**R.T.**
**YILDIZ TECHNICAL UNIVERSITY**
**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE**

# NUMERICAL INVESTIGATION OF THE SINGLE PHASE FORCED CONVECTION HEAT TRANSFER CHARACTERISTICS OF NANOFLUID FLOWING IN ENHANCED TUBES

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**A MASTER OF SCIENCE THESIS**
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**ISTANBUL, 2012**

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This paper , which is prepared by Nurullah KAYACI has been accepted as a **MASTER of SCIENCE THESIS** in the department of Mechanical Engineering of The Graduate School of Natural and Applied Sciences by the juries given below on 01.06.2012.

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## ACKNOWLEDGEMENT

I would like to express a deep sense of gratitude and thanks to my supervisor, Assist. Prof. Dr. Ahmet Selim Dalkiliç. Without his wise counsel and guidance, it would have been impossible to complete the present work. I want to thank to Muhammet Balcılar due to the assistance in ANN analysis. I also want to thank to my colleagues, Mahdi Tabatabaei and Ali Celen from Yıldız Technical University. I also want to thank my God and my family for their support.

This thesis work is based on the numerical investigation of the single phase forced convection heat transfer characteristics of nanofluids flowing in smooth and micro-fin tubes

June, 2012

Nurullah KAYACI

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## LIST of SYMBOLS

| | |
|---|---|
| Cp | Specific heat [J $kg^{-1}K^{-1}$] |
| d | Internal tube diameter [m] |
| h | Heat transfer coefficient [W $m^{-2}K^{-1}$] |
| k | Thermal conductivity [W $m^{-1}K^{-1}$] |
| $k_H$ | Huggins coefficient. |
| L | Length of test tube [m] |
| m | Mass flow rate [ kg $s^{-1}$] |
| Nu | Nusselt number |
| $\Delta P$ | Pressure drop [Pa] |
| Pr | Prandtl number |
| Re | Reynolds number |
| Q | Heat transfer rate [W] |
| q'' | Heat flux [W $m^{-2}$ ] |
| T | Temperature [°C] |
| $\mu$ | Dynamic viscosity [Pa.s] |
| $\rho$ | Density [kg $m^{-3}$] |
| $\tau$ | Shear stress [N $m^{-2}$] |
| $\varphi$ | Volume fraction [ %] |
| $\varphi_m$ | Maximum particle packing fraction |
| $\nu$ | Kinematic viscosity [$m^2$ $s^{-1}$] |
| m | Mass [kg] |
| f | Friction factor |
| W | Work [J] |
| P | Pressure [Pa] |
| A | Area [$m^2$] |
| u | Average velocity [m/s] |
| n | Number of fins |
| e | Height of fin [m] |
| p | Distance between micro-fins [m] |
| $\varphi$ | Sphericity |
| $K_b$ | Boltzmann constant [J $K^{-1}$] |
| T | Temperature [K] |
| U | Overall heat transfer coefficient [W $m^{-2}$ K] |
| t | Fin tip thickness (m) |
| h | Fin height (m) |
| p | Fin pitch (m) |

| | |
|---|---|
| b | Fin root distance (m) |
| $\Delta z$ | Pressure drop length (m) |

## LIST of ABBREVIATION

| | |
|---|---|
| CFD | Computation Fluid Dynamics |
| ANN | Artificial Neural Network |
| TEM | Transmission Electron Microscopy |
| SIMPLE | Semi Implicit Method for Pressure Linked Equations |

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# ABSTRACT

## NUMERICAL INVESTIGATION OF THE SINGLE PHASE FORCED CONVECTION HEAT TRANSFER CHARACTERISTICS OF NANOFLUIDS FLOWING IN ENHANCED TUBES

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Department of Mechanical Engineering
MSc. Thesis

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Forced convection flows of nanofluids containing of water with $TiO_2$ nanoparticles in smooth and micro-fin tubes with constant wall temperature are studied numerically in this paper. A single-phase numerical model having two-dimensional equations is solved with either constant heat flux or temperature dependent properties to determine the hydrodynamics and thermal behaviors of the nanofluid flow by means of a CFD program for the water flow in a smooth tube and several micro-fin tubes having various helix angles ($0^o$,$18^o$). An intensive literature review on the determination of the physical properties (k, $\mu$, $\rho$, $C_p$) of nanofluids is given in the paper. Artificial neural network (ANN) method is used to determine the most agreeable physical properties of $TiO_2$ nanofluid among correlations. After obtaining the best combination of physical properties of $TiO_2$ nanofluid from ANN analyses, the numerical model is validated by means of a CFD program using the experimental smooth tube data as a case study and it is also solved in the CFD program for several micro-fin tubes as a simulation study. Temperature and velocity distributions are shown in the paper. Besides this, the values of experimental and numerical are compared with each other in terms of friction factors, shear stresses, convective heat transfer coefficients and pressure drops. Moreover, the effect of the presence of micro-fins in the inner surface of the test tube on the heat transfer characteristics is investigated in detail.

**Key Words**: Heat transfer coefficient, Pressure drop, ANN, Nanofluid, Single-phase flow, CFD

# ÖZET

## NANOPARTİKÜLLÜ TEK FAZLI AKIŞLARDA İÇ YÜZEYİ İYİLEŞTİRİLMİŞ BORULARIN ISI TRANSFER KARAKTERİSTİKLERİNİN NUMERİK OLARAK İNCELENMESİ

Nurullah KAYACI

Makine Mühendisliği Anabilim Dalı
Yüksek Lisans Tezi

Tez Danışmanı: Yrd. Doç. Dr. Ahmet Selim Dalkiliç

Bu çalışmada sabit duvar sıcaklığında pürüzsüz ve micro kanatlı boruların içinde dolaşan TiO2 nanoakışkanının zorlanmış taşınımı numerik olarak incelenmiştir. Pürüzsüz ve farklı helix açılarına sahip ($0^o$, $18^o$) mikro kanatlı boruların akışında, nanoakışkanların hidrodinamik ve ısı davranışını CFD programı yardımıyla belirlemek için 2 boyutlu denklemler içeren tek fazlı numerik model sabit ısı akısı veya degişken sıcaklık özelliği kullanılarak cözüldü.Bu çalışmada nanoakışkanların fiziksel özelliklerinin ($k$, $\mu$, $\rho$, $C_p$) belirlenmesinde geniş bir literature özeti verilmiştir.Literatürde olan korrelasyonlar arasında $TiO_2$ nanoakışkanının en uygun fiziksel özelliğin belirlenmesi için Yapay sinir ağları (ANN) methodu kullanılmıştır.ANN analizinden $TiO_2$ nanoakışkanının en iyi fiziksel özellikleri alındıktan sonra,deneysel pürüzsüz boru datalarını kullanarak CFD programında numeric model dogrulanmıştır ve bu model çeşitli micro kanatlı borular içinde similasyon çalışması olarak CFD programında çözülmüştür.borular içinde sıcaklık ve hız dağılımı bu çalışmada gösterilmiştir.Numerik ve deneysel çalışmalar sürtünme faktörlerine,kayma gerilmelerine,ısı transfer katsayılarına ve basınç düşümlerine göre birbirleri arasında karşılaştırılmıştır.test borusunun iç yüzeyindeki micro kanatların varlığının ısı transfer karakteristiğine etkisi detaylı olarak çalışılmıştır.

**Anahtar Kelimeler**: Isı transfer katsayısı, basınç düşümü, ANN, nanoakışkan, tek fazlı akış, CFD

# CHAPTER 1

# INTRODUCTION

Conventional heat transfer fluids (such as water, oil, and ethylene glycol mixture) restricts the enhancement of the performance and compactness of heat exchangers which are used in the electronic, automotive and aerospace industries because of their low thermal conductivity. One of the solutions to improve the thermal conductivity of a fluid is suspending small solid particles in the fluid. Thermal conductivity is an important parameter which expresses the heat transfer performance of a heat transfer fluid. Since the thermal conductivity of solid metals is higher than that of fluids, the suspended particles are expected to be able to increase the thermal conductivity and heat transfer performance. Experimental studies on the thermal conductivity of nanofluids are performed by many researchers. Slurries are formed by adding metallic, non-metallic and polymeric particles to fluids. Due to the fact that sizes of these suspended particles are in the millimeter scale, some of problems such as abrasion and clogging can be occurred. For that reason, these kinds of large particles cannot be alternative solution for heat transfer enhancement. Recently, the progresses in manufacturing technologies have made the production of particles in the nanometer scale possible (i.e., from 10 nm to 100 nm as particle diameter). These smaller sized particles allowed forming uniform and stable suspensions. Thus, the nanofluids provide higher heat transfer enhancement than existing techniques. The studies on the use of particles of nanometer dimension were first continuously conducted by a research group at the Argonne National Laboratory approximately a decade ago.

### 1.1 Literature Review

Choi [1] was probably the first one who called the fluids with particles of nanometer dimensions 'nano-fluids'. The term 'nanofluid' refers to a two-phase mixture usually composed of a continuous liquid phase and dispersed nanoparticles in suspension. Xuan and Li [2] stated that nanofluides are easily fluidized and can be nearly considered to behave as a fluid due to the tiny size of solid particles despite the two phase mixture specialty of them. For that reason, flow for nanofluids can be considered as single phase flow. Maxwell [3] assumed that the fluid phase and particles are in thermal equilibrium and moving with the same velocity in certain conditions considering the ultrafine and low volume fraction of the solid particles. The advantage of single phase flow is about its simplicity and required less computational time. It should be emphasized that physical properties of nanofluids have strong impact on experimental, numerical and theoretical solutions. The most well-known nanoparticles are $Al_2O_3$, CuO, $TiO_2$ and they are used by many researchers in their experimental works together with the base fluids of water and ethylene glycol. In terms of different sizes of the particles and types of base fluids, the enhancement of the thermal conductivity was obtained during all the experimental conditions.

Daungthongsuk and Wongwises [4] summarized the published subjects respect to the forced convective heat transfer of the nanofluids both of experimental and numerical investigation in their review paper. Daungthongsuk and Wongwises [5] reported that thermal conductivity of nanofluids increased with increasing nanofluid temperatures and, conversely, the viscosity of nanofluids decreased with increasing temperature of nanofluids. Duangthongsuk and Wongwises [6] studied a comparison of the differences between using measured and computed thermophysical properties to describe the heat transfer performance of $TiO_2$-water nanofluids. They reported that measurement of the thermophysical properties of nanofluids is an important way to address the transport behavior of nanofluids. Duangthongsuk and Wongwises [7] investigated an experimental study on the heat transfer performance and pressure drop of $TiO_2$-water nanofluids flowing under a turbulent flow regime. According to their study, they found that dispersion of the nanoparticles into the base liquid increases the thermal conductivity and viscosity of the nanofluids, and this augmentation increases with increasing particle concentrations. Daungthongsuk and Wongwises [8] reported an experimental study on the forced convective heat transfer and flow characteristics of a nanofluid consisting of water and 0.2 vol.% $TiO_2$ nanoparticles. According to their experimental results, the heat transfer coefficient of the nanofluid increases with an increase in the mass flow rate of the hot water and nanofluid, and increases with a decrease in the nanofluid temperature, and the temperature of the heating fluid has no significant effect on the heat transfer coefficient of the nanofluid. Duangthongsuk and Wongwises [9] studied the effect of thermophysical properties models on the predicting of the convective heat transfer coefficient for low concentration nanofluid. They reported that precise values of thermal and physical properties such as specific heat, viscosity and thermal conductivity of the nanofluids are required in order to study the heat transfer behavior of the nanofluids. Daungthongsuk et al. [10] presented an experimental study on the heat transfer and pressure drop characteristics of $Al_2O_3$-water nanofluids flowing through a microchannel heat sink (MCHS). The effects of Reynolds number and particle concentrations on the heat transfer and flow behavior are investigated. The results indicate that the heat transfer performance of MCHS increases with increasing Reynolds number as well as particle concentrations. Suriyawong and Wongwises [11] studied nucleate pool boiling heat transfer of $TiO_2$-water nanofluids experimentally. Nanofluids with various concentrations of 0.00005, 0.0001, 0.0005, 0.005, and 0.01 vol.% were employed in their study. The experiments were performed to explore the effects of nanofluids concentration as well as heating surface material and roughness on nucleate pool boiling characteristics and the heat transfer coefficient under ambient pressure. Their results showed that based on the copper heated surface which was tested with a concentration of 0.0001 vol.%, higher nucleate pool boiling heat transfer coefficient was obtained when compared with the base fluid. Trisaksri and Wongwises [12] investigated nucleate pool boiling heat transfer of a refrigerant-based-nano-fluid at different nanoparticle concentrations and pressures. $TiO_2$ nanoparticles were mixed with the refrigerant HCFC 141b at 0.01, 0.03 and 0.05 vol%. Pool boiling experiments of nano-fluid were conducted and compared with that of the base refrigerant. Their results indicated that the nucleate pool boiling heat transfer deteriorated with increasing particle concentrations, especially at high heat fluxes.

Dalkilic et al. [13-14] presented the theoretical flow models of homogeneous and separated flow applied to in-tube condensation to predict the pressure drop characteristics of R134a. Numerical analyses are performed to determine the average and local homogeneous wall shear stresses and friction factors by means of a CFD program [15]. The refrigerant side total pressure drops, frictional pressure drops, friction factors and wall shear stresses are determined within a ±30% error band. Demir et al. [16] investigated laminar and turbulent forced convection flows of a nanofluid consisting of water and $Al_2O_3$ particles in a horizontal smooth tube with constant wall temperature numerically. Their CFD [15] results show the heat transfer enhancement due to presence of the nanoparticles in the fluid. Demir et al. [17] studied numerically on the single phase forced convection heat transfer characteristics of $TiO_2$ nanofluids in a double-tube counter flow heat exchanger. In their paper, they used to Palm et al.'s [18] correlations to determine thermophysical properties of nanofluids. According to their study, CFD [15] results showed the heat transfer enhancement due to presence of the nanoparticles in the fluid in accordance with the results of the experimental study used for the validation process of the numerical model. Agra et al. [19] investigated the heat transfer and pressure drop characteristics of smooth, corrugated and helically finned tubes by using FLUENT CFD software [15] and GAMBIT software [15] was used to plot and mesh the model of the test tube. The problem under investigation is a two-dimensional (axisymmetric), steady, forced turbulent convection flow of water flowing inside straight and enhanced circular tubes. In their paper, numerical results were compared with experimental data and the Blasius equation. It was seen that the FLUENT CFD [15] program predicts the experimental data more accurately than Blasius equation does.

Balcilar et al. [20] used computational numerical methods such as ANN to determine compatibility between the most suitable coefficients of the correlations and the large number of experimental data. Bolat et al. [21] and Balcilar et al. [22] studied heat transfer characteristics in their analyses by means of ANN while input of the ANNs are the measured values of test section such as mass flux, heat flux, the temperature difference between the tube wall and saturation temperature, average vapor quality, while the outputs of the ANNs are the experimental condensation heat transfer coefficient and measured pressure drop in the analysis. Balcilar et al. [23-24] investigated the nucleate pool boiling heat transfer characteristics of $TiO_2$ nanofluids to determine the important parameters' effects on the heat transfer coefficient and also to have reliable empirical correlations based on the neural network analysis. In Balcilar et al. [25]'s paper, the condensation and evaporation pressure drops of R32, R125, R410A, R134a, R22, R502, R507a, R32/R134a (25/75 by wt%), R407C and R12 flowing inside various horizontal smooth and micro-fin tubes are predicted by means of the numerical techniques of Artificial Neural Networks (ANNs) and non-linear least squares (NLS). The total pressure drops of in-tube condensation and in-tube evaporation tests are modeled using the artificial neural network (ANN) method of multi-layer perceptron (MLP) with 12-40-1 architecture. Its average error rate is 7.085% considering the cross validation tests of 1485 evaporation and condensation data points.

## 1.2 Aim of Thesis

Heat transfer characteristics of the pure water and of water– $TiO_2$ nanofluid flow inside smooth tube for a validation study and micro-fin tubes for a simulation study with various volume concentrations are investigated for forced flow conditions by using two dimensional governing equations.

For the purpose of this study, the proven computational fluid dynamics (CFD) tools will make it much easier for researchers to analyze different geometrical configurations and various nanofluids without doing additional experimental studies after they perform their validation process on the experimental data**.**

## 1.3 Hypothesis

Over the years, many studies have focused on the development of a model to predict the heat transfer enhancement of nanofluids. In the present paper, almost all correlations in literature are tested to determine the most agreeable physical properties ($k$, $\mu$, $\rho$, $c_p$) of nanofluids with the experimental data. To determine the most suitable physical properties among correlations, an ANN model is developed using experimental results. It should be noted that there is no paper regarding the finding of the proper nanofluid's physical properties by ANN analyses in the literature. Smooth and micro-fin tubes are drawn in SOLIDWORKS [26] software and then imported into ANSYS Fluent [27] software for CFD analysis. Before the modeling process of micro-fin tube in CFD program, validation of the smooth tube model is performed using the agreeable physical properties obtained from ANN analyses and experimental data belonging to the forced convection of nanofluids consisting of $TiO_2$ particles regarding with the comparison of calculated and measured heat transfer coefficients and pressure drops. In addition to this, temperature and velocity distributions of inner surface and the fluids at the inlet and outlet sections of the tube, alteration of pressure drops, wall shear stresses and friction factors with particle concentrations, local heat transfer coefficients and pressure drops along the tubes are also obtained from the numerical study for smooth and microfin tubes. Besides this, the heat transfer enhancement and the increase in pressure drop due to the presence of microfins and nanofluids are also shown in the paper.

## CHAPTER 2

## BASIC CONCEPTS

### 2.1. Smooth Tubes

Flow in a tube can be laminar or turbulent; depending on the flow conditions.Fluid flow is streamlined and thus laminar at low velocities, but turns turbulent as the velocity is increased beyond a critical value. For flow in a circular tube, the Reynolds number is defined as

$$\mathrm{Re} = \frac{VD}{\nu} \tag{2.1}$$

Where V is the mean fluid velocity, D is the diameter of the tube, and $\nu$ is the kinematic viscosity of the fluid. Under most practical conditions, the flow in a tube is laminar for Re < 2300, turbulent for Re >10,000, and transitional in between. [28]

#### 2.1.1 Velocity, Pressure and Temperature Profiles

Not all fluid particles travel at the same velocity within a pipe. The shape of the velocity curve depends upon whether the flow is laminar or turbulent. If the flow in a pipe is laminar, the velocity distribution at a cross section will be parabolic in shape with the maximum velocity at the center being about twice the average velocity in the pipe. In turbulent flow, a fairly flat velocity distribution exists across the section of pipe. The velocity of the fluid in contact with the pipe wall is essentially zero and increases the further away from the wall. The velocity profile in the fully developed region is parabolic in laminar flow and somewhat flatter in turbulent flow due to eddy motion in radial direction [28], as shown Fig 2.1.

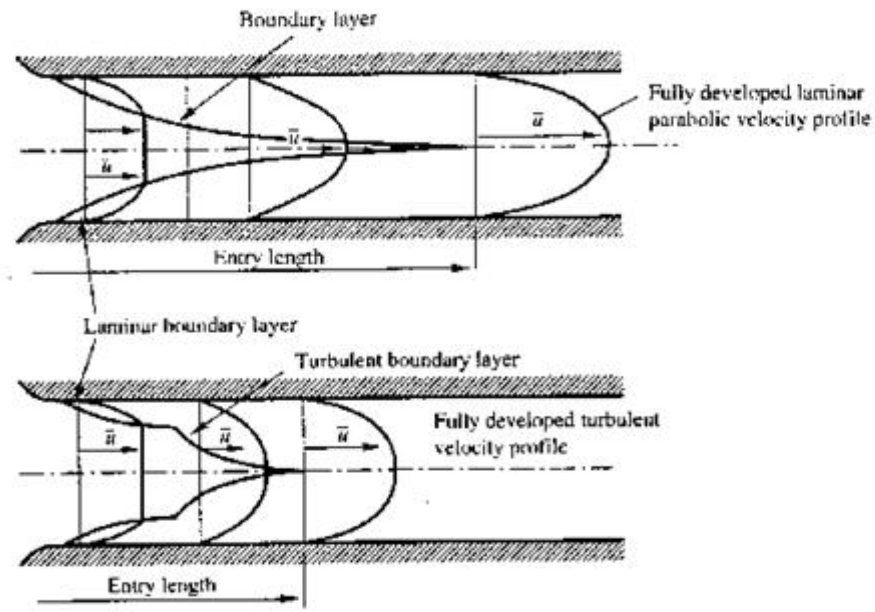



Fig 2.1 Velocity profiles in (a) laminar flow in (b) turbulent flow inside the smooth tube

It is easy to visualise that the forces acting upon the pipe flow are inertial, viscous force due to shear and the pressure forces. Let us ignore gravity, i.e., let the pipe be horizontal. When the flow is fully developed the pressure gradient and shear forces balance each other and the flow continues with a constant velocity profile. The pressure gradient remains constant. A balance is achieved with inertia, pressure and shear forces, as shown Fig 2.2.

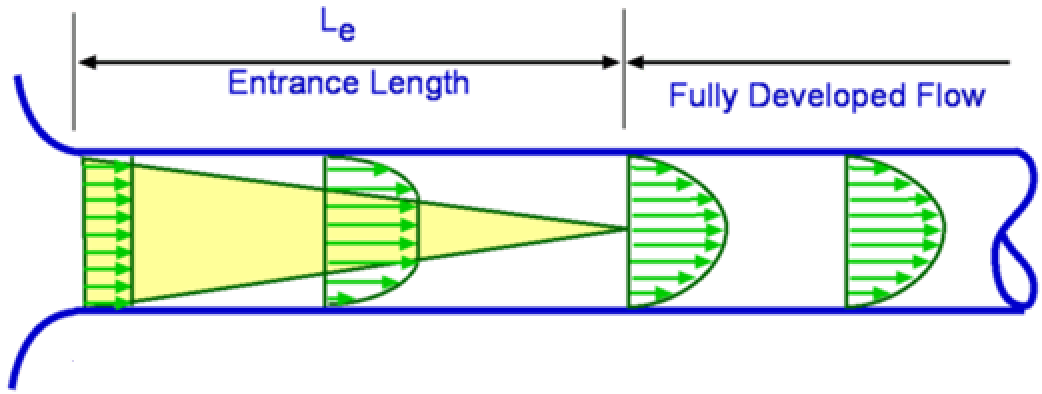



Fig 2.2 View of pressure profiles inside the smooth tube

Now consider a fluid at a uniform temperature entering a circular tube whose surface is maintained at a different temperature. This time, the fluid particles in the layer in contact with the surface of the tube will assume the surface temperature. This will initiate convection heat transfer in the tube and the development of a thermal boundary layer along the tube. The thickness of this boundary layer also increases in the flow direction until the boundary layer reaches the tube center and thus fills the entire tube. The region in which the flow is both hydrodynamically and thermally developed and thus both the velocity and dimensionless temperature profiles remain unchanged is called fully developed flow, as shown Fig 2.3.[28]

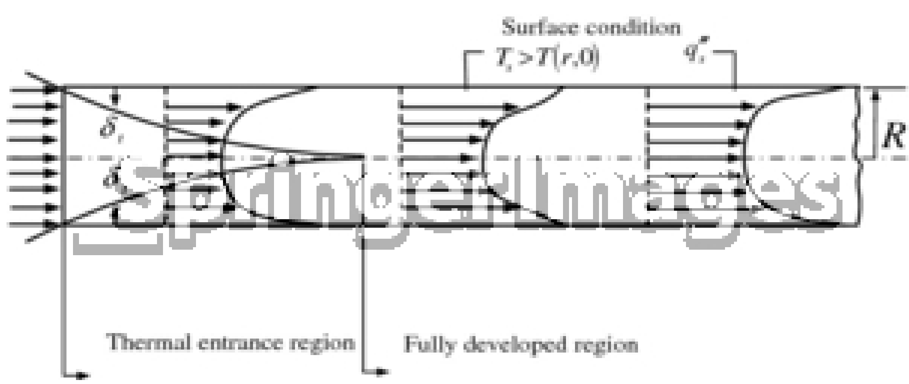



Fig 2.3 View of temperature profiles inside the smooth tube

### 2.1.2 Average Velocity

The fluid velocity in a tube changes from zero at the surface because of the no-slip condition, to a maximum at the tube center. Therefore, it is convenient to work with an average or mean velocity which remains constant for incompressible flow when the cross sectional area of the tube is constant. The value of the mean velocity in a tube is determined from the requirement that the conservation of mass principle be satisfied. That is [28]

$$\dot{m} = \rho V A = \int_A \rho V(r, x) dA \tag{2.2}$$

### 2.1.3 Pressure drop and Friction factor

Pressure drop is directly related to the power requirements of pump to maintain flow. Pressure drop and required pumping power are defined as

$$\Delta P = f \frac{\rho L}{D} \frac{V^2}{2} \tag{2.3}$$

$$W_{Pump} = \Delta P * Q \tag{2.4}$$

In fully developed region, friction factor is defined as in laminar flow,

$$f = \frac{64}{Re} \tag{2.5}$$

Friction factors are given below for smooth surfaces in turbulent flow [29],

$$f = 0.316 * Re^{-1/4} \qquad Re \leq 2 * 10^4 \tag{2.6}$$

$$f = 0.184 * Re^{-1/5} \qquad Re \geq 2 * 10^4 \tag{2.7}$$

Petukhov [30] found a formula for friction factor in turbulent flow,

$$f = (0.7904 InRe - 1.64)^{-2} \qquad 3000 \leq Re \leq 5 * 10^6 \tag{2.8}$$

By using Darcy friction factor, wall shear stress can be calculated as below,

$$\tau = \frac{f\rho V_{avg}^{2}}{8} \tag{2.9}$$

### 2.1.4 Thermal Analysis

Conservation of Energy principle is applied inside pipe flow that the increase in the energy of the fluid is equal to the heat transferred to the fluid from the tube surface by convection. Thus

$$Q = m * c_p * (T_{ave,e} - T_{ave,i}) \tag{2.10}$$

Newton's cooling law is written the heat transferred by convection;

$$Q = h * (T_w - T_{ave}) \tag{2.11}$$

It can be concluded this;

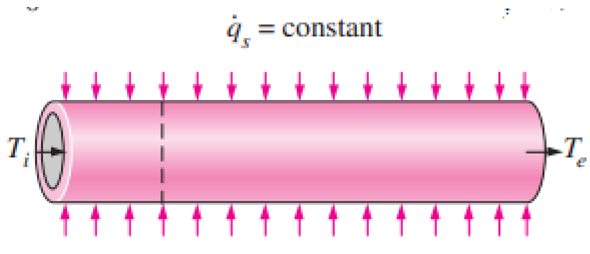
$$m * c_p * \left(T_{ave,e} - T_{ave,i}\right) = h * (T_w - T_{ave}) \tag{2.12}$$

It is investigated for laminar flow theory for two boundary conditions in fully developed region at a constant surface heat flux and constant surface temperature as shown in Fig 2.4.

$$Nu = \frac{hD}{k} = 4.36 \qquad q = constant \tag{2.13}$$

$$Nu = \frac{hD}{k} = 3.36 \qquad T_w = constant \tag{2.14}$$

a-)

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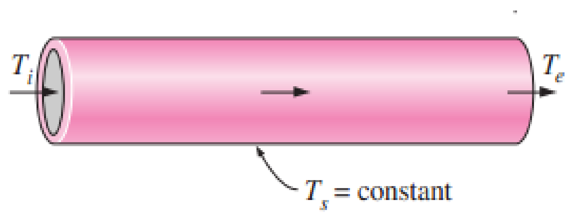



Fig 2.4 Views of (a) Constant surface heat flux (b) Constant surface temperature [29]

Sieder and Tate [31] proposed a correlation about Nusselt number in entry region .That is,

$$Nu = 1.86\left(\frac{Re\ Pr}{L/D}\right)^{0.33}\left(\frac{\mu}{\mu_i}\right)^{0.14} \qquad 0.48 < \text{Pr} < 16700 \tag{2.15}$$

Colburn [32] proposed a correlation for turbulent flow in fully developed region .That is,

$$Nu = 0.023\ Re^{0.8} Pr^{0.33} \tag{2.16}$$

Sieder and Tate [31] studied for turbulent flow in fully developed region. . This correlation is valid for Re>10000, 0.7< Pr <16700.

$$Nu = 1.86\, Re^{0.8} Pr^{0.33} \left(\frac{\mu}{\mu_i}\right)^{0.14} \qquad Re>10000, \quad 0.7< Pr <16700 \tag{2.17}$$

Petukhov [30] also showed for turbulent flow in fully developed region. This correlation is valid for $10^4<Re<5*10^6$, $0.7< Pr <16700$.

$$Nu = \frac{(f/8)\, Re\, Pr}{1.07 + 12.7(f/8)^{0.5}\,(Pr^{0.66} - 1)} \tag{2.18}$$

Gnielinski [33] also proposed for turbulent flow in fully developed region. This correlation is valid for $3000<Re<5*10^6$, $0.5< Pr <2000$ .

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{0.5}\,(Pr^{0.66} - 1)} \tag{2.19}$$

**2.2 Micro- Fin Tubes**

Tubes with rough surfaces have much higher heat transfer coefficient than tubes with smooooth surfaces.Therefore, tubes surfaces are often intentionally roughened,corrugated,or finned in order to enhance the convection heat transfer coefficient and thus the convection heat transfer rate. Heat transfer in turbulent flowin a tube has been increased by as much as 400 percent by roughening the surface. Roughening the surface, also increases friction factor and thus the power requirement for the pump or fan (as shown Fig 2.5). [28]

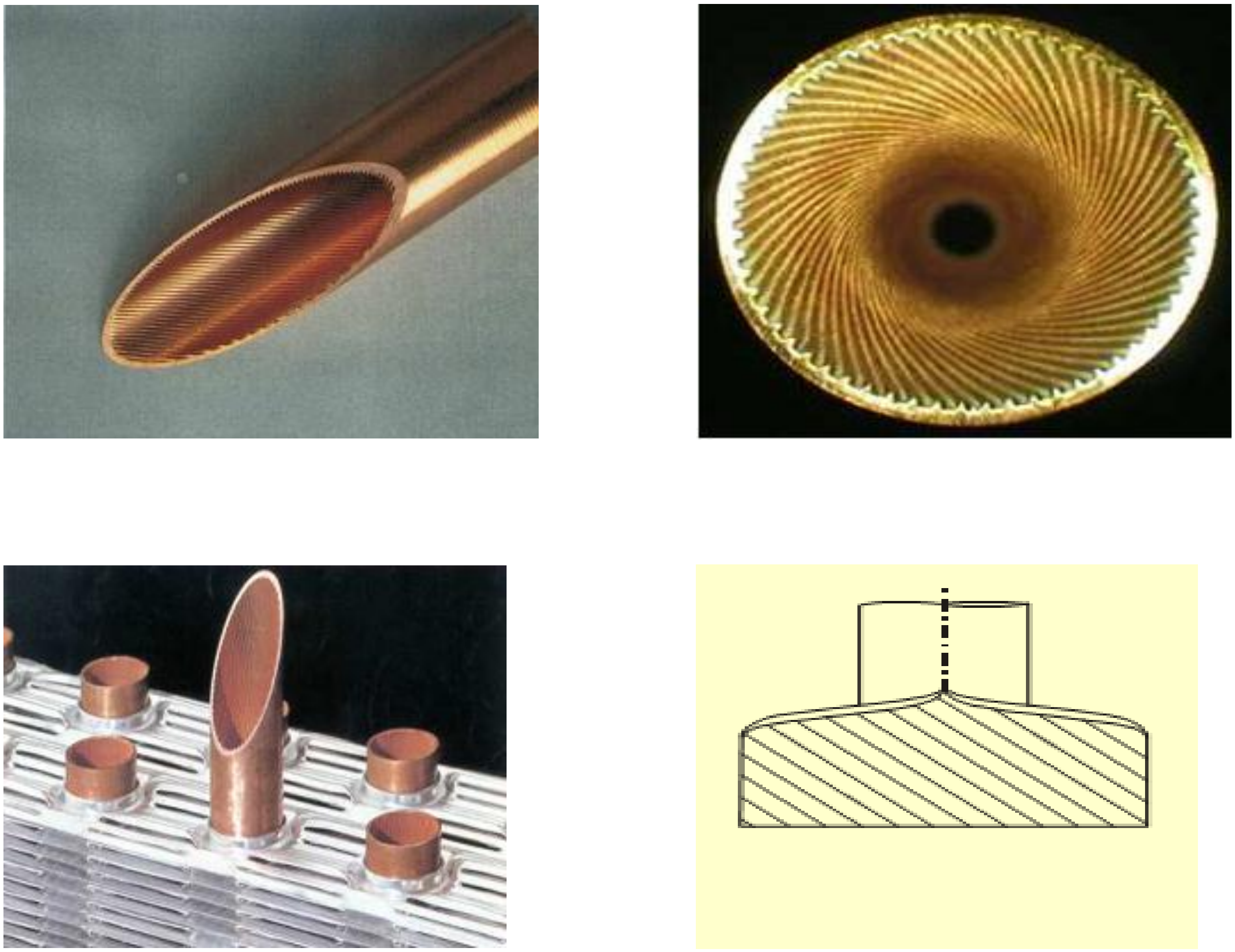


Fig 2.5 Views of helical micro-fin tubes[34]

### 2.2.1 Nusselt number and Friction factor correlations

Al-Fahed et al.[35] found in their study using a single micro-finned tube and the experimentally obtained data were correlated in a Sider–Tate type correlation,that is

$$Nu = 0.039Re^{0.8}Pr^{0.33}(\frac{\mu_b}{\mu_w})^{0.14} \ for\ 10000 < Re < 40000 \tag{2.20}$$

Chiou et al.[36] investigated using two microfinned tubes and the experimentally obtained data were correlated in a Dittus–Boelter type correlation, that is

$$Nu = 0.043Re^{0.8}Pr^{0.4} \ for\ 15000 < Re < 30000 \tag{2.21}$$

Copetti et al.[37] investigated using a single micro-finned tube and the experimentally obtained data were also correlated in a Dittus–Boelter type correlation, that is

$$Nu = 0.034Re^{1.1}Pr^{0.4} \;\; for\ 2300 < Re < 19500 \tag{2.22}$$

Siddique and Alhazmy[38] is studied turbulent single-phase flow and heat transfer inside a micro-finned tube experimentally and they correlated as;

$$Nu = 0.000354Re^{1.294}Pr^{0.403} \;\; for\ 3300 < Re < 22500\ , 2.9 < Pr < 4.7 \tag{2.23}$$

Ravigururajan and Bergles [39]

$$f_{RB} = f_{fi} * (1 + [29.1Re^{a1}\left(\frac{h}{d}\right)^{a2}\left(\frac{p}{d}\right)^{a3}\left(\frac{\gamma}{90}\right)^{a4}(1 + 1.47cos\theta)]^{15/16})^{16/15} \tag{2.24}$$

Where

$$f_{fi} = (1.58In\ Re - 3.28)^{-2} \tag{2.25}$$

$$a1 = 0.67 - 0.06\left(\frac{p}{d}\right) - 0.49 * \left(\frac{\gamma}{90}\right) \tag{2.26}$$

$$a2 = 1.37 - 0.157\left(\frac{p}{d}\right) \tag{2.27}$$

$$a3 = 1.66 * 10^{-6}Re - 0.33 * \left(\frac{\gamma}{90}\right) \tag{2.28}$$

$$a4 = 4.59 + 4.11 * 10^{-6}Re - 0.15\left(\frac{p}{d}\right) \tag{2.29}$$

Wang et al.[40]

$$h^{+} = \left(\frac{h}{d}\right) * Re * \sqrt{\frac{f_{Wa}}{2}} \tag{2.30}$$

Where

$$h^{+} = 0.1407 + 0.09367X_f + 0.58464/In(X_f) \text{ for } h^{+} < 23 \tag{2.31}$$

$$h^{+} = 0.07313 + 0.0951X_f \text{ for } h^{+} > 23 \tag{2.32}$$

$$X_f = Re\left(\frac{h}{d+\alpha}\right)n^{0.25}(sec\gamma)^{0.5} \quad \alpha = 0.019 \tag{2.33}$$

Cavallini et al.[41]

$$f_{cav} = \max(f_1, f_2) \tag{2.34}$$

Where

$$f_1 = \left(\frac{16}{Re}\right) \; for \; Re < 2000 \tag{2.35}$$

$$f_1 = (0.079Re^{-0.25}) \; for \; Re > 2000 \tag{2.36}$$

$$f_2 = 0.25(1.74 - 2\log\left(\frac{2k}{d}\right))^{-2} \tag{2.37}$$

$$\left(\frac{k}{d}\right) = 0.18(\frac{h}{d})(0.1 + cos\gamma)^{-1} \tag{2.38}$$

Al-Fahed et al.[35] investigated results for the isothermal micro-finned tube friction factors. The experimentally obtained friction factor data were correlated in a Blasius type correlation in the experimental data

$$f = 0.9978Re^{-0.2963} \tag{2.39}$$

# CHAPTER 3

# PREVIOUS STUDIES

## 3.1 Some studies of 2012

Alizad et al. [42] investigated thermal performance, transient behavior and operational start-up characteristics of flat-shaped heat pipes with using nanofluids. They used three different primary nanofluid of CuO, $Al_2O_3$, and $TiO_2$. They benefitted from a comprehensive analytical model which has detailed heat transfer characteristics inside inside the condensation and evaporation sections of the tube. The thermal performance of either the flat-plate or disk-shaped heat pipes were increased by higher concentration of nanoparticles.

Bobbo et al. [43] showed some viscosity data for nanofluids. They used water as base fluid and two different primary nanofluids such as single wall carbonnanohorn (SWCNH) and titanium dioxide ($TiO_2$). They determined viscosity of nanofluids using arhometer experimentally and benefitted from the function of the nanoparticles' mass fraction and the shear rate therefore they accounted the possible non-Newtonian behavior for the nanofluid. As a result, different empirical correlations were proposed in their study.

Buschmann [44] studied on ceramic nanofluid's thermal conductivity and heat transfer characteristics. He observed that heat transfer could be increased by using nano fluids in the thermal entrance with test rig. It is revealed that the thermal conductivity of five different ceramic nano fluids were measured by means of a sophisticated ring gap apparatus and the dynamic viscosity is enhanced successfully.

Yang et al. [45] enhanced the heat and mass transfer on the ammonia water absorption refrigeration system. They yielded three different nanofluids by inserting the mixture of carbon black with emulsifier OP-10, $ZnFe_2O_4$ with sodium dodecyl benzene sulfonate (SDBS), and $Fe_2O_3$ with SDBS to the ammonia water solution, respectively. It was found that key parameters for this study were the content of surfactant and nanoparticles, the interaction between surfactant and nano-particles, and the dispersion type were also one of the key parameters that affected the viscosity of ammonia water nanofluid. They correlated mainly two models to predict the viscosity of ammonia water nanofluid.

Colangelo et al. [46] intended to observe the diathermic oil based nanofluids which was used in many areas such as renewable energy, cogeneration and cooling systems. They used the diathermic oil with CuO, $Al_2O_3$, ZnO and Cu particles which had different shapes and concentrations from 0% to 3.0%. It was found that the heat transfer performance of diathermic oil was increased more than water for the same nanoparticle concentrations.

Jamshidi et al. [47] investigated the heat transfer rate and pressure drop in helical coils in their study. They assumed that nanofluid's thermophysical properties were independent from volume fraction and temperature. They utilized from a numerical simulation and Taguchi method to obtain the optimum condition for desired parameter values. Results showed that the use of nanofluids enhanced the thermal-hydraulic performance of helical tube. Although temperature dependent properties changed with the optimum particle volume fraction, nanofluids were not varied by the optimized shape factor.

Giraldo et al. [48] investigated the thermal behavior of a nanofluid loaded with alumina nanoparticles and they developed a direct numerical simulation of the flow. They utilized from the boundary element method to solve moving boundary problems. They observed that strong convective currents occurred as a result of the presence of the nanoparticles, which in time increased the total heat flow in the cavity particle concentration. Particle concentration increased the total heat flow influencing both the conductive part of heat transfer and the convective part expectedly.

Özerinç et al. [49] studied the application of some empirical correlations of forced convection heat transfer developed for the flow of pure fluids and nanofluids. They compared their results with existing theories in the literature and their model underestimated the heat transfer as a result of the numerical solution pointing that single-phase assumption with temperature-dependent thermal conductivity and thermal dispersion was the certain way of heat transfer enhancement analyses of nanofluids in convective heat transfer.

Yu et al. [50] investigated the thermophysical properties and convective heat transfer of $Al_2O_3$-polyalphaolefin (PAO) nanofluids which included not only the spherical but also the rod-like nanoparticles. They determined the viscosity and thermal conductivity of the nanofluids and compared their predictions with several existing theories in the literature. Their results showed that in a convective flow, the shear-induced alignment and specific motion of the particles should be regarded in order to truly interpret the experimental data of the nanofluids including non-spherical nanoparticles.

Farahani and Kowsary [51] intended to clarify a heat conduction method used for defining the local convective boiling heat transfer coefficient of pure water and copper based nanofluid flowing in a mini channel with utilizing three different concentrations of nanoparticles which were 5 mg/L, 10 mg/L and 50 mg/L. They tried to solve the IHCP using sequential specification function method and tried calculating the space-variable convective heat transfer coefficient. Their results showed that two dimensional SFS method could be preferred to have the optimum experiments for the determination of boiling heat transfer coefficients of pure water and nanofluid flowing in mini channel.

Cimpean and Pop [52] studied on the steady fully developed for mixed convection flow of a nanofluid in a channel filled with a porous medium. They used some equations to solve the problem that were non-dimensional and based on mainly the mixed convection parameter, the Péclet number, the inclination angle of the channel to the horizontal and the nanoparticle volume fraction. Their results showed that nanofluid greatly enhanced the heat transfer, even for small additions of nanoparticles in the base water fluid.

Leong et al [53] studied on the flow of nanofluids in shell and tube heat recovery exchangers in a biomass heating plant. They benefited from the literature that included heat exchanger specification, nanofluid properties and mathematical formulations. They found that using nanofluids augmented the convective and overall heat transfer coefficient compared to the ethylene glycol or water based fluids

Mahbubul et al. [54] investigated different characteristics of viscosity of nanofluids which contained nanofluid preparation methods, temperature, particle size and shape, and volume fraction effects. They found that viscosity's augmentation depended on volume concentration' increase and decrease of the temperature rise. They observed that viscosity improves with volume fraction for different concentration of $Al_2O_3$, $TiO_2$.

Wenzheng et al. [55] studied a Molecular Dynamics simulation on Couette flow of nanofluids and showed the microscopic flow characteristics through visual observation and statistic analysis. They presented the even-distributed liquid argon atoms near solid surfaces of nanoparticles could be appeared as a reform to base liquid and had contributed to heat transfer enhancement. Nanoparticles moved rapidly in the shear direction accompanying with motions of rotation and vibration in the other two directions in the process of Couette flow. The motions of nanoparticles were reinforced significantly when the shearing velocity was grown. More enhanced heat transferring in nanofluids was obtained the motions of nanoparticles could disturb the continuity of fluid and strengthen partial flowing around nanoparticles.

### 3.2 Some studies of 2011

Ahmed et al. [56] investigated the characteristics of heat transfer and pressure drop belonging to copper-water nanofluid flow in an isothermally heated corrugated channel. Their model includes the equations of continuity, momentum and energy for laminar flow in curvilinear coordinates using the Finite Difference (FD) approach. Reynolds number and nanoparticle volume fraction varied from 100 to 1000 and from 0 to 0.05 in their study, respectively. They studied the effects of using the nanofluid on the heat transfer and pressure drop inside the channel. Their results showed that increase in the volume fraction of the nanoparticle and Reynolds number caused both an increase in heat transfer enhancement and slightly increase in pressure drop. Their results revealed that increase in the volume fraction of the nanoparticle and Reynolds number caused both an increase in heat transfer enhancement and slightly increase in pressure drop.

Akbarinia et al. [57] investigated the heat transfer enhancement at low Reynolds numbers using $Al_2O_3$-water nanofluid flows in two-dimensional rectangular microchannels. Their results showed that not only the major enhancement in Nusselt number is not due to the increase in the nanoparticle concentrations but also it is due to the increase in the inlet velocity to reach a constant Reynolds number. They reported that constant Reynolds number studies of nanofluids have not sufficient approach to evaluate the heat transfer and the skin friction factor due to the use of nanofluids.

In Bianco et al. [58]' study, turbulent forced convection flow of water-$Al_2O_3$ nanofluid in a circular tube was calculated numerically depending on a constant and uniform heat flux at the wall. Their study was based on two different approaches: single and two-phase models, with particle diameter equal to 38 nm. It is calculated that convective heat transfer coefficient for nanofluids is greater than that of the base liquid. Their study showed that heat transfer enhancement increased with the particle volume concentration and Reynolds number. Comparisons with correlations in literature were carried out and a very good agreement was obtained.

Corcione [59] proposed two empirical correlations and discussed them for predicting the effective thermal conductivity and dynamic viscosity of nanofluids using a high number of experimental data available in the literature. It is observed that at the constant nanoparticle material and the base fluid, the ratio between the thermal conductivities of the nanofluid and the pure base liquid increased with increasing the nanoparticle volume fraction and the temperature, and decreasing the nanoparticle diameter. Moreover, the ratio between the dynamic viscosities of the nanofluid and the pure base liquid increased with increasing the nanoparticle volume fraction, and decreasing the nanoparticle diameter in the case of practically independent from the temperature.

Ehsan et al. [60] used nanoparticles to investigate the heat transfer mechanisms regarding with the thermal conductivity increase, brownian motion, dispersion, and fluctuation of nanoparticles especially near wall which leaded to increase in the energy exchange rates and augmented the heat transfer rate between the fluid and the wall of evaporator section. Their experimental results showed that addition of silver nanofluid in methanol leaded to energy saving around 8.8-31.5% for cooling and 18-100% for reheating the supply air stream in an air conditioning system.

Gherasim at al. [61] presented that heat transfer enhancement capabilities of coolants using suspended nanoparticles ($Al_2O_3$ dispersed in water) inside a confined impinging jet cooling device in their numerical study. A good agreement was found between numerical results and available experimental data. According to their study, heat transfer enhancement was possible in their application using nanofluids. It was observed that the mean Nusselt number increased with increasing particle volume fraction and Reynolds number and also it decreases with increasing in disk spacing. As a result of the study, a significant increase in pumping power may impose some limitations on the efficient use of this type of nanofluid in a radial flow configuration.

Hojjat et al. [62] investigated the forced convective heat transfer using dispersing $\gamma$-$Al_2O_3$, CuO, and $TiO_2$ nanoparticles in an aqueous solution of carboxymethyl cellulose (CMC) experimentally. Their experimental apparatus included a uniformly heated circular tube under turbulent flow conditions through of these nanofluids. Their results showed that the local and average heat transfer coefficients of nanofluids were larger than that of the base fluid. A new correlation was proposed for the prediction the Nusselt number of non-Newtonian nanofluids as a function of the Reynolds and the Prandtl numbers.

Hojjat et al. [63] used $\gamma$-$Al_2O_3$, $TiO_2$ and CuO nanoparticles in a 0.5 wt% of carboxymethyl cellulose (CMC) aqueous solution and calculated thermal conductivity of base fluid and nanofluids with various nanoparticle loadings at different temperatures experimentally. Their results showed that the thermal conductivity varied exponentially with the nanoparticle concentration. In their study, they developed an ANN model for the thermal conductivity as a function of the temperature.

Hojjat et al. [64] investigated the forced convection heat transfer of non-Newtonian nanofluids in a circular tube with constant wall temperature condition under turbulent flow conditions of three types of nanofluids ($\gamma$-$Al_2O_3$, $TiO_2$ and CuO nanoparticles) in the base fluid experimentally. Their base material was the aqueous solution of carboxymethyl cellulose (CMC). Their results showed that convective heat transfer coefficient of nanofluids was higher than that of the base fluid.

Huminic and Huminic [65-66] studied the heat transfer characteristics of two-phase closed thermosyphon (TPCT) with iron oxide-nanofluids. The TPCT with the de-ionic water and nanofluids (water and nanoparticles) were tested. Effects of TPCT inclination angle, operating temperature and nanoparticles concentration levels on the heat transfer characteristics of TPCT were considered. The nanoparticles have a significant effect on the enhancement of heat transfer characteristics of TPCT. The heat transfer characteristics of TPCT with the nanofluids were compared with the based fluid. Their experimental results focused on iron oxide-water nanofluid as the working fluid, heat transfer rate, evaporation and condensation heat transfer coefficients and thermal resistances. Different nanoparticle concentration levels in suspension within the two-phase closed thermosyphon, operating temperatures and inclination angles of the heat pipe (30-$90^0$) were experimentally examined and results were compared with pure water.

Jung et al. [67] developed binary nanofluids using nanoparticle suspensions to enhance the heat and mass transfer performance of absorption refrigeration cycles. To stabilize the nanoparticles in a strong electrolyte, polymer was used as a steric stabilizer. The effective thermal conductivities of the binary nanofluids with the concentrations of nanoparticle up to 0.1 vol% were measured by means of the transient hot wire method. In this study, it was found that the dispersion stability of nanofluids was a dominant factor for enhancing the thermal conductivity of binary nanofluids while thermal conductivity was changing with time. It was also obtained that thermal conductivity of $H_2O$/LiBr binary mixture with $Al_2O_3$ nanoparticles increased with increasing the particle volume concentration and it was enhanced at 2.2% at 0.1 vol% concentration conditions.

Khanafer and Vafai [68] presented a study related with the critical synthesis of the variants within the thermophysical properties of nanofluids. This study showed that it was not clear which analytical model should be used to describe the thermal conductivity of nanofluids. Their results showed that the effective thermal conductivity and viscosity of nanofluids could be estimated using the classical equations at low volume fractions.

Lee et al [69] determined the transmission of electron microscopy and scan of electron microscope images for characterizing the shape and size of SiC nanoparticles. The dispersion behavior for SiC/deionized water (DIW) nanofluids were investigated under different pH values and characterized with the zeta potential values. The isoelectric point of SiC/DIW nanofluid was determined concerning colloidal stability. Thermal conductivity and viscosity as a function of volume fraction was investigated.

Asirvatham et al. [70] performed experiments to investigate the convective heat transfer of nanofluids using silver-water nanofluids under laminar, transition and turbulent flow regimes in a horizontal 4.3 mm inner-diameter tube-in-tube counter-current heat transfer test section. The volume concentration of the nanoparticles varied from 0.3% to 0.9% in steps of 0.3%, and the effects of thermo-physical properties, inlet temperature, volume concentration, and mass flow rate on heat transfer coefficient were investigated. Experiments showed that the suspended nanoparticles remarkably increased the convective heat transfer coefficient, by as much as 28.7% and 69.3% for 0.3% and 0.9% of silver content, respectively. Heat transfer coefficient clearly augments with increasing the combination of particle loading and Reynolds numbers. Based on the experimental results, a correlation was developed to predict the Nusselt number of the silver-water nanofluid, within ±10% deviation band between experimental and predicted values.

Ebrahimnia-Bajestan [71] presented a numerical investigation on the heat transfer performance and pressure drop of nanofluids flowing through a straight circular pipe during laminar flow regime and constant heat flux boundary condition. $Al_2O_3$, CuO, carbon nanotube (CNT) and titanate nanotube (TNT) nanoparticles dispersed in water and ethylene glycol/water with particle concentrations ranging between 0 and 6 vol.% were used as working fluids for simulating the heat transfer and flow behaviours of nanofluids. The proposed model has been validated with the available experimental data and correlations. The effects of particle concentrations, particle diameter, particles' Brownian motions, Reynolds number, type of the nanoparticles and base fluid on the heat transfer coefficient and pressure drop of nanofluids were determined and discussed in detail. The results indicated that the particle volume concentration, Brownian motion and aspect ratio of nanoparticles increased the heat transfer coefficient while the nanoparticle diameter had an opposite effect on the heat transfer coefficient.. Finally, the present study provided some considerations for the appropriate choice of the nanofluids for practical applications.

Raisi et al. [72] studied numerically method for both slip and no-slip boundary conditions in the thermal performance of a microchannel, cooled with either pure water or a Cu-water nanofluid on the flow field and heat transfer .they assumed that the microchannel is partially heated at a constant temperature and cooled by forced convection of a laminar flow at a relatively lower temperature. The effects of pertinent parameters such as Reynolds number, solid volume fraction, and slip velocity coefficient on the thermal performance of the microchannel are investigated. The heat transfer rate is significantly affected by the solid volume fraction and slip velocity coefficient at high Reynolds numbers.

Heris et al. [73] studied numerically laminar flow-forced convective heat transfer of Al2O3/water nanofluid in a triangular duct under constant wall temperature condition. The effects of parameters are investigated such as nanoparticles diameter, concentration, and Reynolds number on the enhancement of nanofluids heat transfer. They compared heat transfer between nanofluid and pure fluid. In non-circular ducts the low heat transfer rate is one the limitations of these systems and use of nanofluid instead of pure fluid because of its potential to increase heat transfer of system can compensate this problem. They obtained that the nanofluid Nusselt number increases with increasing concentration of nanoparticles and decreasing diameter. Also, the enhancement of the fluid heat transfer becomes better at high Re in laminar flow with the addition of nanoparticles.

Bianco et al. [74] studied numerically developing turbulent forced convection flow of a water-Al2O3 nanofluid in a square tube in constant and uniform wall heat flux. The particles size is used in nanofluid flow equal to 38 nm. The optimal working condition is obtained an entropy generation analysis for the given geometry under given boundary conditions. A simple analytical procedure is proposed to evaluate the entropy generation and its results are compared with the numerical calculations. The optimal Reynolds number is determined when minimize entropy generation.

Demir et al. [17] investigated forced convection flows of nanofluids consisting of water with $TiO_2$ and $Al_2O_3$ nanoparticles in a horizontal tube with constant wall temperature are investigated numerically. The horizontal test section is modeled and solved using a CFD program. Palm et al.'s correlations are used to determine the nanofluid properties. A single-phase model having two-dimensional equations is employed with either constant or temperature dependent properties to study the hydrodynamics and thermal behaviors of the nanofluid flow. The numerical investigation is performed for a constant particle size of $Al_2O_3$ as a case study after the validation of its model by means of the experimental data of Duangthongsuk and Wongwises with $TiO_2$ nanoparticles. The velocity and temperature vectors are presented in the entrance and fully developed region. The variations of the fluid temperature, local heat transfer coefficient and pressure drop along tube length are shown in the paper. Effects of nanoparticles concentration and Reynolds number on the wall shear stress, Nusselt number, heat transfer coefficient and pressure drop are presented. Numerical results show the heat transfer enhancement due to presence of the nanoparticles in the fluid in accordance with the results of the experimental study used for the validation process of the numerical model.

### 3.3 Some studies of 2010

Nanoparticles of magnetite $Fe_3O_4$ have been synthesized at various pH values by a method of co-precipitation in Maryam et al [75]'s study. The characteristic properties of the products were determined by transmission electronic microscopy, Fourier infrared spectroscopy and X-ray diffraction. By using a vibrating sample magnetometer, the magnetic properties of the products were found. According to the obtained results, particles were cubic in shape and they exhibit super paramagnetic properties at room temperature. $Fe_3O_4$ nanoparticles were dispersed in water as a base fluid in the presence of a dispersant which was tetramethyl ammonium hydroxide and so the magnetic nanofluids were prepared. As a function of temperature and volume fraction, the thermal conductivity of the nanofluids was measured. The thermal conductivity values of the nanofluids were obtained in terms of volume fraction and temperature. It is shown by the results that an increase in the thermal conductivity ratio of the nanofluids results in an increase in temperature and volume fraction. It is also observed that the thermal conductivity is increased by 11.5% at most at $40^oC$ for the nanofluid which have 3vol% nano particles. The thermal conductivity is increased by 11.5% at most at $40^oC$ for the nanofluids which have 3vol% nano particles because of the Brownian motion of nanoparticles intensifies at high temperatures. Then the experimental results were evaluated and discussed according to the theoretical models.

Under turbulent flow conditions, the measurement of heat transfer characteristics of Gama-$Al_2O_3$ and $TiO_2$/water nanofluids were performed in a shell and tube heat exchanger in Farajollahi et al [76]'s study. It is investigated how the heat characteristics were affected by Peclet number, volume concentration of suspended nanoparticles, and particle type. According to the obtained results, after the nanoparticles were added to the base fluid, heat transfer characteristics were significantly enhanced. When the heat transfer behavior of two nanofluid was compared, it was found that at a definite Peclet number, $TiO_2$/water nanofluid showed greater heat transfer characteristics at its optimum nanoparticle concentration than the heat transfer characteristics of Gama-$Al_2O_3$/water nanofluid. However, heat transfer behavior at higher nanoparticle concentrations of Gama-$Al_2O_3$/water nanofluid was better.

By using a CFD approach, under constant wall temperature condition in a circular tube, the laminar convective heat transfer of nanofluids was studied in a numerical way in Fard et al [77]'s study. Single phase and two-phase models were used for the determination of the temperature, flow field, and calculation of heat transfer coefficient. The effects of some important parameters such as nanoparticle sources, nanoparticle volume fraction and nanofluid's Peclet number on heat transfer rate were investigated. According to their results, as the particle concentration increased, heat transfer coefficient also increased. According to their simulation results, it was seen that when their model was compared to the single phase model, better predictions for heat transfer rate was obtained from the two phase approach.

According to Do et al. [78]'s study, thermal performance of nanofluids were investigated by testing circular screen mesh of wick heat pipes experimentally. In their study, water-based $Al_2O_3$ nanofluids were used by the volume fraction of 1.0 and 3.0 vol.%. According to their study, the use of water based $Al_2O_3$ nanofluids instead of DI water can accomplish the maximum heat transfer rate of pipe. The thin porous coating layer formed by nanoparticles suspended in nanofluids at wick structures were observed experimentally. It was observed that the coating layer formed by nanoparticles at the evaporator section was the primary mechanism on the enhancement of the thermal performance for the heat pipe due to the fact that the layer can not only extend the evaporation surface with high heat transfer performance but also improve the surface wettability and capillary wicking performance.

According to Henderson et al [79]'s study, the experiments were performed at low vapor quality ($x<20\%$) with a specific range of mass flux ($100<G<400$ kg/m$^2$s) for the flow boiling of R-134a and R134a/polyolester mixtures. By using direct dispersion of $SiO_2$ nanoparticles in R-134a, when compared with pure R-134a, it was seen that the heat transfer coefficient decreased as much as 55%. This degradation was stemmed from, partly, the difficulties in producing a stable dispersion. It was concluded that nanoparticles affected the flow pressure drop insignificantly with the R-134a/POE/CuO nanofluid.

According to Godson et al [80]'s study, the unique features of nanofluids, such as enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Brownian motion, thermophoresis, etc. were summarized. Additionally, the recent research in experimental and theoretical studies on forced and free convective heat transfer in nanofluids, their thermo-physical properties and their applications are summarized, and this article identifies the challenges and opportunities for future research.

In Kim et al [81]'s study, it was shown that prior studies of pool boiling have demonstrated that nanofluids can improve critical heat flux (CHF) by as much as 200 %. It was observed that heat transfer coefficient increased with increasing mass and heat flux during flow boiling. Test section was examined by a confocal microscopy and this technique showed that nanoparticle deposition was occurred on the boiling surface. The number of micro cavities on the surface, and also the surface wettability was changed by this deposition. In order to estimate the ensuing nucleation site density changes, a simple model was used; however, a successful correlation between the nucleation site density and the heat transfer coefficient could not be obtained.

In Lotfi et al. [82]'s study, water and $Al_2O_3$ nanoparticle mixtures under forced convective condition was studied numerically. Agreeable correlations of computed results were validated. Eullerian model was implemented to study for two phase flow field as a first study in the literature. The two-phase and single phase models were used in the mixture model formulation. According to calculated experimental values, the mixture model was more precise. It should be noted that Nusselt numbers for single-phase model and the two-phase Eulerian model could not be predicted accurately in the study.

In Meibodi et al. [83]'s study, modeling of the thermal conductivity of the suspensions was done by means of the resistance model approach. In this model, Brownian motion and interfacial layer and also a new mechanism were considered. They reported that this model may be used without any adjustable parameter for estimating the upper and lower limits of nanofluid thermal conductivity. Data of thermal conductivity for CuO nanofluids were acquired experimentally and according to the results, proposed model was consistent with the data. Their model was used to detect the various mechanisms' portions on the thermal conductivity of nanofluids. The results were found to be compatible with the basic knowledge about nanofluids' thermal conductivity mechanism.

According to the theory in Meibodi et al. [84]'s study, convective heat transfer coefficient depends on the parameters of velocity and temperature profiles. Within this study, friction factor and convection coefficient were utilized to compare the profiles for both nanofluids and base fluids. In order to reach this aim, $Al_2O_3$/water and carbon nanotube/water were preferred. It is demonstrated that the velocity profile of a nanofluid was similar to the velocity profile of its base fluid. It was suggested that the only responsible variable for unpredictable convective heat transfer coefficient of nanofluids was the alteration of temperature profile for nanofluids.

In Meibodi et al. [85]' study, thermal conductivity and stability of carbon nanotube (CNT)/water mixture nanofluid were investigated and also proposed an optimum condition for the production and application of nanofluids. They revealed that there are a lot of parameters such as size, shape and source of nanoparticles, surfactants, power of ultrasonic, time of ultrasonication, elapsed time after ultrasonication, pH, temperature, particle concentration and surfactant concentration, which affect this property. It was demonstrated that significant factors on the thermal conductivity and stability were not precisely similar to one another.

Paul et al. [86-87] presented various techniques for the measurement of nanofluid thermal conductivity and developed a unique thermal conductivity measurement device propped up the thermal comparator principle. The constructional details have been elaborated as well. They completed this work with some suggestions to enhance the reliability of the measurement of thermal conductivity. Their results indicated that they benefited from the transient hot-wire technique for measuring thermal conductivity..

Qu et al. [88] analyzed the thermal performance of an oscillating heat pipe (OHP) which contained the effects of filling ratios, mass fractions of alumina particles, and power inputs loaded with base water and spherical $Al_2O_3$ particles of 56 nm in diameter. It was found that the alumina nanofluids developed the OHP's thermal performance, with an optimal mass fraction of 0.9 wt.% for maximal heat transfer increase. When the input power was 58.8 W at 70% filling ratio and 0.9% mass fraction, the maximal thermal resistance was decreased by 0.14 °C/W (or 32.5%) in comparison to the pure water.

Rao [89] presented a brief overview of the important scientific disciplines about nanofluids which contain stability properties, phase diagram, rheology and applications. He informed about future development of this area.

Raykar and Singh [90] investigated to estimate the effective thermal conductivity (ETC) of CNT nanofluids by means of a differential effective medium theory together with Brownian motion. Their results showed that augmentation of ETC, correlated with Brownian motion, was greater in dilute nanofluids remarkably.

Roberts and Walker [91] studied on the mixture of alumina/water's performance of different volume loadings using a commercially available electronics cooling system. Their results indicated that convective heat transfer increased thanks to the addition of nanoparticles in the commercial cooling system with nanoparticles' volume loadings up to 1.5% by volume. They also observed nanoparticle suspensions from hours to weeks depending on the particle's size.

Rostamani et al. [92] investigated the turbulent flow of nanofluids with different volume concentrations of nanoparticles which were copper oxide (CuO), alumina ($Al_2O_3$) and oxide titanium ($TiO_2$) flowing along two-dimensional duct under constant heat flux condition numerically. They used water as based fluid. It was found that when the volume concentration had increased the wall shear stress and heat transfer rates augmented. The wall shear stress increases with increasing volume concentrations for $TiO_2$-water nanofluid. Also the wall shear stress is shown to compare for three different nanofluids at the Reynolds number of 40,000 and 3% volume concentration. Nusselt number was affected better from CuO nanoparticles than $Al_2O_3$ and $TiO_2$ nanoparticles to get a constant volume concentration and Reynolds number.

Singh et al. [93] analyzed entropy generation owing to the flow and heat transfer by using nanofluids theoretically. They used alumina-water nanofluids and mainly three diameters of tube such as a microchannel (0.1 mm), a minichannel (1 mm) and a conventional channel (10 mm) for the sensitivity of entropy. Their results showed that entropy generation behaviour of nanofluids in the microchannel and conventional channel were estimated accurately by the reduced equation with the help of order of magnitude analysis. In conclusion, they reported the existence of an optimum diameter at which the entropy generation rate was the minimum for a specific nanofluid during both laminar and turbulent flow.

Sundar and Sharma [94] studied on the measurement of thermal conductivity and viscosity of $Al_2O_3$ nanofluid via experiments at different volume concentrations and temperatures and verification of them. Researchers used a plain tube and with twisted tape insert and tried to obtain the convective heat transfer coefficient and friction factor at various volume concentrations experimentally. According to the results, the heat transfer coefficient and friction factor, which had 0.5% volume concentration of nanofluid and twist ratio of five conditions, increased heat transfer and friction factor 33.51% and 1.096 times respectively in comparison to the base fluid of water.

Vajjha et al. [95] developed new correlations for the determination of convective heat transfer and the friction factor. They used nanoparticles which contained aluminum oxide, copper oxide and silicon dioxide dispersed in 60% ethylene glycol and 40% water by mass. Researchers measured the properties in the fully developed turbulent regime for the mentioned three nanofluids at several particle volumetric concentrations. They calculated the rheological and the thermophysical properties contained viscosity, density, specific heat and thermal conductivity primarily and then utilized form these properties to improve new correlation as a function of these properties and the particle volumetric concentration.

Vajjha et al [96] analyzed three-dimensional laminar flow and heat transfer with some mixtures which contained $Al_2O_3$ and CuO particles/ethylene glycol and water and also compared these fluids' performance to the base fluid. They developed a new correlation which was about the determination of viscosity and thermal conductivity of nanofluids as a function of particle volumetric concentration and temperature. It was found that the heat transfer coefficient and the friction factor augmentation increased with increasing nanofluids' volumetric concentrations at several Reynolds numbers.

Wei et al [97] investigated the chemical solution method to produce $CuS/Cu_2S$ nanofluids and tried to obtain their thermal conductivity. They mentioned the increase or decrease of the thermal conductivity of nanofluids with proper references.

Wei and Wang [98] presented a microfluidic chemical solution technique, to produce Cu nanofluids. The method changed batch-based macro reactors in the conventional chemical solution method by continuous-flow microfluidic micro reactors, thus they provided the production of nanofluids with several microstructures. The results showed that when Cu nanofluids produced by this technique, they have higher stability performance even after more than 100 h.

Yang and Lai [99] benefited a single-phase approach and focused on creating mathematical model to simulate the forced convection flow of $Al_2O_3$-water nanofluid in the radial flow cooling system. They indicated that the heat transfer coefficient augmentation depended on increasing of the Reynolds number and the nanoparticle volume fraction, but the pressure drop increase is more remarkably related with the increase of particle concentration.

Yu et al. [100] investigated preparation of stable ethylene glycol based copper nanofluids via a two-step method. They utilized polyvinyl pyrrolidone as dispersant which can remain stable for a long term. They observed that thermal conductivity significantly increased for the determined nanofluids. The results showed that they achieved %46 increase for the enhancement ratio under 0.5 vol.% at 50 °C conditions. In addition, they suggested 15 min waiting time at least for getting correct thermal conductivities of ethylene glycol based copper nanofluids.

The applied areas and developing process of nanofluids are summarized by Wong and Leon [101 ]'s review paper thoroughly. Their paper emphases the current and future applications of nanofluids as heat transfer applications (industrial cooling applications, smart fluids, nuclear reactors, extraction of geothermal power and other energy sources), automotive applications (nanofluid coolant, nanofluid in fuel, brake and other vehicular nanofluids), electronic applications (cooling of microchips), biomedical applications (nanodrug delivery, cancer theraupetics, cryopreservation, nanocryosurgery, sensing and imaging) and other applications (nanofluid detergent) generally and they also mentioned the increased heat transfer properties by means of nanofluids which make them appropriate for such applications.

### 3.4 Some studies of 2009

Bergman [102] studied laminar, internal forced convection by using nanofluids. The work was including the descriptions of nanofluid's specific heat experimentally and explaining their two effects. One of them was about the increased thermal conductivity and the other was the reduced specific heat of the nanofluid in comparison to its base liquid. To measure heat transfer augmentation, he presented a dimensionless effectiveness number to observe the nanofluid's performance and compared with base fluid. The results were illustrated the use of different nanofluids can either increase or decrease thermal performance.

Bianco et al. [103] investigated a numerical method in laminar forced convection flow of a water-$Al_2O_3$ nanofluid in a circular tube used to have a constant and uniform heat flux at the wall. The work was examined a single and two-phase model by employing with either constant or temperature-dependent properties. The size of particles was 100 nm. The maximum difference between single and two-phase models regarding results was about 11% in the average heat transfer coefficient. Nanofluids` convective heat transfer coefficient was higher than that of its base liquid. The particle volume concentration increased the heat transfer enhancement but it increased wall shear stress values at the same time. In their study, temperature dependents models had higher heat transfer coefficients and lower shear stresses. They found that the heat transfer always increased with increasing both Reynolds number and shear stress.

He et al. [104] studied numerically single phase method and combined it with Euler and Lagrange method on the convective heat transfer of $TiO_2$ nanofluids which were flowing through a straight tube under the laminar flow conditions. They researched the effects of nanoparticles' concentrations, Reynolds number, and various nanoparticle sizes on the flow and the convective heat transfer behavior. It was found that heat transfer of nanofluids increased importantly in the entrance region. The numerical results were in good agreement with the experimental data and a reasonable good agreement was accomplished.

Hwang et al. [105] quantified the pressure drop and convective heat transfer coefficient of water-based $Al_2O_3$ nanofluids flowing through a uniformly heated circular tube in the fully developed laminar flow regime. According to the experimental results, they found a good agreement with analytical predictions from the Darcy's equation for single-phase flow for the nanofluid's friction factor. They illustrated the flattening of velocity profile, induced from large gradients in bulk properties such as nanoparticle concentration, thermal conductivity and viscosity in numerical solutions. It was suggested that this flattening of velocity profile had a suitable mechanism for the convective heat transfer coefficient enhancement exceeding the thermal conductivity enhancement.

Jung et al. [106] quantitated convective heat transfer coefficient and friction factor of nanofluids in rectangular microchannels. They studied experimentally the effect of the volume fraction of the nanoparticles on the convective heat transfer and fluid flow in microchannels where Aluminum dioxides (Al2O3) with diameter of 170 nm nanofluids at different particle volume fractions were flowing. They measured the convective heat transfer coefficient of the $Al_2O_3$ nanofluid in laminar flow regime and it increased up to 32% comparing with the distilled water at a volume fraction of 1.8 volume percent without friction loss. It was established that the measured Nusselt number increased with increasing the Reynolds number in laminar flow regime. The measured Nusselt number was correlated with Reynolds number and Prandtl number by virtue of the thermal conductivity of nanofluids which came out to be less than 0.5.

Kakaç and Pramuanjaroenkij [107] achieved literature research works on convective heat transfer on the enhancement of heat transfer of nanofluids. The objective of their review study was to collect the significant published articles on the enhancement of the forced convection heat transfer of nanofluids.

Kim et al. [108] showed to examine the effect of nanofluids on convective heat transfer experimentally through a circular straight tube with a constant heat flux condition in the laminar and turbulent flow regime. They studied the effects of thermal conductivity and supernatant nanoparticles of the nanofluids on convective heat transfer under different flow regimes. Thermal conductivity and convective heat transfer coefficient was increased up 8% and 20% respectively, in alumina nanofluids including 3 vol% of suspended particles. They said that the thermal conductivity of nanofluids was similar to that of water, and the convective heat transfer coefficient increased by only 8% in laminar flow in amorphous carbonic nanofluids. It was determined that the augmentation of the convective heat transfer was much greater than that of the thermal conductivity of nanofluids on account of the movements of nanoparticles at the entrance region.

Kulkarni et al. [109] investigated measurements of convective heat transfer and viscosity of nanofluids, and estimated how they performed heating buildings in cold regions. They perfromed experimental works using copper oxide, aluminum oxide and silicon dioxide nanofluids, each in an ethylene glycol and water mixture. They performed some calculations for conventional finned-tube heat exchangers utilizing in buildings in cold regions. The use of nanofluids in heat exchangers decreased volumetric and mass flow rates and resulted in an overall pumping power savings in their study. It was found that the use of nanofluids to heat buildings decreased the size of the heat transfer system and reduced the accompanying pressure loss and the subsequent pumping power. It is observed that the volume concentration increases with the nanofluid viscosity at a specific temperature.

Mintsa et al. [110] indicated that they researched the effects of particle volume fraction, temperature and particle size to measure the effective thermal conductivity of alumina/water and copper oxide/water nanofluids. Readings at ambient temperature as well as over a relatively large temperature range were performed for different particle volume fractions up to 9%. As a result, they obtained an increase in the effective thermal conductivity with an increase in particle volume fraction and with a decrease in particle size. Also, the relative increase in thermal conductivity was understood to be more at high temperatures.

Murshed et al. [111] researched a combined static and dynamic mechanisms based on a model for anticipating the effective thermal conductivity of nanofluids. In their study, the model incorporated the effects of particle size, nanolayer, Brownian motion, particle surface chemistry and interaction potential which were about the static and dynamic mechanisms responsible for the enhanced effective thermal conductivity of nanofluids. Also, the model had logically a good agreement with the experimental results of various types of nanofluids

Namburu et al. [112] studied a numerical analysis of turbulent flow and heat transfer of three different nanofluids (CuO, $Al_2O_3$ and $SiO_2$) in an ethylene glycol and water mixture flowing through a circular tube under constant heat flux condition. They correlated new correlations for viscosity up to 10% volume concentration for these nanofluids as a function of volume concentration and temperature from the experiments. They found out that calculation results had formalized with existing well known correlations. They obtained that nanofluids including smaller diameter nanoparticles have higher viscosity and Nusselt number. They compared the convective heat transfer coefficients of CuO, $Al_2O_3$ and $SiO_2$ nanofluids with each other. They said that Nusselt number improved by 35% for 6% CuO nanofluids over the base fluid at a constant Reynolds number.

Rea et al. [113] studied on laminar convective heat transfer and viscous pressure loss of alumina-water and zirconia-water nanofluids in a flow loop with a vertical heated tube. They observed that the heat transfer coefficients of entrance region and fully developed region increased as 17% and 27%, respectively, for alumina-water nanofluid at 6 vol % according to pure water. Furthermore, the zirconia-water nanofluid's heat transfer coefficient increased as 2% in the entrance region and 3% in the fully developed region at 1.32 vol %. They found that the measured pressure loss for the nanofluids was in general much greater than for pure water .It was indicated the measured nanofluid's heat transfer coefficient and pressure loss were in good agreement with the conventional model predictions of laminar flow.

Pantzali et al. [114] studied the efficiency of nanofluids as coolants. Nanoparticles were mixed for testing nanofluid's thermophysical properties. They used a typical nanofluid, namely a 4% CuO suspension in water and investigated nanofluid's performance in a commercial herringbone-type PHE experimentally. They showed the type of flow inside the heat exchanger equipment and also influence on the efficiency of a nanofluid as coolant. The heat exchanger performance depended on the fluid viscosity due to its significance. They obtained that large volumes of nanofluids were necessary and reported that turbulent flow was usually developed in industrial heat exchangers.

Xie and Chen [115] produced homogeneous and stable nanofluids using suspended and well dispersible multi-walled carbon nanotubes (CNTs) into ethylene glycol base fluid. They said that CNT nanofluids improved the thermal conductivity and the enhancement ratios increased with increasing the nanotube loading and the temperature. Their work showed that the straightness ratio, aspect ratio and aggregation had collective effect on the thermal conductivity of CNT nanofluids.

Pantzali at al. [116] investigated the effect of the use of a nanofluid in a miniature plate heat exchanger (PHE) with modulated surface both experimentally and numerically. Firstly, they worked on thermophysical properties (i.e., thermal conductivity, heat capacity, viscosity, density and surface tension) of a typical nanofluid (CuO in water, 4% v/v).Then The effect of surface modulation on heat transfer augmentation and friction losses were researched by simulating the existing miniature PHE as well as a notional similar PHE with flat plate using a CFD code. Conclusively, they studied the effect of the nanofluid on the PHE performance in comparison to that of a conventional cooling fluid (i.e., water). As a result of t heir study, the required nanofluid volumetric flow rate for a given heat duty was lower than that of water causing lower pressure drop. Shortly, they concluded that use of smaller equipment and less pumping power were required. Besides, when the total volume of the equipment was the main issue, use of the nanofluids seemed to be a promising solution towards designing efficient heat exchanging systems. The only disadvantages were the high price and the possible instability of the nanoparticle suspensions.

Vajjha and Das [117] investigated the determination of the thermal conductivity of three nanofluids comprising aluminum oxide, copper oxide and zinc oxide nanoparticles dispersed in a base fluid of 60:40 (by mass) ethylene glycol and water mixture. According to evaluated particle volumetric concentration, it was up to 10% and the temperature range of the experiments was varied from 298 to 363 K. Their results indicated an increase in the thermal conductivity of nanofluids compared to the base fluids with an increasing volumetric concentration of nanoparticles. In parallel with the thermal conductivity, it also increased substantially with an increase in temperature. They used their experimental data for comparisons with various existing models to determine thermal conductivity. They developed a model which was a refinement of an existing model, and it incorporated the classical Maxwell model and the Brownian motion effect to account for the thermal conductivity of nanofluids as a function of temperature, particle volumetric concentration, the properties of nanoparticles, and the base fluid with these experimental data.

Wen at al. [118] carried out a critical review of research on heat transfer applications of nanofluids with the aim of identifying the limiting factors so as to push forward their further development.

Hadjov [119] studied spherical nanoparticles with a conductive interface in the self-consisted scheme for forecasting the thermal conductivity of nanofluids. They adopted a flux jump in the particle-fluid interface opposite to the assumption for temperature jump in the case of thermal barrier resistance. Upper and lower bounds to the homogenized suspension thermal conductivity were gained by their working to the particle packing.

Ali et al. [120] studied numerically two-dimensional turbulent convective heat transfer behavior of alumina nanoparticle dispersion in water flow in a horizontal circular pipe at constant wall temperature. The finite-volume method is employed and the full range of flow at the entrance length and the fully developed are considered. They showed that the shear stress are observed to increase at any x station along the pipe as the concentration of nanoparticle increase and it achieves its higher value at the beginning of the pipe at the entrance region and then drops to an asymptotic value at the fully developed region. When the velocity increases both Nusselt number and the shear stress increase.as a result Reynolds number is observed to decrease as the concentration increase at fixed inlet velocity.

### 3.5 Some studies of 2008

Bi et al. [121] studied with nanoparticles in the working fluid for observing domestic refrigerator's reliability and performance. They utilized from mineral oil/$TiO_2$ nanoparticle mixtures such as the lubricant instead of Polyol-ester (POE) oil in the 1,1,1,2-tetrafluoroethane (HFC134a) refrigerator. Researchers analyzed that the refrigerator performance with the use of nanoparticles was enhanced regarding with the energy consumption and freeze capacity. Their results showed that HFC134a and mineral oil with $TiO_2$ nanoparticles worked normally and securely in the refrigerator. They also observed that the refrigerator had higher performance than the HFC134a and POE oil system, and the use of nanoparticles with 0.1% mass fraction reduced energy consumption 26.1% compared to the HFC134a and POE oil system.

Hwang et al. [122] tested homogeneous dispersion of nanoparticles in nanofluids. They investigated various physical treatment techniques based on two step methods which contained ultrasonic bath, ultrasonic disruptor and high-pressure homogenizer to confirm their versatility for preparing stable nanofluids. They used CB (carbon black) and Ag nanoparticles with the diameter of 330nm to 585nm. Their results indicated that Ag nanoparticle, which was generated by the modified magnetron sputtering system, dispersed homogeneously and sustained their stability in the silicon oil based fluid.

Karthikeyan et al. [123] studied on synthesizing of CuO nanoparticles that have average diameter of 8 nm using a simple precipitation technique and observed thermal properties of the suspensions. They utilized from water and ethylene glycol as based fluids and 1 vol.% CuO nanoparticles. Their results showed that thermal conductivity increased with increasing finer particle size and monodispersity of nanoparticles. They found some results from experiments that thermal conductivity affected from the nanoparticles size, polydispersity, cluster size and the volume fraction of particles significantly.

Khandekar et al. [124] studied on a closed two-phase thermosyphon's overall thermal resistance. They selected pure water and various water based nanofluids (of $Al_2O_3$, CuO and laponite clay) as working fluids. The results indicated that all these nanofluids had worse thermal performance than pure water. In addition to all nanofluids on copper substrate, which had the same average roughness as that of the thermo syphon container pipe, had greater than that of pure water.

Lee et al. [125] synthesized and characterized aqueous nanofluids including low volume concentrations of $Al_2O_3$ nanoparticles from 0.01 to 0.3 vol.%. Their results pointed out that alumina nanoparticles had the highest dispersion and stabilization performance in DI water at 5 h of ultrasonic vibration out. They observed that the temperature increased with decreasing the $Al_2O_3$-water nano fluids' viscosity. In addition, $Al_2O_3$-water nano fluids' viscosity indicated a nonlinear correlation with the concentration even in the low volume concentration (from 0.01 to 0.3 vol.%.).

Murshed et al. [126] searched the existing theories in the literature on the determination of nanofluids' properties such as synthesis methods, potential application areas, experimental and analytical studies on the effective thermal conductivity, effective thermal diffusivity, convective heat transfer, and electrokinetic properties and compared them with each other.

Oh et al. [127] investigated 3-omega (3 w) method which is new application to measure the thermal conductivity of nanofluids and they give information about it. Their new theoretical model was proposed instead of the transient hot wire method for the determination thermal conductivity. They tested the effective thermal conductivity of $Al_2O_3$ nanofluids in DI water and EG at room temperature. Furthermore, thermal response showed interesting effects owing to agglomeration and sedimentation of nanoparticles.

Kang et al. [128] studied on measuring the vapor absorption rate and heat transfer rate for falling film flow of binary nanofluids which were tested at the same conditions with pure water, and they tried to observe the changes of heat and mass transfer. They used some parameters such as base fluid concentration of LiBr, the concentration of nanoparticles in weight %, and nano-particle constituents. They prepared the mixture of $H_2O$/LiBr solution with nanoparticles of Fe and Carbon nanotubes (CNT). Their results illustrated that the mass transfer increase was more than the heat transfer augmentation in the binary nanofluids with Fe and CNT and the properties of mass transfer of CNT nanoparticles was better than Fe nanoparticles.

Lu and Fan [129] studied on molecular dynamics (MD) simulation method which was applicable for a stationary nanofluids of the volume fractions less than 8%. They used this method to simulate nanofluids' thermophysical properties which included thermal conductivity and viscosity. They compared experimental data with numerical results and obtained good results. They found it very useful to estimate some thermal properties of nanofluids. Their results also showed that thermal conductivity and the viscosity of nanofluids depended on the volume fraction and the size of nanoparticles.

Nguyen et al. [130] focused on the temperature and particle volume concentration's impact on the dynamic viscosity for the water-$Al_2O_3$ mixture experimentally. They benefited from piston-type device which was commercial viscometer for temperatures in room condition. Their results indicated an enhancement on the nanofluid dynamic viscosity respectably with particle volume fraction; however temperature increase had a negative effect on it.

Chen et al. [131] presented the properties of the effective thermal conductivity, their rheological behavior and forced convective heat transfer of the nanofluids. They found that thermal conductivity increased as 3% at 25 °C and 5% at 40 °C for the 2.5 wt.% nanofluid. They observed that nanofluids including spherical titanium nanoparticles had better properties of thermal conductivity and convective heat transfer coefficient. They also suggested new systems to increase the convective heat transfer coefficient.

### 3.6 Some studies of 2007

Ding et al. [132] studied on the forced convective heat transfer using aqueous and ethylene glycol-based spherical titanium nanofluids, and aqueous-based titanate nanotubes, carbon nanotubes and nano-diamond nanofluids experimentally. They accomplished to formulate these nanofluid's specifications. They indicated that all the formulated nanofluids performed a higher effective thermal conductivity than that of predicted by the conventional theories. Apart from the ethylene glycol-based titanium nanofluids, all other nanofluids were observed to be non-Newtonian. They said that the convective heat transfer coefficient enhancement was higher than the thermal conduction enhancement substantially. However, they indicated deterioration of the convective heat transfer for ethylene glycol-based titanium nanofluids at low Reynolds numbers. They recommended on the effective thermal conductivity to be responsible for the experimental observations.

Zhang et al. [133] accomplished to measure the effective thermal conductivity and thermal diffusivity of Au/toluene, $Al_2O_3$/water, $TiO_2$/water, CuO/water and CNT/water nanofluids by utilizing from the transient short-hot-wire technique. In their study, the average diameters of Au, $Al_2O_3$, $TiO_2$ and CuO spherical particles were 1.65, 20, 40 and 33 nm, respectively .Also the average length and diameter of CNFs were 10 lm and 150 nm, respectively. According to their measured results, the effective thermal conductivities of the nanofluids indicated no abnormal enhancements.

Ko et al. [134] published an experimental investigation on the flow characteristics of the aqueous suspensions of carbon nanotubes (CNTs). They used to measure pressure drop to obtain stable nanotube suspensions by utilizing two methods. They studied the effects of CNT loading and various preparation methods and measured the pressure drops in a horizontal tube and viscosities of nanofluids. They found that the CNT nanofluids prepared by the acid treatment have much smaller viscosity than the ones made with surfactant at the same volume fraction. They indicated that the friction factor of stabilized CNT nanofluids (by adding surfactant) was much greater than that of CNT nanofluids prepared by acid treatment, and nanofluids had greater friction factors than distilled water under laminar flow conditions. Inversely, it was found that the friction factors of nanofluids were similar to that of the base fluids as the flow rate improved under turbulent flow conditions. They noticed that nanofluids had low friction factors than pure water flows at definite range of flow rates.

Mansour et al. [135] studied the uncertainty impacts regarding with the physical properties of water-$Al_2O_3$ nanofluid on the determination of the thermohydraulic performance for both laminar and turbulent fully developed forced convection in a tube with uniform wall heat flux. They reported that many experimental data were necessary to determine the real potential of nanofluid

Hong at al. [136] firstly reported that the thermal conductivity (TC) and heat transfer of nanofluids could be enhanced by the external magnetic field. The nanofluids contained carbon nanotubes (CNTs) and magnetic-field-sensitive nanoparticles of $Fe_2O_3$. The sensible explanation for these interesting determinations was that the $Fe_2O_3$ particles formed aligned chains under applied magnetic field and it helped to connect the nanotubes. In that magnetic field, the particles slowly moved and formed large clumps of particles, and caused clumping of CNTs, then decreased the TC.

Li and Peterson [137] pointed out that the Brownian motion of the nanoparticles in these suspensions was one of the potential contributors t to this enhancement and the mechanisms that could contribute to this subject of considerable discussion and debate. The mixing effect of the base fluid in the immediate vicinity of the nanoparticles caused by the Brownian motion was examined, modeled also compared with the experimental data in the literature. Moreover, simulation results showed that the effective thermal conductivity of nanofluids was affected by this mixing effect.

Yoo at al. [138] prepared some nanofluids including $T_iO_2$, $Al_2O_3$, $F_e$, and $WO_3$compounds in a two-step procedure by dispersing in a base fluid. The transient hot wire method was used for the calculation of thermal conductivity. These nanofluids' thermal conductivities were analyzed and compared with each other.

Avsec and Oblak [139] proposed a mathematical model for the calculation of thermophysical properties of nanofluids on the basis of statistical nanomechanics. In this study, they indicated two calculation methods to describe the properties such as classical and statistical mechanics. It was stated that the classical mechanics had no insight into the microstructure of the substance. On the other hand, it calculates the properties of state both on the basis of molecular motions in a space and on the basis of the intermolecular interactions. On the contrary to the classical mechanics, they suggested that the statistical mechanics calculated the thermomechanic properties of state on the basis of intermolecular interactions between particles in the same system of molecules. According to them, it means that the systems composed of a very large number of particles. The results of the analysis were compared with experimental data and indicated a relatively good agreement.

He et al. [140] studied different particle (agglomerate) sizes in stable aqueous $TiO_2$ nanofluids and they calculated their static thermal conductivity and rheological behavior. Heat transfer and flow behavior were investigated in a vertical pipe during both laminar and turbulent flow regimes. Thermal conduction increased with addition of nanoparticles into the base liquid but decreased with increasing particle (agglomerate) size. Increasing particle (agglomerate) size and particle concentration caused to grow the constant viscosity. In both the laminar and turbulent flow regimes, convective heat transfer coefficient increased with increasing nanoparticle concentrations

Lee and Mudawar [141] studied experimentally water-based nanofluids containing small concentrations of $Al_2O_3$ in the micro-channel cooling. They investigated the high thermal conductivity of nanoparticles in the single-phase heat transfer coefficient, especially for laminar flow. In the entrance region of micro-channels, maximum heat transfer coefficients were obtained. Greater sensitivity to heat flux was caused by higher concentrations.

Wang and Mujumdar [142] reviewed convective heat transfer using suspensions of nanometer-sized solid particles in base liquids. The transport properties and heat transfer characteristics of the suspension were found to be dependable to the suspended nanoparticles markedly.

### 3.7 Some studies of 2006

Hwang et al. [143] showed the higher effective thermal conductivity of nanofluid consisting of nanoparticles dispersed in base fluid than its pure fluid. They used four kinds of nanofluids including multiwalled carbon nanotube (MWCNT) in water, CuO in water, $SiO_2$ in water, and CuO in ethylene glycol. They used transient hot-wire method to measure the thermal conductivities. They reported that the increase in thermal conductivity enhancement of water-based MWCNT nanofluid was 11.3% at a volume fraction of 0.01. According to their results, the thermal conductivities of both particles and the base fluid affect the thermal conductivity enhancement of nanofluids.

Hwang et al. [144] used the nanoparticles of multi-walled carbon nanotube (MWCNT), fullerene, copper oxide, silicon dioxide and silver to improve the thermal conductivity and lubrication. DI water, ethylene glycol, oil, silicon oil and poly-a-olefin oil (PAO) were the base fluids. They measured the thermal conductivity and kinematic viscosity to investigate the thermo-physical properties of nanofluids. UV-vis spectrophotometer is used to check the stability estimation of nanofluid. They found that the increase in particle volume fraction has a positive effect on the increase in thermal conductivity of nanofluid increases with increasing particle volume fraction.

Liu et al. [145] presented a study on the enhancement of the thermal conductivity of water in the presence of copper (Cu) using the chemical reduction method. They reported that their method was used firstly for the synthesis of nanofluids containing Cu nanoparticles in water. Their results showed that Cu-water nanofluids having low concentration of nanoparticles had higher thermal conductivities than the water base fluid without Cu. Beside this, thermal conductivity was improved up to 23.8% for Cu nanoparticles at a volume fraction of 0.001 (0.1 vol.%).

Palm et al. [146] investigated the heat transfer enhancement capabilities of coolants' laminar forced convection flow with suspended metallic nanoparticles inside typical radial flow cooling systems. They obtained significant heat transfer enhancement with the use of these fluid/solid particle mixtures. They also indicated the important differences between the use of constant property nanofluids (temperature independent) and nanofluids with temperature dependent properties.

Heris et al. [147] investigated the laminar flow convective heat transfer of nanofluids containing CuO and $Al_2O_3$ oxide nanoparticles in water through circular tube with constant wall temperature boundary condition. They showed experimentally that homogeneous model should be used for the prediction of nanofluids properties regarding with the determination of the single phase heat transfer coefficient enhancement. $Al_2O_3$-water nanofluids have higher heat transfer enhancement during the increase in the volume fraction.

### 3.8 Some studies of 2005

Xuan et al. [148] determined heat transfer process and flow properties of Cu-water nanofluid flowing inside a channel by using the thermal Lattice Boltzmann model. Because it took into consideration the molecular dynamics and bridged the gap of macroscopic or microscopic challenge of the nanofluids, this method had an important advantage. Two existing methods are used for application of this method to model the thermal fluid flow problem. They are the multispeed (MS) and the double-distribution-function (DDF).In this study, double-distribution-function (DDF) was used and led to two separate distribution functions as follow:_The temperature is treated as a passive diffusing scalar, and it is simulated by a distribution function independent of density distribution, respectively. The feature point of the Lattice Boltzmann method is the assumption that the particles are mesoscopically located at a series of lattices and their distributions correspond to the Boltzmann distribution. The viscosity dissipation term in the Lattice Boltzmann equation for energy transport was neglected in order to simulate heat transfer characteristics of the nanofluid. According to numerical results, for 1% volume fraction the Nusselt number of Cu-water nanofluid was 27% higher than that of pure water at the same Reynolds number. Furthermore, random motion of the particles suspended in the fluid may be seen along the main flow direction because of fluctuations of the Nusselt number of the nanofluid.

Liu et al. [149] studied thermal conductivity enhancements in ethylene glycol and synthetic engine oil using multiwalled carbon nanotubes (MWNTs). The volume concentration of CNT-ethylene glycol suspensions and synthetic engine oil suspensions were below 1.0 and 2.0 vol.% respectively. They used a modified transient hot wire method to measure the thermal conductivities of the CNT suspensions and observed significant increase in CNT-ethylene glycol suspensions' thermal conductivities in comparison to the ethylene glycol base fluid without CNT. They noted that CNT–synthetic engine oil suspensions have the similar results with CNT-ethylene glycol suspensions. They obtained 12.4% enhancement on thermal conductivity for CNT-ethylene glycol suspensions at a volume fraction of 0.01 (1 vol.%) and 30% enhancement at a volume fraction of 0.02 (2 vol.%) for CNT-synthetic engine oil suspension, thermal conductivity is enhanced by 30% at a volume fraction of 0.02 (2 vol.%). As a result of their analysis, the thermal conductivity ratio of CNT-synthetic engine oil suspension has a noticeably higher value than the CNT-ethylene glycol suspension.

Maiga et al. [150] used two particular geometrical configurations, namely a uniformly heated tube and a system of parallel, coaxial and heated disks to study the laminar forced convection flow of nanofluids numerically. They used the mixtures of water-$\gamma Al_2O_3$ and Ethylene Glycol-$\gamma Al_2O_3$ and obtained a significant increase in the heat transfer coefficient in the presence of nanoparticles dispersed into the base fluids. They also showed that the heat transfer coefficient increases with increasing the particle concentration which has severe effects on the wall shear stress that increases considerably with the particle loading. The Ethylene Glycol-$\gamma Al_2O_3$ nanofluids have a better heat transfer enhancement and adverse effects on the wall shear stress than water-$\gamma Al_2O_3$.

### 3.9 Some studies of 2004

Wen and Ding [151] performed experiments in order to calculate the convective heat transfer coefficient of $\gamma$-$Al_2O_3$ nanoparticles suspended in deionized water in a copper tube for laminar flow. Under a constant wall heat flux condition, nanoparticles having 0.6 %, 1.0 %, and 1.6 % concentrations are tested in their study. In the experiments, straight copper tube with 4.5±0.02 mm inner diameter, 6.4±0.05 mm outer diameter and 970 mm length was used as a test section. A silicon rubber flexible having 300W heating capacity was used to maintain a constant heat flux boundary condition. A peristaltic pump was used to deliver a maximum flow rate of 10 l/min. The flow rate was controlled by adjusting rotational speed of the pump. Sodium dodecylbenzene sulfonate (SDBS) was used as a dispersant in order to stabilize the nanoparticles.

Maiga et al. [152] reported numerical method and a mathematical formulation for water-$\gamma Al_2O_3$ and ethylene glycol-$\gamma Al_2O_3$ to determine the forced convective heat transfer and wall shear stress for the laminar and turbulent regions of water-$\gamma Al_2O_3$ and ethylene glycol-$\gamma Al_2O_3$ flowing inside a uniformly heated tube. The solid-liquid mixture was considered as a single-phase, so the slip velocity between the phases was neglected. Moreover, symmetry in flow and the local thermal equilibrium of the mixture were considered. In order to define heat flux and stresses of the nanofluids for the turbulent flow, the Reynolds-averaged Navier-Stokes equation and $\kappa$-$\varepsilon$ turbulent model were used.In the numerical simulations, the heated tube having 0.01m diameter and 1.0 m length was used. The conditions of laminar flow were as follows: the Reynolds number was fixed at 250 and the constant heat flux was varied between 10-250 $W/m^2$. The conditions of turbulent flow were as follows: the constant heat flux was fixed at 500,000 $W/m^2$ and the Reynolds number was varied in the range of 10,000-50,000.

Roy et al. [153] performed a numerical investigation to analyze the heat transfer and wall shear stress for radial laminar flow in a cooling system of water-$\gamma Al_2O_3$ nanofluids compared with some base fluids such as water, glycol, and oil. All assumptions used in this study were similar to Maiga et al. [117] and took the nanofluid at an incompressible fluid.

Nguyen et al. [154] introduced a numerical simulation to determine the efficiency of water-$\gamma Al_2O_3$ and ethylene glycol-$\gamma Al_2O_3$ nanofluids for the cooling of a high-heat output microprocessor under laminar forced flow inside a heat sink. The simulation set-up comprised of a 50x50x10 mm rectangular slot having a 3x48 mm fluid flow cross-section. In this article assumptions were uniform velocity and temperature profile at the inlet section and laminar flow. The contact area for exchange heat was 10x10 mm. The numerical results showed that Reynolds number and the volume fraction were mainly parameters effecting average heat transfer coefficient of nanofluids and ethylene glycol-$\gamma Al_2O_3$ nanofluid had higher heat transfer coefficient than the water-$\gamma Al_2O_3$ nanofluid.

Ali et al. [155] reported the mathematical and numerical formulation to determine heat and mass transfer between air and falling solution film in a cross-flow heat exchanger for the dehumidification and cooling process. Effect of Cu nanoparticles to the heat and mass transfer process were tested by adding them into the solution. In this study, two models from literature were used. Moreover, the assumptions of this article were laminar and steady state flow, constant film thickness, thermal properties of the air and the solution are constant except for the thermal conductivity of the solution, gravitational force of the air is neglected, fully developed velocity profile for fluids. According to results of the study, the dehumidification and cooling process increased with high Cu particle volume fraction, low air Reynolds number, decreases in the channel width, increases in the height and length of the channel. In addition, it was revealed that an increase in Cu volume fraction led to more stability of the solution.

Ali and Vafai [156] suggested the numerical and mathematical formulations in order to analyze the effects of the inclination angel of parallel-and-counter-flow on heat and mass transfer between air and falling desiccant film having Cu nanoparticles suspended. As they used the same assumptions in the two approach models in the previous paper. Then, the simulated conditions used in this study are low and high air Reynolds number for the inclined parallel flow arrangement and low and high air Reynolds number for the inclined counter flow configuration.

Zhu et al. [157] developed a method for the preparation of copper nanofluids using the base fluid of ethylene glycol with $CuSO_4 \cdot 5H_2O$ with $NaH_2PO_2 \cdot H_2O$ under microwave irradiation. They investigated the effects of $CuSO_4$ concentration with the additive of $NaH_2PO_2$ and microwave irradiation on the reaction rate and the properties of Cu nanofluids by transmission electron microscopy, infrared analysis, and sedimentation measurements. They obtained nonagglomerated and stably suspended Cu nanofluids at the end of their analysis.

### 3.10 Some studies of 2003 and previous studies

Li and Xuan [158] and Xuan and Li [159] used an experimental set up in order to determine the convective heat transfer coefficient and friction factor parameters of nanofluids for laminar and turbulent flow in a tube. Deionized water with a dispersion of Cu particles with under 100 nm diameter was used in this study. The effect of the nanoparticle concentration on the heat transfer coefficient was determined for different particle volume percentages which are 0.3, 0.5, 0.8, 1, 1.5 and 2%.The Reynolds number of the nanofluids varied between 800 and 25,000. The experimental set up was consisted of a test section, a pipeline, a pump, a cooler, a fluid collection and a reservoir tank. A straight brass tube having 800mm length and 10mm inner diameter was used and a 3.5kW electric heater was placed to test section in order to get a constant wall heat flux boundary condition. A fatty acid was used to prevent the aggregation of the nanoparticles in the base fluid.

Xuan and Li [159] suggested a method for preparing some nanofluid samples and presented theoretical study of thermal conductivity.  The transient hot-wire method was used for measurements in their study. In order to determine the heat transfer performance of nanofluids flowing in a tube, they

proposed a single phase or dispersion model. Cu particles having 100 nm diameter were used as nanoparticles where base fluids are water and mineral oil. The particles in the mineral oil and water were stabilized by using oleic acid and laureate salt respectively. For Cu-mineral oil, suspension stabilization time was nearly 1 week and suspension had no sedimentation with a fill of 22 wt%. For Cu-water, suspension with 9 wt% laureate salt, vibrated by an ultrasonic vibrator, the results indicated that the nanoparticles can more 30 h than in stationary state. This behavior implied that particle stability and dispersion were affected by fluid viscosity. Furthermore, this study showed that and Crosser model [160] and Wasp model [161] can be used for predicting of thermal conductivity in the absence of a sophisticated formula. According to measurements obtained by using transient hot-wire method, the thermal conductivity significantly varied with the volume fraction of the particles.  The heat transfer enhancement is evaluated with two different ways. They are single-phase model and two-phase model. The single phase model assumes that both the liquid and particle phases are in thermal equilibrium and flow at the same velocity. This model is simple and requires less computation time. The two-phase model gives opportunity to understand functions of liquid phase and solid in the heat transfer process but it requires a long time for computation and a high performance computer.

The purpose of their work aimed to develop a modified single-phase model to determine the heat transfer process of nanofluids flowing in tubes.

Xuan and Roetzel [162] presented two different approaches to define some fundamentals for predicting the convective heat transfer coefficient of nanofluids under the assumption that they behaved like a single-phase liquid rather than a normal solid-liquid mixture. In their study, the effects of thermal dispersion and transport properties of the nanofluid were covered. The first model treated as a single-phase and the other model treated as fluid and multi-phase and dispersed fluid. It is assumed that liquid phase and the particles were in thermal equilibrium state and there were no slip velocity between them. The nanofluid acted as a common pure liquid. This implied that the all equation of energy continuity, and motion for a single-phase fluid had been applied directly to the nanofluid.

Similar to the Xuan and Li model [163], the Hamilton and Crosser model [160] and Wasp model [161] give rough results for predicting the thermal conductivity of nanofluid. For a modified conventional approach, which is called the dispersion model, the slip velocity between the solid-liquid mixture may not be zero because of many factors such as gravity, Brownian force, friction force between the solid-liquid mixture, Brownian diffusion, sedimentation, and dispersion to happen simultaneously in the main flow.

Xue [164] presented a model of the effective thermal conductivity for nanofluids, based on Maxwell theory and average polarization theory, considering the interface effect between the solid particles and the base fluid in nanofluids. They found that their theoretical results were in good agreement with the experimental data on the effective thermal conductivity of nanotube/oil nanofluid and $Al_2O_3$/water nanofluid.

# CHAPTER 4

# EXPERIMENTAL STUDY AND DATA REDUCTION

A single-phase numerical model having two-dimensional equations is solved with either constant heat flux or temperature dependent properties to determine the hydrodynamics and thermal behaviors of the nanofluid flow by means of a CFD program for the water flow in a smooth tube and several micro-fin tubes having various helix angles ($0^o$, $18^o$). Artificial neural network (ANN) method is used to determine the most agreeable physical properties of $TiO_2$ nanofluid among correlations. After obtaining the best combination of physical properties of $TiO_2$ nanofluid from ANN analyses, the numerical model is validated by means of a CFD program using the experimental smooth tube data [6] as a case study and it is also solved in the CFD program for several micro-fin tubes as a simulation study.

## 4.1 Nanofluid preparation and Experimental setup

Wongwises et al. studied experimentally about forced convection flow of $TiO_2$ nanofluid.It is used the experimental smooth tube data of Wongwises[6] in this thesis.In their study, nanofluids provided by a commercial source (DEGUSSA, VP Disp. W740x) are used as working fluid. This mixture is composed of TiO2 nanoparticles with an average diameter of 21 nm dispersed in water. The original particle concentration was 40 wt.%. In order to produce other required particle volume fractions, dilution with water followed by a stirring action was effected. Moreover, an ultrasonic vibrator was used to sonicate the solution continuously for about 2 h in order to break down agglomeration of the nanoparticles. The desired volume concentrations used in this study were 0.2%, 0.6%, and 1.0% with pH values of 7.5, 7.1, and 7.0, respectively. From the pH values, it can be seen that the solution chemistry of nanofluids is nearly neutral in nature. A transmission electron microscope (TEM) was used to approximate the size of the primary nanoparticles. As shown in Fig 4.1, it is clear that the primary size of nanoparticles is approximately spherical with an average diameter of around 21 nm.

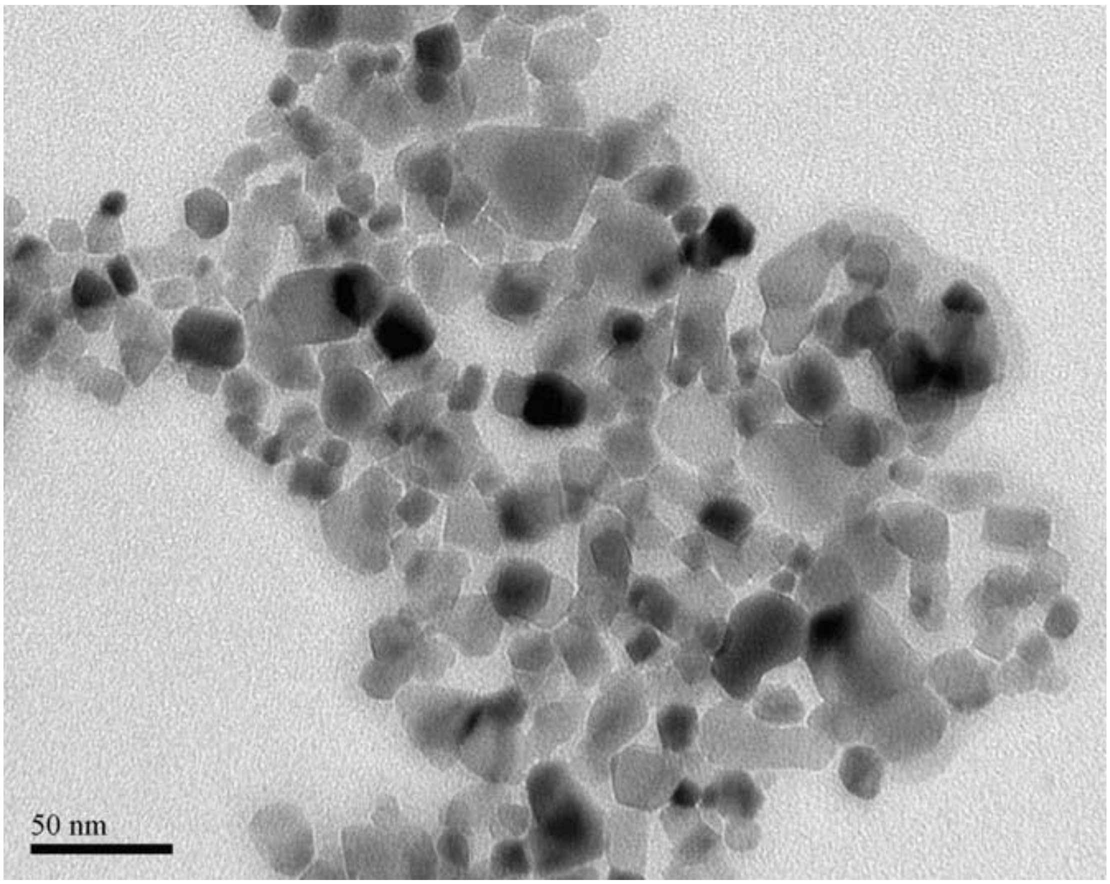



Fig 4.1 TEM image of dispersed $TiO_2$ nanoparticles in water[6]

Their experimental system is shown schematically in Fig 4.2 . It mainly consists of a test section, two receiver tanks, a magnetic gear pump, a hot water pump, a cooler tank, a hot water tank, and a collection tank. The test section is a 1.5 m long counter-flow horizontal double tube heat exchanger with nanofluid flowing inside the tube while hot water flows in the annular. The inner tube is made from smooth copper tubing with a 9.53 mm outer diameter and a 0.7 mm thickness while the outer tube is made from PVC tubing and has a 33.9 mm outer diameter and 3 mm thickness. The test section is thermally isolated from its upstream and downstream sections by plastic tubes in order to reduce the heat loss along the axial direction. The differential pressure transmitter and T-type thermocouple are mounted at both ends of the test section to measure the pressure drop and the bulk temperature of the nanofluid, respectively. Thermocouples are mounted at different longitudinal positions on the inner tube surface of the wall, each with three thermocouples equally spaced around the tube circumference. The inlet and exit temperatures of hot water are measured using T-type thermocouples which are inserted into the flow directly. The receiver tanks of 60 L are made from stainless steel to store the nanofluid and hot water leaving from the test section. The cooler tank with a 4.2 kW cooling capacity and a thermostat is used to keep the nanofluid temperature constant. Similar to the cooler tank, a 3 kW electric heater with a thermostat was installed to keep the temperature of the hot water constant. The nanofluid flow rate was controlled by adjusting the rotation speed of the magnetic gear pump. The hot water flow rate was measured by a rotameter while the nanofluid flow rate was evaluated directly from the time taken for the exact mass of nanofluid to be discharged. For each speed of the pump, five measurements were done. The average of all data was used in the present study.

A portable programmable calibrator was used to calibrate all Ttype thermocouples with a maximum precision of 0.1 °C. The nanofluid mass flow rates were determined by electronic balance. The uncertainty of the electronic balance was ±0.0006 kg. Maximum uncertainty of the nanofluid mass flow rate was evaluated as 2.2%. This uncertainty was taken into account to calculation of the uncertainty of the Nusselt number.

Moreover, the uncertainty of the hot water mass flow rate is ±7% (full scale). As mentioned above, it can be evidently seen that the uncertainty of the measured Nusselt number depends on the temperature measurement, and nanofluid and hot water flow rate measurement. The uncertainty of the measured Nusselt number was evaluated from the Root Mean Sum Square Method and found as 5%.

During the test run, wall temperatures of the test section, mass flow rates of the hot water and nanofluids, and the inlet and exit temperatures of the hot water and nanofluids were measured

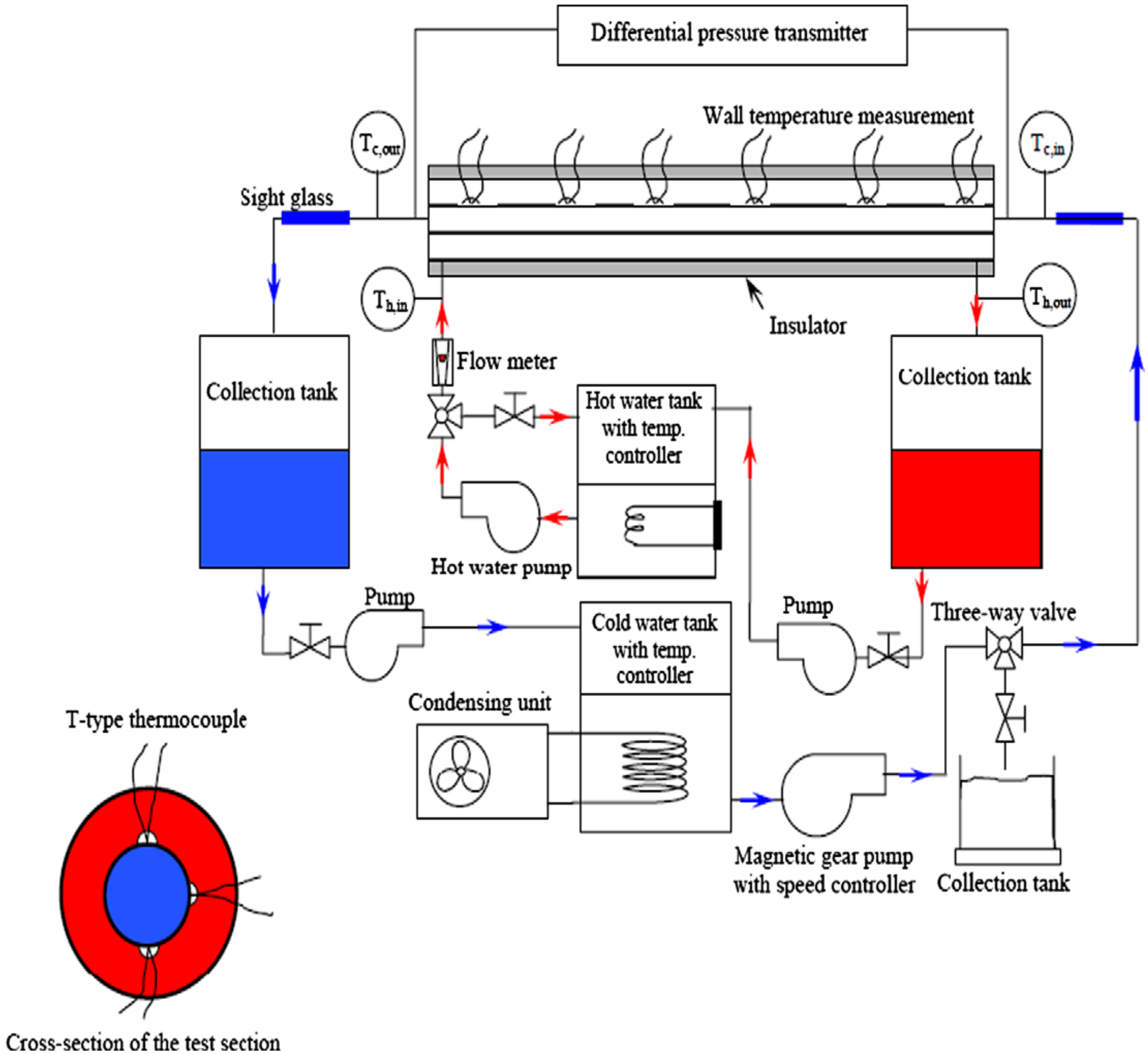



Fig 4.2 Schematic diagram of the experimental apparatus[6]

## 4.2 Physical properties of nanofluids

It is known that the determination of the nanofluid properties is a phenomenon in the literature. There are also some correlations developed for this aim by Williams et al. [165]. Measurement of physical properties is performed by several researchers in the literature such as Rea et al. [113] and Duangthongsuk and Wongwises [5].

Summary of the almost all empirical correlations for dynamic viscosity [166-189], thermal conductivity [190-206] and specific heat capacity at constant pressure [190-191, 207-208] of nanofluids in literature are given in Table 4.1- 2- 3, respectively.

It should be noted that density of the nanofluid is calculated from Pak and Cho [209]'s correlation as follows:

$$\rho_{nf} = \rho_s * \phi + (1-\phi) * \rho_w \tag{4.1}$$

**Table 4.1** Some dynamic viscosity correlations of nanofluids in literature

| Researcher | Correlation |
|---|---|
| Einstein [166] | $\mu_{eff} = (1 + 2.5\varphi)\mu_f$ |
| Brinkman [167] | $\mu_{eff} = \mu_{bf}(1 - \varphi)^{2.5}$ |
| Batchelor [168] | $\mu_{eff} = (1 + \eta\varphi + k_H\varphi^2)\mu_f = (1 + 2.5\varphi + 6.2\varphi^2)\mu_f$ |
| Graham [169] | $\mu_{eff} = (1 + 2.5\varphi)\mu_f + \left[\frac{4.5}{(h/r_p)(2+h/r_p)(1+h/r_p)^2}\right]\mu_f$ |
| Kitano et al. [170] | $\mu_{eff} = \mu_{bf}\left[1-(\varphi-\varphi_m)\right]^{-2}$ |
| Bicerano et al. [171] | $\mu_{nf} = \mu_{bf}\left[1+\eta\phi+k_H\phi^2)\right]$ |
| Wang et al. [172] | $\mu_{nf} = \mu_{bf}\left[1+7,3\phi+123\phi^2\right]$ |
| Tseng and Chen [173] | $\mu_{nf} = \mu_{bf} x 0,4513 e^{0,6965\phi}$ |
| Chen et al. [174] | $\mu_{nf} = \mu_{bf}\left[1+10,6\phi+(10,6\phi)^2\right]$ |
| Nguyen et al. [175] | $\mu_{nf} = \mu_{bf} x 0,904 e^{0,1482\phi}$<br>$\mu_{nf} = \mu_{bf}(1 + 0,025\phi + 0,015\phi^2)$ |
| Khanafer and  Vafai [176] | $\mu_{nf} = \mu_{bf}(1,0538 + 0,1448\phi - 3,363 x 10^{-3} T - 0,0147\phi + 6,735 x 10^{-5} T^2 - 1,337\frac{\phi}{T})$ |

**Table 4.1** Some dynamic viscosity correlations of nanofluids in literature(cont)

| Researcher | Correlation |
|---|---|
| Duanghongsuk and Wongwises [5] | $\mu_{nf} = \mu_{bf}(1{,}013 + 0{,}092\phi + 0{,}015\phi^2)$ |
| Vand [177] | $\mu_{nf} = \mu_{bf} * e^{2.5*\phi+2.7*\phi^2/(1-0.609*\phi)}$ |
| Mooney [178] | $\mu_{nf} = \mu_{bf} * e^{(\frac{2.5*\phi_m*\phi}{1-\phi})}$ |
| Krieger and Dougherty [179], Krieger [180] | $\mu_{nf} = \mu_{bf} * (\frac{\phi_m}{1-\phi})^a$ , $\mu_{nf} = \mu_{bf} * (\frac{\phi_m}{1-\phi})^{1.82}$ |
| Frankel and Acrivos [181] | $\mu_{nf} = \mu_{bf} * 1.125 * (\frac{\phi}{\phi_m})^{1/3} / (1 - (\frac{\phi}{\phi_m})^{1/3})$ |
| Miller et al. [182] | $\mu_{nf} = \mu_{bf} * (537.42 * \phi - 0.188)$ |
| Chow [183] | $\mu_{nf} = \mu_{bf} * (e^{\frac{2.5*\phi}{1-\phi}}) + (A * \phi^2)/(1 - A * \phi^2 * \phi_m)$ |
| Pak and Cho [184] | $\mu_{nf} = \mu_{bf} * (108.2 * \phi^2 + 5.45 * \phi + 1)$ |
| Liu [185] | $\mu_{nf} = \mu_{bf} * ((\frac{1-\phi}{\phi_m})^2 + (\frac{k_1 - 2}{\phi_m}) * \phi + (\frac{k_2 - 6}{\phi_m{}^2}) * \phi^2)$ |
| Wang et al. [186] | $\mu_{nf} = \mu_{bf} * (123 * \phi^2 + 7.3 * \phi + 1)$ <br> $\mu_{nf} = \mu_{bf} * (306 * \phi^2 - 0.19 * \phi + 1)$ |
| Davalos et al. [187] | $\mu_{nf} = \mu_{bf} * (6.17 * \phi^2 + 2.5 * \phi + 1)$ |
| Putra et al. [188] | $\mu_{nf} = 2.9 * 10^{-7} * T^2 - 2 * 10^{-4} * T + 3.4 * 10^{-2}$ For %1 <br> $\mu_{nf} = 3.4 * 10^{-7} * T^2 - 2.3 * 10^{-4} * T + 3.9 * 10^{-2}$ For % 4 |
| Tang et al. [189] | $\mu_{nf} = 2.761 * 10^{-6} * e^{1713/T}$ |

**Table 4.2** Some thermal conductivity correlations of nanofluids in literature

| Researcher | Correlation |
|---|---|
| Maxwell [190] | $k_{nf} = k_f * \frac{k_p + 2k_f + 2\phi(k_p - k_f)}{k_p + 2k_f - \phi(k_p - k_f)}$ |
| Hamilton and Crosser [191] | $k_{nf} = k_f * \frac{k_p + (n-1)k_f - (n-1)\phi(k_f - k_p)}{k_p + (n-1)k_f + \phi(k_f - k_p)}, n = \frac{3}{\Psi}, \Psi = \frac{\phi\rho_f}{\rho_p + \phi\rho_f - \phi\rho_p}$ |
| Hui et al. [192] | $k_{nf} = \frac{1}{4}[(3\phi - 1)k_p + (2 - 3\phi)k_f] + \frac{k_p}{4}\sqrt{\Delta},$ $\Delta = (3\phi - 1)^2(\frac{k_p}{k_f})^2 + (2 - 3\phi)^2 + 2(2 + 9\phi - 9\phi^2)(\frac{k_p}{k_f})$ |
| Wasp and Xuan [193] | $k_{nf} = k_f * \frac{k_p + 2k_f - 2\phi(k_f - k_p)}{k_p + 2k_f + \phi(k_f - k_p)}$ |
| Yu and Choi [194] | $k_{nf} = k_f * \frac{k_{pe} + 2k_f + 2\phi(k_{pe} - k_f)(1+\beta)^3}{k_{pe} + 2k_f - \phi(k_p - k_f)(1+\beta)^3}, \ \beta = \frac{h}{r}, h < 10nm, \beta = 0.1$ |
| Godson et al. [195] | $k_{nf} = 0.9692 * \phi + 0.9508$ |
| Prasher et al. [196] | $k_{nf} = k_f * \frac{1 + A\phi \mathrm{Re}^m \mathrm{Pr}^{0,333} * (1+2\alpha) + 2\phi(1-\alpha)}{(1+2\alpha) - \phi(1-\alpha)}, \alpha = \frac{2R_b k_f}{d_p},$ $A = 40000, m = 2.5, R_b = 0.77 \times 10^{-8}$ |
| Koo and Kleinstreuer [197] | $k_{nf} = k_{MG} + 5\times10^4 \beta\phi\rho_p C_p \sqrt{\frac{K_B T}{\rho_p D}} f(T,\phi), \ k_{MG} = k_f * \left(1 + \frac{3\phi\left(\frac{k_p}{k_f} - 1\right)}{\left(\frac{k_p}{k_f} + 2\right) - \phi\left(\frac{k_p}{k_f} - 1\right)}\right)$ $f(T,\phi) = (-6.04\phi + 0.4705) * T + (1722.3\phi - 134.63), \beta = 0.0137(100\phi)^{-0.8229} \rightarrow \phi \leq 1\%$ |

**Table 4.2** Some thermal conductivity correlations of nanofluids in literature(cont)

| Researcher | Correlation |
|---|---|
| Li and Peterson [198] | $k_{nf} = k_f + k_f(0.764\phi - 0.0187(T - 273.15) - 0.462)$ For $Al_2O_3$ <br> $k_{nf} = k_f + k_f(3.761\phi + 0.0179(T - 273.15) - 0.307)$ For CuO |
| Palm et al. [199] | $Al_2O_3 \quad \begin{pmatrix} k_{nf} = 0.003352T - 0.3708 & \text{For } \phi = \%1 \\ k_{nf} = 0.004961T - 0.8078 & \text{For } \phi = \%4 \end{pmatrix}$ |
| Nguyen et al. [200] | $k_{nf} = k_f(4.97\phi^2 + 2.72\phi + 1)$ For $Al_2O_3$ <br> $k_{nf} = k_f(28.905\phi^2 + 2.827\phi + 1)$ For CuO |
| Bhattacharya et al. [201] | $k_{nf} = k_p\phi + (1-\phi)k_f$ |
| Buongiorno [202] | $k_{nf} = k_f(1 + 7.47\phi)$ |
| Kim et al. [203] | $k_{nf} = 0.65 + 4{,}864 \times 10^{-7} T^3$ |
| Timofeeva et al. [204] | $k_{nf} = k_f(1 + 3\phi)$ |
| Chon et al. [205] | $k_{nf} = k_f * (1 + 64.7\phi^{0.746}(d_f/d_p)^{0.369}(k_p/k_f)^{0.747}Re^{1.2321}Pr^{0.9955})$ <br> $Pr = \dfrac{\mu}{\rho_{BF}\alpha}, Re = \dfrac{\rho_{BF}Vd_p}{\mu} = \dfrac{\rho_{BF}K_BT}{3\pi\mu^2L_{BF}}, \mu = 2{,}414 \times 10^{-5} \times 10^{(\frac{247}{T-140})}$ |
| Murshed et al. [206] | $k_{nf} = \dfrac{k_f * (1 + 0.27\phi^{4/3}(\frac{k_p}{k_f} - 1)(1 + \frac{0.52\phi}{1-\phi^{1/3}}(\frac{k_p}{k_f} - 1)}{1 + \phi^{4/3}(\frac{k_p}{k_f} - 1)(\frac{0.52}{1-\phi^{1/3}} + 0.27\phi^{1/3} + 0.27)}$ |

**Table 4.3** Some specific heat capacity correlations of nanofluids in literature

| **Researcher** | **Correlation** |
|---|---|
| Maxwell [190] | $Cp_{nf} = (1-\varphi)Cp_{nf}\ (1+2.5\varphi_p)\mu_f$ |
| Hamilton and Crosser [191] | $C_{p_{nf}} = \frac{\phi * \rho_s * C_{p_s} + (1-\phi) * \rho_w * C_{pw}}{\rho_{nf}}$ |
| Yang et al. [207] | $\frac{c_{peff}}{c_{pf}} = (1-\phi) + \phi \frac{c_{pn}}{c_{pf}}$ |
| Yu et al. [208] | $c_{pnf} = \frac{\varphi(\rho_s)c_{ps} + (1-\varphi) * (\rho * c_p)}{\varphi\rho_p + (1-\varphi) * \rho_{bf}}$ |

It is given the view of geometrical parameters of micro-fin tubes in Fig 4.8. The dimensional parameters of investigated tubes is given in Table 4.4

**Table 4.4** Geometrical parameters of the investigated tubes

| Tubes | $\alpha$(°) | Θ(°) | e (mm) | p (mm) | $n_f$ | s (mm) | $d_i$ (mm) | $d_o$ (mm) | L (m) | A ($mm^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Smooth | - | - | - | - | - | - | 8,13 | 9,13 | 1,5 | 38311,7 |
| Micro-fin 1 | 0 | 36 | 0,435 | 0,378 | 60 | 0,293 | 8,13 | 9,13 | 1,5 | 92180,86 |
| Micro-fin 2 | 18 | 36 | 0,435 | 0,378 | 60 | 0,293 | 8,13 | 9,13 | 1,5 | 96210,0 |

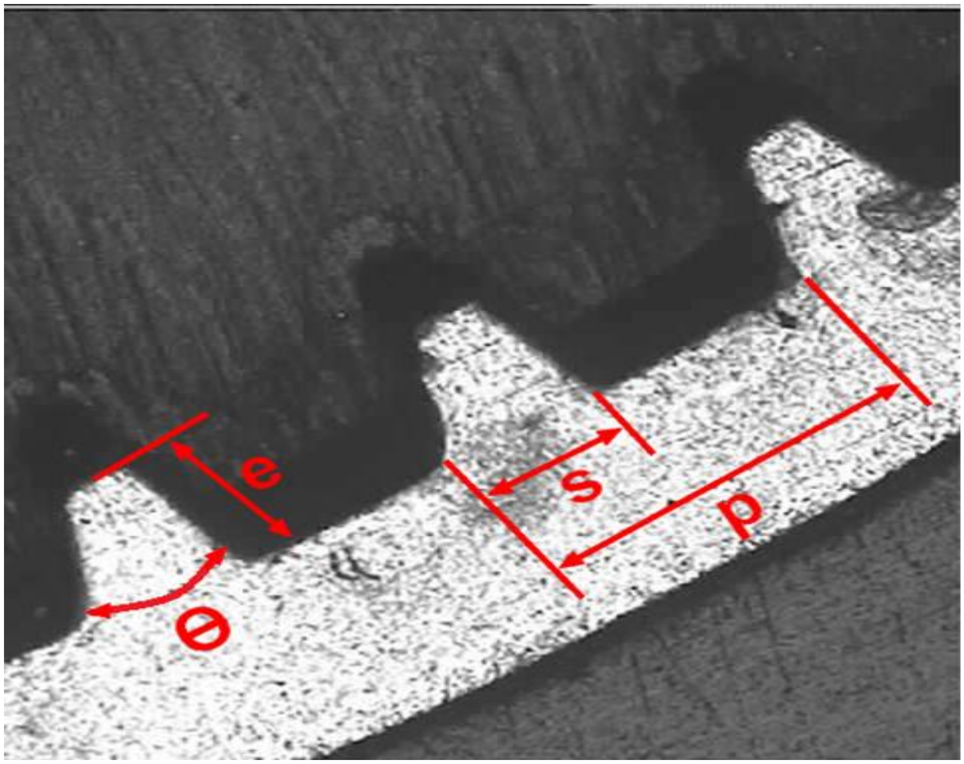


Fig 4.3 View of geometrical parameters of micro-fin tubes

### 4.3. Numerical method – CFD approach

For numerical solving, Fluent CFD program is used. ANSYS Fluent [27] is commonly used software in CFD analysis in the literature and a detailed description of the mathematical models can be found in the Fluent User's Guide. This program uses a technique based on control volume theory to convert the governing equations to algebraic equations so they can be solved numerically.

Each control volume works by performing the integration of the governing equations technique, and then generates discrimination of the equations which conserve each quantity based on control volume.

The Pressure-Based Segregated Algorithm was employed to obtain the numerical results. In this method, the governing equation are solved sequentially, Because the governing equations are non-linear and coupled, the solution loop must be carried out iteratively in order to obtain a converged numerical solution. According to this method the individual governing equations for the solution variables (e.g., u, v, w, T, p, etc.) are solved one after another. Control volume approach which makes possible numerical solution of governing equations by converting them to a set of algebraic equations used for solving single phase conservation equations.

Second order upwind scheme discredited convection terms diffusion terms and other quantities which they are some results of Governing equations. All velocity components and scalar values of the problem are calculated at the center of control volume interfaces (cell center) where the grid schemes are used intensively. Semi Implicit Method for Pressure Linked Equations (SIMPLE) was used to couple the velocity and pressure. ANSYS Fluent CFD program [27] employed a point implicit (Gauss–Seidel) linear equation solver in conjunction with an algebraic multigrid method to solve the linear systems resulting from discretization schemes. k-ε Turbulence Models was chosen in the viscous model. Constant heat flux applied to the pipe surface. Velocity inlet at the pipe inlet, and pressure outlet for the pipe exit were determined Boundary conditions. Monitor of the residuals was done during the iterative process thoroughly. All solutions were assumed to be converged when the residuals for all governing equations were lower than 10−6.to show gird independent solutions,

Boundary conditions:

z=0(at pipe inlet) $V=V_i$ (constant) $\longrightarrow$ velocity inlet

z=1500mm (at pipe outlet) $P=P_i$(constant) $\longrightarrow$ pressure outlet

and constant heat flux is applied at wall along the pipe.

The equation for conservation of mass, or continuity equation, can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = S_m \tag{4.2}$$

Equation (4.2) is the general form of the mass conservation equation and is valid for incompressible as well as compressible flows. The source Sm is the mass added to the continuous phase from the dispersed second phase (e.g., due to vaporization of liquid droplets) and any user-defined sources.

Conservation of momentum in an inertial (non-accelerating) reference frame is described by [210]

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla(\rho\vec{v}\vec{v}) = \nabla p + \nabla(\bar{\tau}) + \rho\vec{g} + \vec{F} \tag{4.3}$$

where p is the static pressure, $\tau$ is the stress tensor, and $\rho\vec{g}$ and $\vec{F}$ are the gravitational body force and external body forces, respectively. $\vec{F}$ also contains other model-dependent source terms such as porous-media and user-defined sources.

Ansys Fluent [27] solves energy equation in the following form:

$$\frac{\partial}{\partial t}(\rho E) + \nabla(\vec{v}\,(\rho E + p)) = \nabla\left(k_{eff}\nabla T - \sum_j h_j \vec{J_j} + \left(\bar{\tau}_{eff}\vec{v}\right)\right) + S_h \tag{4.4}$$

where $k_{eff}$ is the effective conductivity($k+k_t$ , where $k_t$ is the turbulent thermal conductivity, defined according to the turbulence model being used), and $\vec{J_j}$ is the diffusion flux of species j. The first three terms on the right-hand side of Equation (4.4) represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. $S_h$ includes the heat of chemical reaction, and any other volumetric heat sources you have defined. In Equation (4.4)

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \tag{4.5}$$

Where sensible enthalpy h is defined for ideal gases as

$$h = \sum_j Y_j h_j \tag{4.6}$$

and for incompressible flows as

$$h = \sum_j Y_j h_j + \frac{p}{\rho} \tag{4.7}$$

$Y_j$ is the mass fraction of species j and

$$h_j = \int_{T_{ref}}^{T} C_{p,j}\,dT \tag{4.8}$$

Where $T_{ref}$ is 298.15 K

## 4.4. Numerical method – ANN approach

An artificial neural network (ANN) is an information-processing system that has certain performance characteristics in common with biological neural networks. Artificial neural networks have been developed as generalizations of mathematical models of human cognition or neural biology, based on the assumptions as follows . [211]

- Information processing occurs at many simple elements called neurons
- Signals are passed between neurons over connection links
- Each connection link has an associated weight, which, in a typical neural net, multiplies the signal transmitted
- Each neuron applies an activation function (usually non-linear) to its net input (sum of weighted input signals) to determine its output signal.

ANN is the most widely used model, which finds linear or non-linear relationship between input and output patterns. Finding the relationship between input and output sets, firstly, well-known training set are used to generalize relationship. After generalized, ANN tries to predict the outputs of never seen before test set. The performance metrics of ANN is measured by quality of test set prediction value. There are many types of ANN in function approximation literature. These are Multi Layer Perceptron (MLP), Radial Basis Functions Networks (RBFN), Generalized Regression Neural Networks (GRNN) and fuzzy logic-based decision-making systems of the incorporation of ANN Artificial Neural Fuzzy Inference System (ANFIS).

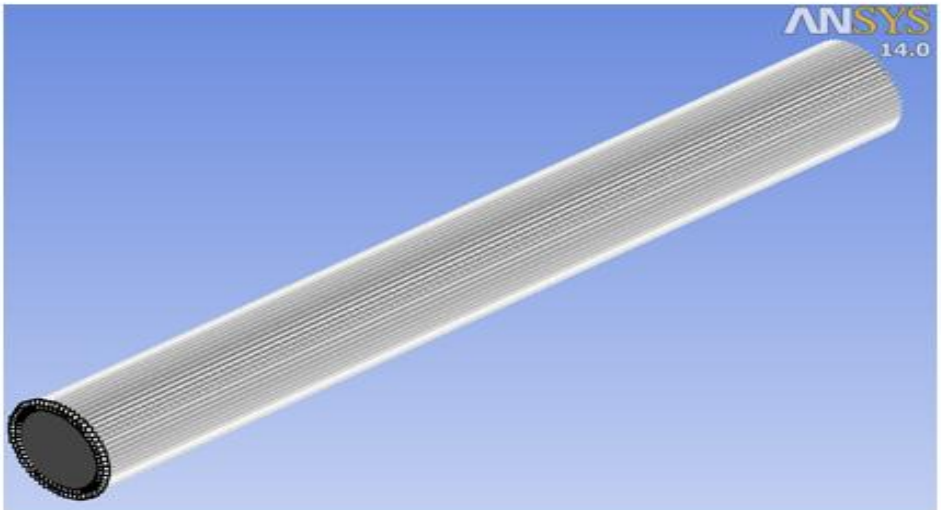
# CHAPTER 5

# RESULTS AND DISCUSSION

A commercial software package ANSYS Fluent [27] is employed in the numerical study. It uses control volume technique to convert the governing equations to algebraic equations so they can be solved numerically. The control volume technique works by performing the integration of the governing equations about each control volume, and then generates discretization of the equations which conserve each quantity based on control volume [27]. Investigated tubes were plotted in SolidWorks program [26]. They were imported to ANSYS Geometry as shown Fig 5.1

After investigated tubes were imported to ANSYS Geometry, they were forwarded in order to do mesh in ANSYS Meshing. The mesh influences the accuracy, convergence and speed of the solution. Furthermore, the time it takes to create a mesh model is often a significant portion of the time it takes to get results from our solutions. Therefore, the better and more automated the meshing tools, the better the solution. The mesh was done so better for investigated tubes as shown Fig 5.2

a-)




b-)

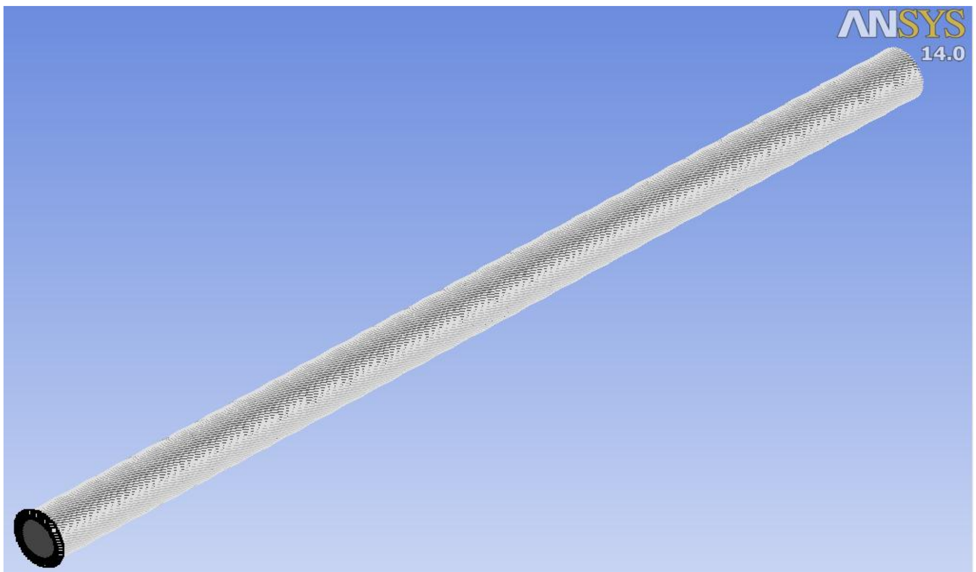
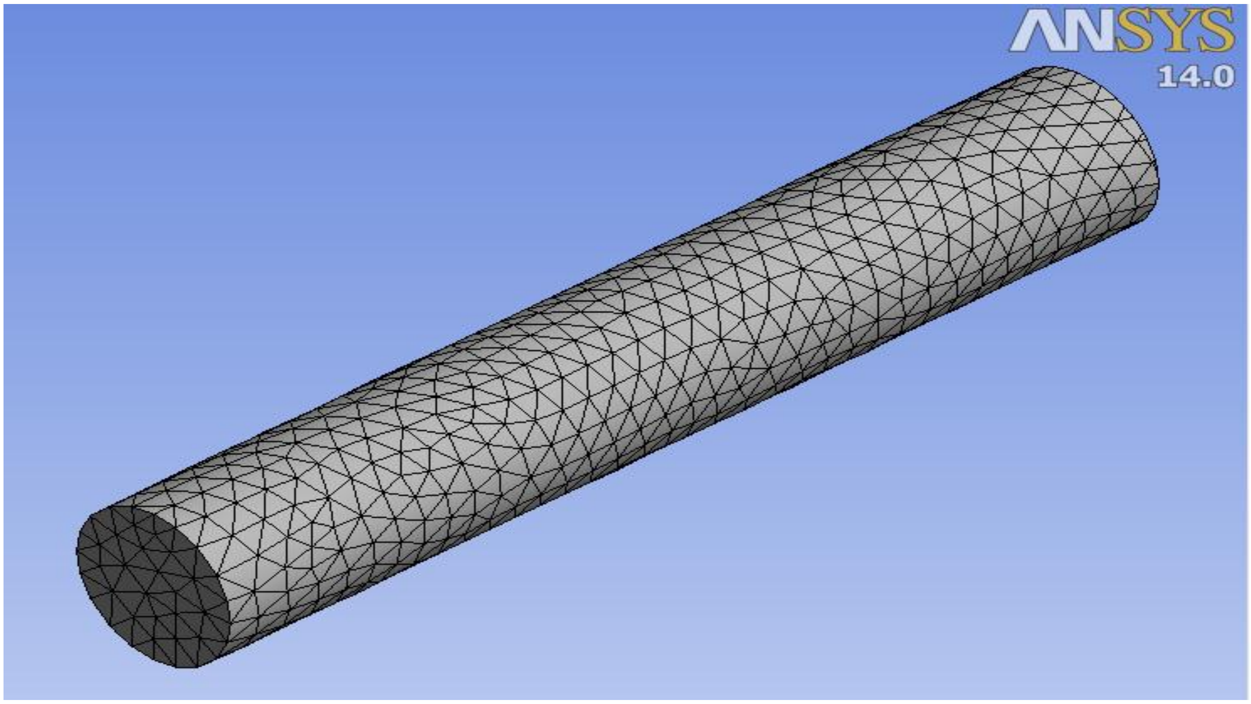



Fig 5.1 Views of different helix angles of micro-fin tubes (a) 0º, (b) 18º

a-)

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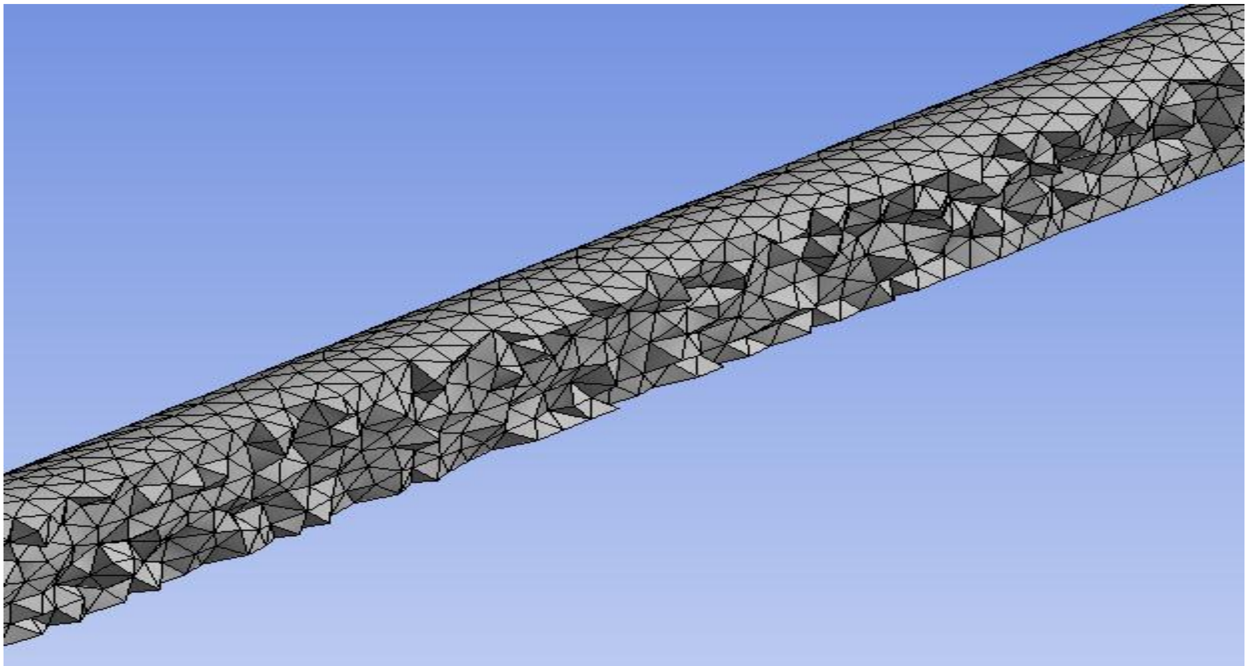


Fig 5.2 Views of meshing (a), detailed of meshing (b) for smooth tube

## 5.1. ANN Results

It is developed 2 ANN models to determine the best combination of physical properties of $TiO_2$ nanofluid. The inputs of ANN model 1 analyses are the correlations of physical properties, the average temperature and velocity of water in the test tube and nanoparticle concentration while the outputs of the analyses are shear stress, ,friction factor ,heat flux, convective heat transfer coefficient and pressure drop. The inputs of ANN model 2 analyses are the correlations of physical properties, inlet and outlet temperature and velocity of water in the test tube while the outputs of the analyses are convective heat transfer coefficient and pressure drop. ANN models are given in Table 5.1. The numerical and experimental of convective heat transfer coefficient and pressure drop in ANN models are obtained so good results, shown in Fig 5.3

To determine the physical properties of nanofluid among correlations was used ANN program. The most agreement correlations was obtained from ANN 1 model for physical properties (k, μ, $C_p$) of nanofluids. They are given below,

$$k_{nf} = k_p\phi + (1-\phi)k_f \tag{5.1}$$

$$\mu_{nf} = \mu_{bf} *(306*\varphi^2 - 0.19*\varphi + 1) \tag{5.2}$$

$$Cp_{nf} = (1-\varphi)\,Cp_{nf}\,(1+2.5\varphi_p)\,\mu_f \tag{5.3}$$

These equations were obtained from ANN results, Equation (5.1) is thermal conductivity correlation of Bhattacharya et al.[201], Equation (5.2) is viscosity correlation of Wang et al.[186], Equation (5.3) is heat capacity correlation of Maxwell.[190]

**Table 5.1** The best inputs numbered in Tables 4.1-2-3

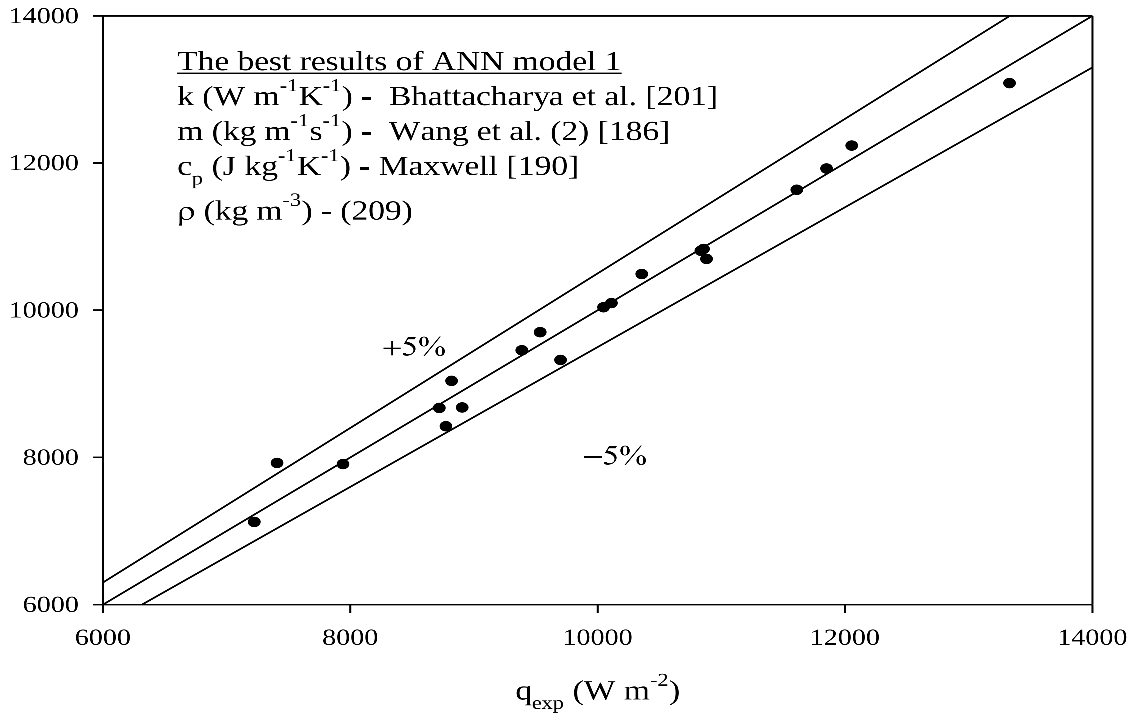
a-) considering the determination of shear stress, friction factor, heat flux, convective heat transfer coefficient and pressure drop as outputs(ANN model 1)

| k (W $m^{-1}K^{-1}$) | μ (kg $m^{-1}s^{-1}$) | $c_p$ (J $kg^{-1}K^{-1}$) | $R^2$ |
|---|---|---|---|
| 12 | 24 | 1 | 0.967465 |
| 10 | 10 | 2 | 0.963421 |
| 6 | 7 | 2 | 0.961502 |
| 12 | 11 | 2 | 0.960374 |
| 13 | 8 | 1 | 0.958547 |
| 16 | 9 | 2 | 0.958514 |
| 14 | 27 | 2 | 0.958276 |
| 5 | 3 | 2 | 0.957927 |
| 11 | 11 | 3 | 0.957073 |
| 1 | 7 | 2 | 0.956864 |

b-) considering the determination of pressure drop and convective heat transfer coefficient as outputs(ANN model 2)

| k (W $m^{-1}K^{-1}$) | μ (kg $m^{-1}s^{-1}$) | $c_p$ (J $kg^{-1}K^{-1}$) | $R^2$ |
|---|---|---|---|
| 18 | 2 | 2 | 0.99290234 |
| 6 | 21 | 2 | 0.99105436 |
| 11 | 1 | 4 | 0.99006633 |
| 15 | 1 | 2 | 0.98885878 |
| 6 | 1 | 1 | 0.98860543 |
| 19 | 26 | 3 | 0.9881786 |
| 7 | 12 | 1 | 0.98806904 |
| 8 | 28 | 2 | 0.98798953 |
| 6 | 7 | 2 | 0.98795459 |
| 16 | 2 | 4 | 0.98774095 |

a-)




b-)

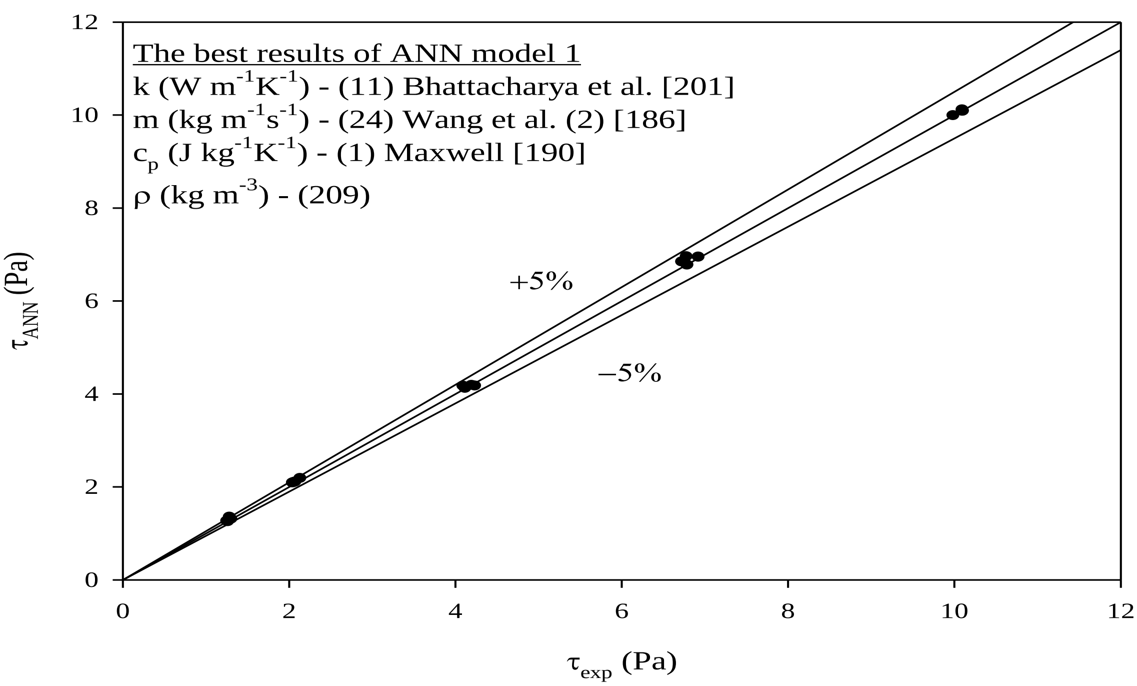



Fig 5.3 The best results of ANN model 1 regarding with the shear stress (a) and heat flux (b)

## 5.2. CFD Results

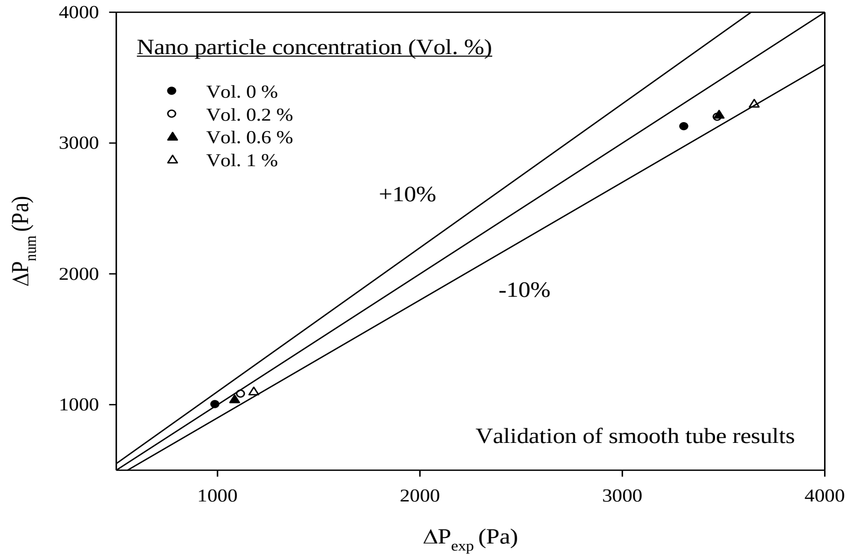
### 5.2.1 Validation check

Validation process of numerical model is performed by means of the experimental data [6] as shown in Fig 5.4 for some heat transfer characteristics of the problem. According to Fig 5.4, it can be clearly seen that the numerical model of ANSYS Fluent [27] is in good agreement with the experimental values [6] in terms of the calculation of heat transfer coefficient within the range of ±20% and pressure drop within the range of ±10% for the in-tube single phase flow of pure water and nanofluids with $TiO_2$ volume concentrations of 0.2, 0.6 and 1%. Beside this, Table 5.2 shows that the error functions is less than 0.141 % between experimental and numerical temperatıre at outlet section. Experimental and numerical studies are conducted for Re numbers between 4516 and 15681 and surface heat fluxes between 7233 and 13340 W $m^{-2}$.

Table 5.2 Comparison of experimental and numerical temperatıre at outlet section using pure water with 0.2%, 0.6% and 1% TiO2 particles data[6].

| Concentration(%) | $T_{exp}$ (K) | $T_{num}$ (K) | Error Function(%) |
|---|---|---|---|
| Pure water | 299,7 | 300,1 | 0,112 |
| 0.2 % | 300,1 | 300,6 | 0,137 |
| 0.6 % | 300,3 | 300,8 | 0,141 |
| 1 % | 300,1 | 300,5 | 0,131 |

a-)

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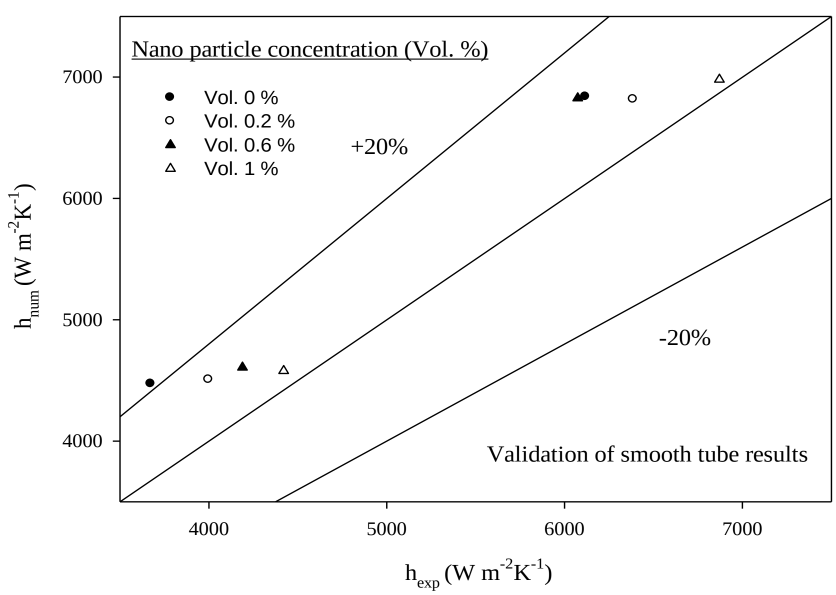


Fig 5.4 Comparison of experimental and numerical heat transfer coefficients and pressure drops using pure water with 0.2%, 0.6% and 1% TiO2 particles data[170]. (a) pressure drop (b) heat transfer coefficient

### 5.2.2. Velocity, Pressure, Temperature profiles of investigated tubes

The velocity of the fluid in contact with the pipe wall is essentially zero and increases the further away from the wall. Velocity profile depends up on the surface condition of the pipe wall. A smoother wall results in a more uniform velocity profile than a rough pipe wall.

The pressure of the fluid in contact with the pipe wall is essentially small and increases the further away from the wall. The pressure of fluid is maximum in etrance of pipe and decreases the further away from etrance.

The temperature of fluid is maximum on the wall because constant heat flux is subjected to pipe surface. The temperature of fluid is minimum in etrance of pipe and increases the further away from etrance due to constant heat flux

This study was conducted in ANSYS Fluent[27] and obtained velocity, pressure and temperature profile at various locations in smooth tube, as shown below.

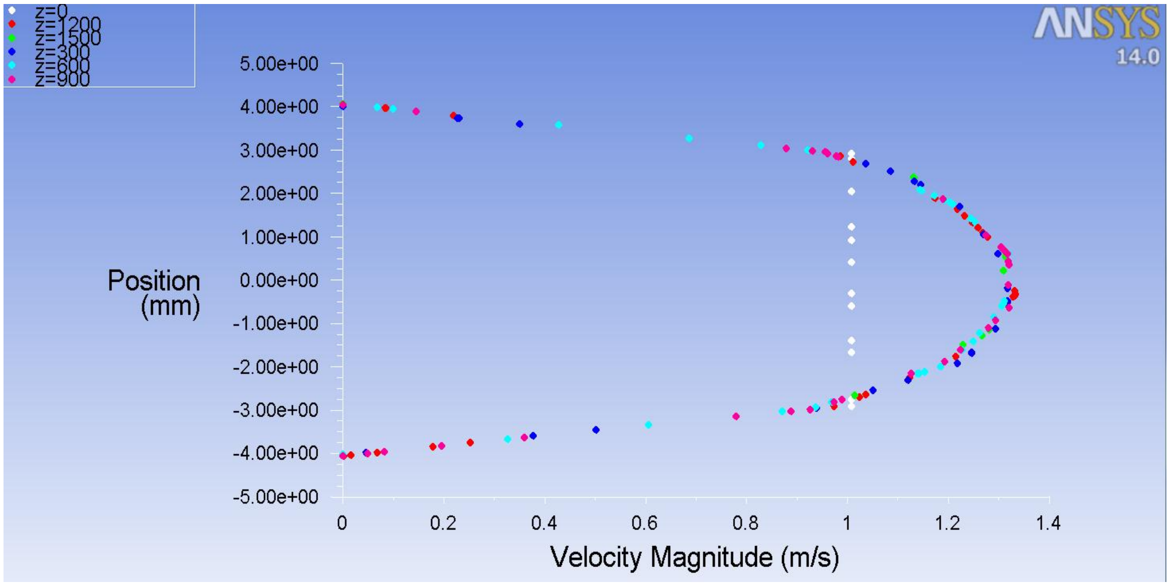


Fig 5.5 Velocity profile at various locations in smooth tube

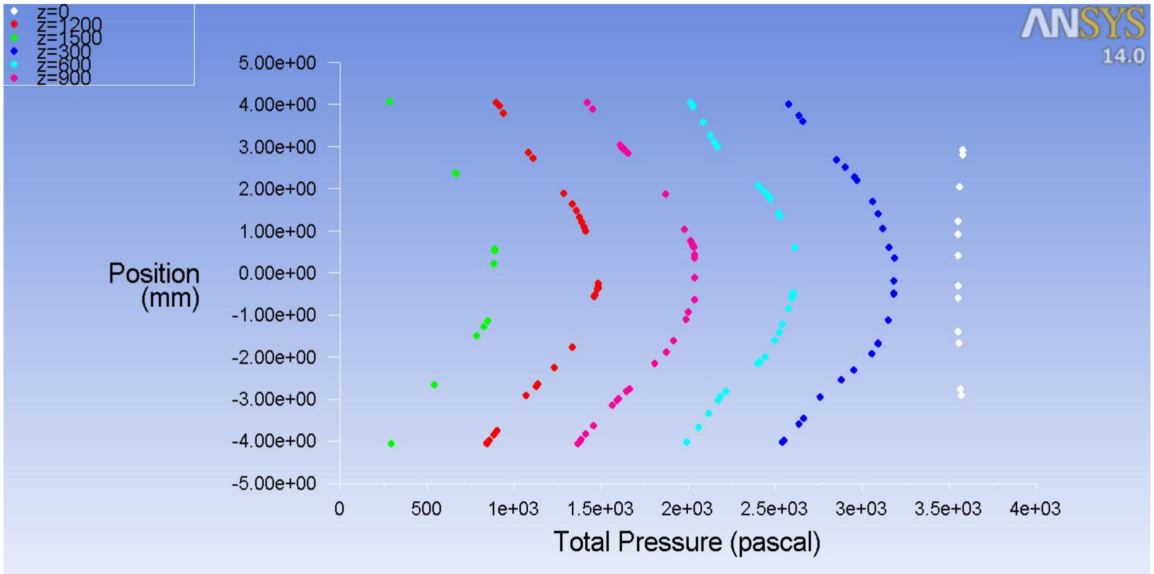


Fig 5.6 Pressure profile at various locations in smooth tube

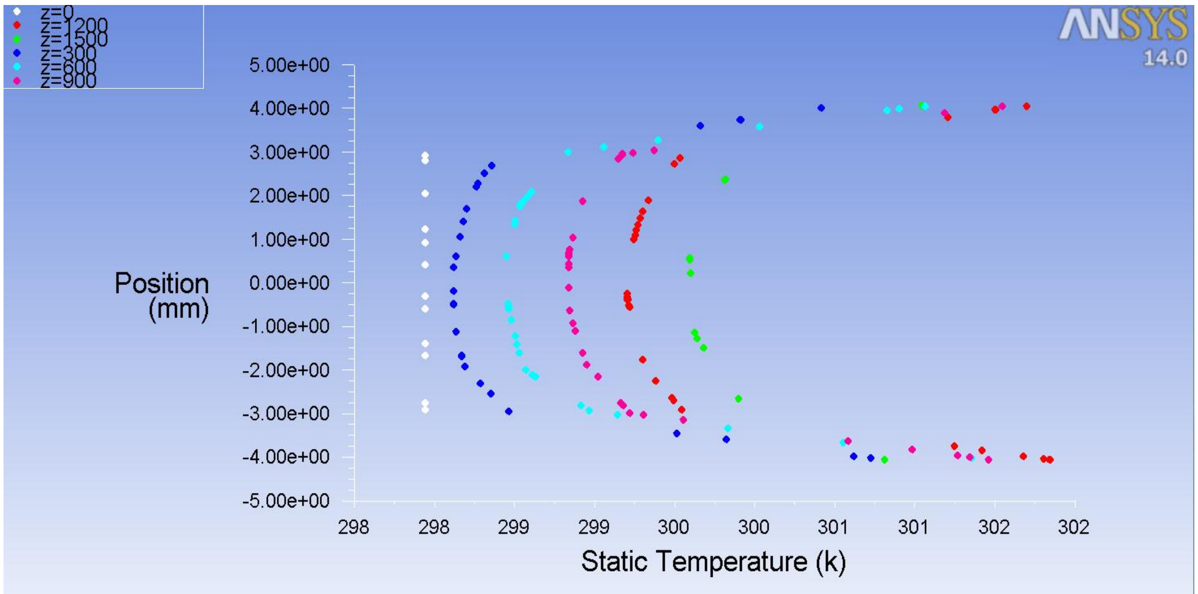


Fig 5.7 Temperature profile at various locations in smooth tube

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This study was conducted for micro-fin tube having helix angle 0º and obtained velocity, pressure and temperature profile at various locations, as shown below.

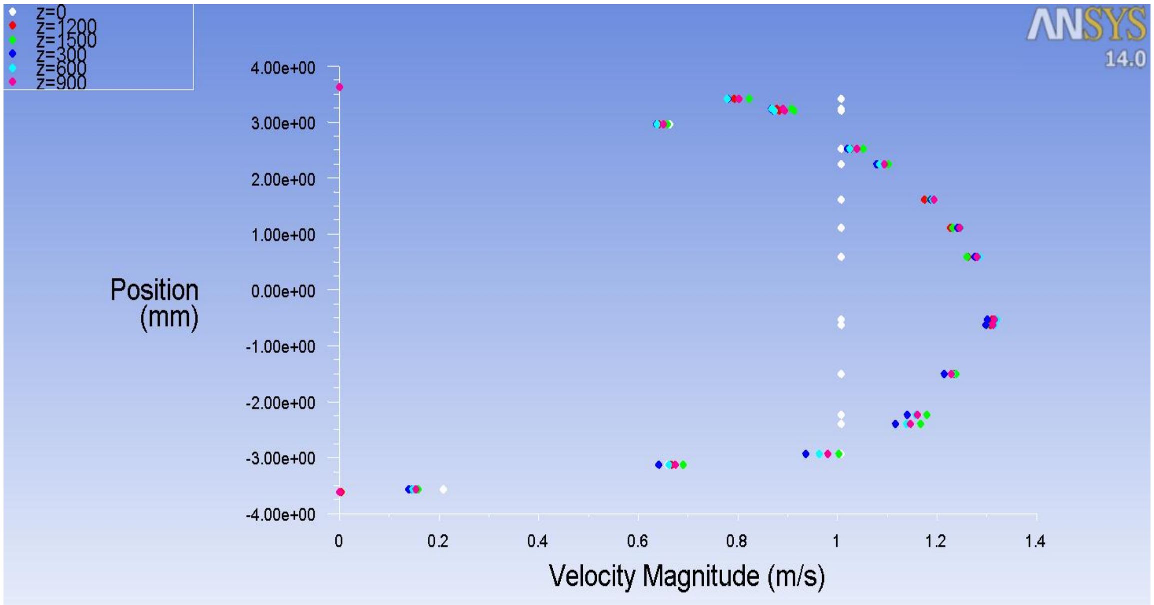


Fig 5.8 Velocity profile at various locations in micro-fin tube having helix angle 0º

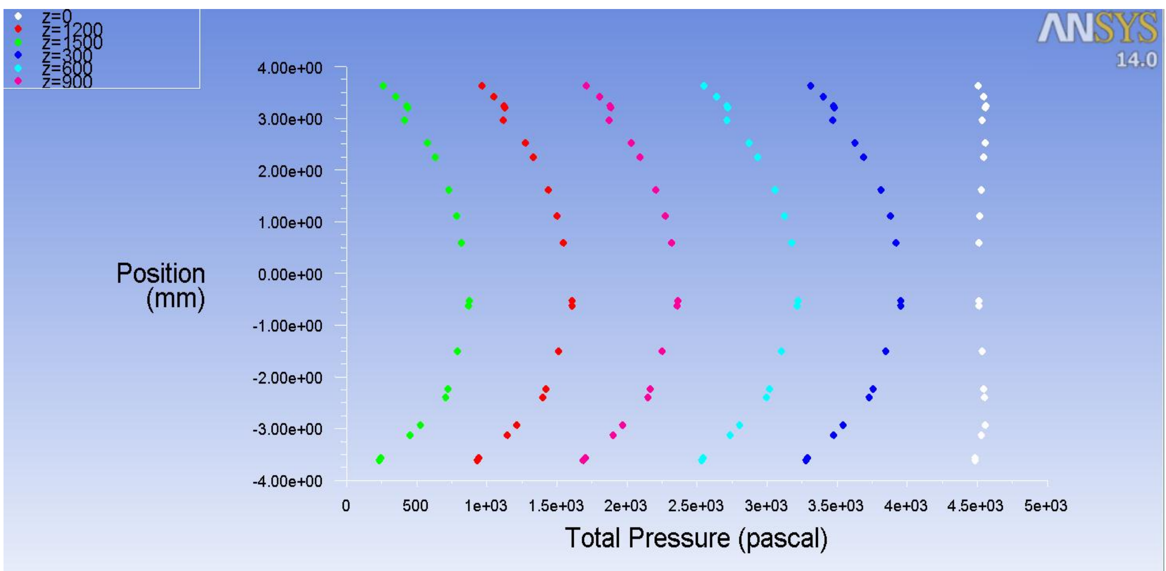


Fig 5.9 Pressure profile at various locations in micro-fin tube having helix angle 0º

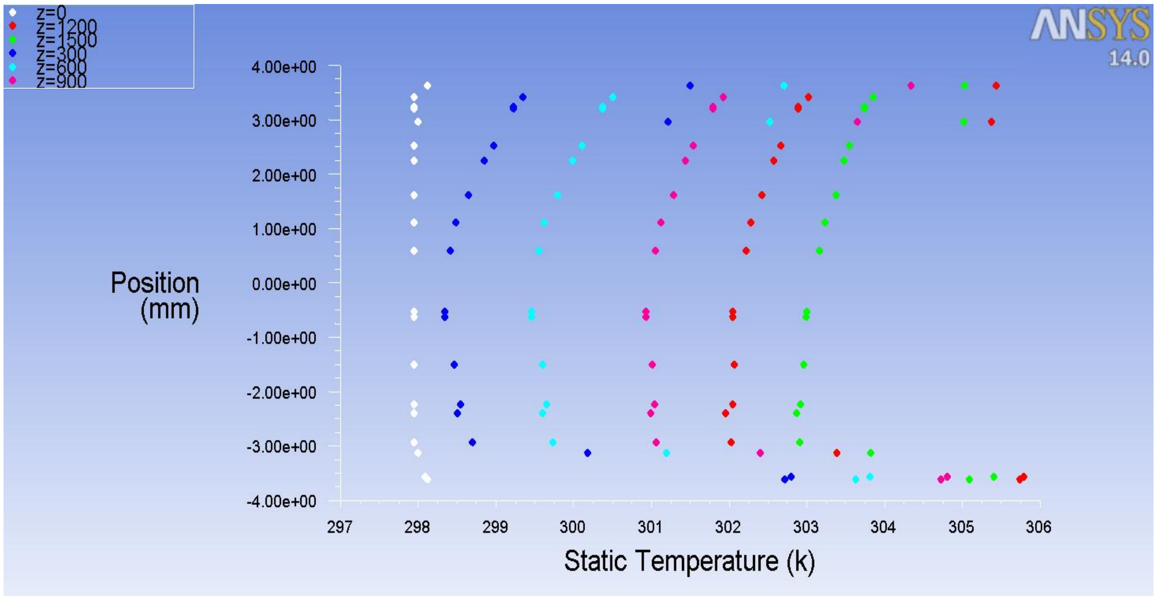


Fig 5.10 Temperature profile at various locations in micro-fin tube having helix angle 0º

This study was conducted for micro-fin tube having helix angle 18º and obtained velocity, pressure and temperature profile at various locations, as shown below.

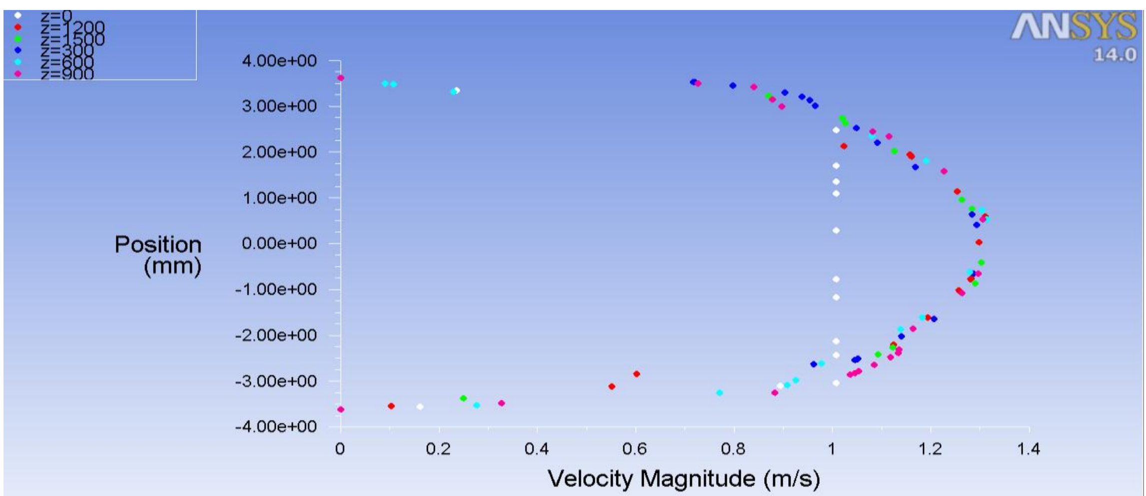


Fig 5.11 Velocity profile at various locations in micro-fin tube having helix angle 18º

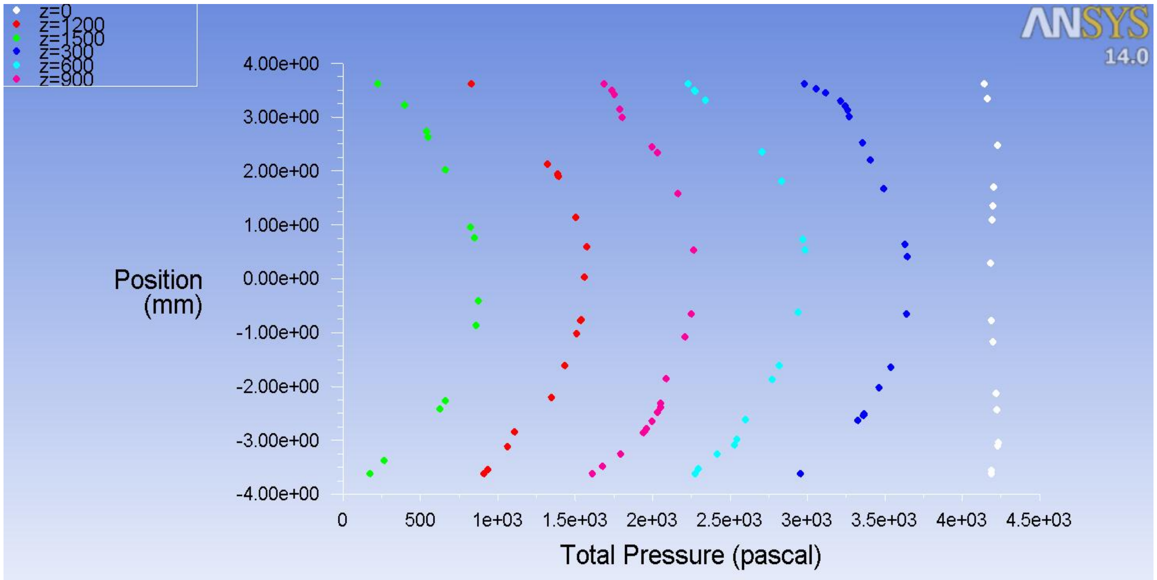


Fig 5.12 Pressure profile at various locations in micro-fin tube having helix angle 18º

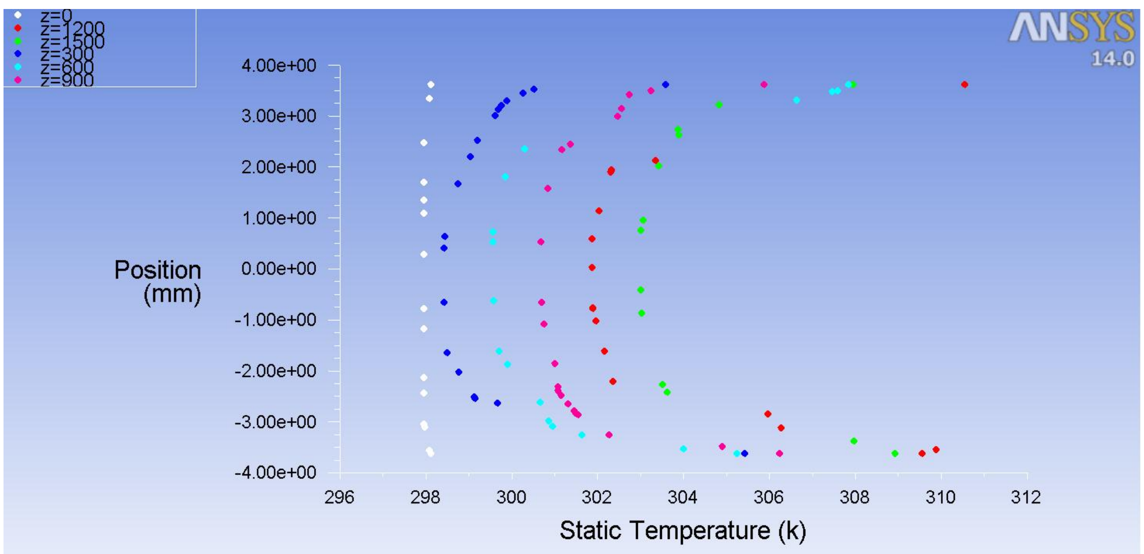


Fig 5.13 Temperature profile at various locations in micro-fin tube having helix angle 18º

### 5.2.3. Heat transfer coefficient results

The variation of average heat transfer coeffcient versus along the pipe length for the flow of pure water and the nanofluids with different particle weight concentrations inside the smooth tube are shown in Fig 5.14. It is found from this figure that the addition of solid nanoparticles to the püre water has led to an increase in average heat transfer coefficient for flow inside smooth tube. As studied before, addition of nanoparticles improves the thermal conductivity of the base fluid. convective heat transfer enhancement of nanofluid may be due to thermal conductivity increase or random movement and dispersion of nanoparticles in nanofluid.Morever, disordered movement of the solid particles in flow will upset the thermal boundary layer formation on the tube wall surface. Due to of this disturbance, the development of the thermal boundary layer is lagged. higher heat transfer coefficients of fluid flow in a tube are obtained at the thermal entrance region, the lag in thermal boundary layer formation concluded by adding nanoparticles will improve the average heat transfer coefficient. At higher weight concentrations of the nanofluids, both the thermal conductivity of $TiO_2$-water mixture and the disturbance effect of the solid nanoparticles will increase. So, nanofluids with higher weight concentrations have generally higher convective heat transfer coefficients.

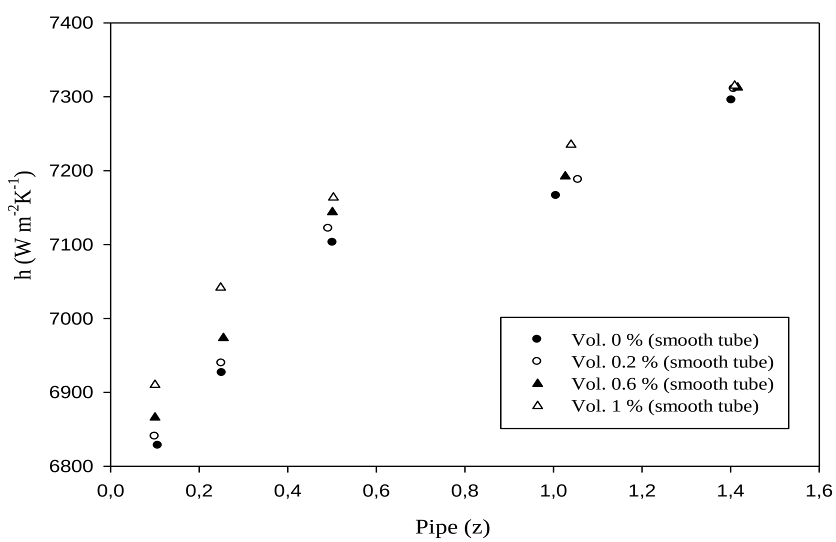


Fig 5.14 Variation of heat transfer coefficient on volume concentration along the pipe

Fig 5.15 shows that nanofluids have better heat transfer performance when they flow inside micro-fin tubes having helix angle 0º,18º instead of flowing inside the smooth tube. It is known in the literature that heat transfer coefficient of micro-fin tube having helix angle 18º is higher than micro-fin tube having helix angle 0º along the tube . The results obviously indicate that the highest heat transfer coeffcient are obtained for micro-fin tube having helix angle 18º at volume concentration 1 %. The characteristics of the Fig 5.15 are found to be compatible with others in the literature

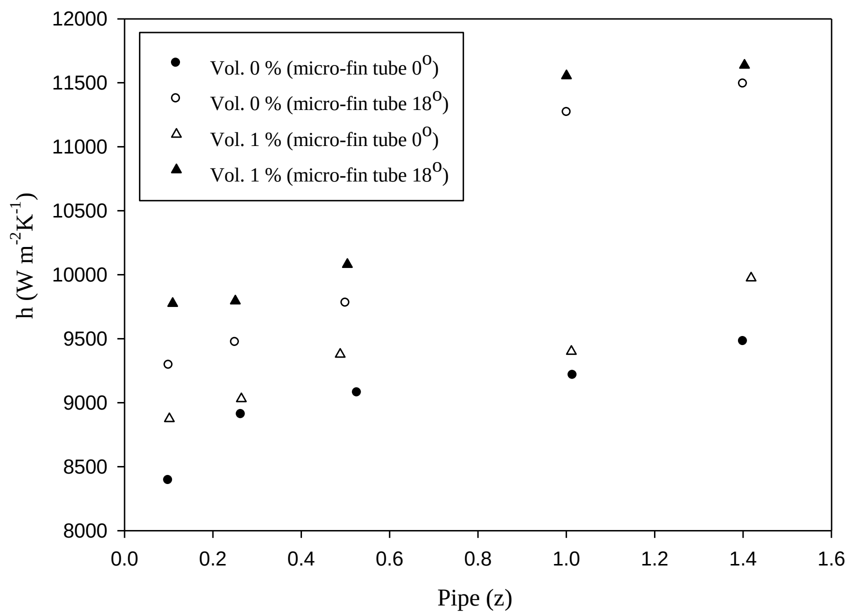


Fig 5.15 Variation of heat transfer coefficient of micro-fin tubes on volume concentration along the pipe

According to Fig 5.16, heat transfer coefficients are compared with smooth and micro-fin tubes. The results show that the heat transfer coefficients of micro-fin tube having helix angle 18º is higher than micro-fin tube having helix angle 0º at nearly the same range of Reynolds number,heat flux and volume concentration along the pipe. Similarly, the heat transfer coefficients of micro-fin tube having helix angle 0º is higher than smooth tube

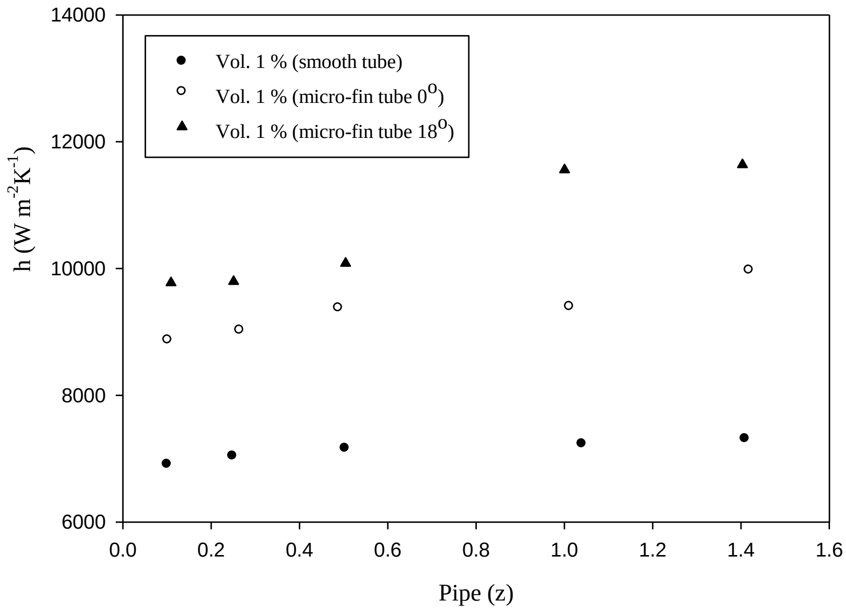


Fig 5.16 Variation of heat transfer coefficient of smooth tube and micro-fin tubes on volume concentration along the pipe

### 5.2.4. Pressure drop, Friction factor and Wall shear stress results

Fig 5.17 shows that there is a remarkable increase in pressure drop of nanofluid with 0.2,0.6,1 wt.% particle concentration compared to the pure water value when they flow inside smooth and micro-fin tubes. This augmentation tends to continue for the nanofluids with higher weight fractions. This is because of the fact that suspending solid particles in a fluid generally increases dynamic viscosity relative to the base fluid. Since, the viscosity is in direct relation with pressure drop, the higher value of viscosity leads to increased amount of pressure drop. The results show that the pressure drop of micro-fin tube having helix angle 18º is higher than micro-fin tube having helix angle 0º. Morever, the pressure drop of micro-fin tube having helix angle 0º is higher than smooth tube. According to Fig 5.18, the pressure drop of micro-fin tube having helix angle 18º is 21.5 % higher than smooth tube and the pressure drop of micro-fin tube having helix angle 0º is 15.5% higher than smooth tube at $\varphi$=1 %. The characteristics of the Fig 5.17 are found to be compatible with others in the literature.

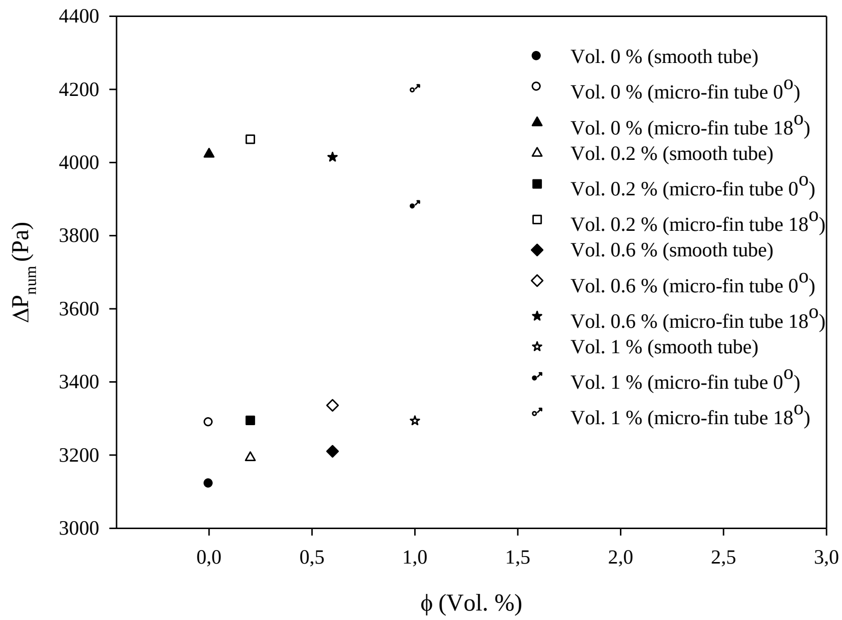


Fig 5.17 Variation pressure drop of smooth tube and micro-fin tubes on volume concentration

From Fig 5.18, friction factor increases with increasing concentration of nanoparticles because of the rise of working fluid viscosity. As observed, the nanofluids with concentrations of 0,2%, 0.6% and 1 % provide friction factors higher than the base fluid by around 1.5, 5.1 and 5.8 %, respectively for smoooth tubes. Similarly, the nanofluids with concentrations of 0,2%, 0.6% and 1 % provide friction factors higher than the base fluid by around 0.33, 2.2 and 3.2 %, respectively for micro-fin tube having helix angle 18º. The characteristics of the Fig 5.18 are found to be compatible with others in the literature.

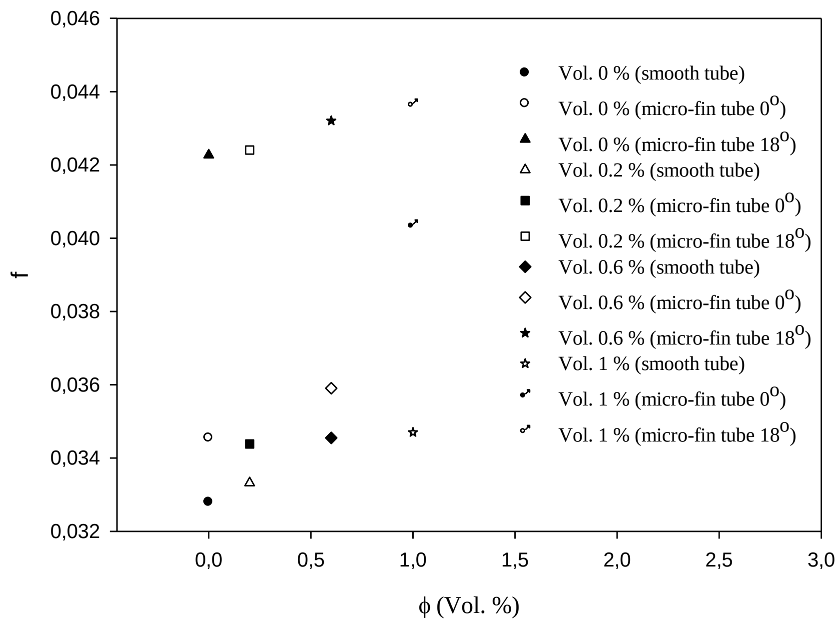


Fig 5.18 Variation friction factor of smooth tube and micro-fin tubes on volume concentration

From Fig 5.19, it is observed that wall shear stress increases with the increasing volume concentration of the nanoparticles and also Reynolds number of the flow as the mixture viscosity is increased strongly due to inclusion of nanoparticles. As indicated, the nanofluids with concentrations of 0,2%, 0.6% and 1 % provide wall shear stress higher than the base fluid by around 2.2, 2.7 and 5.2 % for smoooth tubes, respectively. Similarly, the nanofluids with concentrations of 0,2%, 0.6% and 1 % provide wall shear stress higher than the base fluid by around 1, 1.2 and 4.2 % for micro-fin tube having helix angle 18º, respectively. According to Fig 5.19, the wall shear stress of micro-fin tube having helix angle 18º is 21.1 % higher than smooth tube and the wall shear stress of micro-fin tube having helix angle 0º is 3.77 % higher than smooth tube at $\varphi$=0.6 %. The characteristics of the Fig 5.19 are found to be compatible with others in the literature.

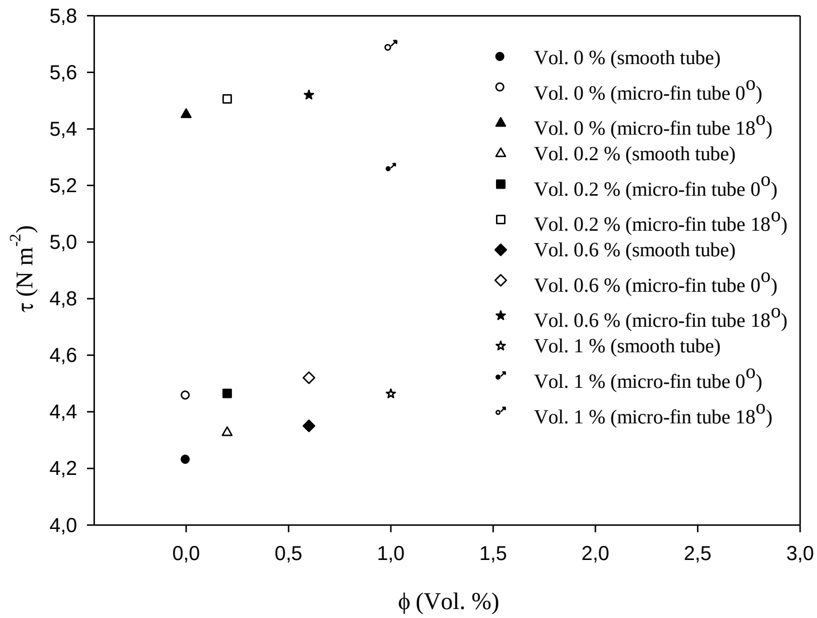


Fig 5.19 Variation wall shear stress of smooth tube and micro-fin tubes on volume concentration

## CHAPTER 6

# CONCLUSIONS AND SUGGESTIONS

In this study, heat transfer characteristics of the pure water and of water– $TiO_2$ nanofluid flow inside smooth tube for a validation study and micro-fin tubes for a simulation study with various volume concentrations are investigated for forced flow conditions by using two dimensional governing equations. The following conclusions are outlined from this study

1-) Heat transfer coefficient is slightly increased with the enhancement of nanofluid volume concentration.

2-) Micro-fin tubes having helix angles 0°,18° enhances heat transfer coefficient significantly at the same flow conditions, the mean heat transfer coefficient is higher 23.5% and 32.5% than smooth tube at $\varphi$=1% ,respectively.

3-) The mean heat transfer coefficient and pressure drop of micro-fin tubes having helix angle 18° are compared to micro-fin tubes having helix angle 0° , it is found higher than 11.8% ,7.55% at $\varphi$=1%, respectively.

4-) The nanofluids with concentrations of 0,2%, 0.6% and 1 % for micro-fin tube having helix angle 18º provide friction factors higher than the base fluid by around 0.33, 2.2 and 3.2 %, respectively

5-) The wall shear stress of micro-fin tube having helix angle 18º is 21.1 % higher than smooth tube and the wall shear stress of micro-fin tube having helix angle 0º is 3.77 % higher than smooth tube at $\varphi$=0.6 %.

6-) Nanofluids with higher volume concentration have higher heat transfer enhancement and also have higher pressure drop. Therefore, judicious decision should be taken when selecting a nanofluid that will and the pressure balance the heat transfer enhancement drop penalty.

For the purpose of this study, the proven computational fluid dynamics (CFD) tools will make it much easier for researchers to analyze different geometrical configurations and various nanofluids without doing additional experimental studies after they perform their validation process on the experimental data.

# REFERENCES

[1] Choi, U.S., (1995). “Enhancing thermal conductivity of fluids with nanoparticles”, ASME FED, 231:99-103.

[2] Xuan,Y. and Li,Q., (2000).“ Heat transfer enhancement of nanofluids”, International Journal of Heat Fluid Flow, 21:58-64.

[3] Maxwell, J.C., Electricity and Magnetism, Clarendon Press, Oxford, UK, 1873.

[4] Daungthongsuk,W. and Wongwises,S.,(2007). “A critical review of convective heat transfer of nanofluids”, Renewable and Sustainable Energy Reviews, 11:797-817.

[5] Daungthongsuk,W. and Wongwises,S.,(2009).”Measurement of temperature-dependent thermal conductivity and viscosity of $TiO_2$-water nanofluids”, Experimental Thermal and Fluid Science, 32:706-714.

[6] Daungthongsuk,W. and Wongwises,S.,(2010).”Comparison of the effects of measured and computed thermophysical properties of nanofluids on heat transfer performance”, Experimental Thermal and Fluid Science, 34:616-624.

[7] Daungthongsuk,W. and Wongwises,S.,(2010).”An experimental study on the heat transfer performance and pressure drop of $TiO_2$-water nanofluids flowing under a turbulent flow regime”, International Journal of Heat and Mass Transfer 53:334-344.

[8] Daungthongsuk,W. and Wongwises,S.,(2009), “Heat transfer enhancement and pressure drop characteristics of TiO2-water nanofluid in a double-tube counter flow heat exchanger”, International Journal of Heat and Mass Transfer 52:2059-2067.

[9] Daungthongsuk,W. and Wongwises,S.,(2008),”Effect of thermophysical properties models on the predicting of the convective heat transfer coefficient for low concentration nanofluid”, International Communications in Heat and Mass Transfer 35:1320-1326.

[10] Daungthongsuk,W., Dalkilic,A.S. and Wongwises,S.,”Convective heat transfer of $Al_2O_3$-water nanofluids in a microchannel heat sink”, Current Nanoscience, (Accepted for Publication-Article in Press)

[11] Suriyawong,A. and Wongwises,S.,(2010).”Nucleate pool boiling heat transfer characteristics of $TiO_2$-water nanofluids at very low concentrations”, Experimental Thermal and Fluid Science 34:992–999.

[12] Trisaksri,V. and Wongwises,S.,(2009)." Nucleate pool boiling heat transfer of TiO2–R141b nanofluids", International Journal of Heat and Mass Transfer 52:1582-1588.

[13] Dalkilic,A.S., Kürekci,N.A. and Wongwises,S.,(2012)."Effect of void fraction and friction factor models on the prediction of pressure drop of R134a during downward condensation in a vertical tube", Heat and Mass Transfer 48:123-139.

[14] Dalkilic,A.S., Kürekci,N.A. and Wongwises,S.,(2011)."Prediction of two-phase friction factor of refrigerants inside a horizontal tube using CFD analysis for the homogeneous condensation flow",ASME-JSME-KSME Joint Fluids Engineering Conference, ASME-JSME-KSME July 24-29, Japan.

[15] Fluent release 6.2.16, Fluent Incorporated, 2005

[16] Demir,H.,Dalkilic,A.S.,Kurekci,N.A.,Kelesoglu,B. and Wongwises,S.,(2010)."A numerical investigation of nanofluids forced convection flow in a horizontal smooth tube", International Heat Transfer Conference, ASME, August 8-13, USA.

[17] Demir,H.,Dalkilic,A.S.,Kurekci,N.A. and Wongwises,S.,(2011)."Numerical investigation on the single phase forced convection heat transfer characteristics of $TiO_2$ nanofluids in a double-tube counter flow heat exchanger", International Communications in Heat and Mass Transfer 38:218-228.

[18] Palm, S.J.,Roy,G. and Nguyen,C.T.,(2006)."Heat transfer enhancement with the use of nanofluids in radial flow cooling systems considering temperature-dependent properties", Applied Thermal Engineering 26:2209-2218.

[19]Ağra,Ö.,Demir,H.,Atayılmaz,Ş.Ö,Kantaş,F. and Dalkılıç,A.S.,(2011)."Numerical investigation of heat transfer and pressure drop in enhanced tubes", International Communications in Heat and Mass Transfer, 38:1384-1391.

[20] Balcılar,M.,Dalkılıç,A.S.,Bolat,B. and Wongwises,S.,(2011)."Investigation of empirical correlations on the determination of condensation heat transfer characteristics during downward annular flow of R134a inside a vertical smooth tube using artificial intelligence algorithms", Journal of Mechanical Science and Technology, 25:2683-2701.

[21]Bolat,B.,Balcilar,M.,Dalkilic,A.S.and Wongwises,S.,(2011)."Optimization of the relationship between the two-phase friction factor and Reynolds equivalent number model by the means of Genetic Algorithm", ASME/JSME 8th Thermal Engineering Joint Conference, ASME March 13-17, Hawaii.

[22] Balcilar,M.,Dalkilic,A.S. and Wongwises,S.,(2011)."Artificial neural network (ANN) techniques for the determination of condensation heat transfer characteristics during downward annular flow of R134a inside a vertical smooth tube", International Communications in Heat and Mass Transfer 38:75-84.

[23] Balcilar,M.,Dalkilic,A.S. and Wongwises,S.,(2010)."Determination of condensation heat transfer characteristics of R134a by means of artificial intelligence method", International Mechanical Engineering Congress and Exposition, ASME November 12-18, USA.

[24] Balcilar,M.,Dalkilic,A.S.,Suriyawong,A.,Yiamsawas,T. and Wongwises,S.,"Investigation of pool boiling of nanofluids using artificial neural networks and correlation development

techniques”, International Communications in Heat and Mass Transfer, (Corrected Proof-Article in Press.)

[25] Balcilar,M.,Dalkilic,A.S.,Agra,Ö.,Atayilmaz,Ş.Ö. and Wongwises,S. ”A correlation development study on the prediction of pressure drop during condensation and evaporation of various refrigerants in horizontal smooth and micro-fin tubes”, International Communications in Heat and Mass Transfer, (Accepted for Publication-Article in Press).

[26] SolidWorks, SolidWorks Corporation, 300 Baker Avenue, Concord, MA 01742. Available from: http://www.solidworks.com/. 17 March 2012.

[27] ANSYS Fluent, ANSYS Inc., 10 Cavendish Court Lebanon, NH 03766 Available from: http://www.ansys.com/. 20 March 2012.

[28] Çengel Y. A. Heat Transfer: A practical approach, 3nd ed. McGraw Hill, 2006.

[29] Incropera F. P., DeWitt D. P., Introduction to Heat Transfer, 4th ed. Wiley 2001

[30] Petukhov,B.S.,(1970). “Heat Transfer and Friction in Turbulent Referred to in Handbook of Single-Phase Convective Pipe Flow with Variable Physical Properties.” In Heat Transfer,ed. T. F. Irvine and J. P.New York: Wiley Interscience, 1987. Hartnett, Vol. 6. New York: Academic Press.

[31] Sieder,E.N., and Tate,G.E.,(1936). “Heat Transfer and Pressure Drop of Liquids in Tubes.” Industrial Engineering 11 Chemistry 28:1429–1435

[32] Colburn,P.,(1933). “Transactions of the AIChE” 26:174

[33] Gnielinski,V.,(1976). “New Equations for Heat and Mass Transfer in Turbulent Pipe and Channel Flow.” , International Chemical Engineering 16:359–368

[34]Rose, J.W. (2004), “Heat-Transfer Coefficients, Wilson Plots and Accuracy of Thermal Measurements”, Experimental Thermal and Fluid Science, 28:77-86.

[35] Al-Fahed, S.F., Ayub, Z.H., Al-Marafie, A.M. and Soliman, B.M.,(1993).” Heat transfer and pressure drop in a tube with internal micro fins under turbulent water flow conditions”, Experimental Thermal and Fluid Science 3:249–253.

[36] Chiou, C.B., Wang, C.C. and Lu, D.C.,(1993).” Single-phase heat transfer and pressure drop characteristics of microfin tubes”,ASHRAE Transactions: Symposia, 1041–1048

[37] Copetti, J.B., Macagnan, M.H., De Souza, D. and Oliveski, R.D.,(2004)” Experiments with micro-fin tube in single phase. International Journal of Refrigeration 27:876–883

[38] Siddique,M. and Alhazmy,M.,(2008).” Experimental study of turbulent single-phase flow and heat transfer inside a micro-finned tube”,International Journal Of Refrigeration 31:234 –241

[39] Ravigururajan, T.S. and Bergles, A.E.,(1996).” General correlations for pressure drop and heat transfer for single-phase turbulent flow in internally ribbed tubes. Augmentation of Heat Transfer in Energy Systems”, ASME - HTD, 52:9 –20; also (1996) “Development and verification of general correlations for pressure drop and heat transfer in single-phase turbulent flow in enhanced tubes” ,Exptl Therm Fluid Sci, 13: 55 –70

[40]Wang C.C., Chiou C.B. and Lu D.C.,(1996). “Single-phase heat transfer and flow friction correlations for microfin tubes”.Int J Heat Fluid Flow 17:5 – 8.

[41] Cavallini,A., DelCol, D., Doretti,L., Longo, G.A.,Rossetto L., (1997).“ Pressure drop during condensation and vaporisation of refrigerants inside enhanced tubes” ,Heat Technol, 15 3 – 10.

[42] Alizad, K., Vafai, K. and Shafahi, M.,(2012).” Thermal performance and operational attributes of the startup characteristics of flat-shaped heat pipes using nanofluids”, Int. J. Heat and Mass Transfer, 55:140-155.

[43] Bobbo, S., Fedele, L., Benetti, A., Colla, L., Fabrizio, M., Pagura, C. and Barison, S.,(2012). “Viscosity of water based SWCNH and $TiO_2$ nanofluids” ,Exp. Therm. Fluid Sci., 36:65-71.

[44] Buschmann, M. H.,(2011).” Thermal conductivity and heat transfer of ceramic nano fluids”, Int. J. Therm. Sci., (Article in Press-Corrected Proof).

[45] Yang, L., Du, K., Ding, Y. H., Cheng, B. and Li, Y. J.,(2012).” Viscosity-prediction models of ammonia water nanofluids based on various dispersion types”, Powder Technol,215-216, 210-218.

[46] Colangelo, G., Favale E., Risi A. and Laforgia, D.,(2011).” Results of experimental investigations on the heat conductivity of nanofluids based on diathermic oil for high temperature applications”, Applied Energy, ( Article in Press-Corrected Proof)

[47] Jamshidi, N., Farhadi, M., Sedighi, K. and Ganji, D.D.,(2011).” Optimization of design parameters for nanofluids flowing inside helical coils”, Int. Commun. Heat Mass Trans., 39:311-317.

[48] Giraldo, M., Sanin, D. and Flórez, W. F.,(2011).” Heat transfer in nanofluids: A computational evaluation of the effects of particle motion”,Appl. Math. Comput, (Article in Press-Corrected Proof.)

[49] Özerinç,S.,Yazıcıoglu,A.G. and Kakaç, S.,(2011).” Numerical analysis of laminar forced convection with temperature-dependent”, Int. J. Therm. Sci., (Article in Press-Corrected Proof)

[50] Yu, L., Liu, D. and Botz, F.,(2011).” Laminar convective heat transfer of alumina-polyalphaolefin nanofluids containing spherical and non-spherical nanoparticles”,Exp. Therm. Fluid Sci.,37:72-83.

[51] Farahani, S.D. and Kowsary, F.,(2011).” Estimation local convective boiling heat transfer coefficient in mini channel”, Int. Commun. Heat Mass Trans, 39:304-310

[52] Cimpean, D. S. and Pop, I.,(2012).” Fully developed mixed convection flow of a nanofluid through an inclined channel filled with a porous medium” Int. J. Heat and Mass Transfer, 55:907-914.

[53] Leong, K.Y., Saidur, R., Mahlia, T.M.I. and Yau, Y.H.,(2012).” Modeling of shell and tube heat recovery exchanger operated with nanofluid based coolants”,Int. J. Heat and Mass Transfer, 55: 808-816.

[54] Mahbubul, I.M., Saidur, R. and Amalina, M.A.,(2011).” Latest developments on the viscosity of nanofluids”. Int. J. Heat and Mass Transfer, 55:874-885.

[55] Cui, W.,Bai1, M., Lv, J. and Li, X.,(2012).” On the microscopic flow characteristics of nanofluids by molecular dynamics simulation on Couette Flow”, The Open Fuels & Energy Science Journal, 5: 21-27.

[56] Ahmed, M.A., Shuaib, N.H., Yusoff, M.Z. and Al-Falahi A.H.,(2011).” Numerical investigations of flow and heat transfer enhancement in a corrugated channel using nanofluid”. Int. Commun. Heat Mass Trans., 38:1368-1375.

[57] Akbarinia, A., Abdolzadeh, M. and Laur, R.,(2011).”Critical investigation of heat transfer enhancement using nanofluids in microchannels with slip and non-slip flow regimes”. Appl. Therm. Eng., 31:556-565.

[58] Bianco, V., Manca, O. and Nardini, S.,(2011).” Numerical investigation on nanofluids turbulent convection heat transfer inside a circular tube”, Int. J. Therm. Sci, 50:341-349.

[59] Corcione, M.,(2011).” Empirical correlating equations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids”, Energy Convers. Manage., 52:789-793.

[60] Firouzfar, E., Soltanieh, M., Noie, S.H. and Saidi, S.H.,(2011).” Energy saving in HVAC systems using nanofluid” Appl. Therm. Eng.,31:1543-1545.

[61] Gherasim, I., Roy, G., Nguyen, C.T. and Vo-Ngoc, D.,(2011).” Heat transfer enhancement and pumping power in confined radial flows using nanoparticle suspensions (nanofluids)”, Int. J. Therm. Sci.,50:369-377.

[62] Hojjat, M., Etemad, S.Gh., Bagheri, R. and Thibault, J.,(2011).” Convective heat transfer of non-Newtonian nanofluids through a uniformly heated circular tube” Int. J. Therm. Sci., 50:525-531.

[63] Hojjat, M., Etemad, S.Gh., Bagheri, R. and Thibault, J.,(2011).” Thermal conductivity of non-Newtonian nanofluids”, Experimental data and modeling using neural network, Int. J. Heat Mass Trans.,54: 1017-1023.

[64] Hojjat, M., Etemad, S.Gh., Bagheri, R. and Thibault, J.,(2011).” Turbulent forced convection heat transfer of non-Newtonian nanofluids” Exp. Therm. Fluid Sci,35:1351-1356.

[65] Huminic, G. and Huminic, A.,” Heat transfer characteristics in double tube helical heat exchangers using nanofluids”, Int. J. Heat Mass Tran ,54: 4280-4287.

[66] Huminic, G. and Huminic, A., “Heat transfer characteristics of a two-phase closed thermosyphons using nanofluids”, Exp. Therm. Fluid Sci., 35:550-557.

[67] Jung, J.Y., Cho, C., Lee, W.H. and Kang, Y.T.,(2011).”Thermal conductivity measurement and characterization of binary nanofluids”, Int. J. Heat Mass Trans., 54:1728-1733.

[68] Khanafer, K. and Vafai, K.,(2011).”A critical synthesis of thermophysical characteristics of nanofluids”, Int. J. Heat Mass Trans., 54:4410-4428.

[69] Lee, S.W., Park, S.D., Kang, S., Bang, I.C. and Kim, J.H.,(2011).” Investigation of viscosity and thermal conductivity of SiC nanofluids for heat transfer applications”, Int. J. Heat Mass Trans.,54: 433-438.

[70] Asirvatham, L.G., Raja, B., Lal, D.M. and Wongwises, S.,(2011).” Convective heat transfer of nanofluids with correlations”. Particuology, 9:626-631.

[71] Ebrahimnia-Bajestan, E., Niazmand, H., Duangthongsuk, W. and Wongwises, S.,(2011). "Numerical investigation of effective parameters in convective heat transfer of nanofluids flowing under a laminar flow regime", Int. J. Heat Mass Trans., 54: 4376-4388.

[72] Raisi, A., Ghasemi, B. and Aminossadati, S. M,(2011)." A Numerical study on the forced fonvection of laminar nanofluid in a microchannel with both slip and No-slip conditions", Numerical Heat Transfer Part A: Applications, 59:114-129.

[73] Heris,Z.,Noie, S., Talaii, S. and Sargolzaei, E.,(2011)."Numerical investigation of Al2O3/water nanofluid laminar convective heat transfer through triangular ducts", 6:1-10.

[74] Vincenzo,B., Sergio,N. and Oronzio,M.,(2011)." Enhancement of heat transfer and entropy generation analysis of nanofluids turbulent convection flow in square section tubes", 6:1-12.

[75] Abareshi, M., Goharshadi, E., Zebarjad, S.M., Fadafan, H.K. and Youssefi, A.,(2010). "Fabrication characterization and measurement of thermal conductivity of $Fe_3O_4$ nanofluids", J. Magn. Magn. Mater., 322:3895-3901.

[76] Farajollah, B.I., Etemad, S.Gh. and Hojjat, M.,(2010)." Heat transfer of nanofluids in a shell and tube heat exchanger", Int. J. Heat Mass Trans.,53: 12-17.

[77] Fard, H. M.,Esfahany, M.N. and Talaie, M.R.,(2010)." Numerical study of convective heat transfer of nanofluids in a circular tube two-phase model versus single-phase model", Int. J. Commun. Heat Mass Trans. , 37:91-97.

[78] Do, K.H., Ha, H.J. and Jang, S.P.,(2010)." Thermal resistance of screen mesh wick heat pipes using the water-based $Al_2O_3$ nanofluids", Int. J. Heat Mass Trans., 53: 5888-5894.

[79] Henderson, K., Park, Y.G., Liu, L. and Jacobi, A.M.,(2010)." Flow-boiling heat transfer of R-134a-based nanofluids in a horizontal tube" Int. J. Heat Mass Trans.,53: 944-951.

[80] Godson, L., Raja, B., Lal, D.M. and Wongwises, S.,(2010)."Enhancement of heat transfer using nanofluids-An overview", Renew. Sust. Energ. Rev., 14:629-641.

[81] Kima, S.J., McKrella, T., Buongiornoa, J. and Hu, L.W,(2010)." Subcooled flow boiling heat transfer of dilute alumina, zinc oxide, and diamond nanofluids at atmospheric pressure", Nucl. Eng. Des. , 240:1186-1194.

[82] Lotfi, R., Saboohi, Y. and Rashidi, A.M.,(2010)." Numerical study of forced convective heat transfer of Nanofluids: Comparison of different approaches", Int. J. Commun. Heat Mass Trans.,37:74-78.

[83] Meibodi, M.E., Sefti, M.V., Rashidi, A.M., Amrollahi, A., Tabasi, M. and Kalal, H.S.,(2010)." Simple model for thermal conductivity of nanofluids using resistance model approach", Int. J. Commun. Heat Mass Trans. , 37: 555-559.

[84] Meibodi, M.E., Sefti, M.V., Rashidi, A.M., Amrollahi, A., Tabasi, M. and Kalal, H.S.,(2010)."An estimation for velocity and temperature profiles of nanofluids in fully developed turbulent flow conditions", Int. J. Commun. Heat Mass Trans., 37:895-900.

[85] Meibodi, M.E., Sefti, M.V., Rashidi, A.M., Amrollahi, A., Tabasi, M. and Kalal, H.S.,(2010)."The role of different parameters on the stability and thermal conductivity of carbon nanotube/water nanofluids", Int. J. Commun. Heat Mass Trans., 37:319-323.

[86] Paul, G., Chopkar, M., Manna, I. and Das, P.K.,(2010)." Techniques for measuring the thermal conductivity of nanofluids: A review", Renew. Sust. Energ. Rev.,14:1913-1924.

[87] Paul, G., Pal, T. and Manna, I.,(2010)." Thermo-physical property measurement of nano-gold dispersed water based nanofluids prepared by chemical precipitation technique", J. Colloid Interf. Sci.,349: 434-437.

[88] Qu, J., Wu, H.Y and Cheng, P.,(2010)." Thermal performance of an oscillating heat pipe with $Al_2O_3$-water nanofluids", Int. J. Commun. Heat Mass Trans. , 37:111-115.

[89] Rao, Y.,(2010)."Nanofluids: Stability, phase diagram, rheology and applications", Particuology, 549-555.

[90] Raykar, V.S. and Singh, A.K.,(2010)." Dispersibility dependence of thermal conductivity of carbon nanotube based nanofluids", Phys. Lett. A, 374:4618-4621.

[91] Roberts, N.A. and Walker, D.G.,(2010)." Convective performance of nano fluids in commercial electronics cooling systems", Appl. Therm. Eng.,30: 2499-2504.

[92] Rostamani, M., Hosseinizadeh, S.F., Gorji, M. and Khodadadi, J.M.,(2010)." Numerical study of turbulent forced convection flow of nano fluids in a long horizontal duct considering variable properties", Int. J. Commun. Heat Mass Trans., 37:1426-1431.

[93] Singh, P.K., Anoop, K.B., Sundararajan, T. and Das, S. K.,(2010)." Entropy generation due to flow and heat transfer in nanofluids" Int. J. Heat Mass Trans.,53:4757-4767.

[94] Sundar, L.S.R. and Sharma, K.V.,(2010)." Turbulent heat transfer and friction factor of $Al_2O_3$ Nanofluid in circular tube with twisted tape inserts", Int. J. Heat Mass Trans., 53:1409-1416.

[95] Vajjha, R. S., Das, D. K. and Kulkarni, D.P.,(2010)." Development of new correlations for convective heat transfer and friction factor in turbulent regime for nanofluids", Int. J. Heat Mass Trans. , 53:4607-4618.

[96] Vajjha, R.S., Das, D.K. and Namburu, P. K., (2010)."Numerical study of fluid dynamic and heat transfer performance of $Al_2O_3$ and CuO nanofluids in the flat tubes of a radiator", Int. J. Heat Fluid Fl., 31:613-621.

[97] Wei, X., Kong, T., Zhu, H. and Wang, L., (2010)." $CuS/Cu_2S$ nanofluids: Synthesis and thermal conductivity", Int. J. Heat Mass Trans., 53:1841-1843.

[98] Wei,X. and Wang, L.,(2010)." Synthesis and thermal conductivity of microfluidic copper nanofluids", Particuology, 8:262-271.

[99] Yang, Y.T. and Lai, F.H. (2010)." Numerical study of heat transfer enhancement with the use of nanofluids in radial flow cooling system" Int. J. Heat Mass Trans., 53:5895-5904.

[100] Yu W., Xie H., Chen L. and Li Y., (2010)." Investigation on the thermal transport properties of ethylene glycol-based nanofluids containing copper nanoparticles", Powder Technol.,197:218-221.

[101] Wong, K.V. and Leon,O.D., (2010)." Applications of Nanofluids: Current and Future", Advances in Mechanical Engineering, 1-11.

[102] Bergman, T.L.,(2009)." Effect of reduced specific heats of nanofluids on single phase, laminar internal forced convection", Int. J. Heat Mass Trans.,52: 1240-1244.

[103] Bianco, V., Chiacchio, F., Manca, O. and Nardini, S.,(2009)." Numerical investigation of nanofluids forced convection in circular tubes", Appl. Therm. Eng., 29:3632-3642.

[104] He, Y., Men, Y., Zhao, Y., Lu, H. and Ding, Y.,(2009)." Numerical investigation into the convective heat transfer of TiO2 nanofluids flowing through a straight tube under the laminar flow conditions", Appl. Therm. Eng., 29:1965-1972.

[105] Hwang, K.S., Jang, S.P. and Choi, S.U.S. ,(2009)." Flow and convective heat transfer characteristics of water-based Al2O3 nanofluids in fully developed laminar flow regime", Int. J. Heat Mass Trans., 52:193-199.

[106] Jung, J.Y., Oh, H.S and Kwak, H.Y. ,(2009)."Forced convective heat transfer of nanofluids in microchannels" Int. J. Heat Mass Trans., 52:466-472.

[107] Kakaç S. and Pramuanjaroenkij, A.,(2009)."Review of convective heat transfer enhancement with nanofluids" Int. J. Heat Mass Trans.,52:3187-3196.

[108] Kim, D., Kwon, Y., Cho, Y., Li, C., Cheong, S., Hwang, Y., Lee, J., Hong, D. and Moon S. ,(2009)." Convective heat transfer characteristics of nanofluids under laminar and turbulent flow conditions", Curr. Appl. Phys.,9:119-123.

[109] Kulkarni, D.P., Das, D.K. and Vajjha, R.S. ,(2009)." Application of nanofluids in heating buildings and reducing pollution" ,Appl. Energ., 86: 2566-2573.

[110] Mintsa, H.A., Roy, G., Nguyen, C.T. and Doucet, D.,(2009)." New temperature dependent thermal conductivity data for water-based nanofluids", Int. J. Therm. Sci.,48:363-371.

[111] Murshed, S.M.S., Leong, K.C. and Yang, C. A.,(2009)."Combined model for the effective thermal conductivity of nanofluids", Appl. Therm. Eng., 29:2477-2483.

[112] Namburu, P.K., Das D. K., Tanguturi, K.M. and Vajjha, R.S.,(2009)."Numerical study of turbulent flow and heat transfer characteristics of nanofluids considering variable properties", Int. J. Therm. Sci. , 48:290-302.

[113] Rea, U., McKrell, T., Hu, L.W. and Buongiorno J.,(2009)." Laminar convective heat transfer and viscous pressure loss of alumina-water and zirconia-water nanofluids", Int. J. Heat Mass Trans.,52: 2042-2048.

[114] Pantzali, M.N., Mouza, A.A. and Paras, S.V. ,(2009)."Investigating the efficacy of nanofluids as coolants in plate heat exchangers (PHE)", Chem. Eng. Sci.,64:3290-3300.

[115] Xie, H. and Chen, L. ,(2009)."Adjustable thermal conductivity in carbon nanotube nanofluids" Phys. Lett., 373:1861-1864.

[116] Pantzali, M.N., Kanaris, A.G., Antoniadis, K.D., Mouza, A.A. and Paras, S.V. ,(2009). "Effect of nanofluids on the performance of a miniature plate heat exchanger with modulated surface", Int. J. Heat Fluid Fl., 30:691-699.

[117] Vajjha, R.S. and Das, D. K.,(2009)." Experimental determination of thermal conductivity of three nanofluids and development of new correlations", Int. J. Heat Mass Trans.,52: 4675-4682.

[118] Wen D., Lin G., Vafaei S. and Zhang K. ,(2009).” Review of nanofluids for heat transfer applications”, Particuology,7, 141-150.

[119] Hadjov, K.B. ,(2009).”Modified self-consisted scheme to predict the thermal conductivity of nanofluids”, Int. J. Therm. Sci.,48: 2249-2254.

[120] Mohamed, A., Zeitoun, O.,(2009).”Nanofluids forced convection heat transfer inside circular tubes”, International Journal of Nanoparticles, 2:164-172.

[121] Bi, S.S., Shi, L. and Zhang, L.L.,(2009).”Application of nanoparticles in domestic refrigerators”, Appl. Therm. Eng., 28:1834-1843.

[122] Hwang, Y., Lee, J. K., Lee, J.K., Jeong, Y.M., Cheong, S., Ahn, Y.C. and Kim, S. H.,(2008).”Production and dispersion stability of nanoparticles in nanofluids”, Powder Technol.,186:145-153.

[123] Karthikeyan, N.R., Philip, J. and Raj, B. ,(2008).”Effect of clustering on the thermal conductivity of nanofluids”, Mater. Chem. Phys.,109:50-55.

[124] Khandekar, S., Joshi, Y.M. and Mehta, B.,(2008).”Thermal performance of closed two-phase thermosyphon using nanofluids”, Int. J. Therm. Sci.,47:659-667.

[125] Lee, J.H., Hwang, K.S., Jang, S.P., Lee, B.H., Kimho, J. and Choi, S.U.S. ,(2008).

”Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of $Al_2O_3$ nanoparticles”, Int. J. Heat Mass Trans.,51:2651-2656.

[126] Murshed, S.M.S.,Leong, K.C. and Yang, C. ,(2008).” Thermophysical and electrokinetic properties of nanofluids -A critical review”, Appl. Therm. Eng., 28:2109-2125.

[127] Oh, D.W., Jain, A., Eaton, J. K., Goodson, K. E. and Lee, J. S. ,(2008).” Thermal conductivity measurement and sedimentation detection of aluminum oxide nanofluids by using the 3w method”, Int. J. Heat Fluid Fl., 29:1456-1461.

[128] Kang, Y.T., Kim, H. J. and Lee, K.I. ,(2008).” Heat and mass transfer enhancement of binary nanofluids for $H_2O$/LiBr falling film absorption process”, Int. J. Refrig.,31: 850-856.

[129] Lu, W.Q. and Fan, Q.M.,(2008).”Study for the particle’s scale effect on some thermophysical properties of nanofluids, by a simplified molecular dynamics method”, Eng. Anal. Bound. Elem.,32: 282-289.

[130] Nguyen, C.T., Desgranges, F., Galanis, N., Roy, G., Maré, T., Boucher, S. and Mintsa, H. A. ,(2008).” Viscosity data for $Al_2O_3$–water nanofluid-hysteresis: is heat transfer enhancement using nanofluids reliable”, Int. J. Therm. Sci.,47:103-111.

[131] Chen, H., Yang, W., He, Y., Ding, Y., Zhang, L., Tan, C., Lapkin, A. A. and Bavykin, D. V. ,(2008).” Heat transfer and flow behavior of aqueous suspensions of titanate nanotubes (nanofluids)”, Powder Technol.,183:63-72.

[132] Ding, Y., Chen, H., He, Y., Lapkin, A., Yeganeh, M., Šiller, L. and Butenko, Y. V. ,(2007).”Forced convective heat transfer of nanofluids”, Adv. Powder Technol.,18:813-824.

[133] Zhang, X., Gu, H. and Fujii, M.,(2007).” Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles”, Exp. Therm. Fluid Sci.,31:593-599.

[134] Ko, G.H., Heo, K., Lee, K., Kim, D.S., Kim, C., Sohn, Y. and Choi M. ,(2007)." An experimental study on the pressure drop of nanofluids containing carbon nanotubes in a horizontal tube", Int. J. Heat Mass Trans., 50:4749-4753.

[135] Mansour, R.B., Galanis, N. and Nguyen, C.T. ,(2007)." Effect of uncertainties in physical properties on forced convection heat transfer with nanofluids",Appl. Therm. Eng.,27: 240-249.

[136] Hong, H., Wright, B., Wensel, J., Jin, S., Ye, X.R. and Roy, W. ,(2007)." Enhanced thermal conductivity by the magnetic field in heat transfer nanofluids containing carbon nanotube", Synthetic Met.,157:437-440.

[137] Li, C.H. and Peterson, G.P. ,(2007)." Mixing effect on the enhancement of the effective thermal conductivity of nanoparticle suspensions (nanofluids)", Int. J. Heat Mass Trans.,50:4668-4677.

[138] Yoo, D.H., Hong, K.S. and Yang, H.S. ,(2007)." Study of thermal conductivity of nanofluids for the application of heat transfer fluids" Thermochim. Acta ,455:66-69.

[139] Avsec, J. and Oblak, M.,(2007)." The calculation of thermal conductivity, viscosity and thermodynamic properties for nanofluids on the basis of statistical nanomechanics", Int. J. Heat Mass Trans.,50:4331-4341.

[140] He, Y., Jin, Yi., Chen, H., Ding, Y.,Cang, D. and Lu, H. ,(2007)." Heat transfer and flow behavior of aqueous suspensions of $TiO_2$ nanoparticles (nanofluids) flowing upward through a vertical pipe", Int. J. Heat Mass Trans.,50: 2272-2281.

[141] Lee, J. and Mudawar, I. ,(2007)."Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels", Int. J. Heat Mass Trans.,50: 452-463.

[142] Wang, X.Q. and Mujumdar, A.S.,(2007)."Heat transfer characteristics of nanofluids: a review", Int. J. Therm. Sci.,46:1-19.

[143] Hwang, Y.J., Ahn, Y.C., Shin, H.S., Lee,C.G., Kim, G.T., Park, H.S. and Lee J.K. ,(2006)."Investigation on characteristics of thermal conductivity enhancement of nanofluids", Curr. Appl. Phys., 6:1068-1071.

[144] Hwang, Y., Park, H.S., Lee, J.K. and Jung, W.H. ,(2006)." Thermal conductivity and lubrication characteristics of nanofluids", Curr. Appl. Phys., 6:67-71.

[145] Liu, M.S., Lin, M.C.C., Tsai, C.Y. and Wang, C.C. ,(2006)." Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method", Int. J. Heat Mass Trans., 49:3028-3033.

[146] Palm, S.J., Roy, G. and Nguyen, C.T. ,(2006)." Heat transfer enhancement with the use of nanofluids in radial flow cooling systems considering temperature-dependent properties",Appl. Therm. Eng., 26: 2209-2218.

[147] Heris, S.Z., Etemad, S.G. and Esfahany, M.N. ,(2006)." Experimental investigation of oxide nanofluids laminar flow convective heat transfer", Int. J. Commun. Heat Mass Trans., 33:529-535.

[148] Xuan, Y., Yu, K. and Li, Q. ,(2005)."Investigation on flow and heat transfer of nanofluids by the thermal Lattice Boltzmann model", Prog.Comput. Fluid Dy.,5:13-19.

[149] Liu, M.S., Lin, M.C.C., Huang, I.T. and Wang C.C. ,(2005)." Enhancement of thermal conductivity with carbon nanotube for nanofluids", Int. J. Commun. Heat Mass Trans., 32:1202-1210.

[150] Maiga, S.E.B., Palm, S.J., Nguyen, C.T., Roy, G. and Galanis, N. ,(2005)." Heat transfer enhancement by using nanofluids in forced convection flows", Int. J. Heat Fluid Fl., 26:530-546.

[151] Wen, D. and Ding, Y. ,(2004)." Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions", Int. J. Heat Mass Trans., 47:5181-5188.

[152] Maiga, S.E.B., Nguyen, C.T., Galanis, N. and Roy, G.,(2004)."Heat transfer behaviours of nanofluids in a uniformly heated tube", Superlattice. Microst., 35:543-557.

[153] Roy, G., Nguyen, C.T. and Lajoie, P.R.,(2004)." Numerical investigation of laminar flow and heat transfer in a radial flow cooling system with the use of nanofluids", Superlattice. Microst.,35:497-511.

[154] Nguyen, C.T., Roy, G., Maiga, S.E.B. and Lajoie, P.R.,(2004)."Heat transfer enhancement by using nanofluids for cooling of high output microprocessor, www.electronics cooling.com/html/2004_nov_techbrief.html, 20 april 2012.

[155] Ali, A., Vafai, K. and Khaled, A.R.A.,(2004)."Analysis of heat and mass transfer between air and falling film in a cross flow Configuration", Int. J. Heat Mass Trans.,47:743-755.

[156] Ali, A. and Vafai K. ,(2004)."An investigation of heat and mass transfer between air and desiccant film in an inclined parallel and counter flow channels", Int. J. Heat Mass Trans., 47:1745-1760.

[157] Zhu, H.T., Lin, Y.S. and Yin, Y.S.,(2004)."A novel one-step chemical method for preparation of copper nanofluids", J. Colloid Interf. Sci.,277:100-103.

[158] Li Q. and Xuan Y.,(2002)." Convective heat transfer and flow characteristics of cu-water nanofluid", Sci. China Ser E, 45: 408-416.

[159] Xuan Y. and Li Q. ,(2003)." Investigation on convective heat transfer and flow features of nanofluids",ASME Journal of Heat Transfer, 125:151-155.

[160] Hamilton R.L. and Crosser O.K. ,(1962)."Thermal conductivity of heterogeneous two-component systems, I & EC Fundamentals 1:187-191.

[161] Wasp E.J.,(1977)."Solid-liquid flow slurry pipeline transportation",Trans Tech Publications.

[162] Xuan Y. and Roetzel W.,(2000)." Conceptions for heat transfer correlation of nanofluids",Int. J. Heat Mass Trans., 43:3701-3707.

[163] Xuan Y. and Li Q.,(2000)."Heat transfer enhancement of nanofluid",International Journal of Heat and Fluid Flow, 21:58-64.

[164] Xue Q.Z. ,(2003).”Model for effective thermal conductivity of nanofluids”,Physics Letters, 307:313-317.

[165] Williams, W.C., Buongiorno,J. and Hu,L.W.,(2008).”Experimental investigation of turbulentconvective heat transfer and pressure loss of alu mina/water and zirconia/waternanoparticle colloids (nano fluids) in horizontal tubes”, Journal of Heat Transfer,

130:042412

[166] Einstein, A.,(1906).”Eine neue bestimmung der moleküldimensionen”,Annals of Physics, 324:289-306.

[167] Brinkman, H.,(1952).” The viscosity of concentrated suspensions and solutions”, Journal of Chemical Physics, 20 :571.

[168] Batchelor, G.,(1977).” The effect of brownian motion on the bulk stress in a suspension of spherical particles”, Journal of Fluid Mechanics, 83:97-117.

[169] Graham, A.L.,(1981).”On the viscosity of suspensions of solid spheres”,Journal of Applied Sciences Research, 37:275-286.

[170] Kitano,T., Kataoka, T. and Shirota, T.,(1981).”An empirical equation of the relative viscosity of polymer melts filled with various inorganic fillers”, The Journal Rheologica Acta, 20: 207-209.

[171] Bicerano, J., Douglas, J.F. and Brune, D.A. ,(1999).” Model for the viscosity of particle dispersions”, Journal of Macromolecular Science Review Macromolecular Chemistry Physics, 39 :561-642.

[172] Wang, X., Xu, X. and Choi, S.U.S. ,(1999).” Thermal conductivity of nanoparticle–fluid mixture”, Journal Thermophysics and Heat Transfer, 13:474-480.

[173] Tseng, W.J. and Chen, C.N.,(2003).”Effect of polymeric dispersant on rheological behavior of nickel-terpineol suspensions”, Materials Science and Engineering A, 347:145-153.

[174] Chen, H., Ding, H., He, Y. and Tan, C. ,(2007).” Rheological behaviour of ethylene glycol based titania nanofluids”, Chemical Physics Letters, 444:333-337.

[175] Nguyen, C.,Desgranges, F.,Roy, G., Galanis, N.,Mare, T.,Boucher, S. and Anguemintsa, H.,(2007).”Temperature and particle-size dependent viscosity data for water-based nanofluids-hysteresis phenomenon”, International Journal of Heat Fluid Flow, 28:1492-1506.

[176] Khanafer, K. and Vafai, K.,(2011).” A critical synthesis of thermophysical characteristics of nanofluids”, International Journal of Heat and Mass Transfer, 54:4410-4428.

[177] Vand, V.,(1948).”Viscosity of solutions and suspensions I.Theory”,The Journal of Physical Chemistry, 52:277-299.

[178] Mooney, M.,(1951).” The viscosity of a concentrated suspension of spherical particles”, Journal of Colloid Science, 6-8.

[179] Krieger, I.M. and Dougherty, T.J. ,(1959).”A mechanism for non-newtonian flow in suspensions of rigid spheres”, Journal of Rheology, 3:137.

[180] Krieger, I.M. ,(1972).” Rheology of monodisperse lattices”,Advances in Colloid and Interface Science, 3:111-136.

[181] Frankel, N.A. and. Acrivos, A. ,(1967).”On the viscosity of a concentrated suspension of solid spheres”, Chemical Engineering Science, 22:847-853.

[182] Miller, A. and Gidaspow, D.,(1992).”Dense, Vertical gas-solid flow in a pipe”, AIChE journal, 38:1801-1815.

[183] Chow, T.S.,(1993).”Viscosities of concentrated dispersions”, Physical Review E, 48:1977-1983.

[184] Pak, B.C. and Cho, Y.I. ,(1998).” Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles”, Experimental Heat Transfer, 11:151-170.

[185] Liu, S. ,(1999).” Particle dispersion for suspension flow”, Chemical Engineering Science, 54:873-891.

[186] Wang, X., Xu, X. and Choi, S.U.S. ,(1999).”Thermal conductivity of nanoparticle-fluid mixture”, Journal of Thermophysics and Heat Transfer, 13: 474-480.

[187] Davalos, L.A., Orozco, L.A. and Del Castillo, L.F.,(2002).” Hydrodynamic behavior of suspensions of polar particles”, Encyclopedia of Surface and Colloid Science, 4:2375-2396.

[188] Putra, N., Roetzel, W. and Das, S.K. ,(2003).” Natural convection of nano-fluids”, Heat and Mass Transfer, 39:775-784.

[189] Tang, G.Y.,Yang, C.,Chai, C.J. and Gong, H.Q. ,(2004).”Joule heating effect on electroosmotic flow and mass species transport in a microcapillary”, International Journal of Heat and Mass Transfer, 47:215-227.

[190] Maxwell, J.C. A Treatise on Electricity and Magnetism, unabridged 3rd ed., Clarendon Press, Oxford, UK, 1891.

[191] Hamilton, R.L. and Crosser, O.K.,(1962).”Thermal conductivity of heterogeneous two component systems”, Industrial and Engineering Chemistry Fundamentals,1:187-191.

[192] Hui, P.M., Zhang, X., Markworth, A.J. and Stroud, D.,(2003).” Thermal conductivity of graded composites: numerical simulations and an effective medium approximation”, Journal of Materials Science, 34:5497-5503.

[193] Xuan, Y. and Li, Q. ,(2000).”Heat transfer enhancement of nanofluids”, International Journal of Heat and Fluid Flow, 21:58-64.

[194] Yu, W. and Choi, S.U.S.,(2003).”The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model”, Journal of Nanoparticle Research, 5: 167-171.

[195] Godson, L., Raja, B.,Mohan Lal, D. and Wongwises, S. ,(2010).”Experimental investigation on the thermal conductivity and viscosity of silver-deionized water nanofluid”, Experimental Heat Transfer, 23:317-332.

[196] Prasher, R.,Bhattacharya, P. and Phelan, P.E.,(2005).” Thermal conductivity of nanoscale colloidal solutions (nanofluids)”, Physical Review Letters, 94 1–4.

[197] Koo, J. and Kleinstreuer, C. ,(2004).”A new thermal conductivity model for nanofluids”, Journal of Nanoparticle Research, 6:577-588.

[198] Li, C.H. and Peterson, G.P.,(2006).”Experimental investigation of temperature and volume fraction variations on the effective thermal conductivity of nanoparticle suspensions (nanofluids)”, Journal of Applied Physics,99:084314.

[199] Palm, S.J., Roy, G. and Nguyen, C.T.,(2006).” Heat transfer enhancement with the use of nanofluids in radial flow cooling systems considering temperature-dependent properties”, Applied Thermal Engineering, 26:2209– 2218

[200] Maiga, S.E.B., Nguyen, C.T., Galanis, N. and Roy, G.,(2004).” Heat transfer behaviours of nanofluids in a uniformly heated tube”, Superlattices and Microstructures,35:543-557.

[201] Bhattacharya, P., Saha, S.K, Yadav, A., Phelan, P.E. and Prasher, R.S.,(2004).” Brownian dynamics simulation to determine the effective thermal conductivity of nanofluids”, Journal of Applied Physics, 95:6492-6494

[202] Buongiorno, J.,(2006).” Convective transport in nanofluids, Journal of Heat Transfer, 128: 240-251

[203] Kim, D., Kwon, Y., Cho, Y., Li, C.,Cheong, S., Hwang, Y., Lee, Y., Hong, D. and Moon, S.,(2009).”Convective heat transfer characteristics of nanofluids under laminar and turbulent flow conditions”, Current Applied Physics ,9 :119–123

[204] Timofeeva, E., Gavrilov, A., McCloskey, J. and Tolmachev, Y.,(2007).” Thermal conductivity and particle agglomeration in alumina nanofluids: Experiment and Theory”, Physical Review E ,76: 061203

[205] Chon, C.H., Kihm, K.D., Lee, S.P. and Choi, S.U.S.,(2005).”Empirical correlation finding the role of temperature and particle size for nanofluid (Al2O3) thermal conductivity enhancement”, Applied Physics Letters, 87

[206] Murshed, S.M.S., Leong, K.C. and Yang, C.,(2006).” A model for predicting the effective thermal conductivity of nanoparticles–fluid suspensions”, International Journal of Nanoscience, 5:23-33

[207] Yang, Y., Zhang, Z.G.,Grulke, E.A., Anderson, W.B. and Wu, G.,(2005).” Heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in laminar flow”,International Journal of Heat Mass Transfer, 1107-1116

[208] Yu, W., France, D.M., Routbort, J.L. and Choi S.U.S.,(2008).” Review and comparison of nanofluid thermal conductivity and heat transfer enhancements”, Heat Transfer Engineering, 29 :432-460.

[209] Pak, B.C. and Cho, Y.I.,(1998).” Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles”, Exp. Heat transfer, 11:151

[210] Batchelor. G.K. An Introduction to Fluid Dynamics. Cambridge Univ.Press. Cambridge, England 1967.

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