Heat Transfer Performance of Oil-Based Nanofluids in Electric Transformers

By

Lim Lian Rui

14740

Dissertation submitted in partial fulfillment of
the requirements for the
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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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(Dr. Rajashekhar Pendyala)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

JANUARY 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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LIM LIAN RUI

ABSTRACT

Natural convection takes place in transformer by its heat dissipating medium - transformer oil which helps in regulating transformer operating temperature. Degradation of transformer oil causes transformer dielectric breakdown because of conductible bubble gas formation. This is because of the low thermal conductivity of transformer oil which results in poor heat transfer performance. Selected naphtha based transformer oil is used as base fluid in this research project. Carbon nanotubes (CNT), graphite, and diamond nanoparticles with various concentrations (0.25 to 2 vol%) are used as dispersant in oil-based nanofluids. Nanoparticles with high thermal conductivity, when mixed with base fluids, can improve the overall heat transfer characteristics of the base fluid. This can help to improve the oil degradation problem in transformer. Computational Fluid Dynamics (CFD) simulation tool – ANSYS Fluent 15.0 is used to perform 3D simulation to visualize the heat transfer performance inside the transformer based on the designed transformer model geometry. Slice model had been developed with defined heat flux as boundary conditions at winding and core area. Specific heat capacity and viscosity of the base fluid (transformer oil) and nanofluids (transformer oil with nanoparticles) are defined as function of temperature while density, thermal conductivity, and thermal expansion coefficient are set as constant for Fluent solver. Results show that CNT, graphite, and diamond nanofluids have better heat transfer coefficient than transformer oil. It is found that CNT and graphite based nanofluids show lower temperature at winding area than transformer oil alone. CNT based nanofluids at 2.0 vol% showed the highest value of overall heat transfer coefficient i.e. 239.36 $W/m^2.K$ with lowest winding temperature i.e. 78.63 ℃. Heat transfer performance of CNT based nanofluids are found to be better than graphite and diamond based nanofluids which can be recommended as a new kind of synthetic fluid specific for transformer usage.

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INTRODUCTION

1.1 Background Study

Heat transfer in transformer can be classified as conduction, convection, and radiation. Conduction includes heat transferred:

i. From the inner part of core and windings to their surface,
ii. Between windings and core,
iii. Inside the insulation material (low velocity oil), and
iv. Through the wall of the transformer tank.

Conduction is governed by Fourier's Law, where one-dimensional form is expressed as:

$$q = -k\nabla T \qquad (1)$$

where,

q= rate of heat flow (W/m^2)

∇T = rate of change of temperature with the direction of the flow of heatv(K/m)

K= thermal conductivity (W/m.K)

Convection in transformer happens when the following situations occur:

i. The heated up transformer oil (hot fluid) moves up and the cool oil moves down.
ii. Surrounding air is heated up by the heat dissipating fins and rises up.

Both situations are known as ***natural convection*** where density is the driving force for the fluid motion. The heat will be transferred from the surface of the core and windings to the transformer oil by the movement of the oil flowing inside the tank. Convection equation is given by Newton's Law of Cooling.

$$q = h(T_s - T_\infty) \qquad (2)$$

where,

h = convection heat transfer coefficient (W/m^2.˚C)

T_s= surface temperature

T_∞= fluid temperature far from the surface

Radiation is given less concern as the heat transfer mechanisms in a transformer are mainly conduction and convection [1].

Fluid or oil is used as heat transfer medium to dissipate the heat generated from windings to ensure transformer at optimal condition and minimal rate of loss-of-life. The oil is normally enclosed in the transformer body which is generally called transformer oil. There are commonly three types of transformer oil available which are mineral, bio-based, and silicon transformer oil. Mineral transformer oil is popular in use nowadays which is a kind of highly-refined mineral oil that is stable at high temperature and having electrical insulating properties. It is often used as insulating and heat dissipating medium in oil-filled transformers, some high-voltage capacitors, fluorescent lamp ballasts, and some high voltages switches and circuit breakers [2].

Transformer oil-based nanofluids are easily prepared by dispersing nanoparticles in transformer oil such as aluminium oxide (Al_2O_3), aluminium nitride (AIN), zinc-oxide (ZnO), silver-silica composite, etc as proposed in literatures. Nanofluid is also defined as fluid that contains dispersed nanoparticles. Thermal conductivity of solid nanoparticles increases the thermal conductivity and overall heat transfer performance of the host fluid. Besides, nanoparticles tend to have long-term stability, higher surface area and rheological properties than millimeter- or micrometer-sized particles [3]. In short, nanoparticle is better to be dispersed in fluid than the course particles for the criteria mentioned above.

Regular checking and analysis of transformer oil helps in keeping the good condition of oil-lubricated equipments. The analysis can provide the quality of the oil and the detection of the possible problems lying in the machine such as contact arcing and insulating paper aging [4]. This could be related to Swift and Molinski [5] as discussed in previous paragraph where the possible problems are mainly due to high winding temperature. Swift and Molinski stated that higher winding hot spot temperatures causes degradation of the winding insulation material, followed by formation of gas bubbles which facilitates the dielectric breakdown characteristic of the transformer oil.

Transformer is an essential device in electric energy transmission to link two regional power grids for stepping up or down power transferred from one station to another. Winding is one of the major components in transformer which undergoes heating as power loss. The winding temperature is usually the core factor limiting the work load of a power transformer. Winding temperature for transformer as standard is set at below 110˚C or an upper limit of 80˚C rise above ambient temperature [5]. This is to prevent transformer dielectric breakdown due to oil degradation.

Heat source is generated from power loss by core and windings. One of the most critical parameters controlling a transformer's life is the hot-spot temperature value [6]. Hot spot temperature is temperature of hottest section of winding. High capacity transformer (>600kVA) would have higher winding temperature from 85˚C to 97˚C under a normal load condition. Winding temperature is recommended at below upper limit of 110˚C [7]. Transformer with capacity of 112.5 to 10,000 kVA should maintain winding temperature below 80 to 90˚C [8]. Oil temperature should be maintained between 20 to 90˚C in which exceeding the limit could cause transformer breakdown. This indicates the transformer is at high risk of breakdown even operating at normal load condition.

Transformer's normal loss of life at winding temperature of 110˚C is estimated to be 0.0369% per day as mentioned in IEEE Standard. This is equivalent to around 7.42 years of transformer lifespan. For contingency overload conditions (few days), the industrial recommendation is to avoid the winding hot spot temperature to exceed 140 ℃ to limit the risk of gas bubbles release [9].

To simplify the literatures, transformer oil is the key material in affecting the performance, maintenance frequency, and lifespan of a transformer. Study in fluid dynamics aspect in heat transfer could help knowing the heat dissipating performance of oil flowing inside transformer.

Computational Fluid Dynamics (CFD) is brunch of fluid dynamics that uses numerical method and algorithms to solve and analyze fluid flow problems such as velocity profile, heat distribution, pressure distribution, etc. There are various kinds of CFD simulation software available in the market such as COMSOL Multiphysics, ANSYS, MATLAB, and etc.

ANSYS is found to be more widely used and user-friendly. Under comparison, ANSYS is more advanced in term of different analysis systems such as Fluid Flow (CFX), Fluid Flow (Fluent), Transient Thermal, and others. For heat transfer, model flow, turbulence, and reactions for industrial applications, it is recommended to use ANSYS- Fluid Flow Fluent.

1.2 Problem Statement

Heat transfer performance of transformer oil is found to be poor due to low thermal conductivity. It can be improved by using nanoparticles with high thermal conductivity and low electrical insulation properties. Increase in thermal conductivity is believed to achieve higher heat transfer coefficient for natural convection. Nusselt number and Rayleigh number can be used as parameter to determine the improvement in natural convection.

Nanoparticles with high thermal conductivity, when mixed with base fluids, can improve the overall heat transfer characteristics of the base fluid. This can help to improve the oil degradation problem in transformer. Electrical load losses contribute thermal stress on active part, namely core and windings. Thermal stress causes thermal degradation of paper insulation on the windings as mentioned by Swift and Molinski [5]. Under thermal stress, there is notable current passing through the insulating medium as reported by Balasubramanian *et al.* [10]. This situation leads to degradation of transformer oil and formation of gas bubbles which can result in dielectric breakdown. andChoi *et al.* [3] supported that transformer oil has relatively low thermal conductivity and faces thermally driven failure from instantaneous overload.

Degradation of transformer oil causes transformer oil replacement or maintenance becomes more frequent. A half-year scheduled maintenance is usually done for transformer oil based on dielectric strength, water content, acidity, sludge content, flash point, and resistivity. It will be replaced if the oil is in low performance [11]. Based on Meshkatoddini [12], transformer oil with operating temperature of 80˚C will have a life limit of 9559 hours which is around 1 year.

Various kinds of transformer oil-based nanofluids are invented and proposed to have relatively higher thermal conductivity to improve the degradation problem and reduce maintenance cost. However, real-life situation testing of suggested transformer oil-based nanofluids in identifying the effectiveness of heat transfer fluid for transformer is still remained as a challenging topic.

1.3 Objective and Scopes

The objectives of this proposed research are

1. To design model of transformer geometry.
2. To analyze the heat transfer performance of selected transformer oil with and without nanoparticles, inside a distribution transformer.
3. To analyze the heat transfer characteristics at different nanoparticles loading.
4. To determine the heat transfer enhancement of nanofluid in transformer.

The scopes of this research are

1. To create 3D model geometry of a transformer with real size dimension for CFD simulation
2. To understand heat distribution and velocity profile of selected transformer oil and transformer oil-based nanofluids with different nanoparticles concentration.
3. To analyze heat transfer and fluid velocity by using dimensionless parameters such as Nusselt, Prandlt, Rayleigh, and Grashof number.

1.4 Relevance and Feasibility

The study of heat transfer performance of various types of transformer oil-based nanofluids in a transformer is important in prevention of electrical power breakdown and energy saving as it practically helps to understand and identify thermal condition inside a transformer, and propose improvement through findings for transformer with various type of insulating or heat dissipating fluids.

CFD is the scientific tool of predicting fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena by solving the mathematical equations which govern these processes using a numerical process. Simulation could provide real situation analysis, meanwhile, save costs and time for purchasing transformer prototype, experiment materials such as nanoparticles and transformer oil, and lab utility.

The research is feasible within the timeframe to achieve its objectives after having discussion with experienced lab personnel, postgraduate student, and getting advice from supervisor. This can be shown in the Work Process Flow and Gantt chart in Chapter 3: Methodology.

CHAPTER 2

LITERATURE REVIEW

2.1 Numerical Studies of Heat Transfer in Transformer

Significant heat transfer in transformer is natural convection in which it helps to dissipate heat energy from winding and core out to surrounding. Natural convection is a heat transfer mechanism in which fluid moves by density differences due to temperature gradient. Typical velocity and temperature profiles for natural convection flow over a hot vertical plate at temperature T_s inserted in a fluid at temperature T_∞ is shown as below:

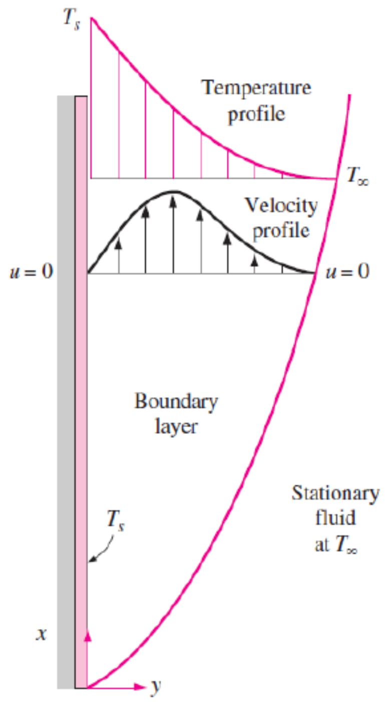


Figure 2.1: Velocity and Temperature Profile of Natural Convection [13]

Natural convection heat transfer correlations are usually expressed in terms of the Rayleigh number. Rayleigh number is the product of Grashof and Prandlt numbers.

$$Ra_L = Gr_L.Pr = \frac{g\beta(T_s - T_\infty)L_c^3}{v^2}Pr \qquad (3)$$

Grashof number, Gr_L is the ratio of buoyancy force to the viscous force acting on the fluid.

$$Gr_L = \frac{g\beta(T_s - T_\infty)L_c^3}{v^2} \qquad (4)$$

where,

g = gravitational acceleration, m/s^2

β=coefficient of volume expansion, 1/K

T_s=temperature of the surface, ˚C

T_∞=temperature of the fluid sufficiently far from the surface, ˚C

v= kinematic viscosity of the fluid, m^2/s

Prandtl number (Pr) is the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity.

$$Pr = \frac{Molecular\ diffusivity\ of\ momentum}{Molecular\ diffusivity\ of\ heat} = \frac{v}{\alpha} = \frac{\mu C_p}{k} \quad (5)$$

Nusselt number is the ratio of convective to conductive heat transfer across the boundary.

$$Nu = \frac{Convective\ heat\ transfer\ coefficient}{Conductive\ heat\ transfer\ coefficient} = \frac{hL}{k} \quad (6)$$

Important surface temperature in transformer must be known for analysis. Wakil *et al.* [14] used 2D Control Volume Method to study heat transfer and fluid flow in power transformer. It was stated that the highest temperature occurs at the cooling channel walls inside secondary windings where hear flux is maximum. They also found that transformer geometry without insulation in cooling channel is the best geometry for better fluid mixing.

Study of heat transfer by convection had been carried out by Smolka *et al.* [15] by using 3D Finite Volume Method by developing an exhaustive procedure to analyze dry-type three-phase transformers considering coupling between both models of electromagnetic field and thermal fields. It was found that cooling mechanism of forced convection by water is better than natural convection by air for dry-type cases. Mufuta and Bulck [16] had studied on laminar mixed convection (natural and forced) inside the vertical and horizontal channels of a disc-type transformer. It is found that mass flow fluctuation occurs in vertical channels is caused by some flow through horizontal channels. They proposed that general heat transfer coefficient depends on different modeled parameters. Oh *et al.* [17] focused on turbulent natural convection of oil inside a cylindrical single-phase transformer using specific low Reynolds number model by using 3D model. The variable used is the percentage of rated load where at 100% load, the winding temperature is at 110˚C. Therefore, it can be said that for oil filled type transformer, natural or forced convection with respect to designed model is highly expected in future research. All these researches showed an early stage of numerical modelling in transformer for heat transfer mostly based on fluid flow parameter.

Oil-filled transformer had been given more focus for its heat transfer performance. Gastelurrutia *et al.* [18] put the effort in developing slice model of oil filled transformer which cooling system is ONAN (Oil Natural Air Natural) by using Finite Volume Method for the study on temperature profile and velocity profile of transformer oil with different capacity transformer. Correlation of Nusselt number and Rayleigh number of transformer oil with respect to surrounding air was developed. They proposed flow pattern is same for geometry with different size. Heat transfer is found to vary in vertical direction and oil is active at upper part of transformer and decreases when moves down. This is the effect of temperature gradient and known as natural convection phenomenon. Although this study showed concern on transformer oil heat transfer performance, nanofluid is not being used in this study for the proof of improvement of heat transfer of transformer oil.

Tsili *et al.* [19] carried out thermal analysis on ONAN power transformer by using coupled 3D heat transfer and fluid flow Finite Element Method model. The study is on temperature distribution of specific transformer part where the maximum temperature is at the upper part of the winding. It is proposed that specific transformer parts are important in the accurate representation of oil flow and heat dissipation such as wining cooling ducts. This study mainly focused on transformer active part rather than heat transfer performance of transformer oil.

The latest effort of study in heat transfer in transformer by using 2D Finite Element Modeling was done by Guan *et al.* [2]. They used transformer oil with silicon Carbide as fluid. They studied the temperature distribution, velocity distribution, and density of nanoparticle of oil in transformer under variables of natural or forced convection. It was found that heat transfer performance of base fluid is significantly improved through suspending nanoparticles. Inlet velocity is the dominant factor of forced convection. Generally heat transfer by forced convection is better. However, heat transfer characteristics are improved under natural convection. This study does not show a clear improvement of heat transfer in transformer by using nanofluid where there is no variation of nanoparticle types and loading to show its relation to improvement of heat transfer.

From literatures, it can be concluded that heat transfer in a 3D modeling of transformer with comparison of conventional transformer oil and transformer oil-based nanofluids with different particle loading is necessary to fill the research gap.

Summary of previous significant numerical modeling of transformer oil studies is shown in the table below:

Table 2.1: Summary of Numerical Studies of Heat Transfer in Transformer

Gastelurrutia *et al.* (2011)	-Temperature profile -Flow pattern -Rayleigh number -Nusselt number	-Transformer sizing -External Thermal Boundary Conditions	-Flow pattern is same for different sizes with similar geometry. -Heat transfer coefficients must vary in the vertical direction. -Oil is active at upper part and decreases when moves down.
Tsili *et al.* (2012)	-Temperature distribution	-Mesh densities	-Maximum temperature at upper part of the winding -Higher mesh densities the more accurate the results.
Guan *et al.* (2014)	-Temperature distribution - Velocity distribution - Density of nanoparticles in fluid	-Natural or forced convection -Transformer oil with and without nanparticles	-Heat transfer performance of base fluid is significantly improved through suspending nanoparticles. -Inlet velocity is the dominant factor of forced convection -Heat transfer characteristics are improved under natural convection.

2.2 Mathematical Model

2.2.1 Heat Transfer Equation

For solution of CFD equations, in solid and liquid materials, heat transfer and viscous fluid flow are governed by Navier-Stokes equation, with basic principles of conservation of momentum, mass, and energy.

Navier-Stokes general equation:

$$\rho\left(\frac{\partial v}{\partial t}+v\cdot\nabla v\right)=-\nabla p+\ \mu\nabla^{2}v+f \qquad (7)$$

Where ∇p = pressure gradient, $\mu\nabla^{2}v$=viscosity, and f is other body forces.

Conservation of continuity (Mass) equation:

$$\left(\frac{\partial\rho}{\partial t}+(\vec{u}.\nabla).\rho\right)+(\nabla.\rho u)=0 \qquad (8)$$

This equation describes the rate of change of density at a fixed point resulting from the changes in the mass velocity vector.
Conservation of momentum equation:

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+(\vec{u}.\nabla u)\right)-\nabla.\bar{\bar{\sigma}}=\rho.\vec{g} \qquad (9)$$

where,

ρ is fluid density (kg/m^3),
$\vec{u}$ is fluid velocity (m/s),
g is gravity (m/s^2)
According to Tsili *et al.* [19], Navier-Stokes equation for conservation of energy principle is described by equation:

$$\rho\left(\frac{\partial E}{\partial t}+\ (\vec{u}.\nabla\mathrm{E})\right)-\nabla.\left(\vec{K}.\Delta T\right)+p\nabla.\vec{u}=0 \qquad (10)$$

where,
E is thermodynamics internal energy (J),
$\vec{K}$ is the magnitude of heat conductivity of the element, and
ΔT is the temperature difference.

In case of incompressible material,

$$\nabla . \vec{u} = 0$$

2.2.2 Boundary Condition

Based on Gastelurrutia *et al.* [18], the most important boundary condition is the heat flux from core and windings. Constant and uniform heat fluxes are imposed on the internal surfaces of the models. Heat fluxes are calculated by dividing the power value corresponding to each solid portion inside the transformer by its total surface area.

Heat flux of core

$$q^{"} = \frac{P_{N,core}}{A_{core}} \tag{11}$$

Heat flux of LV coils

$$q^{"} = \frac{P_{N,LV}\left(\frac{Vol_{i,LV}}{Vol_{Tot,LV}}\right)}{A_{i,LV}} \tag{12}$$

Heat flux of LV coils

$$q^{"} = \frac{P_{N,HV}\left(\frac{Vol_{i,HV}}{Vol_{Tot,HV}}\right)}{A_{i,HV}} \tag{13}$$

Where $P_{N,core}$, $P_{N,LV}$, and $P_{N,HV}$ are the measured power losses. Total surfaces areas are known as A_{core}, $A_{i,LV}$, and $A_{i,HV}$. $Vol_{i,LV}$ and $Vol_{i,HV}$ are the volume of copper coil contained in each portion of the LV and HV windings.

2.3 Significant Properties of Effective Transformer Oil Cooling

For effective cooling, properties such as specific heat capacity, thermal conductivity, viscosity, and density are the main factors. Specific heat capacity is the heat required to increase the temperature of object of 1kg by 1K. Thermal conductivity explains about how an object conducts heat flux from one point to another. It concerns about the total heat transfer in the boundary layer at laminar flow. Density gradient is normally the driving force for natural convection. Viscosity affects the cooling process directly. The lower the viscosity is the better to obtain rapid and efficient cooling in a transformer. Naphthenic type transformer oil with lower viscosity index has better cooling properties [20].

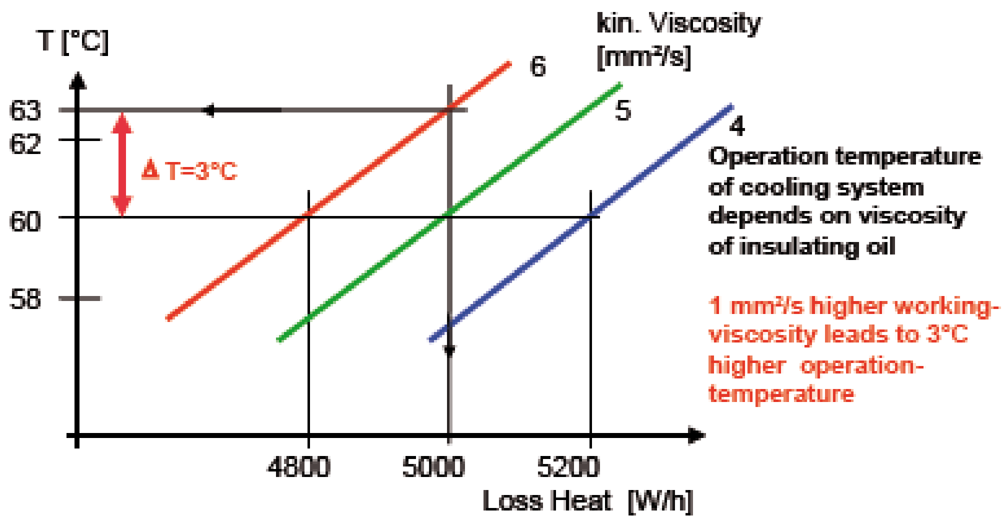


Figure 2.2: Heat transfer performance of oils with different viscosity [20]

2.4 Transformer Oil-based Nanofluids

Transformer oil is categorized by types. There are three types of transformer oils which are mineral oil, silicone, and bio-based. Mineral transformer oil based fluid dominates the global consumption as it possesses better electrical and cooling properties, meanwhile provides good value for money [21].

Mineral type transformer oil consists of Paraffin base and Naphtha base. Naphtha oil is more easily oxidized than Paraffin oil but oxidation product i.e. sludge in the Naphtha oil is more soluble than Paraffin oil. Hence sludge of naphtha based oil is not precipitated in bottom of the transformer which does not obstruct convection circulation of the oil. This means it does not disturb the transformer cooling system. However, in the case of Paraffin oil, although oxidation rate is lower than that of Naphtha oil but the oxidation product or sludge is insoluble and precipitated at bottom of the tank and obstruct the transformer cooling system [22].

Nanoparticles could be added into transformer oil to become transformer oil-based nanofluid. Thermal conductivity of transformer oil with nanoparticles is given focus in this research. Various types of transformer oil, transformer oil-based nanofluids from literatures have been listed down with its thermal conductivity as below:

Table 2.2: Various Type of Transformer Oils and Oil-Based Nanofluids with Thermal Conductivity and Kinematic Viscosity

Fluids	Thermal Conductivity	Kinematic Viscosity	Source
Mineral (Naphthenic) transformer oil	0.310 W/m.K @ 40˚C	19.5 cSt @ 20˚C 9.1 cSt @ 40˚C	NYNAS. Cosemans [20]
Silicon transformer oil	0.150 W/m.K @ 20˚C	55 cSt @ 20˚C 15 cSt @ 100˚C	Kopeliovich [23]
Synthetic transformer oil	0.144 W/m.k @ 20˚C	70 cSt @ 20˚C 5.3 cSt @ 100˚C	
Mineral transformer oil	0.109 W/mK @ 20˚C 0.100 W/m.K @ 80˚C	18.054 cSt @ 20˚C 8.111 cSt @ 40˚C 3.387 cSt @ 80˚C	Beheshti *et al.* [24]
TO + 0.001 wt% Multi-walled carbon nanotube	0.11W/m.K @ 60˚C	17.893 cSt @ 20˚C 4.327 cSt @ 60˚C	
TO + 0.01 wt% Multi-walled carbon nanotube	0.112 W/m.K @ 60˚C	17.908 cSt @ 20˚C 4.422 cSt @ 60˚C	
TO + up to 4 vol% Al_2O_3	*>20% enhancement*	-	Choi, C., H.S. Yoo, and J.M. Oh [3]
TO + up to 0.5 vol% AIN	*8% enhancement*	-	

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

In this research, selected transformer oil as base fluid and transformer oil-based nanofluids will be simulated inside a transformer. Characteristics of the fluids will be studied and analyzed by using ANSYS 15.0. 3D transformer geometry model will be developed to analyze the behaviour of oil flow (velocity profile), heat transfer, and critical surface temperature (temperature profile).

3.2 Software

CFD is used in all stages of the engineering process:

- Conceptual studies of new designs
- Detailed product development
- Optimization
- Troubleshooting
- Redesign

ANSYS contains plenty of analysis systems for users for different analysis conditions. ANSYS Fluent version 15.0 is used for this research.

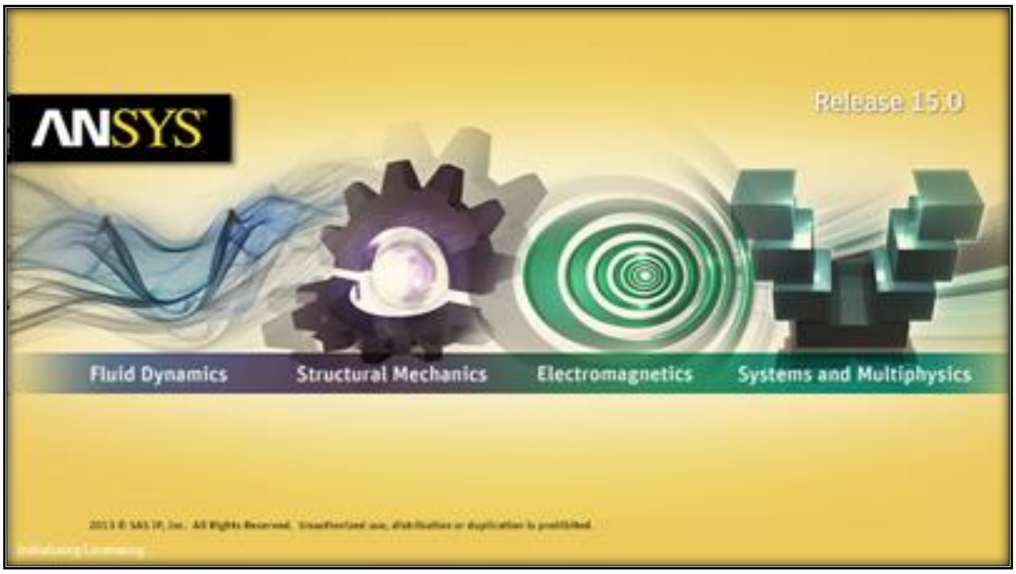


Figure 3.1: ANSYS 15.0 Interface

ANSYS CFD solvers are based on the finite volume method in which the domain is discretized into a finite set of control volumes. General conservation (transport) equations for mass, momentum, energy, species, etc. are solved on this set of control volumes. All CFD simulations are approached using the steps described below

i. Define Your Modelling Goals
ii. Identify the Domain You Will Model
iii. Create a Solid Model of the Domain
iv. Design and Create the Mesh
v. Set Up the Solver
vi. Compute the Solution
vii. Examine the Results
viii. Consider Revisions to the Model

3.3 Materials Selection

In this study, Naphtha based transformer oil is used a based fluid because it does not form sludge or precipitate inside the transformer. Selected Naphtha oil having the properties function is shown as below:

Table 3.1: Properties of Transformer Oil [25]

Properties	Value
Density	887-0.659T (kg/m^3)
Dynamic Viscosity	$0.0000013573 \left[\exp\left(\frac{2797.3}{T+273}\right)\right]$ (kg/m.s)
Specific heat capacity	1960 +4.005T (J/kg.C)
Thermal conductivity	0.1202 (W/m.K) @25˚C

Selected nanoparticles suitable for transformer oil are Carbon Nanotube, Graphite, and Diamond.

Proposed concentration of nanoparticles for dispersing in transformer oil is in the range from 0.5 to 2 vol% with interval of 0.5 vol%. There are total 12 samples of nanofluids for heat transfer simulation. Properties of nanoparticles are listed as below:

Table 3.2: Properties of Selected Nanoparticles [26]

Nanoparticles	**Specific heat (kJ/kg K)**	**Thermal conductivity (W/m K)**	**Density (kg m^3)**
Carbon nanotube (CNT)	0.750 [27]	3000	1350
Graphite	0.701	120	2160
Diamond	0.509	3300	3530

3.4 Geometry Identification

A three phase distribution transformer with 630kVA capacity equipped with dimension as below is selected:

Table 3.3: Dimension of ONAN Distribution Transformer [18]

Descriptions	Dimension
Casing height	1005mm
Casing length	1275mm
Casing width	500mm
Number of fins	84
Fin height	800mm
Fin Length	230mm

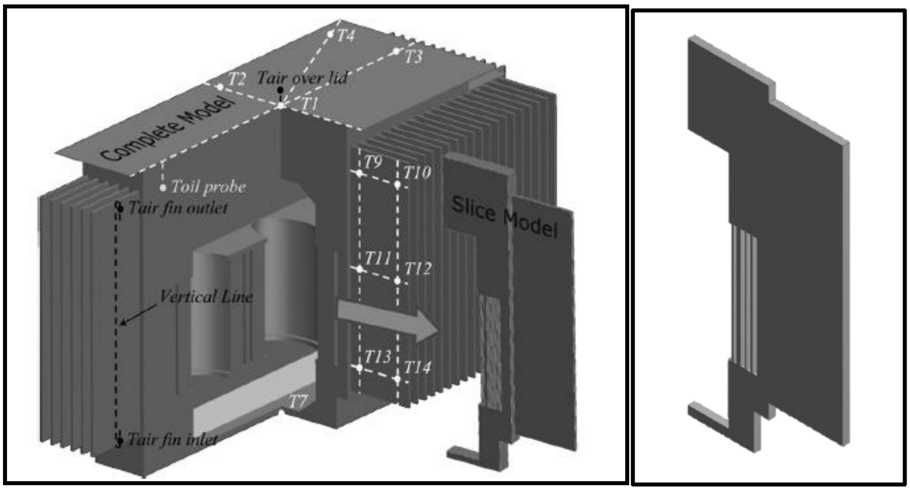


Figure 3.2: Left: Selected geometry of distribution transformer[18], Right: Developed slice model

3.5 Work Process Flow CFD ANSYS Simulation

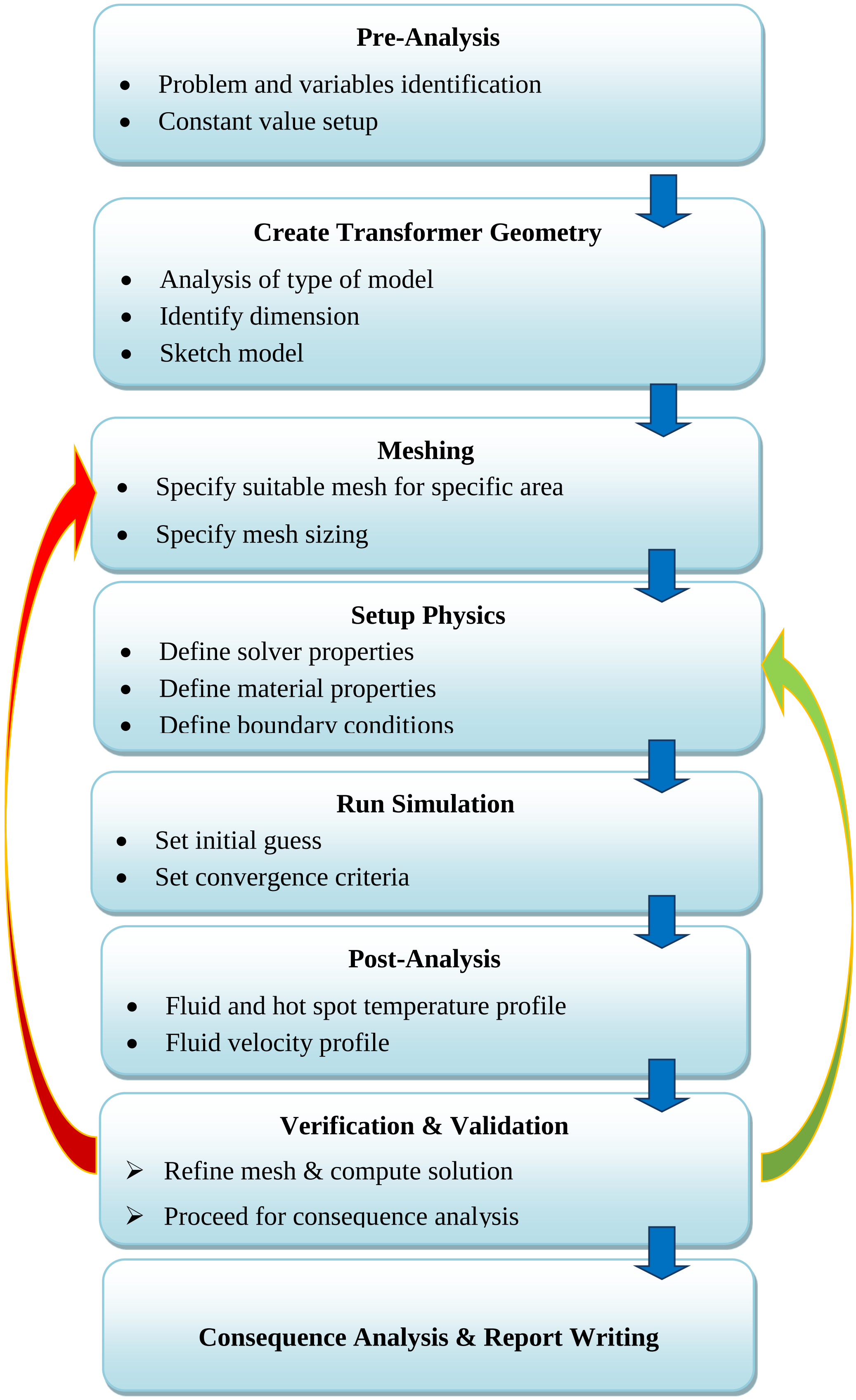


Figure 3.3: Work Process Flow

3.6 Design Modeling

A complete model has been built by using Design Modeller. The sketches had been on all the plane types (XY plane, ZX plane, and YZ plane).

Table 3.4: Technique Used for Geometry Modeling

Geometry part	Technique
Tank fins	Extrude, Pattern
Transformer tank	Extrude
Windings	Resolve, Pattern
Core	Resolve, Pattern

Extrude function was used to produce 3D geometry. Pattern enables user to create same 3D geometry at one time without redraw the same geometry. This function saves time and is practical. Transformer tank geometry had been drawn based on exact dimension of a transformer as stated in previous section.

To differentiate the fluid part and the solid part, Boolean function was used to subtract the solid part (core and windings) from the overall part (tank). This can be seen in result in Figure 4.1.

Slice model has also been designed to study the heat transfer in a portion of transformer. Slice model consists of half of the transformer complete model with slice thickness of 20mm only which can be seen in Figure 4.2.

3.7 Meshing

Meshing had been done for slice model by setting the sizing as below:

Table 3.5: Meshing Settings

Criteria	Settings	Reason
Advanced size function	Proximity	For square body
Relevance centre	Medium	For finer meshing size
Smoothing	High	To enable uniform mesh formation
Transition	Slow	To enable steady meshing development

Proximity min size	0.0099 m	To reduce element number of meshing
Max size	0.055 m	To reduce course element number
Inflation	Chosen Selection: Oil body (fluid part)	To enable solid body meshing independent from oil body.

Fluid body gap in between the solid body is relatively narrow; hence, sweep method with all triangular shape chosen had been taken in place on the fluid body meshing part to avoid non uniform and neat meshing which, at the same time, can assist in maintaining good quality meshing.

Body sizing had been tuned for the fluid body and solid body respectively:

Table 3.6: Body Sizing Settings

Body	Sizing	Behaviour
Fluid	0.0032 m	Hard
Solid	0.005 m	Hard

Hard behavior will force the system to mesh based on the desired sizing for selected body. The system will produce required mesh size without referring to global mesh sizing.

The other functions of meshing are set as default because further tuning can cause meshing synthesis error and conflict.

3.8 Setup

To conduct simulation, setup must be completed to enable calculations by Fluent Solver. Important setup procedures are listed in Table 7.

.

Table 3.7: Setup Settings

Settings	Action	Remarks
Solver	• Type: Density-based • Time: Steady-state • Velocity formulation: Absolute *(Appendix A)*	-Density-based is chose because of introducing turbulent flow -Time is set as steady-state condition. -Absolute option is for non-rotating fluid flow.
Model	• Enable energy equation • Enable viscous k-ε RNG *(Appendix B)*	-Involve heat transfer -Involve fluid flow velocity (renormalization group) for effect of swirl on turbulence.
Materials	• Transformer oil • Transformer nanofluids oil	-Introduce fluid to be used
Boundary condition	• Core = 687W/m^2 • LV windings = 1800.6 W/m^2 • HV windings = 1833.44, 2273.59, 1159.75 W/m^2 *(Appendix C)*	-Introduce heat source surfaces
Solution methods	• Pseudo Transient Method • Scheme: Simple • Pressure: First order • Momentum: First order • Turbulent Kinetic Energy: First order • Turbulent dissipation rate: First order *(Appendix D)*	-Pseudo transient is to get steady-state solution. -Simple scheme is for relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field. -First order option is for initial result computation. Higher order could be used to obtain more detailed results.
Solution Initialization	• Standard initialization *(Appendix F)*	-Standard initialization enables users put value for initial calculation value, helping in convergence.

Although the flow is laminar flow range, RNG model has an additional term in its ϵ equation that significantly improves the accuracy for rapidly strained flows which can be implemented to improve the calculation for the effect of swirl, enhancing accuracy for swirling flows. RNG theory provides an analytically-derived differential formula for effective viscosity that accounts for low-Reynolds-number effects. Effective use of this feature does, however, depend on an appropriate treatment of the near-wall region. Solution method for pseudo transient relaxation factor is set as 0.95, 1.1, and 1.0 for turbulent kinetic energy, turbulent dissipation rate, and turbulent viscosity respectively as shown in Appendix E. Appendix G shows the residual monitor for the simulation.

Table 8 shows the transformer oil properties used for the setup as a function of temperature. Density, specific heat capacity and viscosity change according to temperature except for thermal conductivity set as constant so as to study the effect of different thermal conductivity values on heat transfer performance.

Table 3.8: Transformer Oil Properties Settings

Settings	Function of temperature	Unit
Density	839.22 (average for Boussinesq function)	kg/m^3
Specific heat capacity	1960 + 4.005T	J/mol. C
Thermal conductivity	0.1202 (constant)	W/m.K
Viscosity	$0.02438989 - 0.00041790T + 0.00000195T^2$	kg/m.s
Thermal expansion coefficient	0.00086	-

Nanofluids properties settings have been identified by using equation developed in literatures. For both transformer oil and nanofluids, specific heat is input into Fluent solver as linear function while viscosity is a second order polynomial function of temperature. Thermal conductivity and thermal expansion coefficient is set as constant. Density is given as average value in Boussinesq function.

Density and Specific heat of transformer oil-based nanofluids CNT, graphite, and diamond are formulated by using equations in the following [26]:

Density: $\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_s$ (14)

Specific heat: $(\rho C_p)_{nf} = (1-\varphi)\left(\rho C_p\right)_{bf} + \varphi(\rho C_p)_s$ (15)

Viscosity (Brinkman's model [28]): $\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}}$ (16)

Where,

φ is particle vol fraction

nf is nanofluid

bf is base fluid

s is solid, in this case refers to nanoparticles

Thermal conductivity of graphite and diamond is calculated by using Hamilton and Crosser model [29]:

$$\frac{k_{eff}}{k_f} = \frac{k_p+(n-1)k_f-(n-1)\varphi(k_f-k_p)}{k_p+(n-1)k_f+\varphi(k_f-k_p)} \quad (17)$$

where, n is the empirical shape factor. n=3 for sphere.

Thermal conductivity of CNT is specified in equation given by Xue [30]:

$$k_{eff} = k_b \frac{1-\varphi+2\varphi\frac{k_p}{k_p-k_b}\ln\frac{k_p+k_b}{2k_b}}{1-\varphi+2\varphi\frac{k_b}{k_p-k_b}\ln\frac{k_p+k_b}{2k_b}} \quad (18)$$

Thermal expansion coefficient of nanofluids can be estimated by including volume fraction of the nanoparticles as follows [31]:

$$\beta_{eff} = (1-\varphi)\beta_f + \varphi_p\beta_p \quad (19)$$

3.9 Gantt Chart

Table 3.9: FYP I Gantt Chart

No.	Details / Week	Week														
		1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Confirmation of supervision and title								Mid-semester Break							
2	Preliminary Research Work • Literature review • Problem analysis & parameter setting															
3	Submission of Extended Proposal															
4	Geometry modelling & meshing															
5	Start CFD • Learn ANSYS Fluent															
6	Proposal Defence															
7	Project work continues • Run ANSYS Fluent Simulation															
8	Submission of Interim Draft Report															
9	Submission of Interim Report															

Process Following Delay Key Milestones

Table 3.10: FYP II Gantt Chart

No.	Details / Week	Week													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Project Work Continues														
	• Simulation running														
2	Submission of Progress Report								○						
3	Project Work Continues														
	• Post-processing analysis														
4	Pre-SEDEX										○				
5	Submission of Draft Final Report											○			
6	Submission of Dissertation (Soft Bound)												○		
7	Submission of Technical Paper												○		
8	Viva													○	
9	Submission of Project Dissertation (Hard Bound)														○

Process Following Delay ○ Key Milestones

CHAPTER 4

RESULTS AND DISCUSSION

Results will show the designed model, meshing, and simulation results given by Fluent solver on slice model.

4.1 Geometry

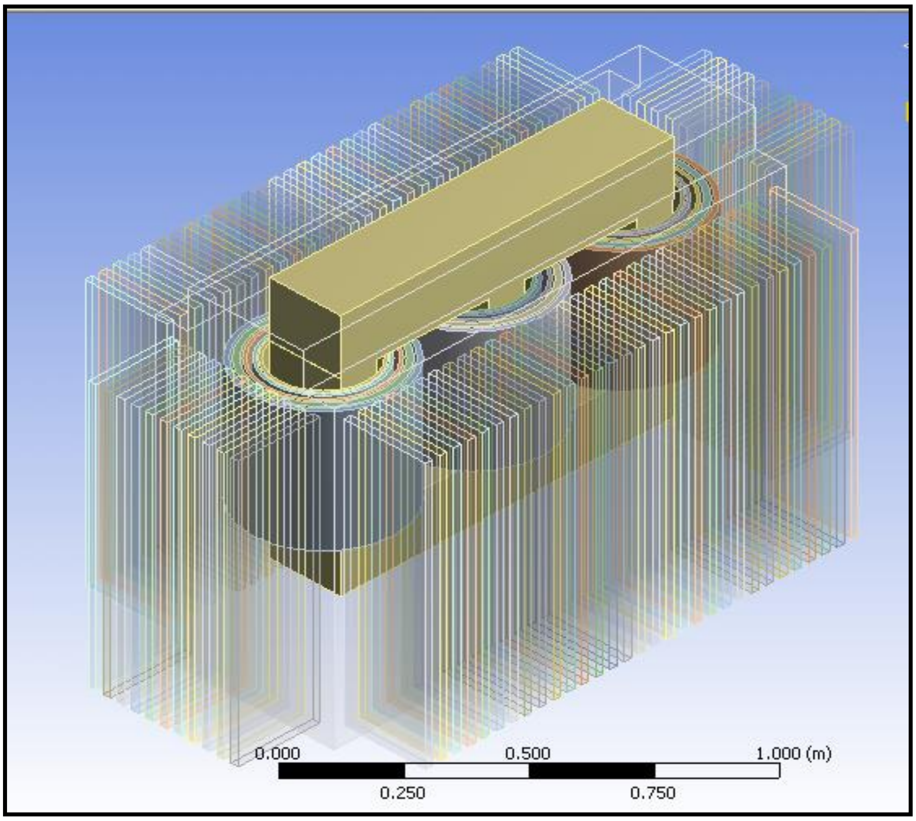


Figure 4.1: Developed transformer geometry

ANSYS software with academic license can only accommodate for meshing of not more than 512,000 elements, hence, a slice model had also been modelled to study the heat transfer in transformer. Same technique had been practiced for slice model.

Based on literature, slice model has high reliability to produce results same as complete model [18]. Figure 4.1 and Figure 4.2 show the complete model and slice model fluid body and the solid body respectively.

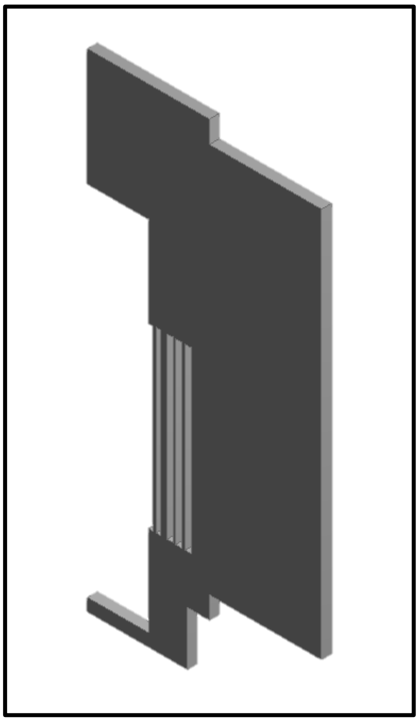


Figure 4.2: Slice model geometry

4.2 Meshing

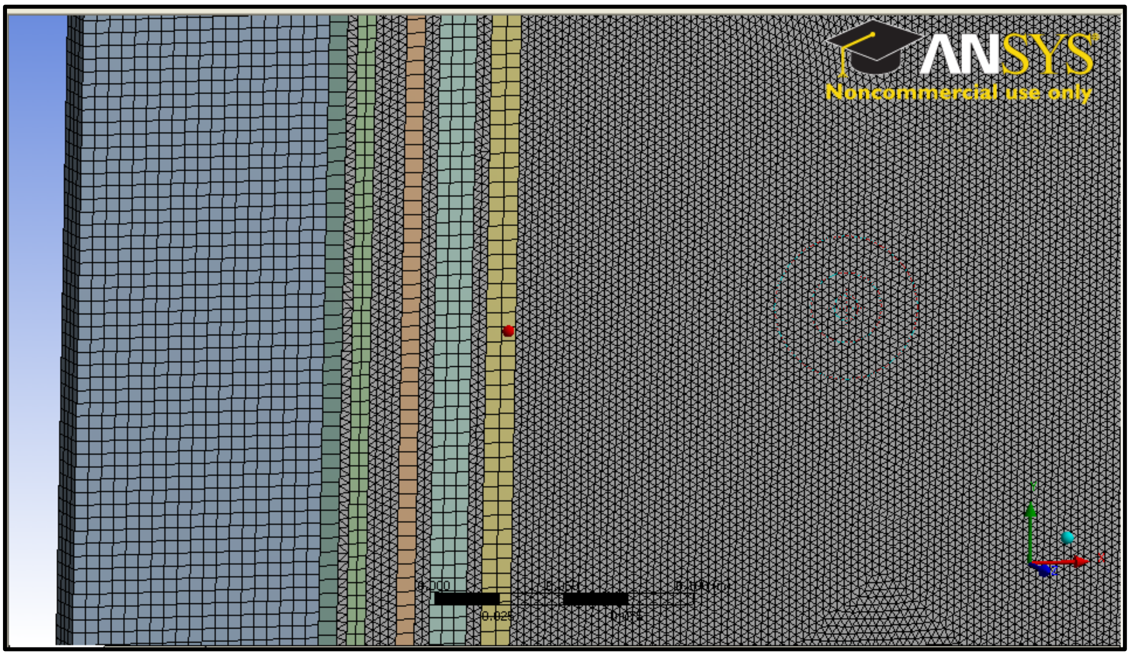


Figure 4.3: Slice model meshing result

Skewness can be used to check mesh quality. The scale of skewness in ANSYS software is shown as below:

Table 4.1: ANSYS Skewness Scale

Excellent	Very good	Good	Acceptable	Bad	Inacceptable
0-0.25	0.25-0.5	0.5-0.8	0.8-0.94	0.95-0.97	0.98-1.00

Based on meshing skewness statistics, slice model meshing based on technique used in Methodology part is with average skewness of 0.05. This indicates the meshing shape is considered uniform throughout the whole geometry. There are total of 505,000 elements for this slice model which is still feasible for the simulation process.

Besides skewness, orthogonal quality is another parameter used to check meshing quality. An orthogonal quality closes to 1.0 means the meshing is at its perfect condition. This meshing is having an average orthogonal quality of near to 0.88 which means the meshing is at the condition of “good” to be processed in Fluent solver.

With element size of 0.001 m, meshing with 505,000 elements is considered as medium size meshing quality for small size geometry. For advanced industrial application, fine mesh should be up to at least 1 million elements.

Meshing had also been done on complete model. However, to synthesize a medium size meshing quality is impossible to be achieved under limitation of 512,000 elements by the ANSYS software. Therefore, the alternative reliable solution is to proceed with slice model.

4.3 Fluent Solver Simulation

This section will show the result and discussion of temperature and velocity profile, overall heat transfer coefficient with respect to nanoparticle loading, percentage enhancement of heat transfer performance, and Nusselt number of each fluid.

4.3.1 Temperature and Velocity

Table 4.2 shows the highest winding temperature and highest fluid velocity reported by ANSYS Fluent solver for each type of nanofluids and transformer oil.

Table 4.2: Highest Winding Temperature and Fluid Velocity

Transformer oil / Nanofluids	**Highest winding temperature (℃)**	**Highest Fluid Velocity (m/s)**
TO	88.73	0.01822
TO + 0.5% CNT	84.30	0.01921
TO + 1.0% CNT	82.17	0.01911
TO +1.5% CNT	80.13	0.01923
TO + 2.0% CNT	78.63	0.01919
TO + 0.5% Graphite	88.48	0.01794
TO + 1.0% Graphite	87.79	0.01797
TO +1.5% Graphite	87.08	0.01802
TO + 2.0% Graphite	83.71	0.01985
TO + 0.25% Diamond	89.41	0.01785
TO + 0.5% Diamond	89.62	0.01782
TO + 0.75% Diamond	89.98	0.01775

From Table 4.2, it can be discussed that all of the oil-based nanofluids report improve the heat transfer of the base fluid (transformer oil) by lowering the winding temperature down by 0.2 to 10.1℃ except for diamond nanofluids. Diamond nanofluids increase the winding temperature by 0.68 to 1.25℃ when comparing to transformer oil winding temperature of 88.73℃. The simulation is set without any inlet velocity.

Velocity of the nanofluids can be interpreted as a result of both temperature and density changes, also known as natural convection. Dispersion of nanoparticles in transformer oil can cause increase in density and viscosity which can result in difficulty in fluid motion although the fluid thermal conductivity can be increased. However, the highest velocity of each nanofluid and transformer oil reported is not at the winding part. It is found to be above the winding part as shown in Figure 4.4.

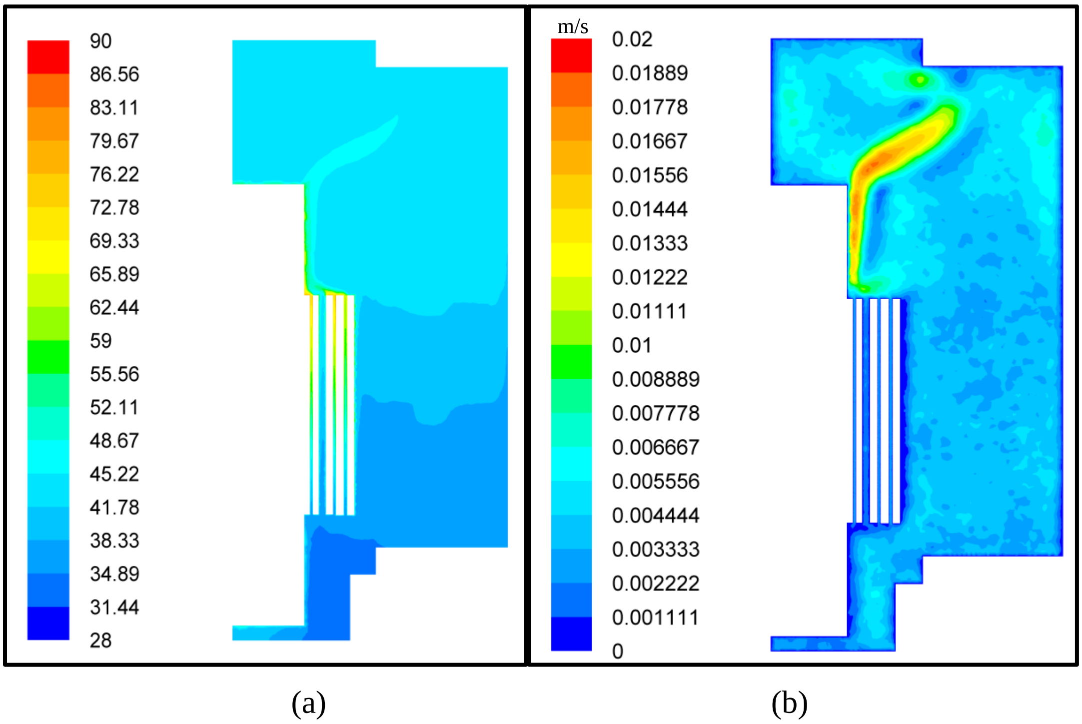


Figure 4.4: Transformer oil (a) Temperature contour and (b) Velocity contour

Figure 4.4 shows the temperature contour and velocity contour of transformer oil. It is found that the fluid is hot at the part of the model. The temperature decreases when the fluid moves down to the bottom of the model. Velocity near wall is close to 0 which indicates oil flow mainly occurs at the center part of the model. Vertical direction oil flow is found more significant than horizontal direction. Oil flows from up to down in fin area and enter winding area cooling channels before coming out at the top part. This proves the occurrence of natural convection in transformer oil.

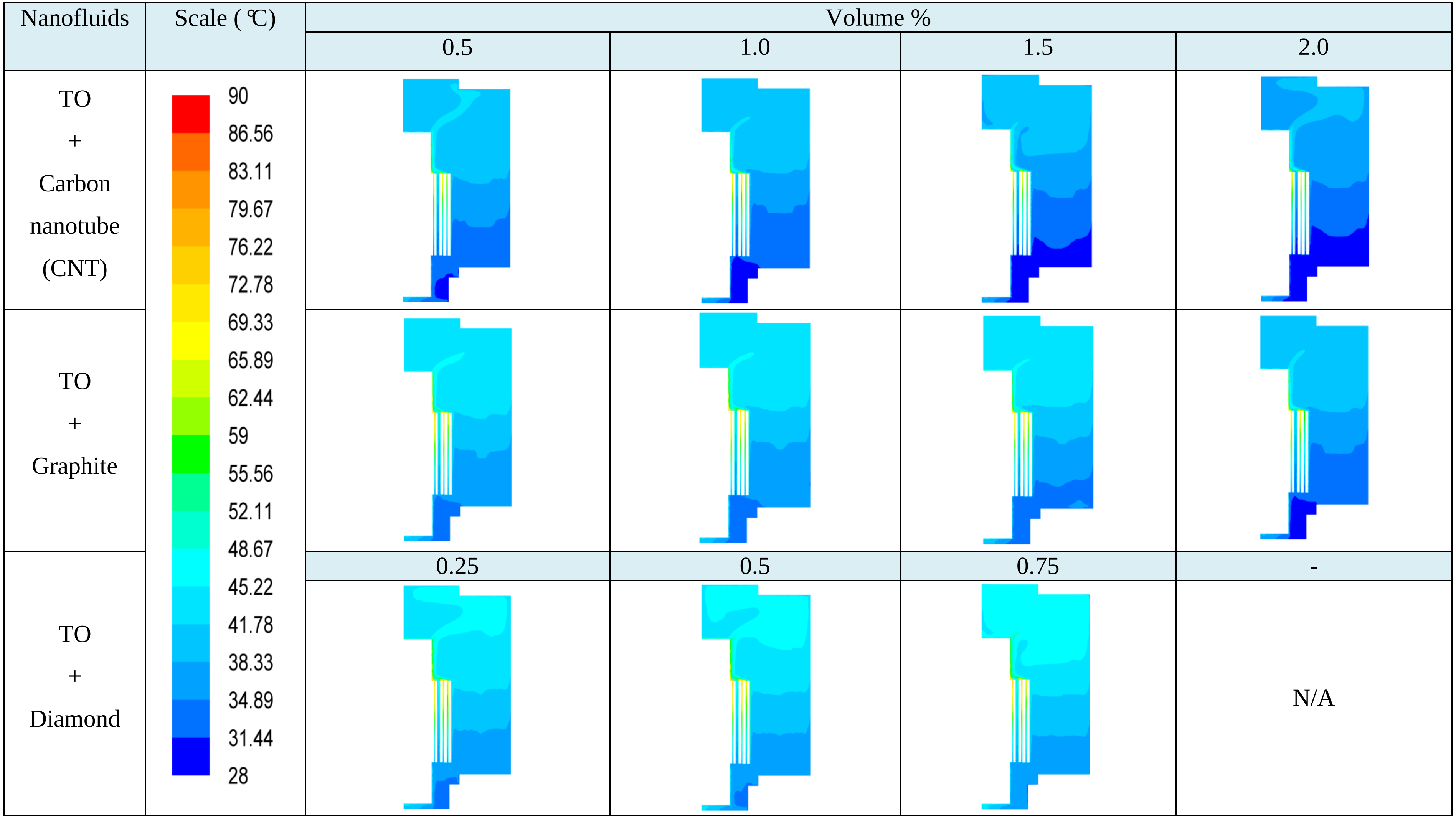


Figure 4.5: Temperature contour of nanofluids

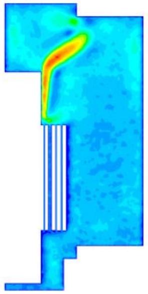
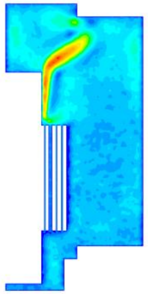
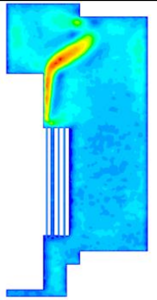
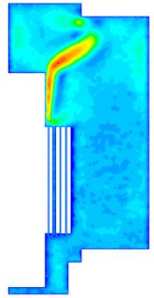
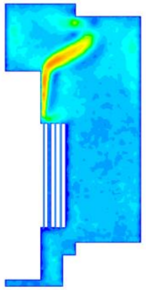
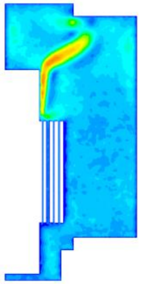
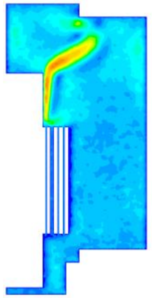
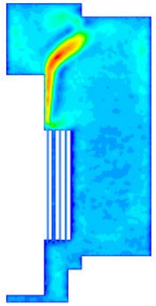
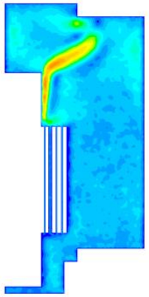
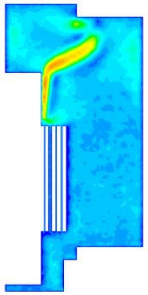
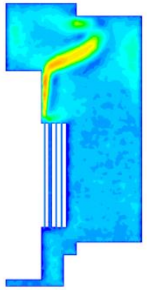
Nanofluids	Scale (m/s)	Volume %			
		0.5	1.0	1.5	2.0
TO + Carbon nanotube (CNT)					
TO + Graphite					
		0.25	0.5	0.75	-
TO + Diamond					N/A

Figure 4.6: Velocity contour of nanofluids

Based on Figure 4.5, all of the nanofluids share the same temperature stratification. Transformer oil and nanofluids temperature stratifications are comparable. This findings can be compared with previous research done by Gastelurrutia *et al.* [18] where temperature contour is presented as layers at the fin area. Besides, all the fluids show that higher temperature is found at upper of winding which achieves the finding done by Tsili *et al.* [19]. This gives confidence to the reliability of the results for nanofluids.

Figure 4.6 shows all the nanofluids share the same velocity contour. At the maximum velocity area, diamond nanofluids show the lowest velocity and CNT nanofluids show the highest. Fluid is active at upper part of transformer and decreases when moving down as mentioned by Gastelurrutia *et al.* [18].

For overall comparison, CNT nanofluids show the lowest temperature profile while diamond nanofluids are having the highest temperature profile among the nanofluids used. Graphite nanofluids are found slightly improves the heat transfer performance of transformer oil only.

4.3.2 Overall Heat Transfer Coefficient

This part shows the overall heat transfer coefficient of transformer oil and nanofluids. Overall heat transfer coefficient is calculated based on the average temperature of heating surface region.

Overall heat transfer coefficient, $U = \frac{\sum h_i A_i}{A_{total}}$ (20)

Where,

$$A_{total} = \sum A_i = m^2$$

$$h_i = \frac{q_i}{T_{s,average} - T_{\infty,average}}, W/m^2$$

$$q_i = heat\ flux, \frac{W}{m^2}$$

There are total of 11 heating surfaces for each nanofluid model to be analyzed for its average difference in temperature. All the results of the calculations are tabulated in Table 4.3.

Table 4.3: Overall Heat Transfer Coefficient of Nanofluids

Transformer oil / Nanofluids	Loading	Overall heat transfer coefficient, U (W/m2.K)
TO	0.00%	159.20
TO + 0.5% CNT	0.50%	195.64
TO + 1.0% CNT	1.00%	210.21
TO +1.5% CNT	1.50%	225.21
TO + 2.0% CNT	2.00%	239.36
TO + 0.5% Graphite	0.50%	182.62
TO + 1.0% Graphite	1.00%	185.08
TO +1.5% Graphite	1.50%	187.23
TO + 2.0% Graphite	2.00%	183.65
TO + 0.25% Diamond	0.25%	181.37
TO + 0.5% Diamond	0.50%	182.49
TO + 0.75% Diamond	0.75%	176.66

A higher heat transfer coefficient of a fluid means a better performance of heat transfer. In this research project, it is expected that nanofluids should give better heat transfer coefficient than base fluid which is the transformer oil.

Based on Table **4.3**, it shows that CNT is having the highest heat transfer coefficient, increasing from 195.64 to 239.36 W/m^2.K .Graphite is having heat transfer coefficient ranges from 182.62 to 187.23 W/m^2.K. These two nanofluids successfully showed higher heat transfer coefficient than transformer oil. This data indicate that heat transfer performance for nanoparticles CNT and graphite inside transformer oil can improve heat transfer performance of transformer oil itself. Diamond shows a lower heat transfer coefficient value compared to transformer oil. Also, diamond nanofluid shows a decreasing trend with increasing nanoparticles volume fraction after an optimal loading of 0.25%. Heat transfer coefficient data has been plotted in graph in Figure **4.7**.

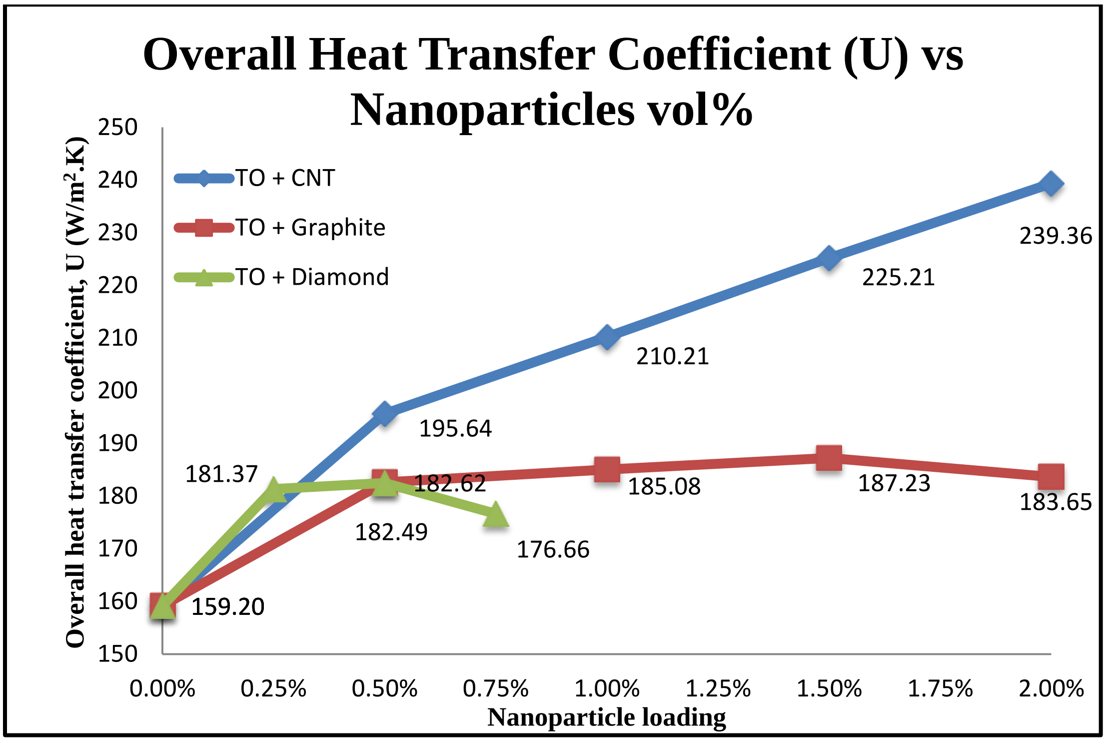


Figure 4.7: Overall heat transfer coefficient of nanofluids with different particle loading

From Figure **4.7**, it can be clearly seen that CNT nanofluids have an increasing trend with increasing loading while graphite nanofluids starts to drop after a maximum of 1.5% loading. Diamond nanofluids have a maximum performance when the loading is at 0.25%. It can be interpreted that all the nanofluids have an increasing trend with increasing nanoparticle loading until they meet an optimal level before increment of density is dominant than increment in thermal conductivity in natural convection. It is because when higher density causes slower fluid motion for natural convection to take place effectively. Although the fluid thermal conductivity has been improved, it might not improve the overall heat transfer coefficient due to density factor.

Diamond nanofluids are expected to have the best heat transfer performance since diamond particle thermal conductivity is the highest compared to CNT and graphite. By comparison at 0.25%, diamond nanofluid shows the highest overall heat transfer coefficient but the temperature for it to breakthrough and achieve natural convection is slightly higher which is not suitable for the transformer operating condition.

Table below shows the average density of the transformer oil and nanofluids.

Table 4.4: Average Density of Transformer Oil and Nanofluids

Transformer oil / Nanofluids	Average Density, ρ (kg/m^3)
TO	839.22
TO + 0.5 % CNT	841.78
TO + 1.0% CNT	844.33
TO + 1.5% CNT	846.88
TO + 2.0% CNT	849.44
TO + 0.5% Graphite	845.83
TO + 1.0% Graphite	852.43
TO + 1.5% Graphite	859.03
TO + 2.0% Graphite	865.64
TO + 0.25% Diamond	845.95
TO + 0.5% Diamond	852.68
TO + 0.75% Diamond	859.40

Based on Table 4.4, it can be related to overall heat transfer coefficient that diamond nanofluids have the highest range of density reported. By comparison of nanoparticle loading at 0.5%, CNT, graphite, and diamond nanofluids give 841.78 kg/m^3, 845.83kg/m^3, and 852.68 kg/m^3 respectively. This shows that with same particle loading, diamond increases the base fluid the most. Graphical comparison can be clearly seen at Figure 4.8.

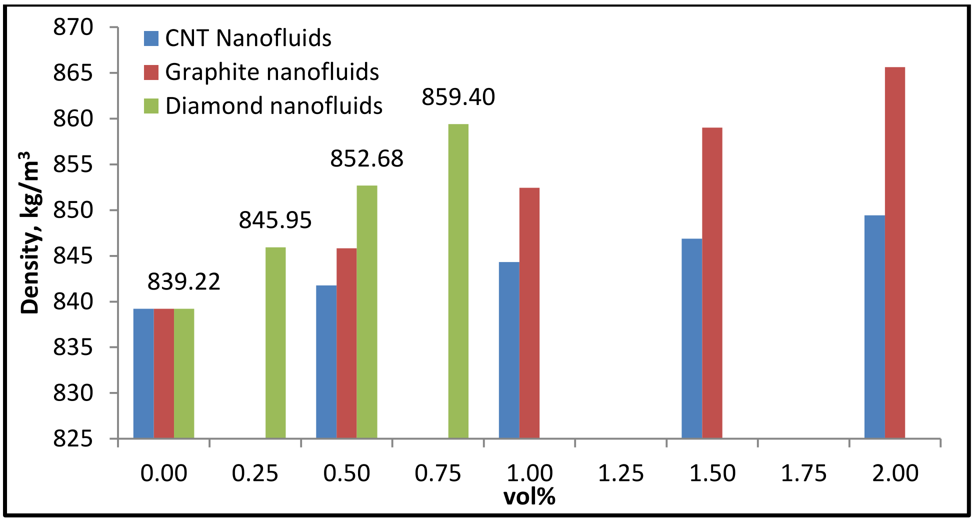


Figure 4.8: Comparison of nanofluids density

4.3.3 Percentage Enhancement of Heat Transfer

Percentage enhancement of heat transfer is analysed based on the overall heat transfer coefficient calculated.

$$\% \, Enhancement = \frac{U_{nanofluid} - U_{transformer\ oil}}{U_{transformer\ oil}} \times 100\% \qquad (21)$$

Table 4.5: Percentage Enhancement of Heat Transfer

Transformer oil / Nanofluids	% Enhancement of Heat Transfer
TO + 0.5 % CNT	22.89
TO + 1.0% CNT	32.04
TO + 1.5% CNT	41.46
TO + 2.0% CNT	50.35
TO + 0.5% Graphite	14.71
TO + 1.0% Graphite	16.25
TO + 1.5% Graphite	17.61
TO + 2.0% Graphite	15.36
TO + 0.25% Diamond	13.93
TO + 0.5% Diamond	14.63
TO + 0.75% Diamond	10.96

From the tabulated result, transformer oil with 2.0% of CNT shows the highest enhancement in heat transfer which is 50.35%. The value indicates that the heat transfer of transformer oi has been improved by 50.35% for its overall heat transfer coefficient.

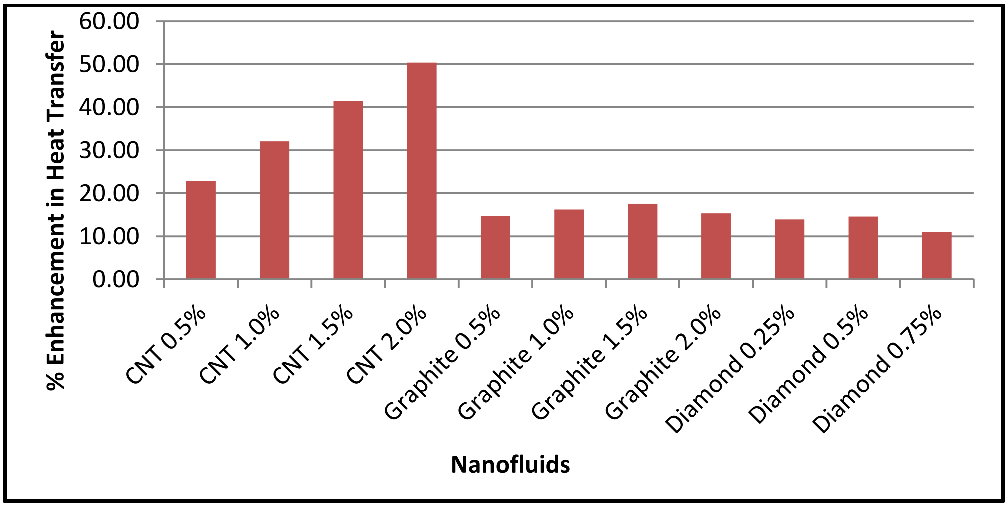


Figure 4.9: Percentage Enhancement in Heat Transfer

4.3.4 Nusselt number

Nusselt number is the ratio of convective to conductive heat transfer across the boundary. Nusselt number is calculated based on equation (6). For the overall Nusselt number, it uses the overall heat transfer coefficient, total characteristics length, and average effective thermal conductivity.

$$Nu = \frac{U \sum L_c}{k} \qquad (22)$$

Where,

U is overall heat transfer coefficient, W/m^2.K

L_c is the characteristic length, m

k is thermal conductivity

Calculated results for Nusselt number is tabulated as below:

Table 4.6: Nusselt Number of Transformer Oil Nanofluids

Transformer oil / Nanofluids	Nusselt number (Nu)
TO	4907
TO + 0.5 % CNT	5508
TO + 1.0% CNT	5450
TO + 1.5% CNT	5394
TO + 2.0% CNT	5326
TO + 0.5% Graphite	5545
TO + 1.0% Graphite	5538
TO + 1.5% Graphite	5520
TO + 2.0% Graphite	5335
TO + 0.25% Diamond	5549
TO + 0.5% Diamond	5541
TO + 0.75% Diamond	5325

From the table above, it shows that all the nanofluids have high nusselt number than transformer oil. This means that the ratio of convective heat transfer to conductive heat transfer is more, compared to transformer oil. However, diamond nanofluids show higher winding temperature compared to transformer oil and other nanofluids. This can be explained that diamond nanofluids require a higher fluid temperature for its fluid motion so that natural convection can happen. This condition does not favour the transformer operating condition, hence, although diamond nanofluids have high Nusselt number and high overall heat transfer coefficient at 0.25%, its breakthrough temperature for natural convection is not acceptable for transformer heat loss load. Therefore, CNT and graphite nanofluids still considered as the better options as a synthetic fluid for transformer usage.

4.3.5 Rayleigh number

Rayleigh number is the product of Grashof and Prandlt numbers as shown in equation (3). Rayleigh number can be described as ratio of buoyancy and viscosity forces times the ratio of momentum and thermal diffusivities. Rayleigh number can be simplified as shown below

$$Ra_L = Gr_L.Pr = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu\alpha} \qquad (23)$$

where,

g = gravitational acceleration, m/s^2
β=coefficient of volume expansion, 1/K
T_s=temperature of the surface, ˚C
T_∞=temperature of the fluid sufficiently far from the surface, ˚C
L_c=characteristic length, m
ν=μ/ρ= kinematic viscosity of the fluid, m^2/s
α=k/ρC_p = thermal diffusivity, m^2/s

ν and α is introduced as function of average temperature of T_s and T_∞, when μ and C_p is a function of temperature.

The overall Rayleigh number is calculated by using area average function as shown below:

$$Ra_{ave} = \frac{\sum zL_cRa_L}{\sum zL_c} = \frac{\sum L_cRa_L}{\sum L_c} \qquad (24)$$

Where,
Z= thickness of the model = constant 0.02m

Results of Rayleigh number of transformer oil and nanofluids are tabulated as shown in Table 4.7.

Table 4.7: Rayleigh number of transformer oil and nanofluids

Transformer oil / Nanofluids	Rayleigh number (Ra)
TO	7.586E+08
TO + 0.5 % CNT	6.635E+08
TO + 1.0% CNT	3.607E+08
TO + 1.5% CNT	4.495E+08
TO + 2.0% CNT	3.944E+08
TO + 0.5% Graphite	6.800E+08
TO + 1.0% Graphite	4.592E+08
TO + 1.5% Graphite	6.407E+08
TO + 2.0% Graphite	8.987E+08
TO + 0.25% Diamond	6.912E+08
TO + 0.5% Diamond	6.815E+08
TO + 0.75% Diamond	9.578E+08

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

Natural convection heat transfer carries vital effect on the performance, lifespan, and maintenance cost for a transformer. Forced convection could be another alternative for better heat dissipating purpose but it is not cost efficient as natural convection. Enhanced natural convection heat transfer through increasing fluid heat dissipating efficiency could improve not only energy saving but also cost saving.

Heat transfer performance by natural convection in 3-Dimentional transformer geometry with selected slice model is studied with various nanoparticle types and loadings. Fluid motion and heat transfer characteristics are numerically studied for transformer oil and oil-based nanofluids. By using selected transformer oil and nanoparticles for the properties, theoretical nanofluids thermal physical properties have been calculated. The simulation results show that the settings for Fluent are applicable. CNT and graphite nanoparticles have been proved to have heat transfer improvement in transformer oil with higher heat transfer coefficient gained meanwhile lower winding temperature, compared to transformer oil. It is found that density and thermal conductivity have significant influence in improving heat transfer characteristics. Nanofluids show a better heat dissipation than transformer oil. Increasing nanoparticle loading could lead to increase in both density and thermal conductivity of the nanofluids. Heat transfer performance of nanofluids start to drop when increment in density is more significant than increment in thermal conductivity where fluid flow becomes small and hence, the breakthrough temperature for natural convection to take place is higher and this situation is not favourable for transformer operating condition. Transformer oil with 2.0% CNT is determined to be the best oil-based nanofluids for heat transfer performance which highest heat transfer coefficient is 239.36 $W/m^2.K$. Highest temperature spot has been reduced to only 78.63 ℃ compared to transformer oil of 88.73 ℃.

CNT and graphite nanofluids can be recommended as a new kind of synthetic fluid specific for transformer usage.

FUTURE WORKS

This research could be continued with 0.25% nanoparticle loading interval for Carbon Nanotubes and Graphite to provide more results. This could help provide more data points for the analysis of overall heat transfer coefficient and correlation of Nusselt number and Rayleigh number.

Besides, solution methods for pressure, momentum, turbulent kinetic energy, and turbulent dissipation rate can be set at higher order to produce a more detailed result for the simulation.

Full geometry of transformer model can be used for simulation with a more advanced meshing setting and commercial license. This could provide a real transformer oil simulation data with consideration of flow in y- and z- axis. On top of that, air domain could be introduced to the full transformer geometry to study the heat transfer near the wall of transformer body.

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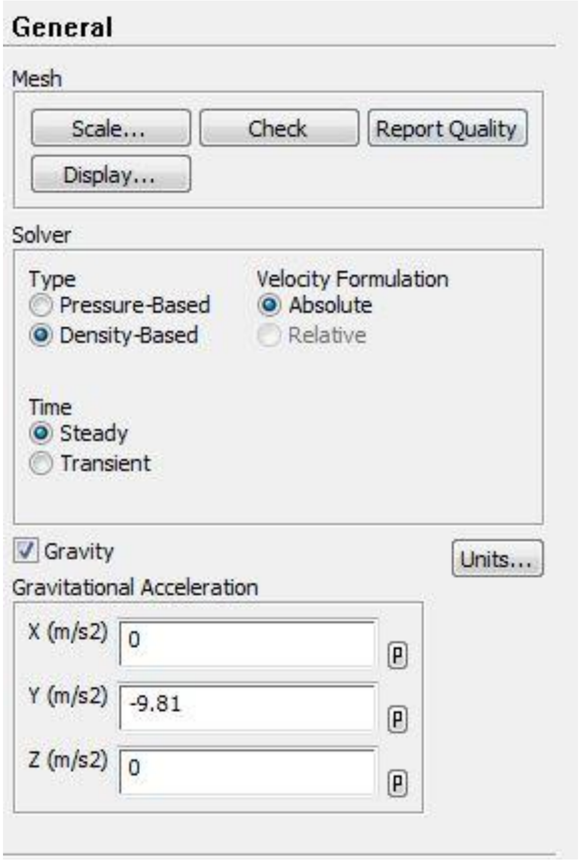
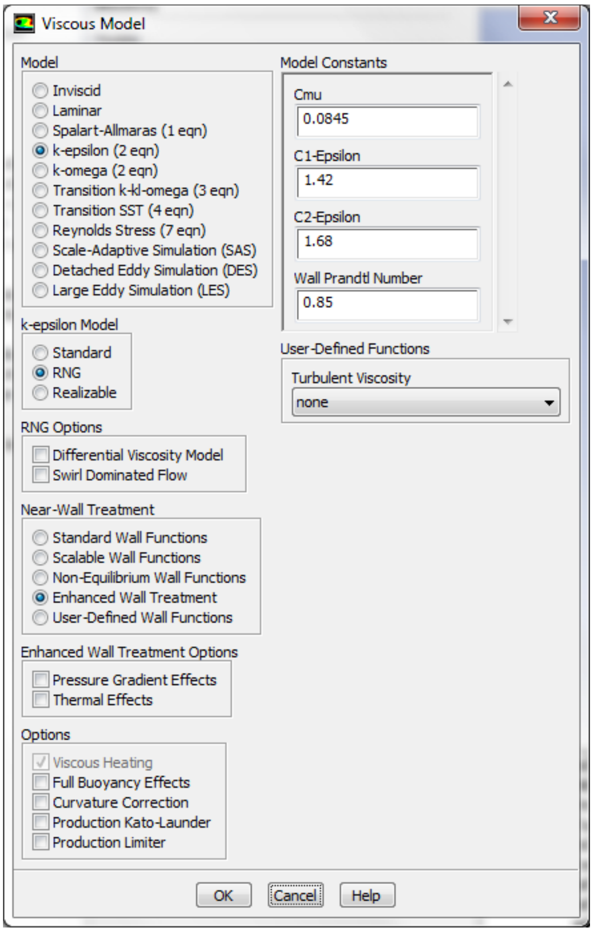
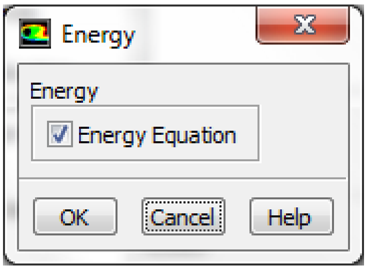
APPENDICES

Appendix A: Setup General Settings

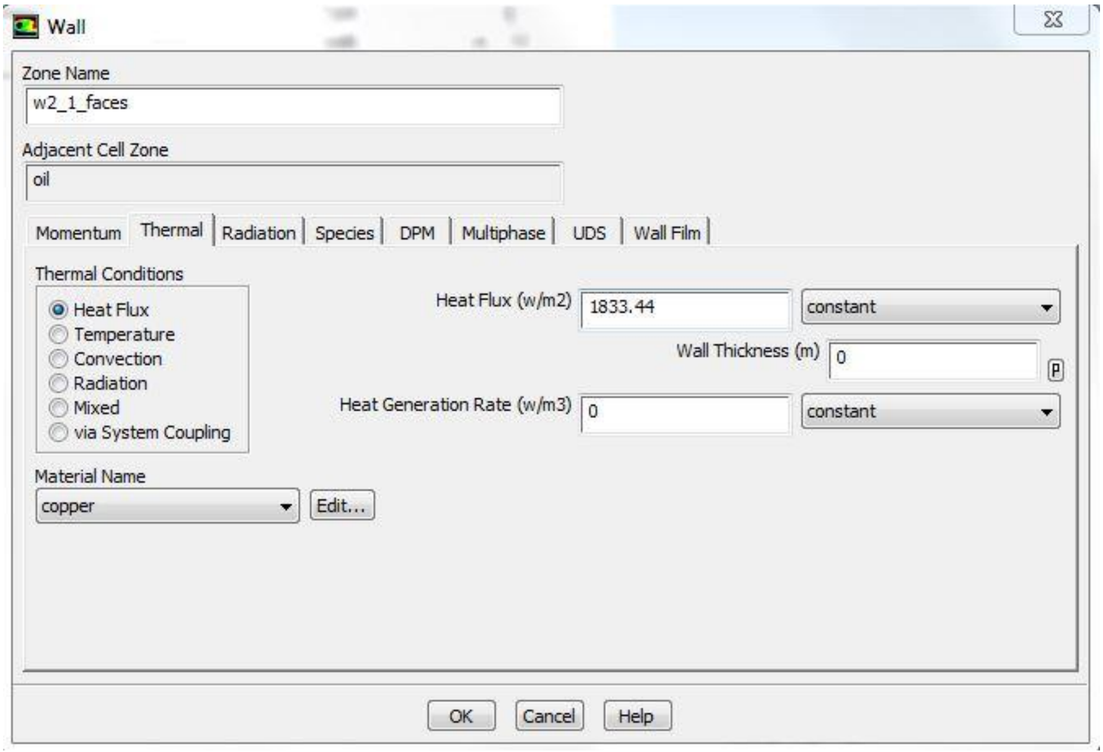


Appendix B: Viscous Model Setup and Energy Model Setup

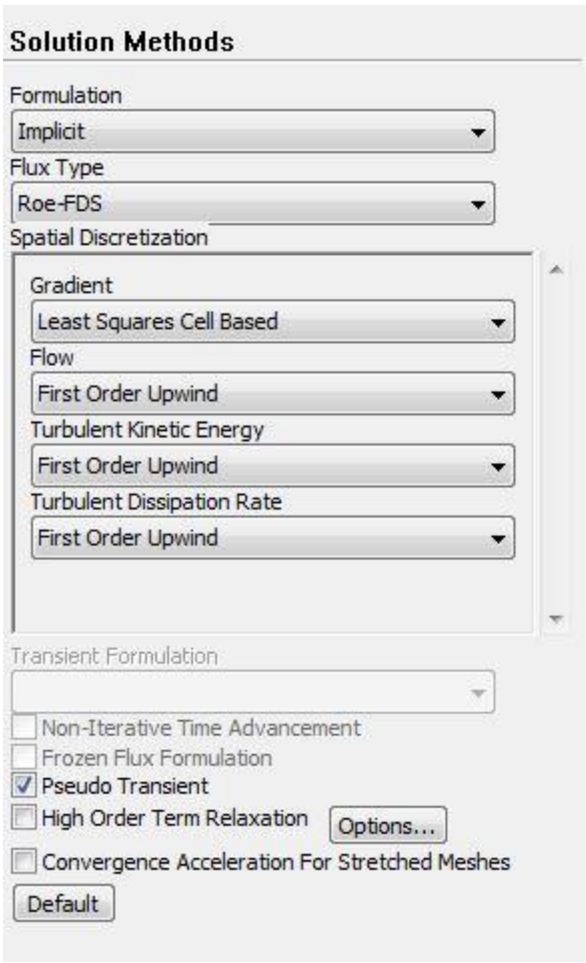




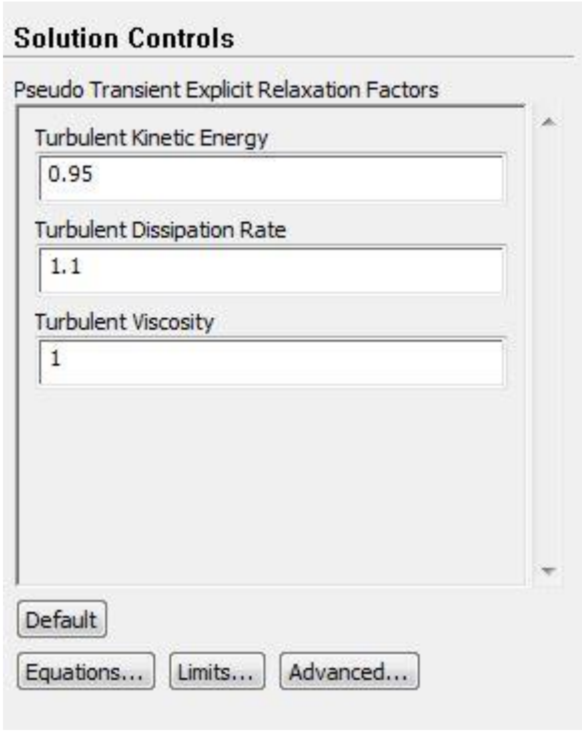
Appendix C: Boundary Condition Setup for Hot Surface



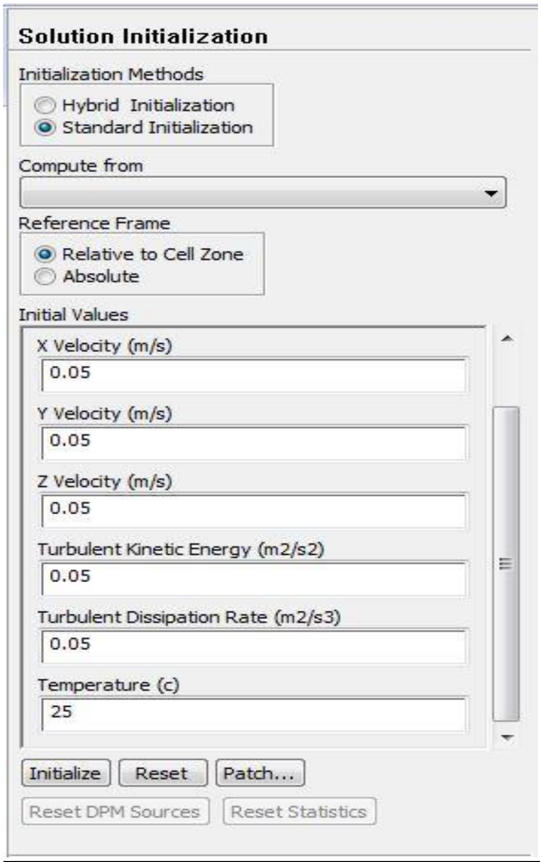
Appendix D: Solution Methods



Appendix E: Solution Controls



Appendix F: Solution Initialization



Appendix G: Residual Monitors