MODELING THERMAL MODEL OF A DISK COIL WITH DIRECTED OIL FLOW USING MATLAB SOFTWARE

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A thesis submitted in partial fulfillment of the requirement for the award of the Degree of Master of Electrical Engineering

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Directed oil flow of a disk transformer in this model is guided by the oil flow washer. The model is established to investigate the temperature rise in the oil-filled transformer windings. Mass flow distribution and pressure drop concept are by using the number, size, location of horizontal ducts, fluid properties and the temperature variables. Pressure drop calculation is a temperature dependent and caused uniform heat distribution. An iterative solution is required to solve the equation to find the oil velocities, oil temperature and disk temperature. Because of the concept in every pass is the same, this model proposed to design in a single pass. The oil velocity and pressure at the last path can be used as input value to calculate the next pass. As disk temperature is very sensitive to the changes of the variables, so designing a suitable parameter for a single power transformer is very important. Matlab perform better in iterate equations and modeling disk transformer where the result is nearly accurate.

Keywords: disk transformer, thermal model, oil temperature rise, oil velocity, pressure, iterative solution
ABSTRAK


Katakunci: pengubah cakera, model haba, peningkatan suhu minyak, halaju minyak, tekanan, penyelesaian berulang-ulang
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<th>Abbreviation</th>
<th>Full Form</th>
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</thead>
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<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineer</td>
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CHAPTER 1

INTRODUCTION

1.1 Overview

The history of transformer starts since 1880 and in year 1950, the first power transformer with 400kV was introduced in a high voltage electrical power system. In 1970's, the transformer was produced with large unit rating, 1100MVA. Meanwhile in 1980, the rating is increased to 800kV and is still increasing today.

In electrical power system network, power transformers are used to step up the voltage at the sending side and then step down to the desired level. This is because the high voltage cannot be distributed to the end user [1]. A good oil power transformer can be operated up to 20 years but today there are a lot of power transformers that their life exceeds for more than 50 years. The extended of the life limit in power transformer relates to the insulation system that depends on the temperature. The cooling component also plays an important role in order to make power transformer perform well.

Theoretically, thermal model is a mathematical model that dynamically predicts the temperature of an object. The accuracy of the model is due the function of its algorithm and the accuracy of the value used for the object thermal capacitance, thermal resistance to its surroundings and heat generated in or removed from the
object [2]. So in a power transformer thermal model it can be used to predict the temperature distribution; at the conductor and at the oil transformer [3].

Predicting temperature distribution is very important in a power transformer as it is very sensitive to temperature rise. A single incensement of the temperature above the standard limit can make a transformer life reduce by half [4]. Figure 1.1 shows a winding schematic diagram for a single transformer Figure 1.2 illustrates a simple 2D model that has been referred in this project in order to find its temperature distribution.

![Winding schematic diagram for a single phase transformer.](image1.png)

Figure 1.1: Winding schematic diagram for a single phase transformer.

![Flow path in winding - vertical section](image2.png)

Figure 1.2: Flow path in winding - vertical section
Unfortunately, the ability of a transformer also depends on ambient condition such as temperature, wind and rain. For example, the transformer operation will become worst during the sunny day as the temperature increase. It will operate at the capacity limit but just monitoring internal and oil temperature. This problem become complicated when the temperature is not uniform inside the transformer and can damaged it due to local hot spot that happen. The oil temperature may become so hot that would sustain an electric arc and a transformer may explode under this condition.

1.2 Problem statement

In liquid-immersed power transformers, the temperature of the winding is very important in order to longer the term-of life of the transformer. Knowing the temperature distribution especially hot spot temperature at each point of transformer is very importance [1, 2, 4, 5, 6] in order to make it operate safety for a long period.

In Malaysia, most of the transformers that are used by Tenaga Nasional Berhad (TNB) use mineral oil as transformer insulating oil. The insulating oil temperature depends on the winding temperature and is usually used to indicate the operating conditions of the transformer [5]. The increase in temperature will influence the insulating material and may cause aging. Depends to the insulating material type, the transformer has a maximum limit of temperature rise [7].

There are a lot of numerical transformer protection relay available today including the protection function that operate on insulating oil temperatures, calculate loss of life due to high oil temperature, and predicted oil temperature due to load.

By the way in this project, software is used to predict the heat distribution in liquid-immersed transformers. There are various ways that can be used in modeling power transformer but some of them are complicated, so by choosing programming in Matlab life becomes easier. When comparing to other programming such as C, C++ and Fortan, Matlab programming is faster because there is no type of declaration needed, automatically handled memory allocation/de-allocation and functions and scripts can be access automatically from path.
1.3 Objectives

The objectives of this project are to:

(i) Investigate the temperature rise and oil velocity along each path segment in the transformer.

(ii) Develop a program that can modulate the suitable parameter that not exceeds maximum temperature rise in disk coil transformer; such as number of disk, oil pressure and velocities, oil nodal temperatures and path temperatures rise and disk temperatures.

(iii) Test the program by using different value in the parameter.

1.4 Scope

There are some limitations in this project to be considered:

(i) This model is limited to disk type winding and directed oil flow where the washer is used to guide oil flow through disk coil.

(ii) The design concept just consider 2D element not 3D (finite element) at the same time assumed conductor temperature is the average disk temperature.

(iii) Modeling and implement a transformer model using Matlab software.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

It is necessary to make some background studies on modeling and theories that are required in order to develop this project. So this chapter will focus more on the specification on this project such as power transformer, core and coil, cooling system, oil flow, and MATLAB software.

2.2 Power Transformer

Transformers are static electrical devices, involving no continuously moving parts and used in power electric system to transform voltage level between two circuits through the use of electromagnetic induction which is discovered by Faraday in 1831. Usually power transformer referred to those transformers rated at 500 kVA and above and located between generators and the distribution circuit [3], see Figure 2.1. Power transformer is used in a system that consists of a large number of generation location, distribution point and interconnection within system. At the generator side, power transformer used for step-up operation and known as generator step-up
transformer (GSU) [6]. Meanwhile, step-down transformer used at distribution side. Power transformers are available at single phase and three phases.

Figure 2.1: Schematic drawing of a power system.

A laminated steel core with copper or aluminum windings are used in power transformer in which the windings have a solid insulation of refined paper and a high quality of mineral oil as insulating and cooling medium for entire transformer. The core, windings and insulation that used all have specific thermal capabilities. Losses in the core and windings can cause temperature rise in the transformer which will transfer to insulating oil. This will effect transformer capabilities and usually caused premature failure. Figure 2.2 represent a simple transformer design nowadays.

Figure 2.2: A simple transformer representation
2.2.1 Liquid-filled transformer

Each of the transformers are constructed according to its application. Indoor transformer intended to use dry type transformer but sometimes can be liquid-filled. But for outdoor use, usually liquid-filled transformers will be chosen. Some of the dry type transformers are not suitable for outdoor because the method of cooling system is by circulating air through the coil and core assembly which is use either by force air flow (fan) or natural convection.

This cooling method is suitable for low voltage - indoor transformer. At higher voltage, oil is needed to insulate the winding due to the losses which are high through the process of conduction, convection and radiation. For effective winding cooling, the moving oil must be able to contact with every conductor for maximum convection and conduction of the conductor heat from the winding to the oil. In the other hand, direct air cooling is not effective for outdoor environment where it can make the windings dirt and moisture.

A Comparison of Liquid-Filled and Dry Type Transformer Technologies written by Tommy Nunn [7] of IEEE-IAS Cement Industry Committee evaluated the comparison both types of the transformers. He stated that both type have pro and cont in terms of loads, environment, purchase cost, safety, availability to operate, materials and manufacturing process. In recent years, transformers technologies have improved especially in less flammable and environmentally friendly fluids in liquid-filled transformers. In dry type transformer, vacuum technology has been introduced to improve the insulation system, core material and computer design programs.

Another research has been done by Jeffery Wimmer, M. R. Tanner, Tommy Nunn and Joel Kern on the specification Installation and operational impact of both types in a marine environment [8]. They found that fiber glass winding will have maximum operating size through 25000kVA and also application of vacuum technologies increased the reliability on tap changing reduced the maintenance. Table 2.1 list some advantage and disadvantage of liquid-immersed transformers.
Table 2.1: Liquid-filled transformer

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer oil is combustible</td>
<td>Needs oil regular checking filtration and replacement of oil</td>
</tr>
<tr>
<td>Smaller size</td>
<td>Costly and need high recurring expense</td>
</tr>
<tr>
<td>Lower cost</td>
<td>Produce a little bit of danger</td>
</tr>
<tr>
<td>Greater overload capability</td>
<td>Located away from the main building</td>
</tr>
</tbody>
</table>

2.2.2 Circular core design

Circular core and coil winding usually does not provide complete circulation of oil to every conductor and every layer of windings. Even the circular layer windings still have significant quantities of windings insulation though the space factor in the core and coils are an improvement [11]. Figure 2.3 shows an example of circular core and coil winding assembly utilizing layer windings.

![Figure 2.3: Circular core and coil winding](image)

The winding constructed of rectangular magnet wire with radial cooling spacer inserted between multiples of layers. By referring to Figure 2.5, the winding conductors were support by vertical rib and allow oil flow vertically for winding cooling. The circulating oil might contact around 60% of the conductors [11]. There is no radial spacer allowing oil to contact with the conductors between turns.
Basically concentric coils are wound over cylinders with spacer attached as to form a duct between conductors and cylinders. The flow of liquid/oil can be based solely on natural convection or controlled through the use of strategically placed barriers within the winding [11].

2.2.2.1 Disk winding

There are several types of windings such as pancake windings, layer (Barrel) windings, helical windings and disk windings. A disk winding can be built from a single strand or several strands of insulated conductors wound in a series of parallel disk in horizontal orientation with the disk connected either at inside or outside as a crossover point. Each disk consists of multiple turns wound over other turn with the crossover (inside and outside). Figure 2.4 shows the basic concept and Figure 2.5 outlines typical crossovers during the winding process [3].

Disk type windings are widely used in 25kV class and above. As its operation and test involve in high voltages, a particular attention is needed to avoid high stress between disk and turns near the end of the winding when voltage surge occur. A lot of techniques have been implemented to ensure an acceptable voltage distribution along the winding under these conditions [3].

![Figure 2.4: Basic disk winding layout](image-url)
2.2.3 Directed oil flow

There are two types of oil flow in liquid-immersed transformer; directed and non-directed oil flow. Sometimes directed oil flow concept also known as guided liquid flow. Figure 2.6 and 2.7 represent windings arrangement comparing non-directed and directed flow. In non-directed flow transformers, the pumped oil flows freely through the tank. Meanwhile, in directed oil flows, oil washer is used at the top and bottom of a pass to induce a zig-zag cooling in the winding of the transformer as illustrated in Figure 2.8.
The oil is forced to enter from one vertical channel and exit from the opposite vertical channel [4], [9]. From the findings, oil velocity affects the recirculation zone where recirculation zone is proportional to the increased oil velocity and efficiency, the insulating oil as a cooling medium will drop. In the other hand, N. El. Wakil [10] et al. had investigated the fluid flow in power transformer and found that directed flow can give better result in reducing the temperature.
2.2.4 Transformer heating

In thermal modeling of power transformer, two significant sources of heating are considered; no-load losses and load losses. Whenever the transformer is energized, no-load losses will present which is made up of hysteresis and eddy loss in the transformer core. Hysteresis loss is caused by the elementary magnet in the material aligning with the alternating magnetic field. While, eddy current is induced in the core by the alternating magnetic field.

Load losses consists of copper loss due to winding resistance and stray load loss due to eddy current in other structural part of transformer. The copper loss consists of both DC resistance loss and winding current loss. DC resistance loss will increase the increasing temperature but others load losses decreased with the increasing oil temperature [5].

Temperature in liquid-filled transformer can be decreased by transferring heat from the core and windings to the insulating oil. Nature circulation of the oil will transfer heat to the external radiators. The radiators are used to increase the cooling surface area of the transformer. Sometimes, pumps are used to increase the oil flow and at the same time radiators efficiency also increasing. For some large transformer (at substation and power plan) required active cooling to remove the heat from the core and windings and usually through circulating oil. Sometimes have two stage of cooling.

There are various cooling modes of transformer that established by IEEE and IEC. IEEE has adopted the IEC designation [11]. The designations totally describe the cooling method for the transformer and the cooling method impact the response of insulating oil to overload condition. Table 2.2 lists the common transformer cooling designations.
Table 2.2: IEC designation (IEEE C57.12.00-2010) [11]

<table>
<thead>
<tr>
<th>Old IEEE Cooling Designation</th>
<th>IEC Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-cooled</td>
<td>OA</td>
</tr>
<tr>
<td>Forced air cooled</td>
<td>FA</td>
</tr>
<tr>
<td>Directed-flow force liquid cooled</td>
<td>FOA</td>
</tr>
<tr>
<td>Water cooled</td>
<td>OW</td>
</tr>
<tr>
<td>Forced liquid and water cooled</td>
<td>FOW</td>
</tr>
</tbody>
</table>

2.2.5 Impact of oil temperature transformer

The temperature of insulating oil will increase if the transformer load is increases, so loading the transformer above the nameplate rating can cause a risk to transformer life [11]. According to the IEEE standard, temperature rise of the oil near to the top main tank should not exceed 65°C.

These risks include reduced mechanical strength, reduced dielectric integrity due to gassing and permanent deformation of structural component such as core and windings, or possible to damage auxiliary equipment likes taps changers, bushing, or current transformer. If the insulation system follow the IEEE Std C57.100[B52], it will get the acceptable thermal aging performance and at least can be used up to 20.5 years (180 000 h). Standard temperature limits are defined in IEEE Standard – Guide for Loading Mineral Oil-Immersed Power Transformer and list in the Table 2.3.

Table 2.3: IEEE standard temperature rise

<table>
<thead>
<tr>
<th>Standard temperature limits</th>
<th>65°C</th>
<th>Above ambient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average windings temperature rise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot-spot temperature rise</td>
<td>80°C</td>
<td>Above ambient</td>
</tr>
<tr>
<td>Top liquid temperature rise</td>
<td>65°C</td>
<td>Above ambient</td>
</tr>
<tr>
<td>Maximum temperature limit</td>
<td>110°C</td>
<td>Absolute</td>
</tr>
</tbody>
</table>

The insulating transformer’s fluid must meet the same criteria similar to those other high voltage equipment such as circuit breaker and capacitors. The criteria are:

(i) The fluid must conduct heat but not electricity
(ii) Must not be chemical reactive
(iii) Must not be easily ionize that can allow arc.

2.3 Technology Development

Robert M., Del Vecchio and Pierre Feghali members of IEEE have introduced a thermal model of a disk coil in 1999 [12]. The model includes temperature dependent oil viscosity, resistivity, oil density and temperature, velocity dependent heat transfer and friction coefficient. They have divided into three main parts of the calculation in the model; oil pressure and velocities, oil nodal temperatures and path temperatures rises, and disk temperatures. Their result shows that the average winding rises and hot spot temperature which the increases the temperature is also effected by ambient temperature.

In 2009, thermal modeling of electrical utility transformer using finite element has been published by Haritha, T. R. Rao, Amit Jain and M. Ramamoorty [13]. The paper is about simulating the thermal behavior in electrical utility transformer using the principle of thermal electrical analogy and the losses in the transformer. The losses in the core are difficult to accurately compute so that’s why they are using Finite Element Analysis. The thermal model include the calculate values of the losses as heat generating sources and combined with the value of thermal resistance that are from the temperature drops at the various elements.

Another research on thermal design has been done by Zoran R. Radakovic and Marko S. Sorgic in 2010 [14]. They have introduced basics detailed thermal hydraulic model for thermal design of oil power transformer. The paper included method for calculation of temperature inside oil power transformers. So, the transformer design is more detail including its construction, physical parameter of applied material, outer cooling system, and power loss. Besides, temperature at the windings, temperature in each cooling channel, and temperature in the core are also being considered. The detail calculation is important in order to reduce used material such as copper, iron and oil. Table 2.4 list the summary of technology development that done by other researcher.
Table 2.4: Summary of technology development

<table>
<thead>
<tr>
<th>Author</th>
<th>Oil Velocity</th>
<th>Pressure</th>
<th>Flow Rate</th>
<th>Findings</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.J. Oliver [15]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>A. Weinhader [9]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>E.P. Childs [16]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>F. Torriano [4]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Del Vecchio [12]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>J. Zhang [17]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>J. Zhang [18]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>L. W. Pierce [19]</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

2.4 Programming in MATLAB

Matrix Laboratory or known as MATLAB is a high level-programming language and it provides interactive environment with hundreds of built-in functions which is very suitable for technical computation, graphics and animation [20].

Figure 2.8 represent the diagram of the main features and capabilities of MATLAB. Built-in function in MATLAB provide excellent tools for various type of scientific computation such as linear algebra computations, data analysis, signal processing, optimization, quadrature and many more. By the way, there are a lot of functions for 2-D, 3-D graphics and also animation. MATLAB also allow user to write his own function and not limited to the built-in function. Once written these function will behave just like built-in function. That’s why MATLAB language becomes very popular because of its features that is easy to learn and to use.
Programming in MATLAB can be written in M-files where M-files are ordinary ASCII text files written in MATLAB’s language. They called M-files because at the end of their name must have a ‘.m’ such as (modelling.m). M-file can be developed using any editor or word processing applications. There are two main points in M-file; script file and function file.
CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology includes the following concepts as they relate to a particular discipline or field of inquiry: collection of theories, concept or ideas; comparative study of different approached; and critique of the individual methods. Methodology refers to more than a simple set of methods; rather it refers to the rationale and the philosophical assumptions that underlie a particular study. Proper process guidance will help to monitor and troubleshoot any problem occurred in the middle of the process and also to make sure the project is successful.

3.2 Project Methodology

This project begins with collecting information regarding the technical issue in order to develop a thermal model of a disk coil using MATLAB. Figure 3.1 illustrate the flow chart that will be used in modeling thermal model of a disk coil.
Figure 3.1: Flowchart in modeling thermal disk coil
Figure 3.1 shows the main flowchart in modeling the disk coil from collecting the information until writing thesis. From all the steps, it can be summarize into three main phases, see Figure 3.2. Phase I will be done in PS 1 meanwhile Phase II and III planning to be done in PS 2.

Figure 3.2: Summarized flowchart of modeling thermal model
3.3 Methods Approach

3.3.1 Model Description

In a real life, there are a number of sections in a transformer but this model is just considering one section because the calculation in each section is the same. In each section it can contain different number of turns, insulation and thickness. Figure 3.3 illustrated the numbering path, disks and nodes which is in the region between two oil flow washers. This model is actually in cylindrical shape that’s why the inner radius has been indicated ($R_{in}$).

![Diagram](image)

Figure 3.3: Numbering scheme for a disk coil with directed oil flow; disk, node and path.
Cross sectional area, \(A\) and diameter, \(D\) of the various path also must be considered in this model, see Figure 3.4. Usually vertical ducts are the same all over the coil but the sometimes horizontal ducts can be different.

![Figure 3.4: Cross sectional areas and hydraulic diameters.](image)

By the way, there are unknown variable to be considered at each nodes and path including nodal temperature \((T)\), nodal pressure \((P)\), path oil velocity \((v)\), path oil temperature rise \((\Delta T)\) and disk temperature \((T_c)\). A uniform temperature assumed at each disk. Figure 3.5 shows the numbering scheme at all the unknown variables.

![Figure 3.5: Numbering scheme for T, P, v, ΔT and Tc.](image)
The model is depends on the equations that proposed in Thermal model of a disk coil with directed oil flow [21] and the geometrical of the model is in Estimation of transformer winding temperatures and coolant flows using a general network method [15]. Figure 3.6 represent the details of the conductor disk and Table 3.1 list the geometrical details in this model.

![Diagram of conductor disk](image)

Figure 3.6: Details of the conductor disk [15]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil duct length (L)</td>
<td>100mm</td>
</tr>
<tr>
<td>Oil duct depth (d_o)</td>
<td>5mm</td>
</tr>
<tr>
<td>Vertical oil duct width (d_v)</td>
<td>15mm</td>
</tr>
<tr>
<td>Width of conductor + insulation (b)</td>
<td>4.5mm</td>
</tr>
<tr>
<td>Thickness of paper insulation (d_p)</td>
<td>0.6mm</td>
</tr>
<tr>
<td>Width of conductor (b_c)</td>
<td>3.3mm</td>
</tr>
<tr>
<td>Depth of conductor</td>
<td>10mm</td>
</tr>
</tbody>
</table>

The model in this project consists of a number of radiator plates that are spaced equally along inlet ad outlet pipes where the plates contain several parallel vertical ducts. Figure 3.6 represent the details of conductor disk in vertical section. The oil will flow up until it past the winding on one side and reached the washers where the washer is used as a separator from one side to the other and between these two washers there are several cooling ducts which known as a pass.
Cooling also occurs from the tank walls through the surrounding air and radiation. The oil can be pump into the radiators but, this model was designed without pumps and assumed that the oil flow in the radiators and coils to be laminar [4]. This project will consider the whole transformer so; all the heat generated by individual coils and stray losses needs to consider in order to achieve a steady-state condition.

In this disk coil transformer modeling, directed oil flow is considered. There are several disks, nodes, paths and inner radius also indicated in the model that the geometry is cylindrical [4]. There can be many sections as desired, but the model in this project just considers one section which contains the region between two oil flow washers. The number of disk, number turns per disk and insulation thickness of each section is different which we can vary from section to another [6]. The same way goes to duct sizes.

3.3.2 Oil Pressure and Velocities

The oil velocities are uniform because the cross sectional area is assumed to remain constant and the gravitational effect also ignored. So the pressure at the beginning and at the end of path 1 and 2 can be note down such as in Equation 3.1

\[ P_1 - P_2 = \frac{1}{2} \rho f \frac{L}{D} v^2 \]  (3.1)

where;
\( \rho = \text{fluid density} \)
\( f = \text{friction coefficient} \)
\( L = \text{path length} \)
\( D = \text{hydraulic diameter} \)
\( v = \text{fluid velocity} \)

\[ D = 4 \times \text{cross sectional area/wetted perimeter} \]  (3.2)

For laminar flow in circular ducts;
\[ f = \frac{64}{Re_D} \]  

(3.3)

Re_D is a Reynolds number;

\[ Re_D = \frac{\rho v D}{\mu}; \quad \mu = \text{fluid viscosity} \]  

(3.4)

For laminar flow in non-circular ducts / rectangular, friction coefficient have change where rectangular ducts have side a and b. When \( a < b \);

\[ f = \frac{K(a/b)}{Re_D}; \quad K(a/b) = 56.91 + 40.31 \left( e^{\frac{3.5a}{b}} - 0.0302 \right) \]  

(3.5)

So, equation (3.3) and (3.5) can be substituting into equation (3.1):

\[ P_1 - P_2 = \frac{1}{2} \frac{\mu KL}{D^2} v \]  

(3.6)

where;

\[ K = K(a/b) \]

\[ \mu = \frac{6900}{(T+50)^4} \]

Another thing that must be considered in calculating pressure and velocity is the mass through a duct cross sectional area per unit time;

\[ \frac{dM}{dt} = \rho A v \quad ; \quad Q = A v \]  

(3.7)

Q = volume flow per unit

By referring to Figure 3.4 and 3.5, typical inner (smallest radii) node 2i-1 can be obtained;

\[ A_1 v_{3i-2} = A_1 v_{3i+1} + A_{0,i} v_{3i-1} \]  

(3.8)

For a typical outer node, 2i;

\[ A_{0,i} v_{3i-1} + A_2 v_{3i-3} = A_2 v_{3i} \]  

(3.9)

Meanwhile at node 1;

\[ A_1 v_0 = A_1 v_4 + A_{0,i} v_2 \]  

(3.10)

At node 2;
REFERENCES


13. T. R Rao, A. Jain, M. Ramamoorthy Haritha V. V. S. S, "Thermal modeling of
electrical utility transformer using finite element modeling technique and thermal-electrical analogy," 2009.


