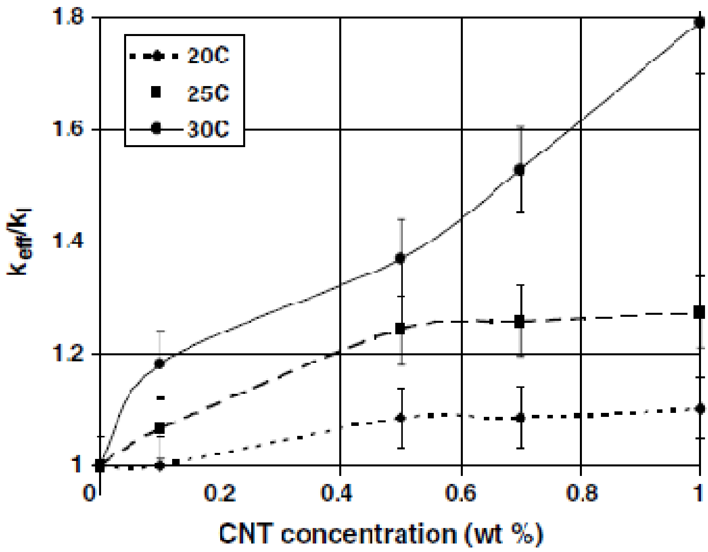


Figure 2.2: Measured value of thermal conductivity of CNT nanofluids with different volume concentration with respect to water

Source: Ding *et al*, 2005

2.4.4 Thermal Conductivity Equations

From Kamali's paper, the equation of thermal conductivity is given by;

$$k = a + bT + cT^2 + dT^3$$

where T is temperature in Kelvin (K), a = -287.6, b = 3.022, c = 0.010557 and d = 1.22885×10^{-5}.

The result of experiment on thermal conductivity from R. Kamali is presented in Figure 2.3.

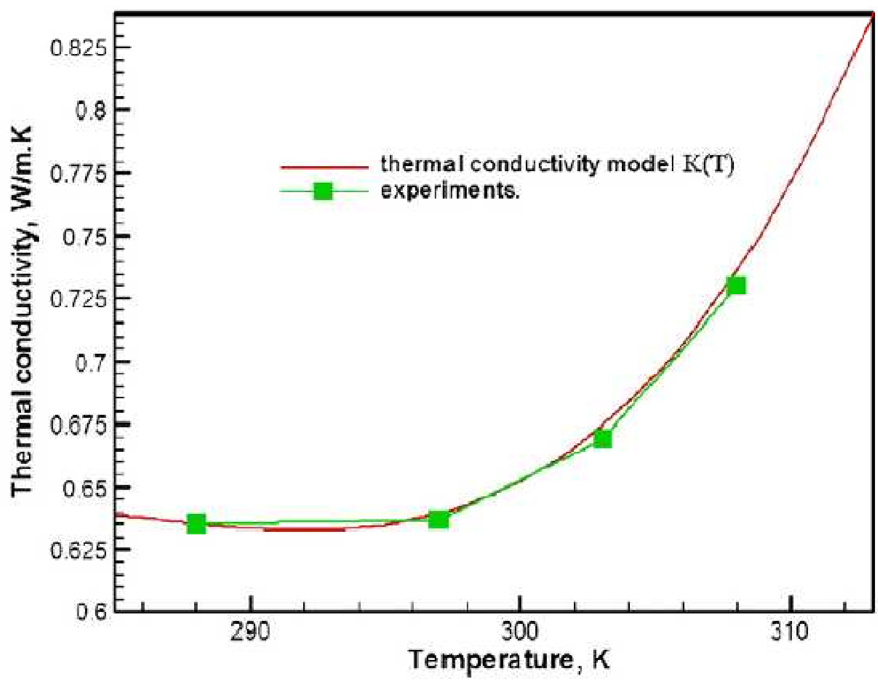


Figure 2.3: 1% MWCNT nanofluid thermal conductivity experimental data and third order polynomial fitting curve

Source: Kamali *et al*, 2010

Other than that, equation of thermal conductivity is also available from Sharma which given by;

$$\frac{k_{nf}}{k_w} = 0.9808 + 0.0142\emptyset + 0.2718\left(\frac{T_{nf}}{70}\right) - 0.1020\left(\frac{d_p}{150}\right)$$

where;

T_{nf} = temperature of nanofluids

d_p = diameter of particle

2.4.5 Preparation of Nanofluids

Preparation of nanofluids is the first key step in experimental studies on nanofluids. Nanofluids are not simply liquid-solid mixtures. Some special requirements are essential such as even and stable suspension, durable suspension, negligible agglomeration of particles and no chemical change of the fluid. Nanofluids are produced by dispersing nanometer-scale solid particles into base liquids such as water, ethylene glycol and oils. In the synthesis of nanofluids, agglomeration is a major problem. There are mainly two techniques used to produce nanofluids which are the single-step and the two-step method. The single-step direct evaporation approach is called the Vacuum Evaporation onto a Running Oil Substrate (VEROS) technique. This method was supposed to produce nanoparticles, but it is difficult to subsequently separate the particles from the fluids to produce dry nanoparticles.

Then a modified VEROS process was proposed and they employed high pressure magnetron sputtering for the preparation of suspensions with metal nanoparticles such as Ag and Fe. The modified VEROS technique had been developed in which Cu vapor is directly condensed into nanoparticles by contact with a flowing low-vapor-pressure liquid. Other researchers also had presented a novel one-step chemical method for preparing copper nanofluids by reducing CuSO4·5H2O with NaH2PO2·H2O in ethylene glycol under microwave irradiation. Results showed that the addition of NaH2PO2·H2O and the adoption of microwave irradiation are two significant factors which affect the reaction rate and the properties of copper nanofluids.

Another method which is Submerged Arc Nanoparticle Synthesis System (SANSS) method has been employed to prepare copper-based nanofluids with different dielectric liquids such as deionized water with 30%, 50%, 70% volume solutions of ethylene glycol and pure ethylene glycol. CuO, Cu2O, and Cu based nanofluids also can be prepared efficiently by this technique. The advantage of the one-step technique is that the nanoparticle agglomeration can be minimized while the disadvantage is that only low vapor pressure fluids are compatible with such a process.

The two-step method is extensively used in the synthesis of nanofluids due to the supply availability of nanopowders by several companies. In this method, nanoparticles were first produced and then dispersed in the base fluids. Generally, ultrasonic equipment is used to intensively disperse the particles and reduce the agglomeration of particles. Other nanoparticles reported to have produced by this method are gold (Au), silver (Ag), silica and carbon nanotubes. By comparing to the single-step method, the two-step technique works well for oxide nanoparticles but it is not quite successful with metallic particles. Except for the use of ultrasonic equipment, some other techniques such as control of pH or addition of surface active agents are also used to attain stability of the suspension of the nanofluids against sedimentation. These methods actually change the surface properties of the suspended particles and thus suppress the tendency to form particle clusters. It should be noted that the selection of surfactants should depend mainly on the properties of the solutions and particles. For example, salt and oleic acid are used as the dispersant to enhance the stability of transformer oil–Cu and water–Cu nanofluids, respectively. Oleic acid and cetyltrimethylammoniumbromide (CTAB) surfactants were used to ensure better stability and proper dispersion of TiO2–water nanofluids.

In general, methods such as change of pH value, addition of dispersant and ultrasonic vibration aim at changing the surface properties of suspended particles and suppressing formation of particles cluster to obtain stable suspensions. However, the addition of dispersants can affect the heat transfer performance of the nanofluids especially at high temperature.

2.5 FUNDAMENTALS OF CONVECTIVE HEAT TRANSFER

2.5.1 Turbulent Flow

Turbulent flow is one of the most complex phenomena in fluid mechanics. When the inertial forces are much higher than the viscous forces, flow does not remain in the form of undisturbed layers but starts fluctuating about the mean value. The mean flow may be steady or time dependent.

2.5.2 Flow inside Tube

Flow and heat transfer for a fluid flowing inside a tube is of special importance in cooling applications. Inside the tube a special case occurs. The boundary layers emerging from all the sides (both hydrodynamic and thermal boundary layers) merge and fill the entire tube. From that time the velocity profile remains unchanged and is called a fully developed flow. The region prior to this is called the entry length or developing flow region. Hence, in pipe flow, laminar flow remains laminar throughout the pipe and turbulent flow remains turbulent as shown in Figure 2.4.

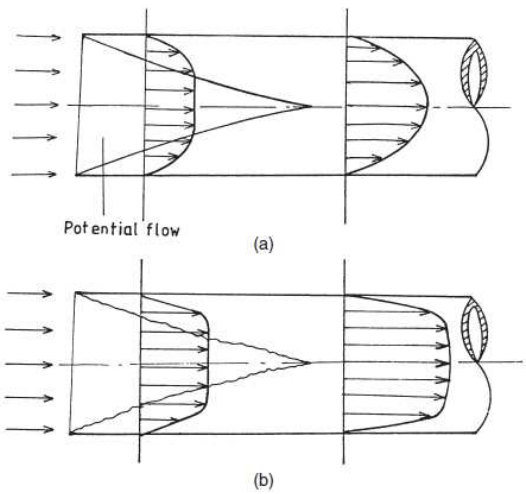


Figure 2.4: Flow development in pipe: (a) laminar, (b) turbulent

Source: Choi *et al*, 2008

The thermal boundary layer developed is not the same as the hydrodynamic boundary layer. Hence, the temperature profile changes continuously, due to heat transfer. Thus, flow inside a tube is called thermally developed if the dimensionless temperature (Θ) profile remains unchanged, where;

$$\frac{T_w - T}{T_w - T_m}$$

The mean temperature at a particular section is given by;

$$T_m = \int_A \frac{\rho u C_p T \, dA}{m C_p}$$

where *m* is the mass flow rate of the fluid.

The real and dimensionless temperatures for flow inside a tube with a wall at a higher temperature are shown in Figure 2.5.

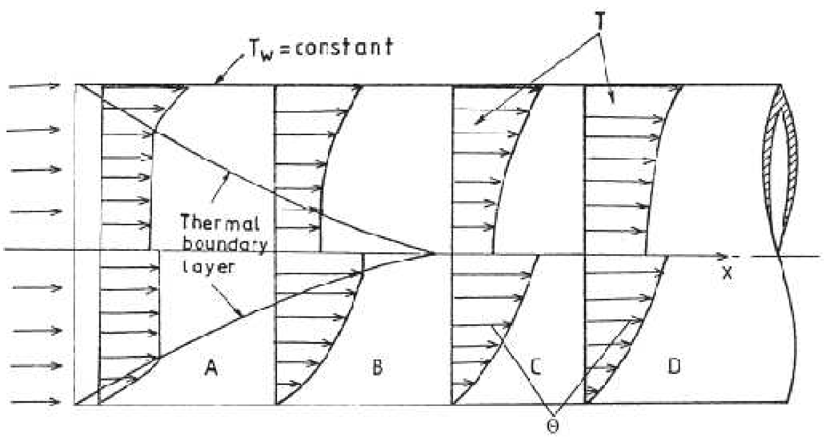


Figure 2.5: The development of thermal boundary layer

Source: Choi *et al*, 2008

2.5.3 Forced Convection Heat Transfer of Nanofluids

The increases in effective thermal conductivity are very important to improve the heat transfer behavior of fluids. However, other variables also play key roles. The heat transfer coefficient for forced convection in tubes depends on many physical quantities related to the fluid or the geometry of the system through which the fluid is flowing. These quantities include intrinsic properties of the fluid such as its thermal conductivity, specific heat, density, and viscosity, along with extrinsic system parameters such as tube diameter and length and average fluid velocity. Therefore, it is essential to measure the heat transfer performance of nanofluids directly under flow conditions.

From previous experiments, scientists have shown that nanofluids have not only better heat conductivity but also greater convective heat transfer capability than that of base fluids. Experimental results showed unexpectedly that the heat transfer coefficients of nanofluids are much better than expected from enhanced thermal conductivity alone in both laminar and turbulent flow. However, for natural convection, nanofluids have lower heat transfer than that of base fluids.

In other experiment, forced convective heat transfer is investigated using aqueous and ethylene glycol-based spherical titania nanofluids, and aqueous-based titanate nanotubes, carbon nanotubes and nano-diamond nanofluids. These nanofluids are formulated from dry nanoparticles and pure base liquids to eliminate complications due to unknown solution chemistry. All the formulated nanofluids show a higher effective thermal conductivity than that predicted by the conventional theories. All other nanofluids are found to be non-Newtonian except for the ethylene glycol-based titania nanofluids. For aqueous-based titania and carbon and titanate nanotube nanofluids, the convective heat transfer coefficient enhancement exceeds, by a large margin, the extent of the thermal conduction enhancement. However, deterioration of the convective heat transfer is observed for ethylene glycol-based titania nanofluids at low Reynolds numbers and aqueous-based nano-diamond nanofluids. Possible mechanisms for the observed controversy are discussed from both microscopic and macroscopic viewpoints. The competing effects of particle migration on the thermal boundary layer thickness and that on the effective thermal conductivity are suggested to be responsible for the experimental observations.

Conventional heat transfer fluid such as water or ethylene glycol generally has poor thermal properties. Thus, many efforts for dispersing small particles with high thermal conductivity in the liquid coolant have been conducted to enhance thermal properties of the conventional heat transfer fluids. The early research, which used suspension and dispersion of micrometer-sized particles, faced major problem of poor suspension stability. Thus, a new class of fluid for improving both thermal conductivity and suspension stability is required in the various industrial fields. This motivation leads to development of nanofluids. Nanofluids are new kind of fluid consisting of uniformly dispersed and suspended nanometer-sized particles or fibers in fluids and have unprecedented thermal characteristics.

Since the discovery of attractive features of nanofluids such as the anomalously high thermal conductivity at very low nanoparticles concentration and the considerable enhancement of forced convective heat transfer. One of particular interests in convective heat transfer of nanofluids is that the increment of convective heat transfer coefficient is generally higher than that of effective thermal conductivity and moreover the exact mechanism of convective heat transfer enhancement of nanofluids has not been explained in detail, although it becomes well known that the enhancement of thermal conductivity of nanofluids is due to Brownian motion of nanoparticles suspended in fluid.

Previous investigations on the convective heat transfer enhancement of nanofluids have been reported that the convective heat transfer coefficient and the Nusselt number of nanofluids increase with the Reynolds number and the volume fraction of nanoparticles under turbulent flow. Compared with water, the Nusselt number of the nanofluids with a 2.0 vol% of Cu nanoparticles is more increased than 39%. It is shown that the enhancement increases with the Reynolds number as well as the volume concentration of nanoparticle.

However, study on fully developed laminar flow is more important for understanding the physical phenomena than any other regime because the boundary layer does not grow any longer, and velocity and dimensionless temperature profiles do not change with axial distance under fully developed laminar flow.

2.5.4 Viscosity Variation in Nanofluids

Convective heat transfer is closely related to the viscosity of suspensions and hence in many of these studies the viscosity variation is discussed before taking up convective issues. Figure 2.6 presents the viscosity of CNTs containing nanofluids.

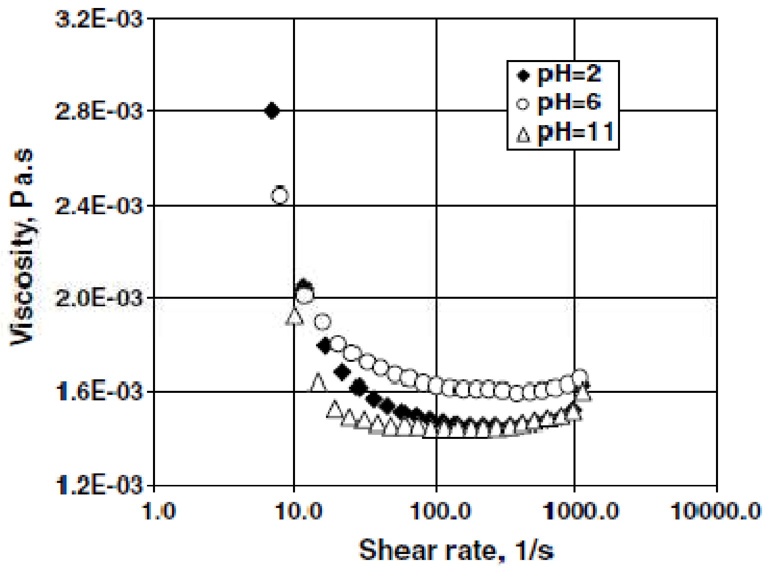


Figure 2.6: Viscosity of CNT–water solution (25°C)

Source: Ding *et al*, 2005

Carbon nanotubes (CNTs) containing nanofluids behave quite differently not only with respect to thermal conductivity but also with respect to viscosity. The study by Yulong Ding and his team on aqueous CNTs containing nanofluids showed interesting the linear shear thinning behavior of the nanofluid at lower shear rates. Since they used gum arabic as the stabilizing agent, they also measured the viscosity of the base water with gum arabic, which showed nonlinear behavior different from that of CNT–water nanofluid as shown in Figure 2.6.

2.5.5 Significant Increase in the Turbulent Heat Transfer Coefficient

Based on past experimental results, it is known that nanofluids exhibit such a significant increase in the turbulent heat transfer coefficient. It is found that at fixed velocities, the heat transfer coefficient of nanofluids containing 2% concentration of Cu nanoparticles was improved by as much as 40% compared to that of water. The Dittus–Boelter correlation failed to predict the improved experimental heat transfer behavior of nanofluids. Another study also showed that the effect of particle size and shape and dispersion becomes predominant in enhancing heat transfer in nanofluids. Even greater heat transfer effects are expected for nanofluids produced by the one-step process. Therefore, there is great potential to develop ultra-energy-efficient heat transfer fluids by choosing the nanoparticle material as well as by controlling particle size, shape, and dispersion.

2.6 THE ENHANCEMENT OF HEAT TRANSFER BY NANOFLUIDS

A substantial increase in liquid thermal conductivity, liquid viscosity, and heat transfer coefficient are the unique features of nanofluids. A colloidal mixture of nano-sized particles in a base fluid called nanofluids, tremendously enhances the heat transfer characteristics of the original fluid and suited ideally for practical applications due to its unique characteristics. There are many unique features of nanofluids, such as enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Brownian motion and thermophoresis.

Enhancement of convective heat transfer and thermal conductivity of liquids was earlier made possible by mixing micro-sized particles with a base fluid. However, rapid sedimentation, erosion, clogging and high-pressure drop caused by these particles has kept the technology far from practical use. A very small amount of nanoparticles, when dispersed uniformly and suspended stably in base fluids, can provide impressive improvements in the thermal properties of base fluids. Nanofluids, which are a colloidal mixture of nanoparticles (1– 100 nm) and a base liquid (nanoparticle fluid suspensions) is the term coined to describe the new class of nanotechnology based heat transfer fluids that exhibit thermal properties superior to those of their base fluids or conventional particle fluid suspensions. The phases in the colloid are distinguishable and interact through weak surface molecular forces, preferably without any chemical reaction. Compared to micro-sized particles, nanoparticles are engineered to have larger relative surface areas, less particle momentum, high mobility, better suspension stability than micro-sized particles and importantly increase the thermal conductivity of the mixture.

This makes the nanofluids a promising working medium as coolants, lubricants, hydraulic fluids and metal cutting fluids. Further, a negligible pressure drop and mechanical abrasion makes researchers subscribe to nanofluids for the development of the next generation miniaturized heat exchangers. Based on their application, nanoparticles have been made of various materials such as oxide ceramics, nitride ceramics, carbide ceramics, metals, semiconductors, carbon nanotubes and composite materials such as alloyed nanoparticles Al70Cu30 or nanoparticle core–polymer shell composites. In addition to nonmetallic, metallic, and other materials for nanoparticles, completely new materials and structures have been used, such as materials ‘‘doped’’ with molecules in their solid–liquid. The goal of nanofluids is to achieve the best possible thermal properties at the least possible volume fraction ($w < 1\%$) in the base fluids. Thus, the suspension of nearly non-agglomerated or mono-dispersed nanoparticles in liquids is the key to significant enhancement in the heat transfer.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

The heat transfer coefficient of nanofluids can be estimated by making use of Colburn analogy. Nanofluids behave like a single phase fluids in low volume concentration. The idea is to come out with an analogy for nanofluids by making use of Colburn analogy and modify it to estimate the heat transfer coefficient of nanofluids. In this chapter, all the procedures and methods used to develop the regression equation is discussed. The equation is developed in the same manner as Colburn analogy.

The methodology of this project is illustrated in a flow chart shown in Figure 3.1 for better understanding. The schematic diagram is very important to ensure the whole process is in the right track instead providing clear picture to readers on what this project is all about. Chronologically, the title of this project was studied and then scopes and objectives were identified. The next process was collecting as many experimental data on nanofluids from past researches such as journals, reference books, related articles and the internet. After that, the thermophysical properties of the nanofluids need to be determined but due to the lack of data from past researches in literature, some of the parameters were obtained numerically. Finally, the experimental data on nanofluids were analyzed by making use of Colburn analogy. Then, by using FORTRAN compiler, it was then modified to suit nanofluids behavior. As the result, the new regression equation based on Colburn analogy was developed. However, the regression equation need to be compared its validity with existing equation available in literature.

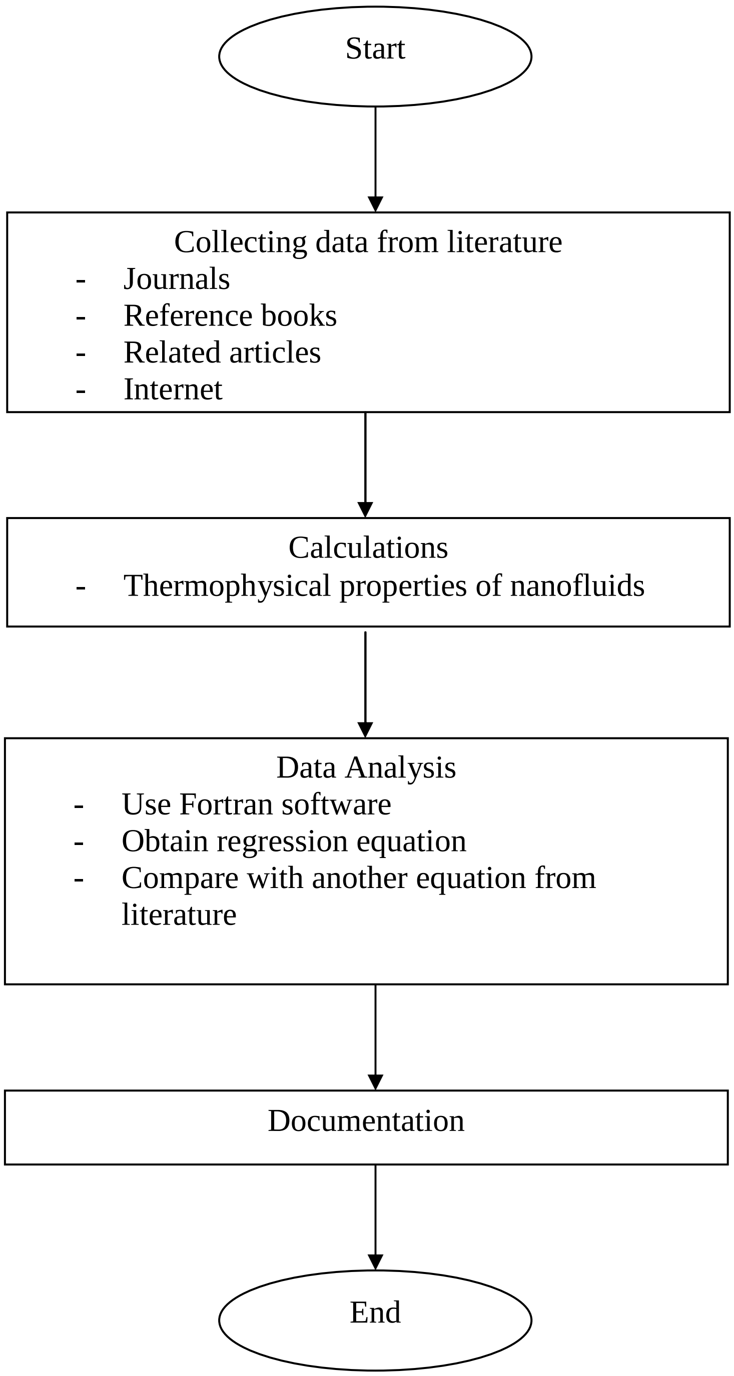


Figure 3.1 Flow chart

3.2 COLLECTING DATA

In order to achieve the objective of this project, experimental data must be collected from any reliable sources such as journals, articles and reference books. The data is based on the parameters which frequently used in heat transfer process such as Reynolds number, Nusselt number, friction factor, density, mass and others. All the information then gathered together and categorized under its particular category so that the whole data can be managed systematically. The quality of the data is determined from where it was taken from and this is very important in order to obtain excellent results.

There are two types of data which are theoretical and experimental data. However, the type of data collected for this project is taken from the experimental data which had been taken from literature. The data in literature was presented mostly in form of graph, thus computer software DigitizeIt was used to take all corresponding data tabulated in those figures from literature.

3.3 CALCULATIONS

3.3.1 Thermophysical Properties of Nanofluids

Thermophysical properties such as density, thermal conductivity and specific heat of nanofluids available in literature can be taken directly but according to some particular journals, the experimental data is presented in form of equations. Thus, calculation procedure is necessary to obtain the particular properties. For example, the density of nanofluids can be calculated using the equation summarized by Buongiorno.

The density of nanofluids is given by;

$$\rho_{nf} = \emptyset\rho_p + (1 - \emptyset\ )\ \rho_{bf}$$

where;

$\emptyset$ = volume fraction of base fluid

ρ_p = density of nanoparticle

ρ_{bf} = density of base fluid

Specific heat of nanofluids;

$$C_{p,nf} \frac{= \emptyset\rho_p c_p + (1-\emptyset)\rho_{bf}c_{bf}}{\rho_{nf}}$$

where;

$\emptyset$ = volume fraction of nanofluid

ρ_p = density of nanoparticle

ρ_{bf} = density of base fluid

c_{bf} = specific heat of base fluid

ρ_{nf} = density of nanofluid

The nanofluids used in this project are treated carbon nanotubes (TCNTs) which had undergone acid treatment and pristine carbon nanotubes (PCNTs) produced by surfactant. Information such as the density and specific heat of both particle and base fluid at particular temperature are essential in order to determine the thermophysical properties. For example, the particle density of CNTs is 2.1 g/cm^3, density of base fluid is 997.0479 kg/m^3 and the specific heat is 4181.3 J/kg.K at 25°C. The viscosity of the nanofluids for TCNT with 0.14% concentration is 2x10^3 Pa.s.

Prandtl number is a dimensionless number used in the study of diffusion in flowing systems which approximating the ratio of kinematic viscosity and thermal diffusivity. In this project, Prandtl number is determined in order to obtain the heat transfer coefficient but several parameters need to be determined first which are thermal conductivity and diameter of the particle. These two parameters were used to estimate the thermal conductivity so that Prandtl number can be calculated.

The equation of thermal conductivity is written as followed;

$$\frac{k_{nf}}{k_{bf}} = 0.9809 + 0.0142\emptyset + 0.2718\left(\frac{T_{nf}}{70}\right) - 0.1020\left(\frac{d_{np}}{150}\right)$$

where;

k_{nf} = thermal conductivity of nanofluid

k_{bf} = thermal conductivity of base fluid

$\emptyset$ = volume fraction of nanofluid

T_{nf} = temperature of nanofluid

d_{np} = diameter of nanoparticle

The formula of Prandtl number is given by;

$$Pr = \frac{c_p \mu}{k}$$

where;

Pr = Prandtl number

c_p = specific heat

μ = viscosity

k = thermal conductivity

3.4 THE DEVELOPMENT OF THE ANALOGY

3.4.1 FORTRAN Software

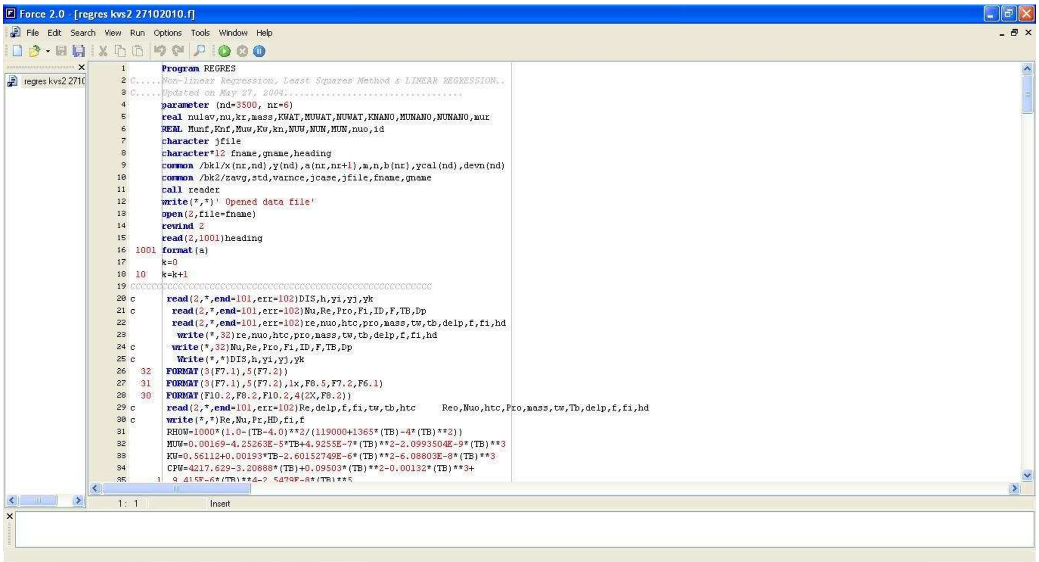
The development of the regression equation by making use of Colburn analogy involved mathematical procedure on principle of heat transfer process inside tubes for turbulent flow. The particular procedure is very complicated because every aspect in heat transfer process such as the velocity and temperature profiles which involved the used of log-law and power law need to be considered. Those are just a few terms out of many other terms that need to be considered in order to develop the regression equation and since the procedure involved a lot of mathematical problem, the use of FORTRAN compiler really helps a lot in this project. Constants obtained by using FORTRAN were then structured to develop the equation.

3.4.2 Equations from Literature

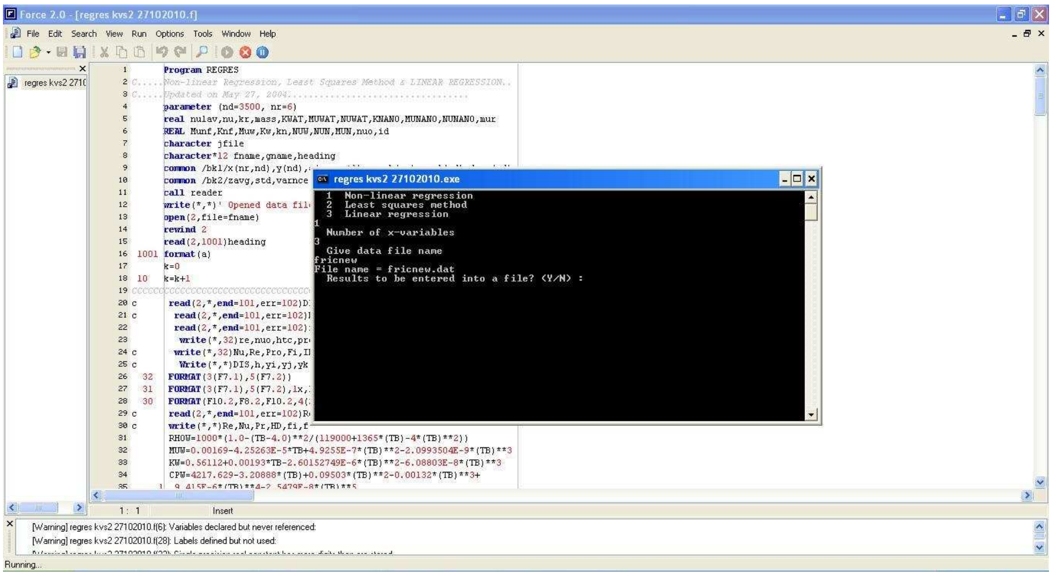
Suitable equations regarding CNTs nanofluids in literature were collected and identified in order to develop the regression equation. The equations were then written in a coding form of FORTRAN so that the program is able to read the equations and do the calculation without errors. List of the equations is presented in Appendix E.

3.4.3 Writing the Programming Language of FORTRAN

In order to develop the regression equation, a set of coding is needed which describes on how the program will be running. It is to be noted that equations stated in Appendix E were included in the coding so that the program will come out with the constants corresponding to the equations. The constants were then used to structure the new regression equation. Figure 3.2 shows the interface of FORTRAN.



(a)

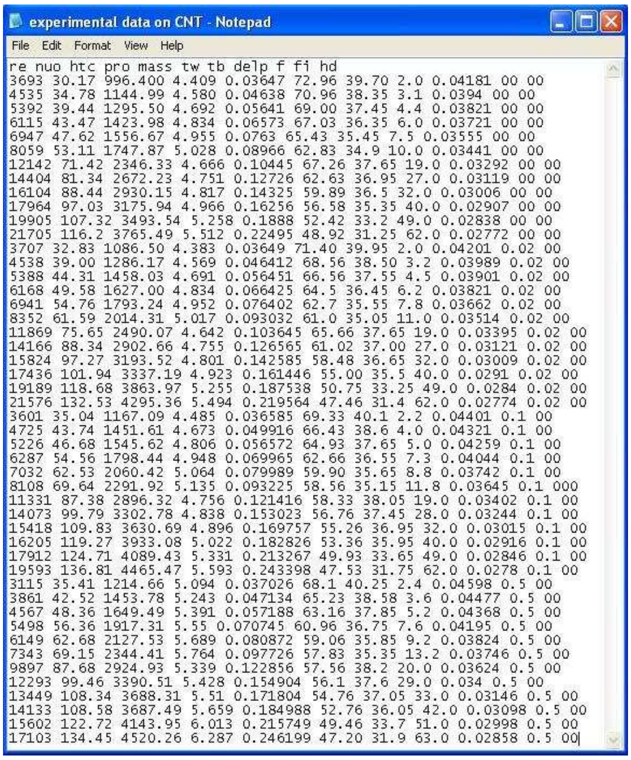


(b)

Figure 3.2: FORTRAN interface (a) with coding (b) when the program runs

3.4.4 Data File

The data file consists of thermophysical properties of nanofluids and water. According to the program, the file name of the data file is required. The computer then read the data file and does the calculation as programmed in FORTRAN to obtain the particular constants. The regression equation is structured based on the constants obtained. Figure 3.3 shows the CNTs data file.



experimental data on CNT - Notepad

File Edit Format View Help

```
re nuo htc pro mass tw tb delp f fi hd
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4535 34.78 1144.99 4.580 0.04638 70.96 38.35 3.1 0.0394 00 00
5392 39.44 1295.50 4.692 0.05641 69.00 37.45 4.4 0.03821 00 00
6115 43.47 1423.98 4.834 0.06573 67.03 36.35 6.0 0.03721 00 00
6947 47.62 1556.67 4.955 0.0763 65.43 35.45 7.5 0.03555 00 00
8059 53.11 1747.87 5.028 0.08966 62.83 34.9 10.0 0.03441 00 00
12142 71.42 2346.33 4.666 0.10445 67.26 37.65 19.0 0.03292 00 00
14404 81.34 2672.23 4.751 0.12726 62.63 36.95 27.0 0.03119 00 00
16104 88.44 2930.15 4.817 0.14325 59.89 36.5 32.0 0.03006 00 00
17964 97.03 3175.94 4.966 0.16256 56.58 35.35 40.0 0.02907 00 00
19905 107.32 3493.54 5.258 0.1888 52.42 33.2 49.0 0.02838 00 00
21705 116.2 3765.49 5.512 0.22495 48.92 31.25 62.0 0.02772 00 00
3707 32.83 1086.50 4.383 0.03649 71.40 39.95 2.0 0.04201 0.02 00
4538 39.00 1286.17 4.569 0.046412 68.56 38.50 3.2 0.03989 0.02 00
5388 44.31 1458.03 4.691 0.056451 66.56 37.55 4.5 0.03901 0.02 00
6168 49.58 1627.00 4.834 0.066425 64.5 36.45 6.2 0.03821 0.02 00
6941 54.76 1793.24 4.952 0.076402 62.7 35.55 7.8 0.03662 0.02 00
8352 61.59 2014.31 5.017 0.093032 61.0 35.05 11.0 0.03514 0.02 00
11869 75.65 2490.07 4.642 0.103645 65.66 37.65 19.0 0.03395 0.02 00
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15824 97.27 3193.52 4.801 0.142585 58.48 36.65 32.0 0.03009 0.02 00
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19189 118.68 3863.97 5.255 0.187538 50.75 33.25 49.0 0.0284 0.02 00
21576 132.53 4295.36 5.494 0.219564 47.46 31.4 62.0 0.02774 0.02 00
3601 35.04 1167.09 4.485 0.036585 69.33 40.1 2.2 0.04401 0.1 00
4725 43.74 1451.61 4.673 0.049916 66.43 38.6 4.0 0.04321 0.1 00
5226 46.68 1545.62 4.806 0.056572 64.93 37.65 5.0 0.04259 0.1 00
6287 54.56 1798.44 4.948 0.069965 62.66 36.55 7.3 0.04044 0.1 00
7032 62.53 2060.42 5.064 0.079989 59.90 35.65 8.8 0.03742 0.1 00
8108 69.64 2291.92 5.135 0.093225 58.56 35.15 11.8 0.03645 0.1 000
11331 87.38 2896.32 4.756 0.121416 58.33 38.05 19.0 0.03402 0.1 00
14073 99.79 3302.78 4.838 0.153023 56.76 37.45 28.0 0.03244 0.1 00
15418 109.83 3630.69 4.896 0.169757 55.26 36.95 32.0 0.03015 0.1 00
16205 119.27 3933.08 5.022 0.182826 53.36 35.95 40.0 0.02916 0.1 00
17912 124.71 4089.43 5.331 0.213267 49.93 33.65 49.0 0.02846 0.1 00
19593 136.81 4465.47 5.593 0.243398 47.53 31.75 62.0 0.0278 0.1 00
3115 35.41 1214.66 5.094 0.037026 68.1 40.25 2.4 0.04598 0.5 00
3861 42.52 1453.78 5.243 0.047134 65.23 38.58 3.6 0.04477 0.5 00
4567 48.36 1649.49 5.391 0.057188 63.16 37.85 5.2 0.04368 0.5 00
5498 56.36 1917.31 5.55 0.070745 60.96 36.75 7.6 0.04195 0.5 00
6149 62.68 2127.53 5.689 0.080872 59.06 35.85 9.2 0.03824 0.5 00
7343 69.15 2344.41 5.764 0.097726 57.83 35.35 13.2 0.03746 0.5 00
9897 87.68 2924.93 5.339 0.122856 57.56 38.2 20.0 0.03624 0.5 00
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15602 122.72 4143.95 6.013 0.215749 49.46 33.7 51.0 0.02998 0.5 00
17103 134.45 4520.26 6.287 0.246199 47.20 31.9 63.0 0.02858 0.5 00
```

Figure 3.3: CNTs data file

3.5 COMPARISON WITH THE EQUATION FROM LITERATURE

The main objective of this project is to develop the regression equation in the similar manner as Colburn analogy. The equation should be valid for both water and nanofluids for estimation of Nusselt number. In order to achieve that, the regression equation needs to be compared with the equation from literature to ensure its validity.

3.5.1 The Gnielinski Equation

Gnielinski equation from literature is compared with the new regression equation developed using FORTRAN. The comparison is definitely in term of estimation of Nusselt number for pure water. Experimental data of pure water in terms of friction factor and Reynolds number obtained from literature were used to calculate the Nusselt number using Gnielinski and the regression equation. It is to be noted that the experimental data was based on the turbulent flow inside a plain tube. A graph of Nusselt number versus Reynolds number then was drawn to compare both equations.

For internal turbulent flow, the Gnielinski equation is given by;

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{2/3} - 1\right)}$$

where $f = (0.79 \ln Re - 1.64)^{-2}$ valid in the range $3000 < Re < 5x10^6$ and $0.5 < Pr < 2000$

3.5.2 The Thermal Conductivity Equations

From Kamali's paper, the equation of thermal conductivity is given by;

$$k = a + bT + cT^2 + dT^3$$

where T is temperature in Kelvin (K), a = -287.6, b = 3.022, c = 0.010557 and d = $1.22885x10^{-5}$.

Other than that, equation of thermal conductivity is also available from Sharma which is given by;

$$\frac{k_{nf}}{k_w} = 0.9808 + 0.0142\emptyset + 0.2718\left(\frac{T_{nf}}{70}\right) - 0.1020\left(\frac{d_p}{150}\right)$$

where;
T_{nf} = temperature of nanofluids
d_p = diameter of particle

3.6 DETERMINATION OF HEAT TRANSFER COEFFICIENT

The regression equation developed was then used to estimate the heat transfer coefficient of water and carbon nanotubes flowing inside a tube in turbulent range by making use of Nusselt number. The equation for the determination of heat transfer coefficient is written as followed;

$$h = \frac{Nu.k}{d}$$

where;

Nu = Nusselt number

k = thermal conductivity

d = diameter of the tube

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

The purpose of this chapter is to provide review and discussion of the results for this project. In this chapter, the equation from the literature which valid for water is compared with the new regression equation developed for CNTs nanofluid. The regression equation is developed analogically in which it is structured by making use of Colburn analogy.

4.2 EQUATIONS FOR FLOW INSIDE TUBE

4.2.1 Gnielinski Equation

For estimation of Nusselt number of a single phase fluid, the equation for internal turbulent flow is written as followed;

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{2/3} - 1\right)}$$

where $f = (0.79 \ln Re - 1.64)^{-2}$ valid in the range $3000 < Re < 5x10^{6}$ and $0.5 < Pr < 2000$

4.2.2 The Colburn Analogy

For a single-phase fluid, the Colburn analogy is written as follows;

For external flow,

$$St.Pr^{2/3} = \frac{C_d}{2}$$

For internal flow,

$$St.Pr^{2/3} = \frac{f}{8}$$

4.2.3 The Regression Equation

The regression equation is the equation developed in the similar manner as Colburn analogy. However the existing Colburn analogy is only valid for pure water but not nanofluids. Thus, in this section the regression equation is developed which is not only valid for pure water but nanofluids also. Then, the regression equation is compared with the Gnielinski equation from literature.

The regression equation is to be written as followed;

$$Nu_{Reg} = \left(\frac{f}{8}\right)(1 + \emptyset^{*}Pr_{nf})^{0.1083}RePr_{w}^{1/3}$$

with average deviation of 6.1%, standard deviation of 7.1% and maximum deviation of 16.5% and $f = \frac{0.3164}{Re^{0.25}}$.

4.2.4 Regression Equation Similar to Dittus–Boelter Correlation

Instead of Gnielinski, Colburn and the regression equation, another equation for the estimation of Nusselt number is also available. The equation is similar to the equation proposed by Dittus-Boelter but it is to be noted that it is not an analogy equation. The regression equation is written as followed;

$$Nu = 0.0304Re^{0.7853}Pr^{0.4}(0.001 + \emptyset)^{0.01398}$$

4.3 PREDICTION OF NUSSELT NUMBER

The thermophysical properties of CNTs were estimated to determine the Nusselt number. Nusselt number is a parameter used to compare the heat transfer process between fluids, volume concentration, temperature and Prandtl number. The Nusselt number is estimated using the regression equation which is also able to predict the heat transfer coefficient of CNTs nanofluids.

Figure of comparison between water and nanofluid were presented in form of graph. It is to be noted that thermophysical properties were obtained in two ways which are numerically and directly taken from the experimental data in literature.

4.3.1 Comparison between Gnielinski Equation and Regression Equation

In order to validate the regression equation, it is compared with Gnielinski equation from literature. The comparison of Nusselt number predicted by Gnielinski equation and regression equation for pure water flowing inside a plain tube in the turbulent range is shown in the Figure 4.1.

The experimental data obtained from literature is presented in Table 4.1.

Table 4.1: Estimation of Nusselt number by Gnielinski equation and regression equation

Reynolds number, Re	Friction factor, f	Nusselt number estimation equation		Percentage of deviation (%)
		Gnielinski Equation	Regression Equation	
12600	0.0299	79.47897	74.66397	6.058205
15100	0.0285	93.46548	85.51964	8.501364
17600	0.0275	106.9893	95.93292	10.3341
20100	0.0266	120.1315	105.9815	11.77871
22000	0.0260	129.9007	113.4097	12.69506
24600	0.0253	143.0019	123.3203	13.76317
27200	0.0246	155.8303	132.9719	14.66879
29900	0.0241	168.8972	142.7534	15.4791

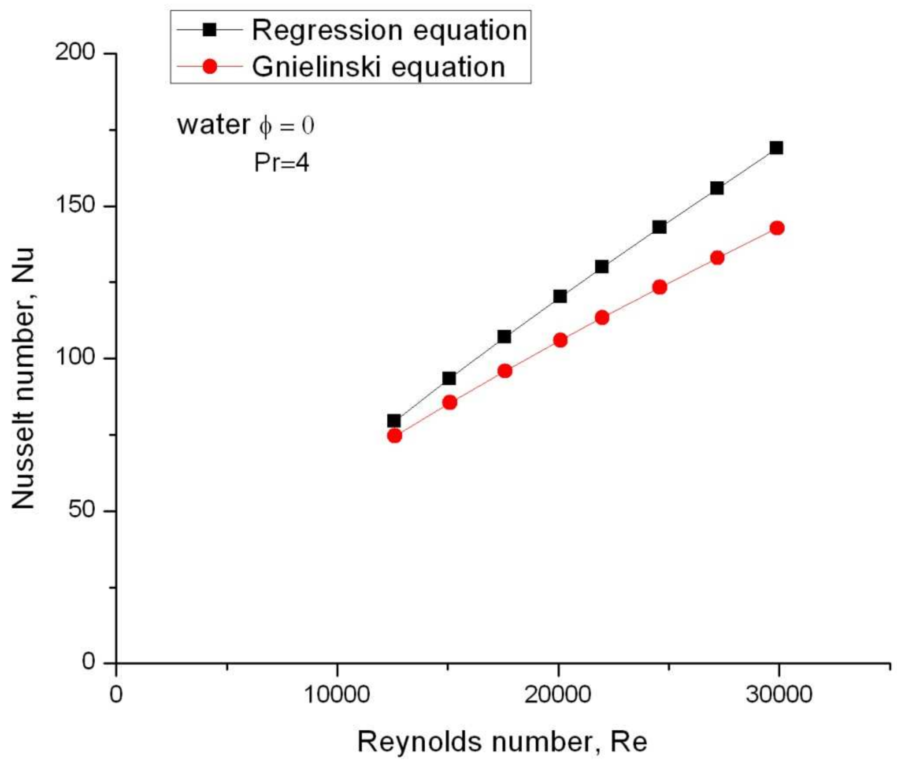

Figure 4.1: Comparison between Gnielinski equation and regression equation for water

Based on Figure 4.1, the prediction of Nusselt number using regression equation for water having the same Prandtl number shows quite similar variation to the Gnielinski equation with some enhancement in the Nusselt number. However it is to be noted that the regression equation is valid for both pure water and nanofluid at 1% concentration but for Gnielinski equation, it is limited to pure water only. Thus, the regression equation is considered valid for pure water also since it is observed that the graph shows considerable deviation of 11.66% with the Gnielinski equation in that particular turbulent range.

4.3.2 Comparison of Water and CNTs with Different Prandtl Number

Instead of developing analogical procedure to structure the regression equation, the scope of this project is also to identify the effect of Prandtl number to the heat transfer rates. The Nusselt number estimated by the regression equation with different Prandtl number is shown in Table 4.2.

Table 4.2: Estimation of Nusselt number of water and CNTs with different Prandtl number

		Water		
Reynolds number, Re	**Friction factor, f**	**Prandtl number, Pr**	**Volume concentration**	**Nusselt number, Nu**
12600	0.0299	4	0	64.22303
15100	0.0285	4	0	73.56066
17600	0.0275	4	0	82.51776
20100	0.0266	4	0	91.16118
22000	0.0260	4	0	97.55059
24600	0.0253	4	0	106.0753
27200	0.0246	4	0	114.3772
29900	0.0241	4	0	122.7909
12600	0.0299	6	0	73.51702
15100	0.0285	6	0	84.20594
17600	0.0275	6	0	94.45925
20100	0.0260	6	0	104.3535
22000	0.0253	6	0	111.6676
24600	0.0246	6	0	121.4259
27200	0.0241	6	0	130.9292
29900	0.0299	6	0	140.5605

Table 4.2: Continued

Carbon nanotubes				
Reynolds number, Re	**Friction factor, f**	**Prandtl number, Pr**	**Volume concentration**	**Nusselt number, Nu**
9880	0.0317	4	1.0	71.76435
13700	0.0292	4	1.0	91.70256
16900	0.0278	4	1.0	107.3386
20000	0.0266	4	1.0	121.7905
22900	0.0257	4	1.0	134.8086
26100	0.0249	4	1.0	148.7036
29000	0.0242	4	1.0	160.9309
31700	0.0237	4	1.0	172.0424
9880	0.0317	6	1.0	83.44497
13700	0.0292	6	1.0	106.6284
16900	0.0278	6	1.0	124.8095
20000	0.0266	6	1.0	141.6136
22900	0.0257	6	1.0	156.7506
26100	0.0249	6	1.0	172.9071
29000	0.0242	6	1.0	187.1246
31700	0.0237	6	1.0	200.0446

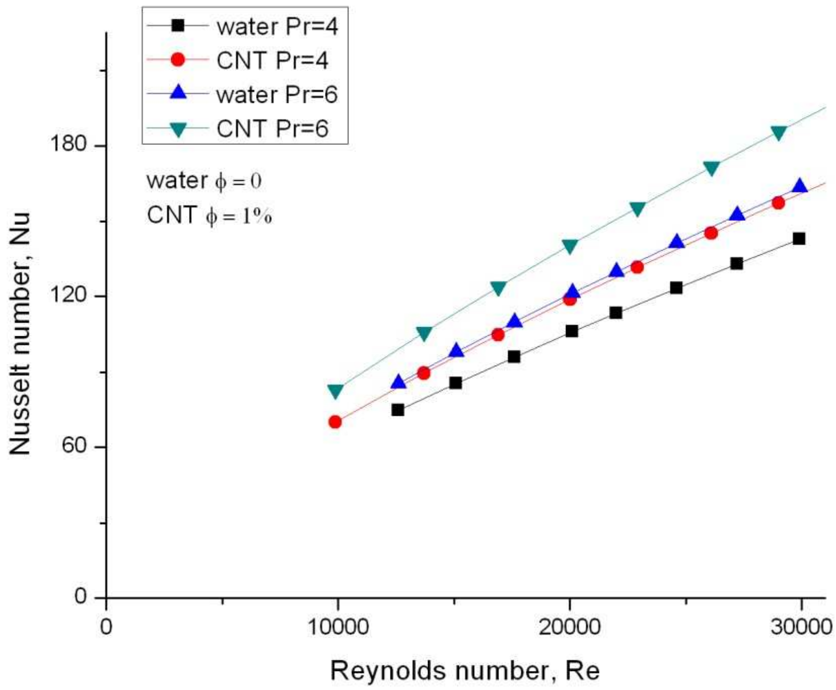

Figure 4.2: Comparison of water and CNTs with different Prandtl number

The data were then tabulated in form of graph for comparison of Nusselt number predicted between water and CNTs as shown in Figure 4.2. Based on the figure, CNTs shows greater enhancement in term of Nusselt number when compared with water having the same Prandtl number. The enhancement is due to the concentration of CNTs compared with water at the same temperature. Comparison to water has significantly showed the enhancement caused by CNTs.

On the other hand, we can also conclude that Nusselt number predicted by regression equation for CNTs with higher Prandtl number gives higher heat transfer rates when compared with other CNTs with lower Prandtl number.

As expected, the pressure drop is higher for CNTs than for pure water and increases with increasing Prandtl number marginally.

4.3.3 Comparison of Water and CNTs Using Properties from Literature

The thermophysical properties such as density and specific heat of CNTs are obtained from literature along with other properties such as diameter of the tube and diameter of the nanoparticle. Based on literature, at temperature of 300K, the thermal conductivity of CNTs is equal to 0.65 W/m.K. The density of CNTs nanofluid is 1151.076 kg/m^3 with density of nanoparticle equal to 2.1 g/cm^3 and the specific heat is 3690.249 J/kg.K. The diameter of tube is 1.55mm while the diameter of particle is 25nm. The estimated Nusselt number and heat transfer coefficient for both water and CNTs are presented in Table 4.3.

Table 4.3: Values of Nusselt number and heat transfer coefficient for both water and CNTs at T=300K

Reynolds number, Re	Water		CNTs	
	Nusselt number, Nu	Heat transfer coefficient, h ($W/m^2.K$)	Nusselt number, Nu	Heat transfer coefficient, h ($W/m^2.K$)
3000	28.88323	11370.68	35.60842	1.49E+04
6000	48.57561	19123.12	59.75001	2.50E+04
9000	65.83953	25919.54	80.87603	3.38E+04
12000	81.69412	32161.13	100.261	4.19E+04
15000	96.57691	38020.15	118.4314	4.95E+04
18000	110.7285	43591.29	135.7087	5.67E+04
21000	124.2995	48933.9	152.2686	6.37E+04
24000	137.3926	54088.36	168.2367	7.03E+04

Comparison of water and CNTs at T=300K with properties obtained from literature is shown in Figure 4.3.

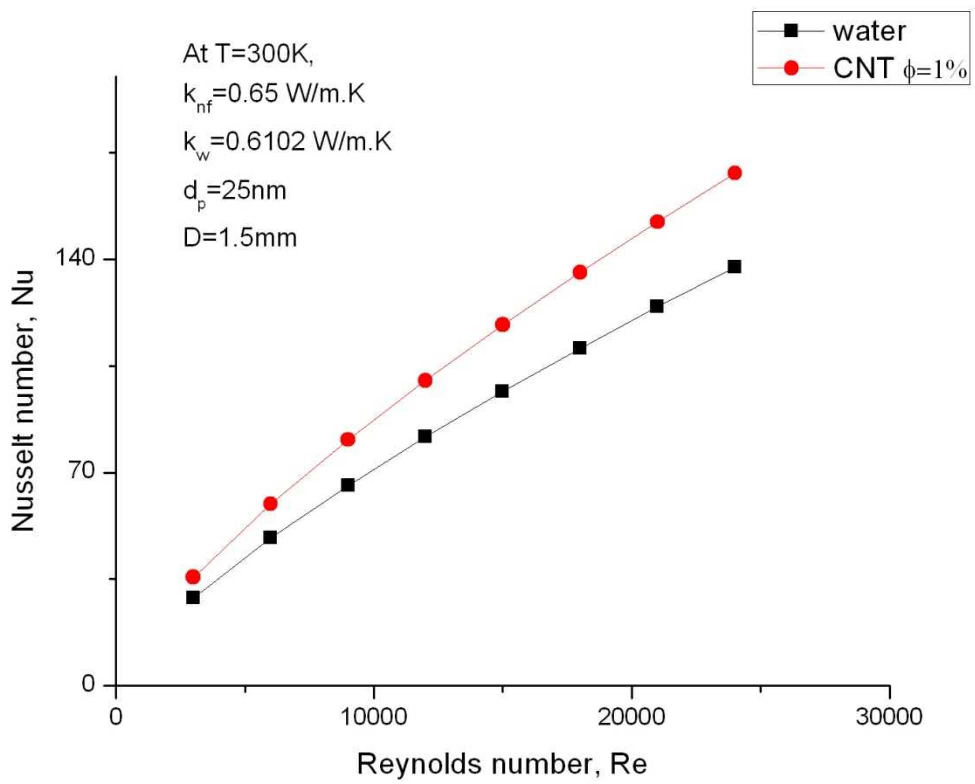

Figure 4.3: Comparison of water and CNT at T=300K with properties from literature

Figure 4.3 shows that CNT with 1% concentration exhibits higher Nusselt number than water in the same range of Reynolds number at temperature of 300K. The enhancement is due to the higher value of thermal conductivity presents by CNTs which is 0.65 W/m.K compared with water of 0.61 W/m.K. Higher value of thermal conductivity is also contributes to the enhancement.

Figure 4.4 shows the enhancement of CNTs compared with water in term of heat transfer coefficient.

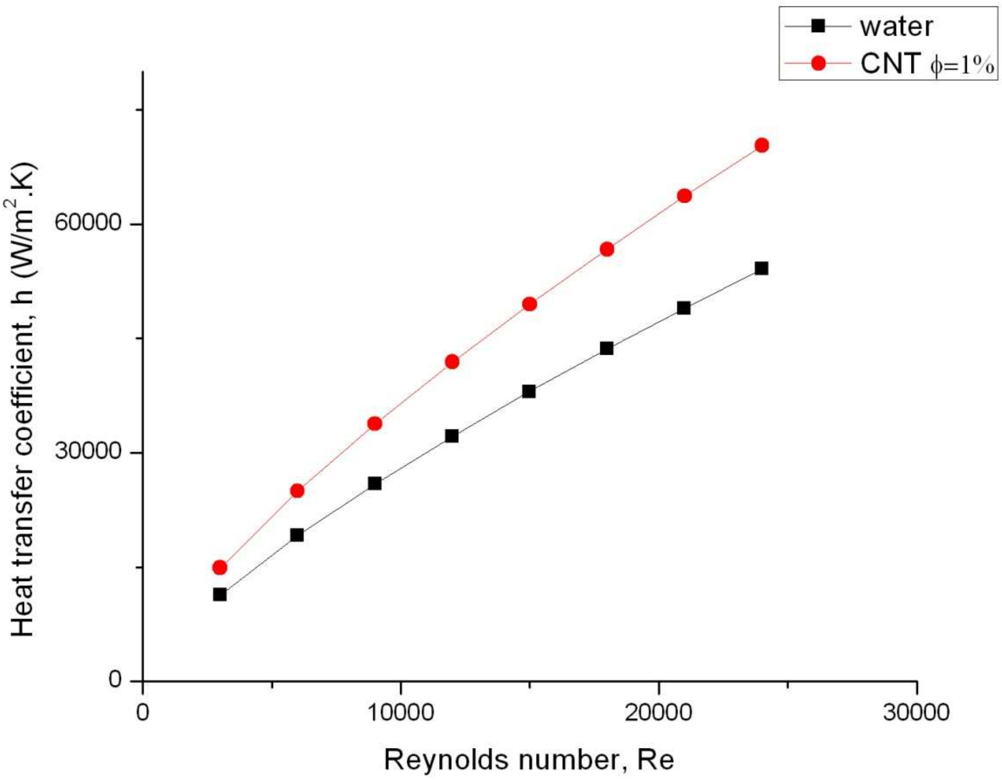

Figure 4.4: Enhancement of CNT nanofluid compared with water at T=300K

4.3.4 Comparison of Nusselt Number between Sharma's Regression Equation and Kamali's Equation

The validity of an equation is determined by comparing it to the other similar equation developed by others. In this case, the thermal conductivity equations from Sharma and Kamali are being compared in term of Nusselt number with the variation of Reynolds number. The data is presented in Table 4.4 and tabulated in Figure 4.5.

Table 4.4: Calculated values from Sharma's and Kamali's equation on thermal conductivity at T=300K

Reynolds number, Re	Nusselt number, Nu	
	Sharma's equation	Kamali's equation
3000	35.50346	35.60842
6000	59.57452	59.75001
9000	80.63902	80.87603
12000	99.96763	100.261
15000	118.0853	118.4314
18000	135.3125	135.7087
21000	151.8244	152.2686
24000	167.7463	168.2367

Based on Figure 4.5, it is observed that Sharma's and Kamali's equations are in the same agreement in term of thermal conductivity properties. This is because the graph shows both lines lie in the same line for the same range of Reynolds number. It means that both equations are valid for the estimation of thermal conductivity for CNTs.

It is to be noted that even though both equations are in the same agreement, there is always a limitation for every particular equation where in this case the Kamali's equation is only valid for temperature between 300K and 310K only. However, Sharma's equation is far beyond Kamali's equation where the temperature range is wider which is from 20°C until 70°C.

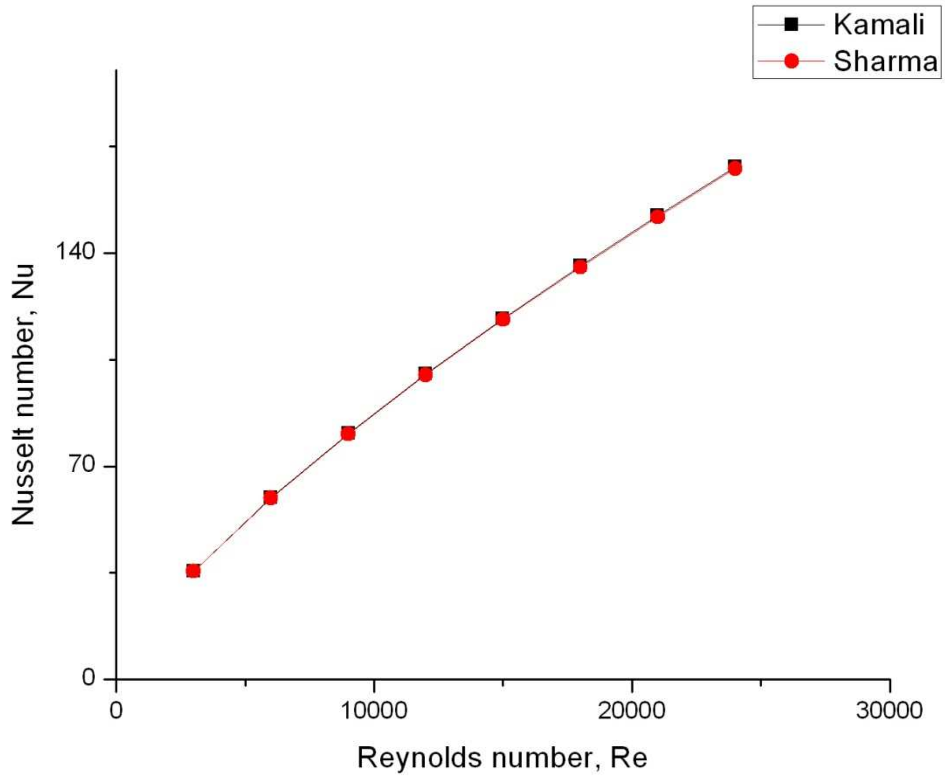

Figure 4.5: Comparison between Sharma's and Kamali's equations on thermal conductivity

4.3.5 The Effect of Temperature with Prandtl Number on Nusselt Number

Based on the discussion, it is well known that CNTs nanofluid exhibits higher thermal conductivity properties which results to higher Nusselt number when compared with water for flow inside tube. However, thermal conductivity is not the only factor of the enhancement as the effect of temperature and Prandtl number are also play crucial role in this case. The data presented in Table 4.5 were calculated from Kamali's equation.

Table 4.5: Calculated values of Nusselt number from Kamali's equation

Reynolds number, Re	Nusselt number, Nu Temperature, T (K) 300K	 320K	 340K
3000	35.60842	34.05738	31.96484
6000	59.75001	57.1587	53.67172
9000	80.87603	77.37772	72.67756
12000	100.261	95.93191	90.12162
15000	118.4314	113.3259	106.4799
18000	135.7087	129.8649	122.0343
21000	152.2686	145.7181	136.9453
24000	168.2367	161.0054	151.3258

Figure 4.6 shows the effect of temperature with different Prandtl number on Nusselt number at temperature of 300K, 320K and 340K.

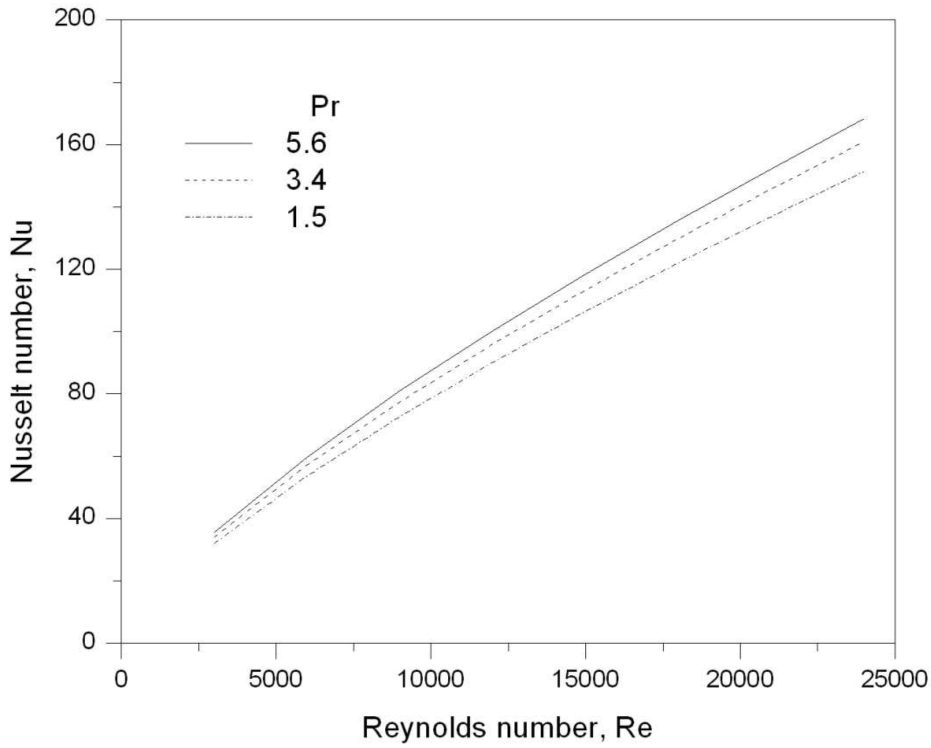

Figure 4.6: The effect of temperature with different Prandtl number on Nusselt number

Based on the figure, Nusselt number is increases when Reynolds number is varies until 24000 along with the increase of Prandtl number. It is to be noted that Nusselt number is inversely proportional to the temperature as it decreases when the temperature is increases. To conclude, Nusselt number is enhanced when Prandtl number varied.

CHAPTER 5

CONCLUSIONS

5.1 INTRODUCTION

This paper is concerned about the determination of heat transfer coefficient using experimental values of pressure drop of a single phase fluid. The development of equation analogically for estimation of heat transfer coefficient of carbon nanotubes in turbulent flow for forced convection heat transfer is achieved. This chapter will conclude the results discussed in previous chapter.

5.2 CONCLUSIONS

The following are the conclusions from the present study;

1. The regression equation developed is proved valid for both water and CNTs having volume concentration of 1%. The equation is given by;

$$Nu_{Reg} = \left(\frac{f}{8}\right)(1 + \emptyset^{*} Pr_{nf})^{0.1083} Re Pr_{w}^{2/3}$$

2. The regression equation deviates by the average of 11.66% when compared with well-known Gnielinski equation for estimation of Nusselt number for pure water.

3. The heat transfer enhancement of CNTs nanofluid inside a plain tube with Pr=4 is 12.21% and 17.68% at 20,000 and 30,000 Reynolds number respectively when compared with water.

4. The use of carbon nanotubes produced by surfactant had significantly enhanced the convective heat transfer in turbulent range for flow inside plain tube. The enhancement for CNTs having the same Prandtl number with water increases as Reynolds number increases, together with the increase of concentration and Prandtl number as shown in Figure 4.2.

5. Further enhancement of heat transfer coefficient is observed in Figure 4.3 with carbon nanotubes having volume concentration of 1% showing the increase of 34.44% at 21000 Reynolds number when compared with water.

6. The comparison of heat transfer coefficient between water and CNTs with 1% concentration as a single phase fluid is shown in Figure 4.4. The enhancement is 34.33% at 21000 Reynolds number when compared with water.

5.3 RECOMMENDATIONS FOR THE FUTURE RESEARCH

The regression equation is developed using the analogical procedure with the helps of FORTRAN software. The equation is proved valid for both water and nanofluids as it showed considerable deviation with the Gnielinski equation from literature.

However, the regression equation is developed based on limited knowledge and experimental data on nanofluids flowing inside plain tube in particular turbulent range. Thus, several recommendations are listed as followed;

1. Use different type of nanofluids instead of CNTs to develop the regression equation and compared with the equation developed in literature.

2. Conduct an experiment on different type of nanofluids flowing inside a plain tube or a square duct with twisted-tape insert and come out with a regression equation.

3. Since the range of Reynolds number used in this project is 10,000 to 30,000 due to limited data, develop another analogical procedure of higher range of Reynolds number to estimate the heat transfer coefficient.

4. In this project, the effect of temperature, Prandtl number and volume concentration were analyzed. Further the study on the impact of particle size, shape, concentration, temperature and pH on heat transfer coefficient.

REFERENCES

The information and experimental data were referred from the following reference:

Gwon Hyun Ko, Kyoungyoon Heo, Kyoungjun Lee, Dae Seong Kim, Chongyoup Kim, Yangsoo Sohn and Mansoo Choi 2007. *An experimental study on the pressure drop of nanofluids containing carbon nanotubes in a horizontal tube.* Seoul National University, Republic of Korea.

Yulong Ding, Hajar Alias and Dongsheng Wen, Richard A. Williams 2005. Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids). University of Leeds, UK.

Raghu Gowda, Hongwei Sun, Pengtao Wang, Majid Charmchi, Fan Gao, Zhiyong Gu and Bridgette Budhlall. *Effects of Particle Surface Charge, Species, Concentration, and Dispersion Method on the Thermal Conductivity of Nanofluids***.** University of Massachusetts Lowell, USA.

A. Behzadmehr, M. Saffar-Avval, N. Galanis 2006. *Prediction of turbulent forced convection of a nanofluid in a tube with uniform heat flux using a two phase approach***.** University of Sistan and Baluchestan, Zahedan, Iran.

Lazarus Godson Asirvatham, Nandigana Vishal, Senthil Kumar Gangatharan and Dhasan Mohan Lal 2008. *Experimental Study on Forced Convective Heat Transfer with Low Volume Fraction of CuO/Water Nanofluid.* Anna University, Chennai, India.

V Vasu, K Rama Krishna And A C S Kumar 2006. *Analytical prediction of forced convective heat transfer of fluids embedded with nanostructured materials (nanofluids).* V R Siddhartha Engineering College, Vijayawada.

V. Bianco, F. Chiacchio, O. Manca, S. Nardini 2008. *Numerical investigation of nanofluids forced convection in circular tubes.* Seconda Università degli Studi di Napoli, Via Roma 29, 81031 Aversa (CE), Italy.

Ventsislav Zimparov 2003. *Prediction of friction factors and heat transfer coefficients for turbulent flow in corrugated tubes combined with twisted tape inserts. Part 1: friction factors.* Gabrovo Technical University, 4 Hadji Dimitar Str., BG-5300 Gabrovo, Bulgaria.

Sami AI-Fahed and Walid Chakroun. *Effect of tube-tape clearance on heat transfer for fully developed turbulent flow in a horizontal isothermal tube*. Kuwait University, Safat, Kuwait.

P. Sivashanmugam, S. Suresh 2006. *Experimental studies on heat transfer and friction factorcharacteristics of laminar flow through a circular tube fitted with regularly spaced helical screw-tape inserts.* National Institute of Technology, Tiruchirappalli 620 015, Tamil Nadu, India.

L. Syam Sundar, K.V. Sharma 2009. *Turbulent heat transfer and friction factor of Al2O3 Nanofluid in circular tube with twisted tape inserts*. Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia.

Xiang-Qi Wang, Arun S. Mujumdar 2006. *Heat transfer characteristics of nanofluids: a review. National University of Singapore, 10 Kent Ridge Crescent, Singapore.*

Yulong Ding, Haisheng Chen, Yurong He, Alexei Lapkin, Mahboubeh Yeganeh, Lidija Šiller And Yuriy V. Butenko 2007. *Forced convective heat transfer of nanofluids***.** *University of Leed, UK.*

Sarit K. Das, Stephen U. S. Choi, Wenhua Yu and T Pradeep 2008. *Nanofluids – Science and Technology.* John Wiley & Sons, Inc., Publication USA.

Ulzie L. Rea 2008. *Experimental Study of Alumina-Water and Zirconia-Water Nanofluids Convective Heat Transfer and Viscous Pressure Loss in Laminar Regime*. Massachusetts Institute of Technology USA.

Wen, D. and Y. Ding (2004). *Experimental investigation into convective heat transfer of nanofluid at the entrance region under laminar flow conditions*. International Journal of Heat and Mass Transfer 47, (24) (2004) 5181–5188

Fotukian S.M., Esfahany and M.Nasr (2010). *Experimental study of turbulent convective heat transfer and pressure drop of dilute CuO/water nanofluid inside a circular tube*. International Communications in Heat and Mass Transfer, 37, 214-219, 2010.

Gnielinski, V. (1976). *New equations for heat and mass transfer in turbulent pipe and channel flow*. International Chemical Engineering, Vol. 16, pp. 359-368.

Yurong He, Yubin Men, Yunhua Zhao, Huilin Lu and Yulong Ding (2009). *Numerical investigation into the convective heat transfer of* TiO_2 *nanofluids flowing through a straight tube under the laminar flow conditions*. Applied Thermal Engineering, 29, 1965 – 1972.

Izadi M., A.Behzadmehr and D.Jalali-Vahida (2009). *Numerical study of developing laminar forced convection of a nanofluid in an annulus.* International Journal of Thermal Sciences, 48, 2119 – 2129, 2009.

Bianco. V., F.Chiacchio, O.Manca and S.Nardini (2009). *Numerical investigation of nanofluids forced convection in circular tubes*. Applied Thermal Engineering, 29, 3632 – 3542.

Pak, B. C., and Cho, Y. I. (1998). *Hydrodynamic and Heat Transfer Study of Dispersed Fluids with Submicron Metallic Oxide Particles*. Exp. Heat Transfer, 11, pp. 151– 170.

Xuan, Y., and Roetzel W. (2000). *Conceptions for Heat Transfer Correlation of Nanofluids.* Int. J. Heat Mass Transf., 43, pp. 3701–3707.

Eastman, Choi, J., Li, S., Yu, S., Thompson, W., L. (2001). *Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles*. Appl. Phys. Lett. 78, 718-720.

APPENDIX A

GANTT CHART FOR FYP 1

PROJECT ACTIVITIES	SEMESTER 1														
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15
Research on topic															
Discuss topic with supervisor															
Literature review															
Collecting experimental data															
Conceptualization															
Research on methodology															
Documentation															
Presentation															
Report submission															

Figure 6.1: FYP 1 project planning

APPENDIX B

GANTT CHART FOR FYP 2

PROJECT ACTIVITIES	SEMESTER 2															
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16
Discussion with supervisor																
Methodology discussion																
Literature study																
Software integration																
Validating equation																
Analyze results and discussion																
Documentation																
Report submission																
Presentation																

Figure 6.2: FYP 2 project planning

APPENDIX C

EXPERIMENTAL DATA

Table 6.1: Experimental data used to obtain the regression equation

Nu	Re	Pr	Fi	ID	F	TB	Dp
30.17	3692	4.4	0	0.019	0.04181	39.7	0
34.78	4534	4.58	0	0.019	0.0394	38.35	0
39.44	5391	4.69	0	0.019	0.03821	37.45	0
43.47	6114	4.83	0	0.019	0.03721	36.35	0
47.62	6946	4.95	0	0.019	0.03555	35.45	0
53.11	8058	5.02	0	0.019	0.03441	34.9	0
71.42	12141	4.66	0	0.019	0.03292	37.65	0
81.34	14404	4.75	0	0.019	0.03119	36.95	0
88.44	16102	4.81	0	0.019	0.03006	36.5	0
97.03	17964	4.96	0	0.019	0.02907	35.35	0
107.32	19905	5.25	0	0.019	0.02838	33.2	0
116.2	21705	5.51	0	0.019	0.02772	31.25	0
32.83	3706	4.38	0.02	0.019	0.04201	39.95	47
39	4537	4.56	0.02	0.019	0.03989	38.5	47
44.31	5387	4.69	0.02	0.019	0.03901	37.55	47
49.58	6186	4.83	0.02	0.019	0.03821	36.45	47
54.76	6941	4.95	0.02	0.019	0.03662	35.55	47
61.59	8351	5.01	0.02	0.019	0.03514	35.05	47
75.65	11869	4.64	0.02	0.019	0.03395	37.65	47
88.34	14166	4.75	0.02	0.019	0.03121	37	47
97.27	15824	4.79	0.02	0.019	0.03009	36.65	47
101.94	17436	4.94	0.02	0.019	0.0291	35.5	47
118.68	19188	5.25	0.02	0.019	0.0284	33.25	47
132.53	21576	5.49	0.02	0.019	0.02774	31.4	47
35.04	3600	4.48	0.1	0.019	0.04401	40.1	47
43.74	4724	4.67	0.1	0.019	0.04321	38.6	47
46.68	5226	4.8	0.1	0.019	0.04259	37.65	47
54.46	6286	4.94	0.1	0.019	0.04044	36.55	47
62.53	7031	5.06	0.1	0.019	0.03742	35.65	47
69.64	8107	5.13	0.1	0.019	0.03645	35.15	47
87.38	11305	4.75	0.1	0.019	0.03402	38.05	47
99.79	14072	4.83	0.1	0.019	0.03244	37.45	47
109.83	15418	4.89	0.1	0.019	0.03015	36.95	47
119.27	16204	5.02	0.1	0.019	0.02916	35.95	47
124.71	17910	5.33	0.1	0.019	0.02846	33.65	47
136.81	19592	5.59	0.1	0.019	0.0278	31.75	47
35.41	3115	5.09	0.5	0.019	0.04598	40.25	47
42.52	3861	5.24	0.5	0.019	0.04477	38.58	47
48.36	4557	5.39	0.5	0.019	0.04368	37.85	47

56.36	5497	5.55	0.5	0.019	0.04195	36.75	47
62.68	6149	5.68	0.5	0.019	0.03824	35.85	47
69.15	7342	5.76	0.5	0.019	0.03746	35.35	47
87.68	9898	5.33	0.5	0.019	0.03624	38.2	47
99.46	12293	5.42	0.5	0.019	0.034	37.6	47
106.15	13449	5.51	0.5	0.019	0.03146	37.05	47
108.58	14133	5.65	0.5	0.019	0.03098	36.05	47
122.72	15602	6.01	0.5	0.019	0.02998	33.7	47
134.45	17103	6.28	0.5	0.019	0.02858	31.9	47
37.1	4388	4.6	3.7	0.00227	0.03887	56	170
41.6	4755	4.6	3.7	0.00227	0.0381	56	170
43.8	5202	4.6	3.7	0.00227	0.03726	56	170
48.3	5581	4.6	3.7	0.00227	0.03661	56	170
51.2	5964	4.6	3.7	0.00227	0.036	56	170
55.7	6392	4.6	3.7	0.00227	0.03539	56	170
58.7	6786	4.6	3.7	0.00227	0.03486	56	170
63.1	7225	4.6	3.7	0.00227	0.03432	56	170
65	7669	4.6	3.7	0.00227	0.03381	56	170
70.2	8077	4.6	3.7	0.00227	0.03338	56	170
71.7	8532	4.6	3.7	0.00227	0.03292	56	170
72.4	8907	4.6	3.7	0.00227	0.03257	56	170
75.7	8990	4.6	3.7	0.00227	0.03249	56	170
79.1	9454	4.6	3.7	0.00227	0.03209	56	170
84.7	9965	4.6	3.7	0.00227	0.03167	56	170
86.9	10438	4.6	3.7	0.00227	0.0313	56	170
91.3	10915	4.6	3.7	0.00227	0.03095	56	170
93.6	11573	4.6	3.7	0.00227	0.03051	56	170
99.5	12150	4.6	3.7	0.00227	0.03014	56	170
101	12596	4.6	3.7	0.00227	0.02987	56	170
106	13273	4.6	3.7	0.00227	0.02948	56	170
32.7	3265	7.1	3.7	0.00227	0.04186	39	170
37.1	3557	7.1	3.7	0.00227	0.04097	39	170
41.6	3854	7.1	3.7	0.00227	0.04016	39	170
43.8	4217	7.1	3.7	0.00227	0.03926	39	170
48.3	4524	7.1	3.7	0.00227	0.03858	39	170
51.2	4835	7.1	3.7	0.00227	0.03794	39	170
55.7	5182	7.1	3.7	0.00227	0.03729	39	170
58.7	5501	7.1	3.7	0.00227	0.03674	39	170
63.1	5857	7.1	3.7	0.00227	0.03617	39	170
65	6217	7.1	3.7	0.00227	0.03563	39	170
70.2	6548	7.1	3.7	0.00227	0.03517	39	170
71.7	6916	7.1	3.7	0.00227	0.0347	39	170
72.4	7220	7.1	3.7	0.00227	0.03432	39	170
75.7	7288	7.1	3.7	0.00227	0.03424	39	170
79.1	7664	7.1	3.7	0.00227	0.03382	39	170
84.7	8078	7.1	3.7	0.00227	0.03337	39	170
86.9	8462	7.1	3.7	0.00227	0.03299	39	170
91.3	8852	7.1	3.7	0.00227	0.03262	39	170
93.6	9382	7.1	3.7	0.00227	0.03215	39	170

99.5	9849	7.1	3.7	0.00227	0.03176	39	170
101	10211	7.1	3.7	0.00227	0.03148	39	170
106	10759	7.1	3.7	0.00227	0.03107	39	170
135.4394	20699.79	5.572125	0.9	0.0094	0.03463	30.5	46
206.3429	32351.62	6.395195	0.9	0.0094	0.0066	25.76	46
225.8237	41299.36	4.826427	0.9	0.0094	0.01308	35.57	46
213.4837	45070.77	3.91102	0.9	0.0094	0.00773	43.33	46
121.8104	20410.32	5.380445	1.8	0.0094	0.02101	33.6	46
172.2258	28566.98	6.726556	1.8	0.0094	0.00766	25.83	46
195.6944	35915.34	5.377383	1.8	0.0094	0.0185	33.62	46
206.9235	42439.04	4.357428	1.8	0.0094	0.01808	41.3	46
191.2945	39689.25	4.513475	1.8	0.0094	0.01726	39.98	46
239.4767	63257.28	2.504851	0	0.0094	0.02825	70.32	0
183.381	44287.89	2.598928	0	0.0094	0.0296	67.79	0
153.6021	23603.55	5.207064	0	0.0094	0.05975	31.56	0
211.9292	40834.33	4.057484	0	0.0094	0.0321	42.93	0
169.8729	33146.85	3.590031	0	0.0094	0.05843	48.99	0
77.6532	13868.75	3.717203	0.2	0.0094	0.02448	45.59	60
126.1204	21698.93	4.749778	0.2	0.0094	0.02273	36.47	60
188.4556	36540.61	4.584301	0.2	0.0094	0.02014	37.75	60
190.2213	42352.18	3.660113	0.2	0.0094	0.01954	46.19	60
184.6761	41070.74	3.757057	0.2	0.0094	0.02006	45.18	60
124.5604	22832.42	4.654064	0.5	0.0094	0.02249	37.93	60
187.7851	35341.95	5.387854	0.5	0.0094	0.02049	32.69	60
189.2713	39144.17	4.540171	0.5	0.0094	0.01993	38.84	60
195.8961	46254.44	3.607248	0.5	0.0094	0.01918	47.56	60
187.4182	42559.65	3.914559	0.5	0.0094	0.01962	44.38	60
72.9	10300	6.61	0.3	0.01	0.03141	21.74	35
80.2	11200	6.92	0.3	0.01	0.03076	20.21	35
96.4	13700	6.88	0.3	0.01	0.02925	20.41	35
105	15100	6.8	0.3	0.01	0.02854	20.8	35
122	17500	7.05	0.3	0.01	0.02751	19.6	35
127	18700	6.68	0.3	0.01	0.02706	21.39	35
135	20400	6.37	0.3	0.01	0.02647	22.98	35
143	21800	6.31	0.3	0.01	0.02604	23.29	35
148	22800	6.2	0.3	0.01	0.02575	23.88	35
76.5	10100	6.88	0.5	0.01	0.03156	20.9	35
87.8	11500	7.2	0.5	0.01	0.03055	19.39	35
99	13100	7.19	0.5	0.01	0.02957	19.43	35
100	14200	6.12	0.5	0.01	0.02898	24.82	35
117	16000	6.88	0.5	0.01	0.02813	20.9	35
129	18700	6.13	0.5	0.01	0.02706	24.77	35
138	20200	6.07	0.5	0.01	0.02654	25.1	35
143	20900	6.13	0.5	0.01	0.02631	24.77	35
151	23600	5.31	0.5	0.01	0.02553	29.68	35
86.8	10700	7.09	0.8	0.01	0.03111	20.6	35
96.3	11900	7.19	0.8	0.01	0.03029	20.13	35
107	13700	6.76	0.8	0.01	0.02925	22.19	35
121	15700	6.71	0.8	0.01	0.02827	22.44	35

133	18200	6.04	0.8	0.01	0.02724	25.99	35
145	20100	5.96	0.8	0.01	0.02657	26.45	35
158	23100	5.36	0.8	0.01	0.02566	30.1	35
89.6	10600	7.18	1	0.01	0.03118	20.63	35
104	13000	6.51	1	0.01	0.02963	23.91	35
116	14600	6.54	1	0.01	0.02878	23.75	35
131	16700	6.5	1	0.01	0.02783	23.96	35
144	19100	6.04	1	0.01	0.02691	26.45	35
166	22500	5.9	1	0.01	0.02583	27.26	35
88.6	10400	6.74	1.2	0.01	0.03133	23.18	35
95.9	11200	6.92	1.2	0.01	0.03076	22.29	35
103	12600	6.31	1.2	0.01	0.02986	25.41	35
123	14600	6.99	1.2	0.01	0.02878	21.95	35
131	15800	6.82	1.2	0.01	0.02822	22.78	35
152	18900	6.54	1.2	0.01	0.02698	24.19	35
159	20100	6.35	1.2	0.01	0.02657	25.19	35
96.7	10500	7.37	1.5	0.01	0.03126	20.8	35
114	12600	7.29	1.5	0.01	0.02986	21.16	35
132	14600	7.49	1.5	0.01	0.02878	20.26	35
139	15600	7.31	1.5	0.01	0.02831	21.07	35
147	16700	7.18	1.5	0.01	0.02783	21.67	35
161	18800	6.86	1.5	0.01	0.02702	23.21	35
92.5	9790	6.62	2	0.01	0.03181	25.39	35
109	11700	6.61	2	0.01	0.03042	25.44	35
129	13700	7	2	0.01	0.02925	23.49	35
96.7	13800	9.45	0	0.01	0.02919	10	0
105	15300	9.15	0	0.01	0.02845	11.1	0
120	17600	9.24	0	0.01	0.02747	10.77	0
124	18900	8.51	0	0.01	0.02698	13.46	0
132	20600	8.16	0	0.01	0.02641	14.74	0
140	22100	8.03	0	0.01	0.02595	15.28	0
144	23100	7.78	0	0.01	0.02566	16.44	0
56.5	6620	4.68	0.015	0.005	0.03964	41.69	50
70.1	9800	3.4	0.015	0.005	0.03721	58	50
88.5	13350	3.12	0.015	0.005	0.03385	59.73	50
95	15470	2.81	0.015	0.005	0.03404	67.92	50
103.5	18710	2.44	0.015	0.005	0.03084	70.37	50
124.8	20810	2.91	0.015	0.005	0.03161	65.66	50
134.6	24550	2.6	0.015	0.005	0.02932	67.92	50
154	27470	2.8	0.015	0.005	0.03047	70.37	50
167	29990	2.84	0.015	0.005	0.03053	70.37	50
50.9	5870	4.86	0.031	0.005	0.0441	45.85	50
71.7	9810	3.54	0.031	0.005	0.03656	54.86	50
75.9	12250	2.7	0.031	0.005	0.03639	70.43	50
91.3	16230	2.42	0.031	0.005	0.03336	75.94	50
108.7	18380	2.74	0.031	0.005	0.03315	70.43	50
122.6	21730	2.64	0.031	0.005	0.02997	67.99	50
141	24340	2.86	0.031	0.005	0.03014	65.72	50
146.7	26880	2.65	0.031	0.005	0.03089	73.07	50

145.7	29750	2.27	0.031	0.005	0.03276	89.96	50
67.1	9400	3.36	0.039	0.005	0.03535	53.41	50
81.2	12990	2.78	0.039	0.005	0.03616	70.46	50
88.1	15530	2.43	0.039	0.005	0.03401	75.97	50
102.9	18670	2.43	0.039	0.005	0.03005	68.02	50
108.1	20430	2.32	0.039	0.005	0.03361	82.46	50
121.5	24670	2.17	0.039	0.005	0.0303	82.46	50
137	26940	2.35	0.039	0.005	0.03136	82.46	50
144.6	30130	2.2	0.039	0.005	0.03218	90	50
61	6340	6.08	0.078	0.005	0.04113	35.07	50
73.2	10100	3.5	0.078	0.005	0.03787	58.21	50
83.3	12770	3	0.078	0.005	0.03631	65.9	50
98	15840	2.86	0.078	0.005	0.033	65.9	50
104.6	17760	2.7	0.078	0.005	0.03289	70.62	50
116.6	20630	2.61	0.078	0.005	0.03036	68.17	50
130.1	22870	2.72	0.078	0.005	0.03113	70.62	50
149.9	26980	2.74	0.078	0.005	0.02938	68.17	50
156.5	29370	2.61	0.078	0.005	0.03214	79.26	50
61.1	7740	4.01	0.118	0.005	0.03508	42.96	50
75	10500	3.43	0.118	0.005	0.03532	55.14	50
89.5	13930	2.97	0.118	0.005	0.03262	60.09	50
106.7	17550	2.85	0.118	0.005	0.03051	61.95	50
117.6	20290	2.72	0.118	0.005	0.02916	63.93	50
129.6	22290	2.81	0.118	0.005	0.0303	66.05	50
145.7	26070	2.74	0.118	0.005	0.02913	66.05	50
184.2	30400	3.32	0.118	0.005	0.02875	60.09	50
68.6	8410	4.33	0.157	0.005	0.03767	46.22	50
89.2	11850	3.89	0.157	0.005	0.03245	46.22	50
100.4	14590	3.42	0.157	0.005	0.03167	52.38	50
111.9	16930	3.29	0.157	0.005	0.03134	56.83	50
122.6	19360	3.15	0.157	0.005	0.03111	60.23	50
160.1	24450	3.58	0.157	0.005	0.02707	49.75	50
180.5	28840	3.47	0.157	0.005	0.02646	52.38	50
183.1	30990	3.19	0.157	0.005	0.02909	62.09	50
59.6	8100	3.5	0.236	0.005	0.03702	52.62	50
81.1	12670	2.89	0.236	0.005	0.0337	62.37	50
93.5	15380	2.75	0.236	0.005	0.03267	66.49	50
104.2	18170	2.59	0.236	0.005	0.03079	68.78	50
120.7	21970	2.53	0.236	0.005	0.02885	66.49	50
139.1	25750	2.57	0.236	0.005	0.02847	68.78	50
171.1	31110	2.81	0.236	0.005	0.02692	64.36	50
33.5	5180	2.67	0	0.005	0.0373	66.25	0
43.8	7250	2.36	0	0.005	0.03429	74.41	0
56.5	9960	2.2	0	0.005	0.03167	80.71	0
66.8	12300	2.13	0	0.005	0.03004	84.29	0
66.8	16300	1.42	0	0.005	0.028	97.5	0
92.5	18900	1.98	0	0.005	0.02698	88.33	0
98.7	20500	1.97	0	0.005	0.02644	88.33	0
103.4	21200	2.04	0	0.005	0.02622	88.33	0

112.6	24100	1.97	0	0.005	0.02539	88.33	0
117.5	25500	1.96	0	0.005	0.02504	88.33	0
127.8	28300	1.95	0	0.005	0.02439	88.33	0
135.4	30400	1.95	0	0.005	0.02396	88.33	0
144.2	32900	1.95	0	0.005	0.02349	92.73	0

APPENDIX D

CALCULATED PRANDTL NUMBER USING EXPERIMENTAL DATA

Table 6.2: The effect of temperature on Prandtl number

Reynolds number, Re	Prandtl number, Pr											
	Temperature, T (K)											
	300		310		320		330		340		350	
	Sharma	Kamali	Sharma	Kamali	Sharma	Kamali	Sharma	Kamali	Sharma	Kamali	Sharma	Kamali
3000	5.722963	5.908739	5.386648	4.93027	5.097797	3.579385	4.850569	2.37813	4.63179	1.549911	4.442147	1.027744
6000	5.583977	5.765241	5.25583	4.810535	4.973993	3.492457	4.732769	2.320376	4.519304	1.512271	4.334266	1.002785
9000	5.502765	5.681393	5.179391	4.740572	4.901653	3.441664	4.663937	2.286629	4.453576	1.490277	4.27123	0.988201
12000	5.449078	5.625964	5.128859	4.694321	4.853831	3.408086	4.618434	2.26432	4.410126	1.475737	4.229559	0.978559
15000	5.401823	5.577174	5.084381	4.653611	4.811738	3.378531	4.578383	2.244683	4.37188	1.462939	4.192879	0.970073
18000	5.368684	5.54296	5.053189	4.625063	4.782219	3.357804	4.550295	2.230913	4.34506	1.453964	4.167157	0.964122
21000	5.340809	5.51418	5.026952	4.601049	4.757389	3.34037	4.52667	2.219329	4.3225	1.446415	4.14552	0.959116
24000	5.316224	5.488796	5.003812	4.579869	4.735489	3.324993	4.505832	2.209113	4.302602	1.439757	4.126437	0.954701

APPENDIX E

CALCULATED NUSSELT NUMBER USING EXPERIMENTAL DATA

Table 6.3: The effect of temperature on Nusselt number

Reynolds number, Re	Nusselt number, Nu											
	Temperature, T (K)											
	300		310		320		330		340		350	
	Sharma	Kamali	Sharma	Kamali	Sharma	Kamali	Sharma	Kamali	Sharma	Kamali	Sharma	Kamali
3000	35.50346	35.60842	35.30668	35.02432	35.13015	34.05738	34.97304	32.95349	34.82898	31.96484	34.70002	31.18138
6000	59.57452	59.75001	59.24558	58.77368	58.95054	57.1587	58.68798	55.31754	58.44729	53.67172	58.23184	52.37033
9000	80.63902	80.87603	80.19479	79.55758	79.79638	77.37772	79.44187	74.89466	79.11691	72.67756	78.82606	70.92674
12000	99.96763	100.261	99.41777	98.62912	98.92466	95.93191	98.48592	92.86125	98.08377	90.12162	97.72385	87.96004
15000	118.0853	118.4314	117.4367	116.5065	116.8551	113.3259	116.3376	109.7067	115.8633	106.4799	115.4389	103.9359
18000	135.3125	135.7087	134.57	133.5052	133.9042	129.8649	133.3118	125.7243	132.7689	122.0343	132.2831	119.1268
21000	151.8244	152.2686	150.992	149.7983	150.2456	145.7181	149.5816	141.0783	148.973	136.9453	148.4284	133.6902
24000	167.7463	168.2367	166.8272	165.5094	166.0032	161.0054	165.2701	155.8852	164.5983	151.3258	163.9972	147.7363

APPENDIX G

LIST OF EQUATIONS

a) $Nusselt\ number, Nu = \frac{h\ x\ 0.019}{k_n}$

b) $Reynolds\ number, Re = \frac{4m}{\pi x 0.019 x \mu_n}$

c) $friction\ factor, f = (1.58 log Re - 3.82)^{-2}$

d) $friction\ factor, f = \frac{0.0791}{Re^{0.25}}$

e) $Nusselt\ number, Nu = \frac{\left(\frac{f}{2}\right)(Re-1000)Pr_n}{1+12.7\left(\frac{f}{2}\right)^2 (Pr^{2/3}-1)}$

f) $Density, \rho_{water} = \frac{1000(1.0-(T_b-4.0)^2}{(119000+1365T_b-4T_b^2}$

g) $Viscosity, \mu_{water} = 0.00169 - 4.2526x10^{-5} x T_b + 4.9255x10^{-7}(T_b^2) - 2.0993504x10^{-9}(T_b^3)$

h) $Thermal\ conductivity, k_w = 0.56112 + 0.00193(T_b - 2.60152749x10^{-6} x(T_b^2 - 6.08803x10^{-8} x T_b^3$

i) $Specific\ heat, c_{p,w} = 4217.629 - 3.20888(T_b) + 0.09503(T_b)^2 - 0.00132(T_b)^3 + 9.415x10^{-6}(T_b)^4 - 2.5479x10^{-8}(T_b)^5$

j) $\alpha_{water} = \frac{k_{water}}{\rho_{water} c_{p,water}}$

k) $Nusselt\ number, Nu_{water} = \frac{\mu_{water}}{\rho_{water}}$

l) $Prandtl\ number, Pr_{water} = \frac{\mu_{water} c_{p,water}}{k_{water}}$

m) $Density, \rho_{nf} = \rho_{water}(0.9973 + 0.03479\emptyset + 0.004333(\frac{T_b}{70})$

n) $Viscosity, \mu_{nf} = \mu_{water}(0.9042 + 0.1245\emptyset) + 0.6436\left(\frac{d_p}{170}\right) - 0.08445(\frac{T_b}{72})$

o) $Thermal\ conductivity, k_{nf} = k_{water}(0.9808 + 0.0142\emptyset + 0.2718\left(\frac{T_b}{70}\right) - 0.102(\frac{d_p}{150})$

p) $specific\ heat, c_{p,nf} = c_{p,water}(1.036 - 0.0298\emptyset - 0.07261(\frac{T_b}{70}))$

q) $\alpha_{nf} = \frac{k_{nf}}{\rho_{nf} c_{p,nf}}$

r) $Nusselt\ number, Nu = \frac{\mu_{nf}}{\rho_{nf}}$

s) $Prandtl\ number, Pr_{nf} = \frac{\mu_{nf} c_{p,nf}}{k_{nf}}$

t) $Q = 0.2(1.0 + \frac{1.7}{\sqrt{0.5+HD}})$

u) $Specific\ heat, c_{p,w} = 4217.629 - 3.20888(T_w) + 0.09503(T_w)^2 - 0.00132(T_w)^3 + 9.415x10^{-6}(T_w)^4 - 2.5479x10^{-8}(T_w)^5$